Long Jump: the developing technique in young females

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A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy

June 2011

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Dedicated to my father,

Derrick Griffiths (Sept 1927- Dec 2010)

Acknowledgements

Many thanks to Professor A. Lees without whose patience and guidance this would never have been completed.

A huge thank you to my parents. Words cannot really express my gratitude for their support and sacrifice throughout my education, particularly my mother over the last few years.

Thanks to all those family and friends who have been patient, helpful, kind, understanding, supportive......the list goes on.

To all those work colleagues who assisted me in any way, with wise words and empathy.

Finally a huge hug for Teri who has been patient, loyal and above all a great listener

Abstract

Long jump technique has been investigated at both elite female and more substantially, elite male levels. Whilst most studies have investigated mainly kinematic variables, more recent studies have investigated kinetic variables associated with long jumping, some using three dimensional analysis. However little has been done to establish how technique develops in young, female long jumpers which may be of use in identifying the key performance characteristics of elite performers. To enable this, this study focused on young females aged 11-16 yrs (n=40, 4 groups of 10), dividing the subjects by both age and ability to produce four groups, two good (old and young) and two poor (old and young). In addition, a young and old (both good) jumper were observed in two consecutive years. Three dimensional kinematic and kinetic data were collected from touch-down to take-off, using eight 240 Hz Qualysis cameras and this was processed using Visual 3D software to obtain a range of kinematic and kinetic variables. The main findings supported previous research which found that faster run-up speeds generate larger jump distances. In addition the better jumpers were able to produce larger vertical velocities at take-off with less loss of horizontal velocity, and older jumpers show improved strength related 'pivot' like characteristics. It was difficult to identify characteristics in the young jumpers but it was concluded that work at the ankle joint increased with ability. Also, practice reflecting the technique, particularly with the leg at extended angles, to develop eccentric and concentric leg strength, may be useful to assist the continuous development of knee angular velocity after maximum knee flexion.

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List of Abbreviations

OG	Old good group
OP	Old poor group
YG	Young good group
YP	Young poor group
YG_{case}	Young good case subject
OG_{case}	Old good case subject
TD	Touch-down
MKF	Maximum knee flexion
TO	Take-off
TD-MKF	Touch-down to maximum knee flexion
MKF-TO	Maximum Kknee flexion –take-off
TD-TO	Touch-down to take-off
eCM	Estimated centre of mass
CM	Centre of mass
GRF	Ground reaction force
V_H	Horizontal velocity
V_V	Vertical velocity
$Foot_{TD}$	Foot segment angle at touch-down
$Shank_{TD}$	Shank segment angle at touch-down
$Thigh_{TD}$	Thigh segment angle at touch-down
$Foot_{MKF}$	Foot segment angle at maximum knee flexion
$Shank_{MKF}$	Shank segment angle at maximum knee flexion
$Thigh_{MKF}$	Thigh segment angle at maximum knee flexion
$Foot_{TO}$	Foot segment angle at take-off
$Shank_{TO}$	Shank segment angle at take-off
$Thigh_{TO}$	Thigh segment angle at take-off
$A_{(PelvLab)}$	Pelvis angle relative to the Lab (sagittal plane)
$A_{(ThighLab)}$	Thigh angle relative to the Lab (sagittal plane)
$A_{(ShankLab}$	Shank angle relative to the Lab (sagittal plane)
$A_{(FootLab)}$	Foot angle relative to the Lab (sagittal plane)
$A_{(TD)}$	Angle of leg at touch-down (sagittal plane)
gen	Generate
abs	Absorb
Peak flex	Peak flexion
Peak ext	Peak extension

In legends,

X	YZ
Y	XZ
Z	XY
sag	sagittal plane
front	frontal plane
trans	transverse plane
BSP	Body Segment Parameters

1.0 Introduction

Long Jump technique has been investigated by many researchers over the past few decades. In these investigations the long jump is generally broken down into several phases, i.e. run-up, preparation for touchdown, contact and flight (Hay,1993a). These phases last for varying amounts of time and have been investigated separately, and in some instances interactions between phases have attracted attention. Much of the research investigating the long jump has been based on identifying the technique adopted by elite athletes in order to develop their large jump distances (Hay, Miller and Canterna, 1986; Ridka-Drdacka, 1986; Hay and Nohara,1990; Lees, Fowler and Derby,1993; Graham-Smith and Lees, 2005). These studies have shown that athletes lowered their centre of mass (CM) and increased their horizontal velocity in order to improve distance jumped. The speed of approach has been identified as the major influencing factor on the distance jumped (Hay, 1993b). A more detailed understanding of jumping technique has been gained by modelling the jumper taking muscle physiology as well as physical structure into account (Alexander, 1992). This approach also identified that both run-up speed and the leg angle at touch-down was important to performance. The model gave values close to those used by elite athletes. The lowering of the CM enables the touch-down leg to be placed on the ground with a greater leg angle which in turn provides means to generate vertical velocity. As the approach in the long jump is based mainly on a fast run-up giving a high horizontal velocity, there has to be some vertical velocity generation in order to propel the CM of the jumper as far as possible following the principles of projectile motion. The difficulty faced by all long jump athletes is the generation of this vertical velocity during the contact phase without an undue loss of horizontal velocity. In order to do this an effective touch-down technique is required.

Lees, Graham-Smith and Fowler (1994) described a pivot mechanism operating during the initial part of the contact period of elite athletes in which the lowered CM pivots around the touch-down foot to create vertical velocity. The effect is more pronounced the greater the leg angle and the stiffer the TD leg. They identified this as the single most important mechanism acting creating over 65% of vertical velocity at take-off. When investigating this pivot, the contact phase of jumping was divided into two phases, compression and extension, which were defined by the three key moments of touch-down (TD), maximum knee flexion (MKF) and take-off (TO). They outlined that the leg angle created by a placement of the leg in front of the CM enables the downward vertical velocity to be minimised and increases the vertical distance over which the CM can be moved enabling vertical velocity to be generated. Additionally, the increased leg angle enables an increased time for vertical impulse generation, places the leg in a position to enable it to be stretched and store elastic energy and allows more work to be absorbed at the joints. The pivot develops vertical velocity by utilisation of horizontal velocity, appropriate body and leg position and eccentric leg strength (Lees et al., 1994). Following the findings of Lees and Graham-Smith (1996), Seyfarth, Blikhan and Van Leeuen (2000) adapted the previous model of Alexander (1990) and found that high leg stiffness strategies using varying leg angles at touch-down are possible to achieve distances close to the theoretical maximum. Thus, the ability to generate leg stiffness seems to influence the strategy and can be 'offset' by changing the touch-down leg angle. The previous factors highlight the complexity of the long jump, the inter-relationship of factors during the contact phase and the possibility of differing strategies.

The pivot has been identified as the main technique utilised by jumpers to gain vertical velocity within a jump (Lees et al.,1994). However this is rarely, if at all, taught to young athletes and would seem to be acquired through practice. Investigations into the long jump have primarily been focussed around elite athlete characteristics and development, so it has not been established whether this action develops in all jumpers or just skilled jumpers. In particular, there has been little investigation into the development of long jump in the years around maturation, when children are initially introduced and given the opportunity to develop their ability of the activity. Griffiths (2000) investigated young females (11-15 yrs) using a two dimensional analysis but there are generally limited data on young female and male jumpers and therefore limited knowledge about the development of the pivot and related performance variables of i) run-up speed, ii) low centre of mass and, iii) leg angle at touch-down. Both Berg and Greer (1995), and Glize and Laurent (1997) have investigated jumping in male students (16-22 yrs) reporting a limited amount of kinematic data, however little research has been carried out on school age females, particularly into the kinematics of TD, MKF and TO. Stephanshyn and Nigg (1998) and Muraki, Ae, Koyama and Yokozawa (2008) extended their work into kinetic analysis, by investigating work and power in the running long jump of male long jumpers. At this point in time there is no research into the kinetics of young female long jumpers.

During puberty there is a difference in the adaptations of males and females. Whilst males show a neuromuscular spurt which is defined as increased power, strength and co-ordination, similar supporting correlations are not observed in girls (Quatman, Ford, Myer and Hewett, (2006). Hewett, Ford and Myer (1999) point out that in female athletes a lack of neuromuscular adaptation alongside increased lever size and mass may lead to inappropriate force attenuation strategies and may limit force production capabilities in dynamic tasks. This maturational variable could have notable effect on long jumping. Thus, it is not known what effect age (maturational and chronological) has on this development as it affects the speed, strength and motor ability of young adolescents, a factor which is particularly unpredictable in females.

There are several other factors that may influence performance, particularly at a young age such as practice, genetics and experience. As Marshall and Bouffard (1997, cited in Haga, 2008) point out, the more time spent practicing motor skills, the more opportunity there is for improved performance. Additionally, Haga (2008) stated participation in a range of physical activity will give rise to learning new and improving previously learned motor skills (quantitative and qualitative changes in motor development). Developing this idea, Rousanoglou, Georgiadis and Boudolos (2008) point out that participation in jumping activities may result in different adaptations to the pattern of muscular function. When considering young and older athletes, Vescovi and

McGuigan (2008) suggested that there is a potential effect of age or experience when examining the relationship between counter movement jump (CMJ) and sprinting, implying improved jumping with age. In addition, girls' peak power reaches a plateau around 16 yrs and is therefore increasing through puberty (Martin, Dore, Twisk, van Praagh, Hautier and Bedu, 2004). Thus, the amount of practice, type of activities performed and specific adaptations following these could all influence performance. All of these may have an impact on ability, but Holmes (1999) noted that 'some elite junior high jumpers come to the World stage without any real training behind them'. This implies that although there are many factors that may influence performance some individuals produce elite performance with very limited activity specific training implying a 'natural ability'. The nature of this natural ability has never been explored for long jump athletes.

As maturation affects young female development it will also influence their ability to perform the long jump as both the relevant factors of speed and strength may be affected. However, the influence of maturation on jumping performance of females is unclear. It would be beneficial and informative, for both coaching and teaching practice to examine how long jump technique develops, and differs with both ability and maturation. In order to answer this, an analysis of the long jump (in particular the variables surrounding the pivot theory) performed by young females of differing abilities and ages would be required.

1.1 Aims and Objectives

The aim of the study is to identify the characteristics of performance in young and developing females of varying ability performing the long jump. This aim will be achieved by the following objectives.

1) To develop methods in order to obtain relevant kinematic and kinetic data.

2) To obtain kinematic and kinetic data of younger females with a range of abilities performing the long jump.

3) To obtain kinematic and kinetic data of older females with a range of abilities performing the long jump.

4) To investigate longitudinally, by way of case studies, changes in kinematic and kinetic characteristics of performance of one younger and one older female long jumper.

2.0 Literature Review

This section provides an overview of jumping, a review of the basic mechanics of the long jump and an overview of the findings related to technique in long jumping. In addition it also explores the effects of maturity and development on jumping performance in young girls. Following this, factors influencing 3D data collection, including marker sets and body segment parameters, are reviewed.

2.1 General overview of the long jump

2.1.1 General overview of long jumping

Evans (1984) describes the long jump simply as a 'sprint with a high jump at the end'. At a basic level it is indeed an event which needs a quick run followed by a long and high jump. This is the teacher's view of the long jump within schools and reflects the general approach to teaching the event. The two main factors involved in the development of distance are therefore the run-up speed and leg power for take-off. Generally, the long jump can be broken down into four main phases which have differing degrees of influence on its performance (Larkin, 1989; Hay,1993a). These phases include, i) approach, ii) preparation and execution for take-off, iii) take-off and iv) flight. The approach needs to be accurate and consistent to ensure a good take-off. The distance of this approach differs between individuals and is dependent also on the performer's age. Johnson's (2004) 'rule of thumb guide' indicates that one running stride to one year of a childs' age should be adopted for the run-up. Johnson led the British Athletic Federation Coach Education programme from 1980 to 1997, coaching athletes to Olympic and World champion status and is generally seen as an innovative, experienced coach of the long jump. However where youngsters are physiologically more mature than their chronological age, adjustments (i.e. an increase to the number of strides in the run-up) need to be made. Assuming the run-up (phase 1) is 'good' the final steps (phase 2) can be described as a 'coast' or 'gather' readying the body for take-off (Rodda, 1978). At this point Rodda (1978) notes that the hips sink and the CM is lowered as novice jumpers are advised to maintain speed and relax over the final three to four strides of the approach. Bowerman and Freeman (1991) and Johnson (1990) agree that the last stride is shorter and quicker than the other approach strides, so essentially the jumper 'runs off the board'. Touch-down velocity and body position at take-off influence the variables which relate to the execution of take-off (Pfaff, 1989). This involves a longer penultimate stride combined with a more erect torso, lowered CM and placement of the touch-down leg in the appropriate position. Pfaff (1989) concluded that this change in body position is less obvious in faster jumpers as this has greater detriment to their performance. The appropriate foot placement is a balance between a 'braking' action and one that produces forward rotation. During the last two strides of the approach the athlete makes a series of adjustments in body position to prepare for take-off (phase 3). The take-off phase itself is one of the most difficult phases of the long jump as athletes have to execute a series of complicated movements in a fraction of a second. Identifying the strategies important for vertical velocity generation is difficult as a variety of actions occur in a very short period of time. At take-off, the athlete concentrates on driving upwards with a full extension of the leg on the board, a high, free leg knee lift and an exaggerated pumping action of the arms, which raises the arms, shoulders and chest. Jarver (1981) stated the main points for take-off are:

1) A faster take-off stride, concentrating on explosive placement of the foot.

2) Heel touches the board shortly before the foot rolls forward at take-off. A gripping of the board should be complemented by kicking it backward.

3) Energetic stretching of the ankle, knee, hip joints, whilst the lead leg is brought up with thigh horizontal to the foot.

4) Trunk is upright and eyes are forward.

5) Arms assist the take-off through alternate swings.

Bosen (1971), Paish (1976), Pfaff (1989) and Lohmann (1990) stress different movements at this time but they agree on a high knee lift and use of the arms to assist lift. There is some disagreement between Paish (1976), who suggests knee bend should be avoided and Lohmann (1990) who advocates flexing the knee. The flight (phase 4) phase and jump distance are dictated by the take-off velocity, angle of take-off and height of the CM which are dictated by actions within the contact part of the jump and the initial preparation for that contact. Body position at take-off also has influence on the outcome. At the moment of leaving the board (ground) the trajectory of CM flight is set and movements in the air serve to maintain balance and prepare for landing (Pfaff, 1989).

The sum total of these events is to produce an efficient 'jump' for length. However, whilst the previous statements outline a complicated set of actions occurring over a short time period basic coaching and teaching often uses phrases such as ' run strong to the board', 'body upright at take-off', 'extend take-off leg', 'sink at the board', 'extend take-off foot', head upright'.

2.1.2 Basic characteristics of the long jump technique

Jump distances for elite male athletes have been found to be over 7 m (Hay,1993b ; Lees et al., 1994 and Graham-Smith and Lees, 2005) whilst Berg and Greer (1995) and Laurent and Glize reported mean values of 5.5 - 5.62 m for unskilled male jumpers. Griffiths (2000) reported mean jump distances of 3.94 m for skilled young female jumpers and Lees et al. (1993) investigating female student athletes found values of 6.51 m. It seems (not unsurprisingly) that elite males jump furthest and 'skilled' young females jump considerably less, at least some of which is likely to be explained by lower run-up speeds.

The actual jump distance differs from the official distance by the toe-to-board distance (Hay et al.,1986). The jump distance can also be broken down into separate distances (take-off, flight and touch-down distances) the sum of which is the actual jump distance. Hay et al. (1986) found that the flight distance contributes 90% of this total whilst take-off distance and landing distance contributed 5.1% and 4.9% to the overall distance jumped, respectively. This highlights the importance of the phase responsible for the transition from horizontal velocity to vertical velocity, as it is this that provides the basis for the important flight phase. Hay et al., (1986) broke the flight distance down by categorising the variables that would influence this distance (see Fig 2.1 overleaf).

In building run-up speed, approach length is important but this differs according to age and experience (Johnson, 2004) and in turn influences the accuracy of the approach. Generalising, Glize and Laurent (1997) stated unskilled jumpers normally use 14 strides.

Figure 2.1 Factors that determine flight distance (Hay and Reid,1988).

The importance of horizontal and vertical velocity, and therefore run-up speed in developing large flight distances are clear from Fig 2.1 above.

The accuracy of the approach is generally viewed as the toe-to-board distance for the take-off stride and for both elite and novice males, Hay (1988) and Berg and Greer (1995) found the average error to be 11 cm. However Scott, Li and Davids (1997) found that for non-long jumpers this error was 25 cm. As elite jumpers have a reduced toe-to-board distance they improve their official distance. Hay et al. (1986) point out the faster the approach speed the greater the jump distance but run-up speeds vary dependent on gender, ability and age. Hay et al. (1986) quoted mean touch-down velocities of above 10 m/s for elite males; Berg and Greer (1995), 8.14 m/s for novice jumpers; Bedi (1975 cited in Adrian and Cooper,1995), 8.1 m/s for medium skilled performers whilst Glize and Laurent (1997) quoted mean velocities of 6.7 m/s in unskilled jumpers. Generally, faster runners should jump further but this is a very simple statement which fails to embrace some of the complexities occurring at touch-down when large forces are generated. It should also be noted that although speed of approach has been highlighted as a very important feature, comparison between studies is difficult due to the fact that although the term 'novice' has been used in several studies the standard of jumpers investigated seems to vary and so any comparison must acknowledge these differences.

Viewing the model relative height at take-off is also an important factor and influenced by touch-down leg angles. The touch-down angles of the lead leg relative to the horizontal have been found by Hay (1986) to be 64 - 69 $^{\circ}$ whilst Lees et al., (1993) reported angles in the range of 60.5 - 66.1° and Bridgett and Linthorpe (2006) found angles of 61.0 ± 3.0°.The placement of the foot in front of the body creates a resultant reaction force that causes a braking action and a loss of horizontal velocity. Alongside this is a greater horizontal distance between the body CM and the foot at touch-down. This has been quantified by Hay et al. (1986) as 0.5 m, by Lees et al. (1994) as 0.45 m and by Lees et al. (1993) as 0.44 m. The overall effect of this is a lowered CM at the time of foot placement which begins the contact period and a raising of the CM height at take-off which, following the principles of projectile flight, should increase flight distance. Strong correlations between the horizontal velocity of the athletes' centre of mass at the instant of touchdown and the jump distance have consistently been reported with correlation coefficients in the order of 0.7 (Hay, 1993b). However, as the level of performance increases, the strength of correlation decreases when the sample of athletes are of similar ability (Lees and Graham-Smith, 1996). This could be interpreted as good technique becoming more important than running speed as the strength and overall fitness of an athlete increases (Hay, 1993b). At elite level Lees and Graham-Smith (1994) outlined that there is a balance between speed and strength domination within a jump and knowing this can assist in the development of an athlete. This was further demonstrated by Linthorne, Guzman and Bridgett (2005) when investigating take-off angles at differing run-up speeds. They found that the ability to produce higher take-off angles was dependent on reduced speed and a shorter run-up.

At touch-down, Lees et al. (1994) found that the mean CM vertical velocity to be - 0.15 m/s indicating that elite jumpers have a small negative CM velocity at this time. After this point in time, the need to develop vertical velocity becomes important. Hay et al. (1987) quantified an increase in vertical velocity on average 2.5 times the loss in horizontal velocity that is supported by Nixdorf and Bruggerman (1990) and Koh and Hay (1990) who reported that the loss in horizontal velocity is associated with high gains in vertical velocity. Relating to this Koh and Hay (1990) reported a significant correlation of -0.59 when considering the distance between the foot placement and CM at touch-down, and the loss in horizontal velocity. In addition Bosco et al. (1975), found that the first part of contact time correlated negatively (-0.87) with the horizontal velocity and correlated positively (0.90) with the horizontal velocity during the second half of contact time implying that increased contact time during compression increases horizontal velocity loss.

Bosco et al. (1975) found that 60% of the total vertical velocity gained was in the first period of contact. Lees et al. (1993) supported this, quantifying it as 65%. The majority of vertical velocity is generated during the compression phase while some vertical velocity was developed in the extension phase by a concentric muscle extension of the support leg, (i.e., a jump) and the vigorous use of the arms and legs to provide lift. Lees and Graham-Smith (1996) quantified these contributions as jump (leg extension) = 20% and lift (arm elevation) = 15%. Whilst Stewart (1981) quantified the arms providing 12.5% of the total vertical force, 61% being provided by the legs and the remaining 26.5% generated from the trunk, due to its elevation during the take-off phase. Although the majority of vertical velocity increase occurs before MKF both leg extension and arm elevation contribute to the remaining increase after MKF.

Lees et al. (1994) indicated that better performers were able to increase the height of their CM immediately after the first touch on the platform, but in a poorer jump the CM remained at about the same height during the early contact phase (see Fig 2.2). Interestingly, by MKF there was an increase in vertical velocity gain even though studies have shown that knee flexion occurs between

TD-MKF (Graham-Smith and Lees, 2005; Lees et al., 1994; Lees et al., 1993). The same studies reported knee angles at touch-down ranging between 160.1° -166.7° (indicating a straightened leg) to 138.5 ° -144.1 ° at MKF, leading to changes of angle ranging from 21.6 ° - 26.5 °.

Figure 2.2 CM height during the last stride and take-off of elite long jumpers (Lees et al.,1994). TOLS=touch-down last stride, TD= touch-down, MKF= maximum knee flexion, TO= take-off.

At take-off, the jumpers will have lost horizontal velocity and gained vertical velocity (see Fig 2.3). Hay et al. (1986) found horizontal velocity losses of 1.1 - 2.1 m/s, Lees et al., (1994) found mean losses of 1.12 m/s and Graham Smith and Lees (2005) quoted losses of 1.38 m/s. Correspondingly they found vertical velocity gains of 3.4 - 4.3 m/s, 3.16 m/s and 3.55 m/s. The horizontal and vertical velocities dictate the angle of take-off indicating that long jumpers need to influence these factors in order to further their jump distance. Hay et al. (1986) quoted angles of between 18.7 ° - 22.8 °. In addition, Lees et al. (1993) cited data from major championships which showed angles of 18.8 ° - 22.°, whilst Hay and Nohora (1990) and Linthorne et al. (2005) found elite jumpers have optimum TO angles of between 20 - 25 $^{\circ}$ .It would seem that the smaller (below ideal for a projectile) take-off angles are due to an inability to generate vertical velocity.The generation of 'good' take-off characteristics outlined within the Hay et al.(1986) model above, becomes crucial as is timing of generation of some key factors.

Figure 2.3. Horizontal and vertical velocity during the long jump (Lees et al.,1994)

The importance of the technique and timing from touch-down to take-off was highlighted by Lees et al. (1994) who indentified three key moments of touch-down (TD), maximum knee flexion (MKF) and take-off (TO) and the two phases of compression and extension (Fig 2.4). They used these key moments to identify the nature of vertical velocity generation within a jump.

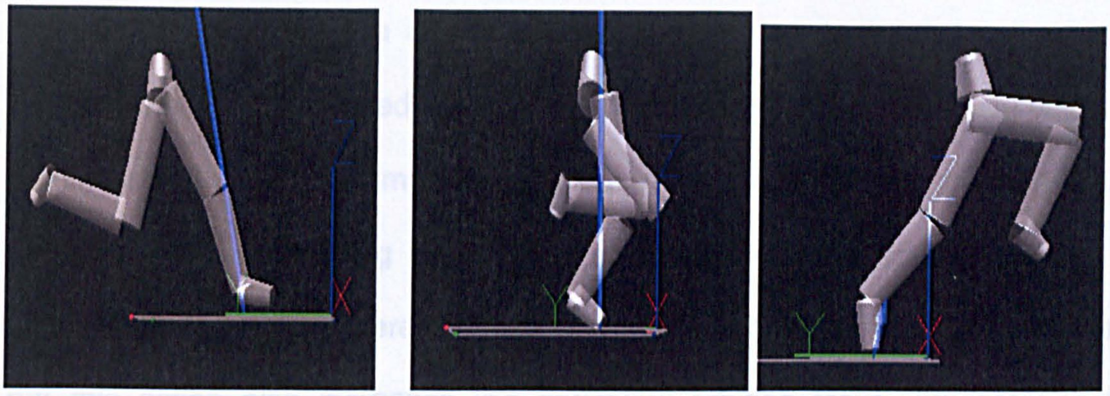


Figure 2.4 Key moments during contact in the long jump.

They suggested the term ‘pivot’ as important in the development of an effective technique, particularly in relation to the timing of vertical velocity generation. Lees et al. (1994) concluded that ability to develop vertical velocity (particularly TD-MKF) with limited loss of horizontal velocity is clearly important (see Fig 2.3) and, reflecting the empirical findings outlined previously, is aided by an increased approach velocity and foot placement well in front of the body at touch-down.

Clearly at high speeds this foot placement increases the braking force and would require strength, so whilst simplistically jumping success is mainly related to the athlete's ability to develop a large flight distance, generating the vertical velocity required over a short period of time is complex and reliant on several factors.

Summary

At touch-down there is a continuing reduction in the horizontal velocity as vertical velocity is increased. It would seem that the majority of vertical velocity is generated during the compression phase but at the expense of the horizontal velocity lost. In extending the leg, to increase the touch-down distance, a jumper lowers the CM, therefore providing a longer time for force to be applied but this action also increases the horizontal braking force. An increase in approach speed is likely to increase the resulting horizontal velocity at take-off but it reduces contact time and therefore the time for vertical velocity generation. Athletes are not able to take-off at an effective projection angle, in line with the laws of projectile motion, but produce much smaller angles at take-off reflecting their inability to generate vertical velocity. Good jumping is therefore a balance between horizontal velocity loss and vertical velocity gain, and elite technique relies on a straight leg, lowered CM and high run-up speeds to achieve large jump distances. This elite technique is based on a continuous raising of the CM height and vertical velocity after touch-down by way of a 'pivot' action. The nature of the balance that is required to facilitate this and the variables which may influence it, has led to the development of models from which jump performance may be predicted and technique critiqued.

2.2 Models of long jumping

The description of basic long jump technique has identified that there are several factors influencing the achievement of maximum jump distance. The interactions between these factors that are influential at touch-down may assist in the understanding of how jump distance can be optimised. This has been attempted by several researchers using models of performance and the key models are outlined below.

2.2.1 The pivot

The pivot is a conceptual model based on generalised empirical findings following research into elite performers. The outstretched leg at touch-down acts as a point over which the body rotates and creates vertical velocity. The term 'pivot' has been suggested (Lees et al., 1994) as during the compression phase the CM pivots over the foot generating vertical velocity. This vertical velocity increase occurs with a consistent loss of horizontal velocity (Hay, 1986; Koh and Hay, 1990; Graham-Smith and Lees, 2005) (see fig 2.3). This pivot mechanism is highlighted during the compression phase with the knee undergoing flexion whilst the CM height increases. It is enhanced by an increase in velocity and TD leg angle. Lees et al. (1994) also emphasised the necessity for eccentric muscular leg strength for resisting leg flexion so as to enhance the mechanical pivot mechanism during the compression phase. That is to say, large knee flexion during the compression phase is an inhibiting factor for the pivot. Lees et al. (1993) concluded that the essential feature of long jumping at touch-down is the placement of the leg well in front of the body at touch-down and an ability to prevent it from undergoing too much flexion, which may cause collapse of the leg or be detrimental to its extension. A fast run-up and lowered centre of mass help to determine the initial conditions. If the leg is placed well in front of the body, the centre of mass can ride up over the base to create substantial vertical velocity by the time maximum knee flexion is reached.

Further investigation of the pivot and surrounding variables by Graham-Smith and Lees (2005) identified that work in the frontal plane, at the hip particularly, may also influence the horizontal velocity loss and be important to technique development.

The pivot allows a relatively easy observation of simple but key variables exhibited by long jumpers. In doing this it allows the identification of jumpers who are able to use the pivot. From this, observers can identify whether i) the correct approach conditions were used and, ii) if a jumper is able to utilise them to continually increase CM height and vertical velocity.

2.2.2 Alexander's model

This is a 2 segment model, which takes into account the mechanical properties of muscle and predicts optimum take-off techniques that agree well with those observed in athletes (Alexander,1990). The rationale of the model is to identify key biomechanical variables that optimise performance, for both high and long jumping. This model consisted of two massless rigid segments of length *a*, which form the leg, and one point mass representing the body. The point mass being located at the proximal end of the proximal rigid segment, and the foot being a point at the distal end of the distal leg segment. One single torque generator at the knee was used to represent the contributions at the ankle, knee and hip together.

Figure 2.3 Diagram of Alexander's Model (Alexander, 1992)

As athletes differ in stature, and in order to make calculations as applicable as possible, dimensionless quantities were used. In design and evaluation of the model, Alexander (1990) stated 'the subtleties are ignored in this paper, which is concerned only to find the take-off technique that optimises performance'. Alexander confirms that the model is grossly simplified having no foot segment or foot compliance. This would estimate both unrealistic impact forces at touch-down and unrealistic ground contact duration. The findings from the model were that a long jumper should run up as fast as possible (relative to ability) whilst setting down the leg at an angle of 60-65° to the horizontal. This is because higher velocity produces a large horizontal component and a greater angle increases the duration of foot contact and vertical impulse. The 'negative' horizontal force component this creates causes the muscles to contract eccentrically explaining the net negative work that is done during take-off. As Alexander (1990) points out, an athlete must exert a downward impulse on the ground in order to obtain an upward momentum required for a jump. Crucially, the impulse (force integrated over time) depends on the duration of foot contact. A 'relatively' shallow leg angle lowers the CM of the body and increases the duration of foot contact and the vertical impulse. It would seem that these two variables are the main components in a complex and compensatory interaction designed to generate vertical velocity. This simple model had two input technique variables, run-up velocity and leg angle at touch-down giving rise to output values for TO angle, duration of contact, jump distance and ground reaction force. The model reflects the previously discussed values of a leg angle at touch-down of 60-65°, a take-off angle of 22° and a jump distance of at least 7.5 m. Alexander (1990) pointed out that reduced foot contact time of .064 s was probably due to the lack of a foot segment within the simplified model. However, taking the overall simplification of the model into account, when comparing the values of angles, distances and forces obtained from the model and those from the findings listed previously, the values generally agree, or are within acceptable limits.

2.2.3 Spring-Mass model

The model described by Seyfarth, Friedrichs, Wank and Blickhan (1999) is a spring-mass model, enabling it to model the dynamics of the CM during the take-off phase of the jump. The design (fig 2.4) includes a distal mass coupled with nonlinear visco-elastic elements (simulating soft tissue) and a linear leg spring (simulating the leg) with the ability to lengthen. The rationale for the model is that modelling the leg as a spring is suitable for describing the landing if the body mass, initial conditions and leg stiffness are known. However, the impact at touch-down influences the system dynamics and accounts for approximately 25% of the total momentum, and therefore cannot be neglected. To account for the passive peak force production, a mass was coupled to the rigid frame of the spring leg. This represented the rigid skeleton, during touch-down and the relative movement of the soft tissue with respect to the rigid frame. The model used a minimal set of parameters that included the experimentally comparable values of leg stiffness, leg lengthening constant, initial velocity of swing mass, initial direction of velocity (downwards) and a non-comparable spring damper constant.

Figure 2.4 The planar model for the long jump (Seyfarth et al.,1999)

Both the stiffness and leg lengthening used in this model were similar to values found in running. The model highlighted that at high stiffness values different strategies with varying angles of attack are possible to achieve distances close to (95% of) the theoretical maximum. The ability to generate this stiffness seems to dictate the strategy and can be 'offset' by changing the leg angle at touchdown (Seyfarth et al., 1999). They argued that the leg lengthening at take-off is an active process that increases the distance of the acceleration phase and compensates for the losses in the initial stages (compression) of the take-off. In addition they point out that jumpers take advantage of, and actively increase the passive peak, particularly in the vertical plane because this increases vertical momentum required for long jumping. Seyfarth et al. (1999) suggested that the velocity vector at TO was restricted by the muscle properties and the ability to generate this stiffness seems to dictate the strategy and can be 'offset' by changing the leg angle. Seyfarth et al. (1999) suggested that 'problems occur at higher knee flexion due to the increasing demand of muscle force and the properties of connecting tissues'. In explanation, a higher take-off angle is accompanied by a smaller take-off velocity, and thus a shorter jumping distance. They concluded that there is an optimum jump distance for a given leg angle and leg stiffness.

The main finding from this model was that as leg stiffness increases, touch-down leg angle changes become more important, and additionally leg angle is less dependent on approach speed. Therefore strategies used by athletes may differ, according to the touch-down leg angle (angle of attack), yet similar jump distances will be achieved.

Figure 2.5 The relationship between jump distance (contours), leg stiffness and touch-down angle (Seyfarth et al.,1999).

Interestingly, athletes are able to achieve distances that come close to the theoretical maximum suggesting, several techniques generate the same jump distance and are related to the ability to generate leg stiffness. Figure 2.5 above shows that the proper strategy for an athlete depends on the ability to generate leg stiffness. This can be compensated for by changing the touch-down leg angle, highlighting that different strategy can achieve the same jump distance.

2.2.4 Seyfarth et al.'s two segment model

Seyfarth, Blickhan and van Leeuwen (2000) modified the Alexander model (1990) and used a more detailed representation of the musculo-tendon unit (Fig 2.6). The extensor muscle had eccentric force enhancement with nonlinear serial and parallel elastic components. The rationale for the model design was to more realistically represent tendon and muscle properties so as to demonstrate the advantages of eccentric force enhancement and tendon properties in force generation.

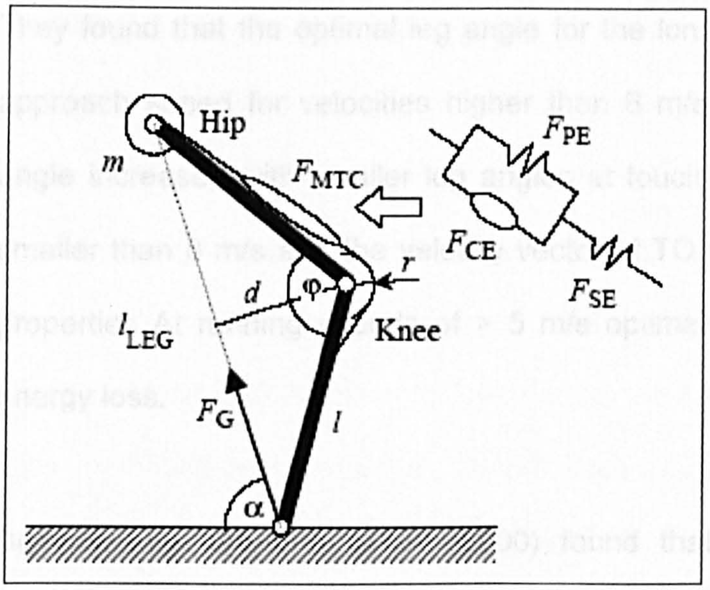


Figure 2.6 Schematic drawing showing the planar spring-mass model

Seyfarth et al. (2000) reported that a more extended knee angle at touch-down leads to a larger jump distance, a higher take-off angle and a reduction in the fraction of mechanical energy that is lost at take-off.

Figure 2.7 Relationship between leg angle, approach speed and jump distance (Seyfarth et al., 2000).

They found that the optimal leg angle for the long jump was insensitive to the approach speed for velocities higher than 6 m/s (Fig 2.7). Also, the take-off angle increased with smaller leg angles at touch-down if run-up speeds were smaller than 8 m/s and the velocity vector at TO was restricted by the muscle properties At running speeds of > 5 m/s optimal performance required a net energy loss.

Summarizing, Seyfarth et al. (2000) found that jumping performance was insensitive to changes in muscle speed and tendon compliance, but was greatly influenced by eccentric force enhancement and muscle strength. Of relevance to less able jumpers were the findings that high approach speeds (> 6 m/s) and optimal leg angle (approx. 65-70°) were insensitive to approach speeds. Seyfarth et al. (2000) found that at run-up speeds less than 8 m/s if the touch-down leg angle relative to the horizontal decreased (i.e. CM was lowered) the take-off angle increased. However at speeds above 8 m/s the take-off angle was insensitive to the angle of attack.

2.2.5 Wobbling mass models

Crucially the spring-damper-mass models (e.g. Seyfarth et al., 1999) do not account for non-rigid masses and may be justified to study only slow quasi-static movements and low impact situations (Liu and Nigg, 2000). The long jump however is a high impact activity with a shock landing and subsequent spring-like elastic operation of the leg (Seyfarth et al., 2000). Gruber, Ruder, Denoth and Schneider (1998) concluded that during the impact phase the analysis with rigid body models yield completely incorrect internal torques and forces whilst kinematics are only slightly altered. Nigg and Liu (1999) when modelling impact force peaks in running (having a rigid and wobbling mass for upper and lower body) found that changes in damping had a greater influence on the impact force than the changes in stiffness of a system. Nigg and Liu (1999) found that at higher impact forces the lower rigid mass decelerates more slowly therefore there is less interaction with the upper rigid body and lower wobbling mass reducing impact force peaks. Therefore, extending this work from running to jumping may indicate that manipulation of leg angle, leg stiffness and the wobbling mass could help to influence the impact force and initial jump conditions. As leg angle and stiffness may have an effect on the stretch-shortening use of muscles within jumping, modelling a wobbling mass may perhaps influence touch-down conditions. Lindstedt, Reich, Keim and LaStayo (2002) summarise that eccentric contractions are important in storing elastic energy which when recovered result in enhanced force, work and power supporting the concept that the ability of muscle to store elastic strain energy is important within a running long jumping.

Summary

The models of the long jump highlight the influence and interaction of different mechanical variables. The run-up speed, leg angle and leg stiffness are all important, particularly as their interaction can dictate different strategies in developing the long jump technique. In effect this makes analysis, observation and feedback more complex as it points to physiological differences also influencing technique. When comparing elite athletes or athletes at similar stages in development this becomes slightly simpler as maturation and physical development may have been achieved or be near its completion. However, when investigating technique development at younger ages the physiological effect of growth and maturation may have a major influence on the technique adopted particularly when leg strength and eccentric muscle strength are needed. In young jumpers, the ability to generate the same jump distance with varying strategies may influence the technique they adopt, due to their stage of development and its impact on their physiological attributes. The findings of Seyfarth et al. (2000) clearly highlight that there are differences between 'poor' and 'elite' jumpers which may be relevant to maturation and age.

2.3 Further findings

Following on from the model developments and the identification of key variables, some detailed examination of these interactions has taken place. Strong correlations between the horizontal velocity of the athletes' CM at the instant of touch-down and the jump distance have consistently been reported with correlation coefficients in the order of 0.7 (Hay, 1993b). However, as the level of performance increases, the strength of correlation decreases when the sample of athletes are of similar ability (Lees and Graham-Smith, 1996). This was further demonstrated by Linthorne et al. (2005) when investigating take-off angles at differing run-up speeds.

During the contact phase, knee angle changes generate an initial eccentric contraction of the knee extensors occurs which is then followed by concentric contraction to extend the knee angle and increase vertical velocity. Lees, Fowler and Derby, (1993) and Lees et al. (1994) concluded that this foot placement enables the take-off leg to store elastic energy through stretch reflex loading which then contributes to the change in vertical velocity through muscle shortening (concentric action) a moment later. Supporting this Hay, Thorson and Kippenhan (1999) concluded that the evidence suggested it was fast eccentric actions earlier in the take-off that enabled the muscles to exert large forces, and thus, generate large gains in vertical velocity. Also Seyfarth et al. (2000) stated that during the take-off phase the highly stretched leg extensor muscles are able to generate vertical momentum. At this point the increase in vertical velocity is exchanged for a decrease in horizontal velocity.

In addition to the importance of foot placement, limiting knee flexion has been highlighted as crucial to good performance. Muraki, Michiyoshi, Toshiharu and Suzuki (2001) found that in the TD leg angular velocity of the thigh related significantly to knee flexion arguing that less knee flexion of the support leg at touch-down would stiffen the support leg, suggesting that jumpers should swing the thigh backward before touch-down (a preparation strategy) therefore extending the hip and avoiding excessive knee flexion. This was further supported by the investigations of Muraki, Ae, Yokozawa and Koyama (2005).
It is the placement of the foot far enough ahead of the body at touch-down, which straightens the leg and lowers the CM, that therefore benefits the

distance jumped by assisting a reduction in knee flexion and promoting the development of vertical velocity during the support phase.

As elite athletes have larger run-up speeds and large touch-down angles the importance of leg strength increases. Bridgett and Linthorne (2006) found that increasing run-up speed increased the touch-down leg angle concluding that minimum knee flexion with a touch-down leg angle of 61° at maximum run-up speed is needed to produce the greatest jump distance. Further highlighting the importance of strength, Bridgett and Linthorne (2006) suggested that among athletes the variations in ability are mainly caused by differences in the dynamic muscular strength. This relates to the speed strength relationship highlighted by Lees and Graham-Smith (1994).

Nagano, Komira, Fukashiro and Himeno (2005) found that muscles such as hip external rotators, adductors and abductors are all highly activated during jumping and continued that these muscles have limited influence on jumping performance. However, their results implied that they play a substantial role in stabilising the movement of the hip joint. Further to this the importance of the hip has been highlighted by Graham-Smith and Lees (2005) who concluded that loss of horizontal velocity was influenced by a large hip adduction and a small range of hip extension. This was supported by their observation that the hip did not flex following touch-down but continued to extend throughout take-off. They continued by suggesting the importance of utilising a 3D model when studying jumping motions in support. Several investigations have highlighted that the work done within the long jump is generated in more than one plane, particularly at the hip. Muraki, Michiyoshi, Toshiharu and Suzuki (2001) indicated that the utilisation of the hip would seem to have significant impact on the technique used. As Pollard, McClay Davis and Hamill (2004) point out, during a dynamic lower extremity task, it is possible that the hip abductor weakness could result in increased hip adduction or relatively decreased hip abduction. The influence of the hip would seem to be not only in flexion/ extension (sagittal plane motion) but also in adduction and rotation movements (frontal and transverse plane motion).

There are indications (Linthorne et al., 2005; Lees and Graham-Smith, 1994) that different strategies can achieve the same distances. These contradictions may be explained by Kakhana and Suzuki (2001) who cited the work of Fukashira, Wakayama, Iton, Kojima, Yamamoto and Ae (1992*)* to highlight that although there are similarities in performance technique the strategies used to generate vertical velocity vary amongst individuals. As an example, the styles of Lewis and Powell at the 3rd World Championships in 1991 could be described as 'low' and 'high' jumps respectively. That is, Powell achieved a greater vertical velocity and take-off angle of 23.1° (=0.40 rad) due to trunk inclination, larger hip rotation and a more extended support leg. Contrastingly, Lewis limited extension of the support leg and preserved horizontal velocity resulting in a lower take-off angle of 18.2° (=0.32 rad). The athletes had similar run up velocities of 11.0 m/s and 11.06 m/s respectively, and similar jump distances of 8.95 m and 8.9 m. Kakhana and Suzuki (2001) investigating electromyographic (EMG) activity and take-off angle supported the idea of different strategies by highlighting the difference between the CM velocity at touch-down and take-off.

One jumper (N° 1) consistently (at different run-up steps) had greater touch-down horizontal velocity than take-off horizontal velocity whilst jumper (N° 2) displayed the opposite. The vertical velocity at take-off was consistently greater for N° 1 as was the take-off angle. Interestingly, subject N° 1 had a less flexed knee at touch-down. The different strategies adopted by the two jumpers highlighted kinematic differences leading to a greater vertical velocity for N°1. These were, i) greater backward trunk lean at touchdown (TD) and take-off (TO), ii) a lesser range of motion of the thigh in the support phase, iii) more extended angles at the knee and ankle at TD and iv) a more flexed knee at TO. In kinetics, N°1 generated greater braking impulses and smaller propulsion impulses in the anterior/posterior component of the ground reaction force.

Summary

Research reviewed in this section highlights the balance required between influencing variables. For the production of an optimum take-off angle (according to projectile motion) both vertical and horizontal velocity must be the same. However in the long jump it is physiologically difficult to generate the vertical velocity, whilst maintaining horizontal velocity and therefore a compromise occurs. It is clear in generating vertical velocity that both eccentric and concentric muscle action is important whilst eccentric action is important to limit knee flexion. In doing this jumpers adopt a touch-down position which, although a compromise, allows the jumper to improve their mechanical position/advantage. The compromise is reliant on the approach speed and strength of the jumper. So whilst models propose 'optimum' values within the long jump technique there seems to be agreement in the literature and later models particularly, that there are differing strategies utilised by elite jumpers to gain maximum jump distance. Later investigations have highlighted the importance of viewing the technique in 3D, particularly in relation to hip action, rather than making assumptions based on 2D analysis only.

2.4 Joint kinetics

The importance of the hip has been highlighted above but there has been little investigation into joint kinetics within the *running* long jump. Seigel, Kepple and Stanhope (2004:69) outline that 'positive power represents the rate at which mechanical energy is added to the body via concentric muscle activity, and negative power the rate at which mechanical energy is removed via eccentric muscle activity'. By examining the mechanical powers at each joint an assessment of the importance of muscles around the hip, knee and ankle can be ascertained (Winter,1983). Most previous investigations into long jumping have been concerned with technique analysis, approach strategies, modelling and technique interpretation but few have investigated the work done and power around the lower extremity joints. Both Prilutsky (1993) and Stephanyshyn and Nigg (1998) have studied the joint power production during the running long jump. Identifying mechanical joint power can provide important information to assist in the understanding of the technique used.

2.4.1 Joint kinetics in long jump

Stephanyshyn and Nigg (1998) reported peak net joint moments at the ankle, knee and hip as 250-400 Nm, 150-300 Nm and 300-500 Nm respectively whilst Muraki et al. (2005) graphically indicated corresponding mean values as roughly 5 Nm/kg, 7 Nm/kg and 10 Nm/kg. Following this, Stephanyshyn and Nigg (1998) reported mean values of 133.4 J, 79.6 J and 28.1 J for energy absorption at the ankle, knee and hip and for generation at the same joints mean values of 103.9 J, 52.0 J and 55.8 J respectively. In the standing long jump Horita et al. (1991) found that the total % work done was 49% at the hip, 14% at the knee and 16% at the ankle in adults and correspondingly 45%, 12% and 22% in children. Stefanyshyn and Nigg (1998) compared the mechanical energy contribution of the hip, knee, ankle and metatarsophalangeal joints in both running and vertical jumps. This study highlighted that the contribution of each joint seemed to differ dependent on the type of jump. In both the running long jump and vertical jump the contribution of the knee and metatarsophalangeal joint seems similar (running long jump = 15-16% energy absorption, the latter generating 25% and absorbing 30%). The ankle was the largest energy generator and absorber for both types of jump, responsible for 47% of absorption and 49% generation of energy. In contrast, Muraki, Ae, Koyama and Yokozawa, (2008) indicated that the energy generation occurred mainly at the ankle, then knee and hip. Stefanshyn and Nigg (1998) found that the hip joint absorbed 10% and 16% energy in the running v standing long jump and generated 36% v 21% energy in the same jumps. Thus, in the running long jump the importance of the hip joint seems to be increased and "the requirement of large hip extension moments during the stance phase of the long jump indicates that development of the hip extension muscles is also extremely important for long jumpers" (Stefanyshyn and Nigg, 1998:186). In support of these findings Muraki et al. (2008) found that in the compression phase the hip was the largest generator whilst in the extension phase, the largest absorber.

As the running long jump is a jump extending from a run, for understanding, it is important to note how joint work differs as the speed of impact increases. Thorpe, Li, Crompton and Alexander (1998) found for running, that peak moments at the hip occurred slightly before peak knee moments and peak ankle moments. They found peak joint moments for running as 210 Nm, 284 Nm and 100 Nm for the ankle, knee and hip respectively. For jumping they found that the peak joint moments were 153 Nm, 162 Nm and 215 Nm at the ankle, knee and hip. This highlights an increase in hip moments when moving from running to jumping. These are similar to the findings of Vanrenterghem, Lees, Lenoir, Aerts and De Clercq (2004). Both Lees, Vanrenterghem, and De Clerq (2003) and Vanrenterghem et al. (2004) suggested that as performance in the vertical jump moves towards maximal the hip joint extensor muscle activity increases, which infers that for generating maximum jump height the utilisation of the hip is important. This group of findings indicate that the hip muscle moments increase from running through standing long jump to running long jump. In standing jumps this is due to the need for height generation however in the running long jump this could be due to both high ground reaction forces and the need to generate height.

Essentially the ability to move the CM in a projectile path to maximise the translational motion in the long jump relies upon the co-ordinated production of work. It is clear that work at the ankle, knee and hip joints do not clearly follow patterns obtained for running or standing long jumps. Knee moments decrease and hip moments increase as the need for vertical velocity increases, and the manner in which it is achieved in the running long jump becomes more reliant on work at the hip. In addition, Stephanyshyn and Nigg (1998) document an increase in ankle work as large ankle extensor moments and ankle absorption that seem to be important in the jump.

It could be argued that, as the forces that develop in the running long jump, particularly at touch-down, differ from those in standing jumps and running, it could be expected that joint moments and work done may differ. The need to increase the CM height and vertical velocity drive the technique of long jump. Explaining this, and the strength required should aid understanding of the work required at the joints.

During the contact phase, knee angle changes generate an initial eccentric contraction of the knee extensors which is then followed by concentric extension to extend the knee angle and increase vertical velocity. Relating to this the importance of strength, Bridgett and Linthorne (2006) suggested that among athletes the variations in ability are mainly caused by differences in the dynamic muscular strength. This relates to the speed strength relationship highlighted by Lees and Graham-Smith (1994).

Investigation into joint kinetics in gait has also concluded that work at all joints occurs outside the 2D plane. Movement in 3D was reported by Liu and Lockhart (2006) as internal moving to external rotation at all joints in the transverse plane, initial knee and hip adduction moving to abduction and at push-of back to adduction, with mainly ankle adduction moments throughout. Supporting this, Dumas and Cheze (2008) found that during gait the hip and knee are stabilised by abduction actions and this occurs mainly during the stance phase. Similarly, Chester and Wrigley (2008) found larger hip abduction when walking in 9-13 yr olds which according to MacKinnon and Winter (1993) maintain head, arm, trunk and swing leg balance through stabilisation of pelvic motion. Basically, in simple activities, children seem to have developed both adult movement and power patterns by around 9 years including the utilisation of movements outside the sagittal plane to assist their stability.

In relation to children, a joint kinetic analysis has yet to be carried out on the running long jump but studies into gait, running and standing jumps have been reported by Chester, Tingley and Biden (2006), Ganley and Powers (2005) and Horita, Kitamura and Kohno (1991). These studies, which include generally less complex movements and incur reduced forces, have found that patterns of movement in young children become adult like between 9-13 yrs. Although Horita et al. (1991) found skilled young performers could produce similar patterns at 6 yrs although not producing the same work or power during standing long jump impulse phase. Interestingly, when looking at jump landing, an activity with increased forces, Hass, Schick, Chow, Tillman, Brunt and Papangelou (2002) concluded pre-pubescents land in a more flexed position, utilising less flexion range of motion than post-pubescents and indicating mature patterns occur at a later age in this activity. In counter movement jumping Wang, Huang, and Yang (2002) also found that range of motion was limited in the extension (pushing) phase of the jump. This has obvious implications for the patterns of long jump development in young female long jumpers, as this to has high force development within it.

There seems to be important utilisation of the hip (perhaps mainly for stability) and the ankle which seems to increase its propulsive output. Hip work seems to be important in both the sagittal and frontal planes. As jumping becomes more difficult (e.g. long jump), the patterns demonstrated by elite performers are likely to be adopted later than in other, more simple activities, and is likely to limit the jumping performance and technique of young immature females (11-16 yrs). It is clear that during the development of children there are several factors that impact on their ability to successfully imitate the adult motion patterns and whilst the generation of power and joint contributions may be an indication of developmental technique and mature patterns in any physical activity, the later development of elite patterns may indicate a more complex activity. That is to say that physiological limitations may hinder 'elite' technique development particularly as long jumping differs from the simpler activities most children frequently experience. It also follows that earlier adoption of more adult like patterns may be used to indicate ability, talent and its development.

Summary

The limited studies on long jump kinetics have sought to clarify the role of the joints within the contact phase of the long jump. In the long jump, large force generation is required at the muscles to both resist and initiate joint movement in order to move the body from the touch-down position to take-off. Generally, the actions within walking and running increase hip and knee energy generation, and decrease ankle joint energy generation as speed increases. However in the running long jump, Stefanyshyn and Nigg (1998) found that the ankle was the largest energy generator and absorber, and pointed out the importance of the hip extension moments within the jump. Additionally, studies into gait and long jumping, highlight the role of hip movement in the frontal plane. In relation to children, investigations have concentrated mainly on standing jumps, where mature patterns are achieved by age 9 years, but in a running jump little research has been conducted on young children (10-16yrs).

Summary of the Long Jump

The models of Alexander (1990), Seyfarth et al. (2000) alongside the 'pivot' concept outlined by Lees et al. (1994) have enhanced understanding of the variables influencing performance and have highlighted the importance of CM height, touch-down leg angle and run-up speed, but have also indicated that eccentric force enhancement and muscle strength are important. The importance of the compression phase is highlighted by the large (65%) vertical velocity gains observed. The knee flexion angle and leg stiffness during this phase, and therefore the ability of the jumper to resist flexion, has been identified as crucial and important in the maintenance of a high CM and vertical velocity development. In addition, and more recently, the role of the hip and muscle co-ordination around the leg joints has been suggested as important to long jumping. hip muscles in all planes have been found to be highly activated, and perhaps important, at least in a stabilising role in the contact phase.

There is general agreement on specific important factors in the long jump take-off, although the integration/interaction of all these factors is complex and can be used in different ways, by jumpers with differing strengths, to produce 'good' quality jumping techniques. This highlights the opportunity that physiological differences have on influencing the technique as development takes place (both in technique and maturation). As children's activity patterns develop according to the complexity of the activity, it is likely that due to the complexity of long jumping, these patterns develop later. In addition, the development of strength and motor ability within young females around the puberty is not clearly understood or documented. It is clear that strength and speed are required for good long jumping therefore puberty is likely to impact on long jump development. Certainly at elite level, technique may differ and is mainly dictated by the complex interaction of variables at touch-down, which, due to maturation may be even more complex to identify in young jumpers.

2.5 Children and Maturation

2.5.1 Maturation

Many of the studies outlined above for the long jump investigate adults i.e. subjects above 18yrs old. However, the development of physical ability throughout children's growth is a reflection of changes in physical maturity, changes in body size and the type/range of motor experiences (Rarick, 1982). This, and general maturation patterns, have obvious implications for any study involving children and should somehow be taken into account. In general, the most used classification of children in physical activities is chronological age, however observation of one school class leaving primary school would highlight the variation in development of children at this time. Katzmarzyk, Malina and Beunen (1997) concluded that skeletal and chronological maturity rarely progress at the same rates. This is further supported by Jones, Hitchen and Stratton (2000) who found that boys falling in the fourth stage of sexual maturation could range from 11.7 yrs to 14.9 yrs. In general participants in youth sport/activities are most often grouped by the child's age based on the date of birth (Malina and Beunen,1996). However Barker-Jones (1995) points out that there is a chronological versus maturational age debate in competitive sport. Growth refers to size increases in the body and development refers to the stage of progress toward a mature adult. Maturation is referred to as an individual's biological age. Malina (1994) referred to frequent reports that maturation is directly related to growth and to exercise performance characteristics. Mafulli (1996) acknowledging the advantages and disadvantages of chronological classification suggested performance standards should take into account the biological age of the participants more than chronological age, therefore making activities a fairer competition for those concerned. Volver, Viru and Viru (2000) stated that the variability in development complicates the organisation of physical education particularly during the pre-pubertal period. This pubertal period varies between boys and girls, and whilst boys initiation is around 11 to 15 yrs, onset is 1 to $1^1/_2$ years earlier in girls (Rarick, 1982). Borms (1986) stated that girls experience their adolescent growth spurt and peak height velocity on average 2 years earlier than boys.

2.5.2 Influence on performance

Maturational development has an impact on motor performance, physical and physiological characteristics. The importance of this on specific physical fitness measures such as power, speed and flexibility differs through the onset to the end of puberty although this impact varies most greatly with boys (Jones et al. 2000). In girls, Jones et al. (2000) found that when mass and stature are taken into account, no significant differences were found when considering the activities of vertical jump, hand-grip strength and the 20 m shuttle run test. However, in contrast Volver et al. (2000) found that whilst agility is improved by maturational stage II, muscle explosive strength and trunk flexibility improve up to stage III. Baxter-Jones (1995) concluded advanced maturity positively influences aerobic power, muscular endurance and muscular strength. He also states that this depends on the activity but for those which require power, strength and height, the early maturer is at a distinct advantage. Additionally, physical maturation, as reflected by height and mass, is a major contributor to increases in motor performance (Bale, Mayhew, Piper, Ball and Willman 1992). This could be seen to support the previous proposal of Mafulli (1996) and would be relevant to long jump performance. Volver et al. (2000) found that reaching Tanner's Stage II is critical for an improvement in agility and for increase in both leg explosive strength and trunk flexion reaching Tanner's stage III is critical.

Loko, Aule, Sikkut, Ereline and Viru (2000) stated that during the period of sexual maturation general physical performance gets worse. There are disturbances in technique and the amount of unnecessary movement increases, which in motor abilities occurred at the age of 13-14 yrs. In contrast, Davies and Rose (2000) suggested that this is not the case, finding that motor performance increased from the prepubertal stage to the pubertal stage and if ackwardness occurs it is not very robust and it is not seen in all adolescents. Volver et al. (2000) found before sexual maturation is completed the pattern of sexual maturation process exerts more significant influence on the improvement of trunk flexibility and explosive power of the legs than chronological age. In addition, Barber-Wetsin, Noyes and Galloway (2006) found females gradually increase knee extension peak torque by 20% in females 9-13 yrs, and Ellenbecker, Roeter, Sueyoshi and Riewald (2007) found female subjects did not show significant increase in the normalised knee extension or flexion strength across the ages 11-21 yrs. Most of the above factors are relevant to jumping. Reviewing the evidence, it seems that maturation may have influence but perhaps the lack of robustness occurs as some females have already developed technique /strength which masks the influence of some factors associated with maturation.

The ability of children to simulate adult patterns in different activities is likely to depend on their experiences as they mature. In addition the timing of this ability is likely to differ dependent on the complexity of the activity, alongside their time experiencing it. Walking is the most basic and the first to be experienced so it is likely that children reflect adult patterns earlier rather than later in comparison to more complex activities. Chester, Tingley and Biden (2006) found when walking, children aged 9-13 yrs generated similar mean peak plantar moments of 1.40 Nm/kg similar to those found for adults (significantly different to other younger children) but also suggested peak ankle power absorption did not approach adult-like values until 9 yrs. Ganley and Powers (2005) reported values of similar peak hip and knee joint moments and powers in adults and children. They found that peak plantar flexor moments (1.15 compared to 1.56 Nm/kg) were significantly smaller and both peak ankle power absorption (-0.56 compared to -1.05 W/kg) and generation (2.79 compared to 3.46 Nm/kg) in late stance were also significantly smaller in 7 yr olds. Chester et al. (2006) also found that knee extension moments (0.36 Nm/kg) in this age group were consistent with reported adult values. So in the sagittal plane there are noticeable differences at the ankle before, at least, 9 years of age.

In the frontal plane, differences at the hip were identified. Chester et al. (2006) also found that throughout stance phase older children have larger hip abduction moments which are required to stabilise the upper body and pelvis, and to counteract the effects of gravitational and ground reaction force. Similarly, Chester and Wrigley (2008) found larger hip abduction when walking in 9-13 yr olds which according to MacKinnon and Winter (1993) maintain head, arm, trunk and swing leg balance through stabilisation of pelvic motion. They supported the hypothesis of Sutherland (1997) that children rely more on hip power and less on ankle power during terminal stance due to maturational factors associated with decreased torque and power producing capabilities at the plantar-flexors. This seems to indicate that children are less able to utilise their ankles, or more able to use their hips, when compared to adults. This would possibly suggest that different strategies in long jumping could occur as puberty progresses. Malina et al. (2004) found that there is an under representation of early maturing females in competitive sports programmes which implies early maturation is a disadvantage for females, and selection of athletes likely to continue competing occurs early in young girls. That is to say that there are likely to be fewer early maturing athletes than later maturing athletes.

Walking patterns are practiced and therefore established early in children although jumping is a less practiced activity. Looking at jumping specifically Loko, Aule, Sikkit, Ereline and Viru (2000) found that standing long jump ability did not improve from age 12 yrs onwards. Between the ages of 13-14 yrs performance in tests of motor ability (vertical, quintuplet and standing long jump) stabilised. Also the annual differences in performance scores between active and non-active girls, were significant up to 15 yrs except in the standing long jump. This developmental difference in jumping is outlined by Wilkerson and Satern (1987) 11-13 yr olds exhibited more mature jumping patterns in their vertical jumps than in their long jumps. This suggests that the increased variability in long jumping compared to vertical jumping indicates reduced development at the skill, which is perhaps due to its greater complexity. Wilkerson and Satern (1987) suggested that if increased horizontal distance is required both 'increased degree of trunk flexion relative to the horizontal and increased range of motion at the hip relative to the trunk and thigh segments' are required, highlighting the relevance of the hip within the activity. It is possible that the increased variability and complexity of the long jump mentioned previously may possibly be due to developmental differences at the hip. These results were similar to the study of Horita et al. (1991) that found total work done and peak power were significantly different between adults and children at the hip and knee. They concluded that in 6yr old children skilled performers achieve both the mature skilled form and joint functioning pattern during the impulse generation phase.

Summary

Skeletal and maturational maturity progress at different rates and frequent 'spurts' in both are seen at varied times which complicates observation of technique development. In addition, there are concerns about disturbances in performance during maturation however there are similar findings on maturation improving muscular strength, agility and power. Basically, in simple activities, children seem to have developed both adult movement and power patterns by around 9 years including the utilisation of movements outside the sagittal plane to assist stability. In jumping, more mature patterns are observed earlier in vertical jumps than in standing long jumps highlighting the increased goal complexity (height and distance) needed to achieve the outcome. The limited appearance of early maturing females in competitive sports indicates that, for whatever reason, maturation is a barrier to achievement in these females. This is particularly important as the use of chronology for grouping is widespread within studies of children, however the interaction of task and biological maturation highlights the difficulties of identifying and isolating characteristics relevant to activities.

2.6 The Biomechanical Model

Body segment parameters are needed if a biomechanical model is to be used and this consists of segment mass, segment centre of gravity and segment moment of inertia therefore from kinematics, kinetic data can be derived. In order to develop and understand the use of a model the literature relevant to body segment parameters, markers and marker sets, joint centres and task dependency needs to be explored.

2.6.1 Body segment parameters

The physical characteristics of the relevant segments/limbs need to be determined before undertaking a kinetic analysis of human movement. These characteristics include mass, location of mass centre and the rotational inertia (moment of inertia) of the segments and are known as body segment parameters (BSP). Many studies have been undertaken but probably the most influential was that by Dempster (1955). This documents the procedures for measuring BSP and includes tables for determining BSP, and hence to biomechanically analyse human motion. Pearsall and Costigan (1999) point out that the significance of using generalised BSP has not been extensively reviewed but that it has been noted that errors in segment parameters may be only as damaging as errors in acceleration data (Davis, 1994) although contrastingly Wu and Ladin (1993) suggested these errors may affect lower order derivatives.

Therefore, in studies of young girls, data of adults or boys must be used. Frequently, the regression equations (Jensen, 1986) determined from mathematical modelling and segment zoning of boys have been used for young children. Several studies (Ganley and Powers, 2004; Bauer, Pavol, Snow and Hayes, 2007) have sought to clarify the impact of using 'non-specific' BSP, typically derived from indirect methods and/or previously published data scaled to the height and weight of the subject. Lenzi, Cappello and Chiari (2003) point out that these methods are known to be inaccurate and many problems associated with the selection of BSP are due to the fact that accurate estimates have been limited because of measurement, ethical, and sample constraints (Pearsall and Costigan,1999).

The extent to which kinematic and kinetic data are affected by inaccuracies in BSP is a relevant topic, particularly when quantifying joint powers and moments. Although there are many data sources for the estimation of BSP these have generally derived their data from adults (Dempster 1955; Clauser, McConville and Young, 1969; Chandler, Clauser, McConville, Reynolds and Young, 1975). Jensen (1986) used stereo photographic measurements to derive regression equations to calculate limb segment masses for a paediatric population but this has limited application as the development of these was from studying a small sample (n=12) of boys aged 4-15 yrs. From this the kinetic joint functions and joint torque of children are estimated but as these differ in gender and cover the growth spurt period they may be likely to cause error when applied to young developing females. Recently studies (Ganley and Powers,2004; Kuemmerle-Deschner, Hansmann, Rapp and Dannecker, 2007) have expanded the base of knowledge surrounding BSP but there is still little related to young adolescent girls. Limited research has been done on the BSP of children and whilst some studies have sought to clarify the impact of using 'non-specific' data the impact on girls above 13 yrs is unknown.

Due to this lack of data, the suitability of previously generated data (mainly adult male) for use with other populations is seen as a relevant topic for investigation by researchers. Li and Dangerfield (1993) believed that differences found in the centre of gravity and radius of gyration between many studies (e.g. Ackland, Blanksby and Bloomfield, 1988; Clauser et al., 1969; Dempster, 1955; Chandler et al., 1975), was mainly due to the different methods used to define limb segments with population differences as a second important reason. Pearsall and Costigan (1999) compared recent studies pointing out that mean estimates of segment mass for one thigh varied from 9.5% to 14% of total body mass. In addition, they stated the ability of regression equations to estimate CM accurately may be weak. Interestingly Pearsall and Costigan (1999:174) state that " improved confidence occurs if subject specific anthropometric measurements are used", however this is not generally widely adopted due to its impracticality in subject testing.

Jensen's investigations made a substantial contribution to the estimation of inertial parameters for children and adolescents. However, there are several factors that could limit the effectiveness of the regression equations (Ackland et al.,1988). Individuals vary in terms of chronological age, growth speed and the timing of the growth spurt (Tanner, Whitehouse, Mar and Re, 1976). Jensen used only the variable chronological age and also the population has changed in the last 25 years. This could lead to errors in estimation of BSP, particularly as the data collected was on a small sample of young males (Ackland et al.,1988). Bauer et al. (2007) compared MRI estimates to Jensen's estimates and found that BSP, with a few exceptions differed between the two methods of calculation. Specifically, the regression equations predicted greater shank masses, smaller thigh masses, more distal thigh centres of mass and greater thigh transverse axis radii of gyration. During gait these differences showed statistically significant but small differences in joint moments and power (Bauer et al., 2007). In support Nguyen, Baker and Pandy (2007) found significant differences in segment inertial properties do not translate to large variability in joint moment output. Sabick, Kipp and Pfeifer (2005) concluded that the use of inappropriate BSPs may influence the results of a gender comparison either positively or negatively. Unsurprisingly, Durkin and Dowling (2003) conclude that greater accuracy of subject specific body segment parameters can lessen the error in an individual's calculated kinetics.

Looking at gender differences, Sabick et al. (2005) found that joint force and moment components were not significantly different when computed with different BSP. Given the differences outlined previously the use of adult data is questionable, but according to Zatiorsky, Seluyanov and Chugunova (1990) using equations for boys of the same age, BSP for girls aged 9-10yrs can be calculated with little error. Bothner, Alderink, and Fischer, (2002) compared two different models (Dempster 1955 : Vaughan 1992) and reported their effects on hip moments in children and adults, and found there were differences between the BSP estimates and the resultant hip joint kinetics. However, the difference between peak joint moment values was between 22-28 % across a wide range of body masses. In contrast Sabick et al. (2005), when using male and female BSP on female joint kinetics during landing found that in most cases the joint force and moment components were not significantly different when computed with the different BSP data. These differences ranged from –8.8% to 7.3% and were usually more pronounced for components in which the ground reaction force had little effect. Sabick et al. (2005) suggested that it is not necessary to apply different BSP models based on body mass. It could be however that different ways of calculating BSP and their application to different activities may affect calculations made.

Kuemmerle-Deschner et al. (2006) when comparing a Cylinder Brick model and a Polynomial Regression Equation using water displacement method to a calculation model (Jensen, 1987) found that in neither method of calculation did girls above 8.5 yrs show greater differences in leg segment mass. Using gait analysis, Ganley and Powers (2004) investigated/compared dual energy X ray absorptiometry (DXA) anthropometric parameters and cadaver based estimates when looking at 7-13 yr olds. They found that there was a statistical difference but the absolute and relative differences were minimal. Generally DXA derived inertia of centre of mass values were less than cadaver based estimates. They concluded from their graphical output that the differences between DXA and cadaver based estimates would have negligible effect on the calculation of net joint moments for 7-13 yr old children whilst walking. Additionally. they found that the greatest differences between moment curves occurred during the swing phase of gait when the inertial terms dominate the moment calculation. Pearsall and Costigan (1999) when investigating effect on walking, found that using different BSP, even those which generate 40% difference in mass location and inertia values, only showed small differences in the kinetics measured. Although half of the measures showed significant differences when BSP were varied most were less than 1% body weight. They proceeded to explain this by saying the BSP variations themselves were small in absolute terms and therefore the absolute magnitude of change in mass is small, thus of little consequence to the kinetics.

There seems to be conflicting information on the accuracy of applying the work of Dempster 1955; Clauser et al., 1969; Chandler et al., 1975 and Jensen 1986 in young (and female) subjects. Initial concerns about the application of adult BSP to children seems to have been investigated and a consensus seems to be that under 13 yrs this adult data is reliably applicable. Above this age although research shows that differences are measured, they would seem to be either within acceptable error limits or apparent during redundant phases of the movement (swing). The effect on kinetics has shown that although statistical differences have been obtained in practice the absolute or relative differences are acceptable. In some cases no significant difference has been found. As yet there does not seem to be a 'best practice' solution or relevant female child data to work with.

2.6.2 Marking and marker sets

It is difficult in more dynamic activities to maintain joint centre markers, in position and on the body. The use of 3D motion analysis requires the determination of the poses (position and orientation) of the body segments from skin mounted markers before their kinematics and kinetics can be calculated. Cerveri, Pedotti and Ferrignio (2005) state that biomechanical models are used to infer the position of body segments for the measured positions of markers placed on a subject. Bauman, Plamondon and Gagnon (1998) explain that existing markers sets use different types of markers, such as superficial stickers and spherical balls. Bauman, Plamondon and Gagnon (1998; p476) continued by stating that stickers are not practicable for 3D studies 'as most cameras would not have a direct view of the joint'. Assuming markers allow a 'good' view the joint centre location, axes can be generated and the flexion/extension, abduction/adduction and internal/external rotation can be obtained. Joint moments are determined using inverse dynamics and standard motion analysis methods. Within this methodology the musculo-skeletal system is generally modelled as a rigid multi – link chain with each body segment as a rigid link. Generally a marker array of at least three markers per segment is needed for definition of a segment-embedded reference frame which represents the pose of the segment (Lu and O'Connor, 1999).

Whereas gait and slow moving studies often use skin mounted markers to locate joint centre there are several inherent problems as indicated above. States (1997) classified these as being;

i) movement of skin over the bone,

ii) numerous assumptions

iii) joint movement through multiple degrees of freedom, and

iv) centre of joint rotation shifting as a function of joint angle

Recent methods to overcome this have included the use of multiple markers (marker set) on limb segments using 6 degrees of freedom models. One suggestion for minimising error in kinematic data is to locate markers on to rigid plates and not onto the skin directly (Manal, McClay, Stanhope, Richards and Galinat, 2000; Holden, Orsini, Siegel, Kepple, Gerer and Stanhope, 1997, Leardini, Benedetti, Catani, Simoncini and Giannni, 1999). However whilst this might eradicate relative movement between markers it not necessarily reduces errors due to skin movement (Nester, Jones, Liu, Howard, Lundberg, Arndt, Lundgren, Stacoff and Wolf, 2007). Manal et al. (2000:38) stated that, 'it is likely that the efficacy of tracking markers is related in part, to several factors', In this statement they refer to i) the method of attachment to the leg, ii) the location of the markers on the leg and iii) the physical characteristics (constrained: unconstrained) of the marker sets. Their main findings were that when comparing, over/underwrapping, medial/lateral/proximal/distal displacement and marker sets (constrained)/skin mounting (unconstrained), the lateral shank was the only marker set that showed significant difference. They found tibial rotation estimates were best realised by placing the marker arrays more distally than proximally. Additionally their 2nd and 3rd best ranked sets were seen to be the medial border of the tibia (overwrapped). Therefore, distal and lateral was seen to be the best placement and an "optimal set of markers can reduce the effect of soft tissue movement on kinematic estimates" (Manal et al., 2000:45).

However Manal et al. (2000) acknowledged this position may not be viable in a typical clinical data collection situation. They found that selecting the better set of markers (distal, lateral underwrap) could reduce error in estimating knee joint internal/external rotation. They investigated these parameters under natural cadence walking conditions. Supporting this methodology, Bendetti, Vataani, Leardini, Pignotti and Giannini (1988) recommended the use of plate mounted markers for clinical applications and Cappozo, Catani, Leardini (1992) found that plate fixed configurations showed smaller artifacts than direct skin mounted markers. In contrast, Vogt, Portscher, Brettman, Pfeiffer and Banzer, (2003:183) in their investigation did not find differences in relative errors between skin and plate mounted markers but from their work they concluded that "method of plate-mounted marker tracking is sufficiently accurate and convenient for routine adaptation in a clinical gait analysis setting". In support of these findings, Nester et al. (2007) found the match between kinematic data from skin, plate and bone protocols was reasonable or good. They hypothesised that difference between the skin and plate protocols is likely to be negligible due to the large overlap of standard deviations. They pointed out that tracking of single body surface markers could be prone to errors to a higher degree therefore resulting in the loss of pertinent data. Reinschmidt, van den Bogert, Nigg, Lundberg and Murphy, (1997b) when investigating running concluded that knee rotations other than flexion/extension may be substantially different when derived from skin or skeletal markers. They concluded by surmising that although there was no significant differences for movement and range of motion error between marker setups the results did not imply that the marker configurations studied were identical or equivalent.

Baumann et al. (1998) when comparing different marker sets found that joint ball estimates and marker set agreed the best (average difference 6 mm-16 mm) whilst a ball method and marker set method varied the most (15 – 31 mm). Reinschmidt et al. (1995 cited in Fuller, Liu, Murphy and Mann, 1997) found that whilst the shape of pin and skin mounted marker data were similar, the skin markers over-predicted the actual skeletal motion indicating soft tissue motion was the difference. Nester et al. (2007) considered the difference between skin and plate protocols is likely to be negligible and concluded that it is unlikely that one particular rigid body model nor one method to attach markers is always preferable over another. However Marin, Allain, Diop, Maurel, Simondi and Lavaste (1999; 613) stated that 'as one of their main objectives was to avoid skin motion artefact from the use of skin markers, rigid plates were mounted onto the shank and thigh'. Whilst Holden, Orsini, Siegel, Kepple, Gerber and Stanhope (1997) using three subjects and looking at percutaneous skeletal tracking markers versus target shell markers found errors in displacement of up to 10mm and in rotation a peak error of 8^{c} along the long axis of the shank when walking. When an optimal surface mounted tracking target configuration is used, Manal, McClay, Richards, Galinat and Stanhope (2002) suggested that soft tissue movement of the shank has only a small effect on knee moment estimates during natural cadence walking. Sangeux, Marin, Charleux, Durslen and Ho Ba Tho (2006) found that thigh marker sets' relative movement demonstrated an increase of the relative movement distance with the flexion angle, the same trend for all subjects. Displacement of the thigh marker set increased ranging from 3-22 mm whilst the shank marker sets were almost stable around 4.5 mm for all subjects. Supporting this, Reinschmidt, van der Bogert, Lundberg, Nigg, Murphy, Stacoff and Stano (1997a) concluded that knee rotations outside the sagittal plane may be affected with substantial errors when using skin markers and found that error due to skin movement artefact at the shank did not exceed 5° for all subjects and rotations. From this it seems that the shank marker sets remain quite stable during flexion whilst the thigh marker set increases its inaccuracy. This statement opposing the conclusions of Nester et al. (2007) that the overall mean differences between data would suggest that the effect of rigid body assumptions and skin movement is minimal.

The research seems to suggest that marker sets are perhaps the most accurate way to identify joint positions without introducing, or whilst limiting, error caused by soft tissue movement. However, as previously stated, the efficacy of the markers is likely to be due to several factors (Manal et al., 2000). Fuller, Liu, Murphy and Mann (1997) concluded a) that rigid skin mounted arrays do not track rotation of the bone well, particularly on the femur and b) that the soft tissue displacement was task dependent. This conclusion highlights two factors that may further influence accuracy and therefore joint moment estimation. It may also be difficult to separate the influence of these two factors however it is clear that a dynamic movement such as long jumping with a high impact at touch-down is likely to cause soft tissue movement. This alongside the infiltration of sand undermining adhesion to the skin may be task dependent factors which dictate the type of fixation necessary and make optimisation of that fixation the over-riding factor.

2.6.3 Task dependency effects on error

Fuller et al. (1997) found distinct differences between patterns of motion of markers during cycling and gait tasks, indicating that the soft tissue displacement is task dependent. They also found that the marker system lagged the pin mount system and hypothesised that this was due to skin movement artefact as the motion was tracked accurately. They suggested most thigh errors were caused by muscle activity, and errors due to inertial effects were rather small. Additionally they observed that the skin movement artefact could be even higher during the swing phase. Reinschmidt, van den Bogert, Nigg Lundberg and Murphy (1997b) found skin movement errors were consistently higher for running compared to walking. Quantifying the angular errors, Reinschmidt et al. (1997b) looking at errors in skin versus bone markers for running activities indicated net knee rotation errors of up to 10° and task dependent activities produced up to 20 mm error. Reinschmidt et al. (1997b) found that during running trials the agreement between skin and bone maker based kinematics for *abduction/adduction and internal/external rotation* was poor, also finding that discrepancies between external and skin knee motion were mainly caused by the skin movement artefact at the thigh. The motion of the skin relative to underlying bone is a known problem but is poorly understood, especially during movements with large impact forces for which accurate bone motion data has been generally unavailable (Tashman and Anderst, 2002; Holden and Stanhope,1998) They also found that during their research on one legged hopping, skin motion artefact seemed to be a combination of relatively high frequency damped oscillation following impact along with a low frequency offset. The timing, frequency and magnitude of the transient component was dependant on subject, marker and direction. Benoit, Ramsay, Lamontagne, Xu, Wretenberg and Renstrom (2005) found that there appears to be greater agreement in error curves derived from cutting movements than from walking for both adduction/abduction and internal/external rotation, although cutting produced greater absolute error. Stagni, Leardini, Cappozzo, Benedetti and Cappello (2000) found that experimental errors in kinematic data, including skin artefacts and digitising errors in joint centre locations, approximate 10% of the relative segment length. The literature seems to agree that there are notable errors in rotations outside the flexion/extension plane of movement, which although relevant to long jump, is the plane of movement which perhaps contains the least movement.

2.6.4 Joint centre location

Studies vary in the numbers of markers, methods of attachment, anatomical landmarks and sites for marker placement. They also differ in their definition of local segment co-ordinate axes and algorithms used for determining joint centres (Marika, Issam, Ewins and Ghoussayni, 2006). In short, it is difficult to compare methods accurately and whilst some research shows agreement other research demonstrates contrasting opinion. Reiner and Edrich (1999) identified joint angle and moment measurement being subject to sources of error created by skin movements, erroneous estimation of limb axes and joint centres. They did however indicate the small intra-subject variability indicated these problems remained within acceptable limits. Nester et al. (2007) pointed out, that on average, skin mounted markers under-estimated the total range of motion in sagittal and frontal plane motion. In contrast, within the study of Westbad, Hashimoto, Winson, Lundberg and Arnt (2002) there was found to be over estimation for these. The extent of movement of the ASIS under both skin and shorts had implications for marker placement in 3D analysis where movement of the pelvis is likely to be underestimated. Study results indicate that marker attachment may be preferable on close fitting garments rather than directly onto the skin and this would give the additional benefit of more dignity and comfort for the subject (Hazlewood, Hillman, Lawson and Robb, 1997).

The movement of skin and garments is only part of the problem as there are inherent difficulties in determining joint centres, especially with the hip, as they are covered by muscle and tissue and change position during movement. Application of rigid body mechanics in analysis, modelling and simulation of human motion would be best served by optimal representation. In biomechanics this representation should be such that its joint centres or central axes most closely approximate the centres or axes of the relative rotations between two neighbouring body segments, and the link lengths are constant or vary minimally (Zhang, Lee and Braido, 2003). As Zhang et al. (2003) point out non-rigidity in these link segments can be a major source of error. Holden and Stanhope (1998) stated that the calculation of muscular moments are most sensitive to changes in joint axis locations. They also concluded that variation may be particularly important to consider during the interpretation of net knee moments that are small in magnitude although they did find that there was a minimal change in knee centre location across a wide range of walking speeds. States (1997) suggests that even if markers do track the bones perfectly determining the location of the joint centre from surface markers requires numerous assumptions. Crisco, Chen, Panjabi and Wolfe (1994) stated that the hip joint centre (HJC) is highly sensitive to noise in the marker points. Schwartz and Rozumalski (2005) stated HJC errors stem from three sources: anthropometric measurements, marker location and regression uncertainty. Delp and Maloney (1993; p493) concluded that, '2 cm changes in HJC ...along the superior/ inferior axis has the greatest effect on muscle performance'. Ferber, McClay, Davis, Williams III and Laughton (2002) acknowledged the importance of anatomical marker placement to the reliability of 3D studies stating that cross talk between planes of motion or simple offset shift in data may occur. Despite using one single well-trained investigator within their study acknowledged that differences in marker placement may have influenced measurement repeatability. Ferber et al. (2002; p1139) point out that there are problems with the "day to day variability that may occur due to placement of markers over the skin". In support, Panjabi (1979) states placement of marker points can significantly affect the accuracy of location of the centre of joint rotation. Kaufman, Moitoza and Sutherland (1991) reported that it is possible to place skin mounted markers within 5° of the anatomically defined axes derived from computer models. Burkhart, Arthurs and Andrews (2008) found significant differences between measurers but the differences were relatively small i.e. 75 % - 80 % of these were less than 1 cm and that in most cases within measurer measurement differences were smaller and more consistent than those between measurers. Carson, Harrington, Thompson, O'Connor and Theologis (2001) cited in MacWilliams, Cowley and Nicholson (2003) when looking at foot segment models found that overall repeatability of marker placement was acceptable and that this was a greater source of error than skin motion artefact. Holden and Stanhope (1998) concluded that, the motion of the skin markers relative to bone appears to be complex, time varying and correlated to the movement. However, the literature acknowledges the problems but generally agrees that marking errors are acceptable particularly on bony landmarks and marker movement can be limited by placement on these landmarks.

Summary

In developing a model for analysis there are several problems that may cause error in the results, these include choice of BSPs, marking error, skin movement error, and task error. Most studies have been based around adult populations and have used the long standing body segment parameters of Jensen and Dempster. However these are not specific to young females but in comparison more recent studies have shown that for the younger age group up to 13 years there is little difference in the outcomes using adult parameters. Additionally, several studies have concluded that little or non-significant effects occurred on the joint kinetics and this was more noticeable on the 'swing phases' of activities. These markers generate the kinematic data but in addition the force plate values are needed to determine moments and powers. In determining the kinetics from inverse dynamics the force data is crucial and accuracy of the force plate is decreased on the edges of the plate so in long jumping it is important to aim for the centre of the force plate to minimise this effect. Clear agreement occurs in the problems associated with skin based markers particularly when placed away from bony landmarks, the obvious and generally approved solution being to use marker plates, preferably distal and underwrapped from the relevant joint and away from large muscle masses. There is general consenus that errors are larger in running than walking, although there is also agreement that this error is task dependent, and that the greatest reliability occurs in the sagittal plane. However, there is limited work on marker movement during explosive/ dynamic movements such as the Long Jump

2.7 Overall summary

The long jump although generally perceived as a simple event is, quite complex. In particular, it contains a complex phase of movement (TD-TO), which is crucial to its main aim of vertical velocity development alongside the limitation of horizontal velocity loss. As this occurs in a very short period of time it increases the difficulty in identifying important performance factors. Research shows that elite jumpers have developed a technique which is determined by some specific variables e.g. touch-down angle, knee flexion, leg stiffness and run-up speed to gain maximum jump distance. Some variability occurs in all athletes due to the interplay between these variables and has been identified in two of the best elite male athletes. The specific variables generally relate to individual strength and speed, so this complexity is increased in young jumpers due to maturational effects. Very little investigation has been carried out into the development of long jump technique in young athletes, particularly developing female jumpers. Specifically, there has been no investigation into the kinetics of jumping in young female jumpers.

There are several methodological factors that need to be considered in order to obtain accurate data. It is clear that there are limited data on junior female long jumpers and that there are no gender specific body segment parameters for this age group. The problem that is perhaps the most difficult to address, is the lack of BSP data for females aged 14-16 yrs of age, as it would seem the younger age group (11-13 yrs) may realistically use (according to research) previously obtained male data. There have been several studies into long jumping that outline the importance of movement outside the sagittal plane but relatively limited use of 3D software to investigate the technique. Combining these areas would allow for the investigation of technique development in long jump and the provision of 'new' comparative (kinematic and kinetic) data in the long jump.

3.0 Pilot Study

The aim of the pilot study was to develop a methodology for effective data collection. Within this the key objectives were,

a) to develop a suitable marking system,

b) to optimise the camera layout, laboratory space and tracking plates,

c) select appropriate segmental data

3.1 Design of the marker plate

The placement of segment markers over the joints was not possible in this study due to i) the motion during run-up and take-off causing disturbance to the markers and ii) their position hindering the run-up action. Therefore attachment of markers on the segments was necessary using plated marker sets. However Manal et al. (2000) found that the errors associated with these differed with location. In addition, the nature of the activity in the present research (jumping into sand) raised further problems including loss of markers or loosening of markers. To develop a suitable marking system the issues investigated were i) tracking the plated marker set, ii) position and attachment of the tracking marker sets, iii) subjects clothing and iv) subject marking. A common marking system was used initially and used to guide the pilot study investigations. http://pdb.cc.nih.gov/resources/instr/degrees/degrees.htm). This used tracking marker plates over the shank and thigh, with foot markers placed over specific landmarks palpable whilst the foot was in a running shoe (Ronsky, Nigg and Fisher, 1995) and hip markers placed over bony landmarks.

Plates were designed for ease of use for the subject when running and to ensure clarity of tracking. Additionally, the subject's age (therefore size) and the possibility of sand infiltration were considered. Some of the important issues to be addressed were movement of the markers, mass, unobtrusive design and ease of tracking.

Tracking marker requirements were:

I. Light weight yet rigid and flexible to adapt to different size/shape of subjects
II. As unobtrusive as possible for the subject
III. Three markers seen by at least 2 cameras
IV. Limited marker merging and easy labelling by the tracking software
V. Functional in a high impact situation (limited movement)
VI. Functional in sand i.e. markers must stay in a fixed position after landing in a sandpit
VII. Adequate fixation to the leg and body.

Initially, a layout was identified as ideal and easy to use for all 4 plates (Holden and Stanhope, 1998; Vogt et al., 2003). The reflective spheres were positioned at an angle for ease of identification and four spheres used, as tracking of a minimum of three was necessary (Lu and Connor, 1999; Manal et al., 2000). Plates tested included a variety of shin pads and plastic protective pads. The rigidity and mould of some plastics was found to be both uncomfortable and lacked flexibility necessary for use with legs of varying shapes and sizes. To ensure the spheres were unlikely to merge, the initial trials had a small wooden plate at the base of the shank plates. This was found to be quite intrusive and increased the mass of the plate significantly. To solve this, the plates were made wider at the base so the spheres could be placed a workable distance apart (Benoit, Ramsay, Lamontagne, Xu, Wretenberg and Renstrom, 2005). Additionally, the mass was also not practicable for use with some subjects, particularly those of a younger age/smaller size. The plates were initially trialled on one leg with both smaller and larger subjects who had already agreed to participate in the research. More flexible and lightweight plastic was sought with both shank and thigh templates produced. Several thicknesses were used and trialled.

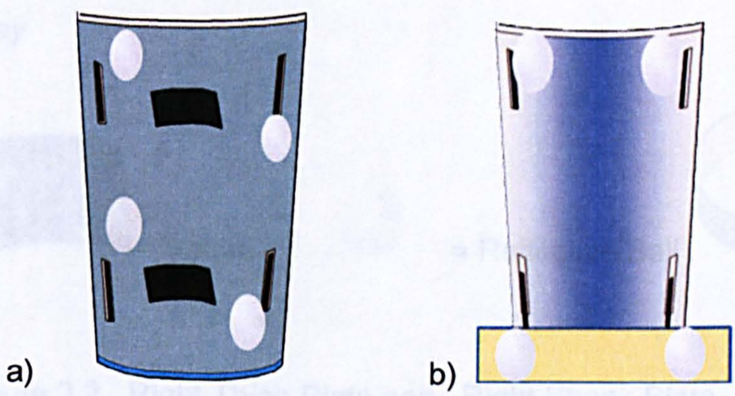
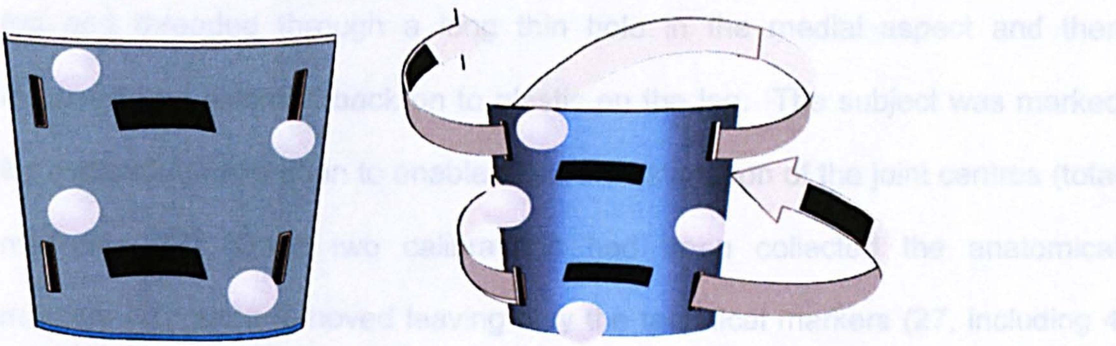


Figure 3.1 Trialled marker plates for shin, a) too small and ridged, b) wooden base (made to separate the markers as the plate wraps around the ankle) but plate too heavy. Markers size 25 mm (diameter).

Once the plate mass was deemed unobtrusive (relatively) by verbal and visual feedback and the plate used successfully on different leg shape/sizes, the tracker plates were trialled to ensure an eight camera system could track the movement adequately. The marker layout was similar to that of Holden and Stanhope (1998). However due to problems tracking the shank (particularly on right foot jumpers) changes were made to the configuration to enable more effective viewing of the tracker plate in the camera field of view and therefore improve consistency (Muijtjens, Roos, Arts, Hasman and Reneman, 1997).

Eventually the design of the plates was as Fig 3.2, made from high impact polystyrene.



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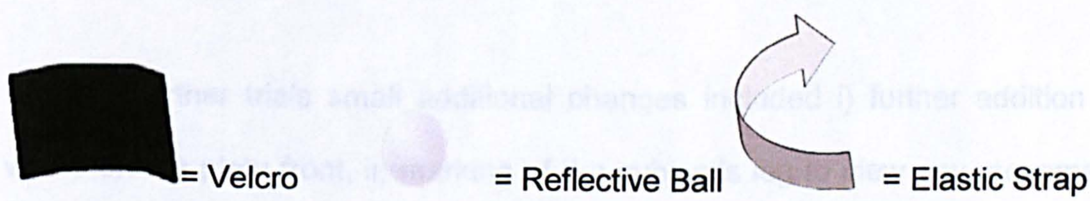


Figure 3.2 Right Thigh Plate and Right Shank Plate (with elastic straps)

3.2 Plate fixation

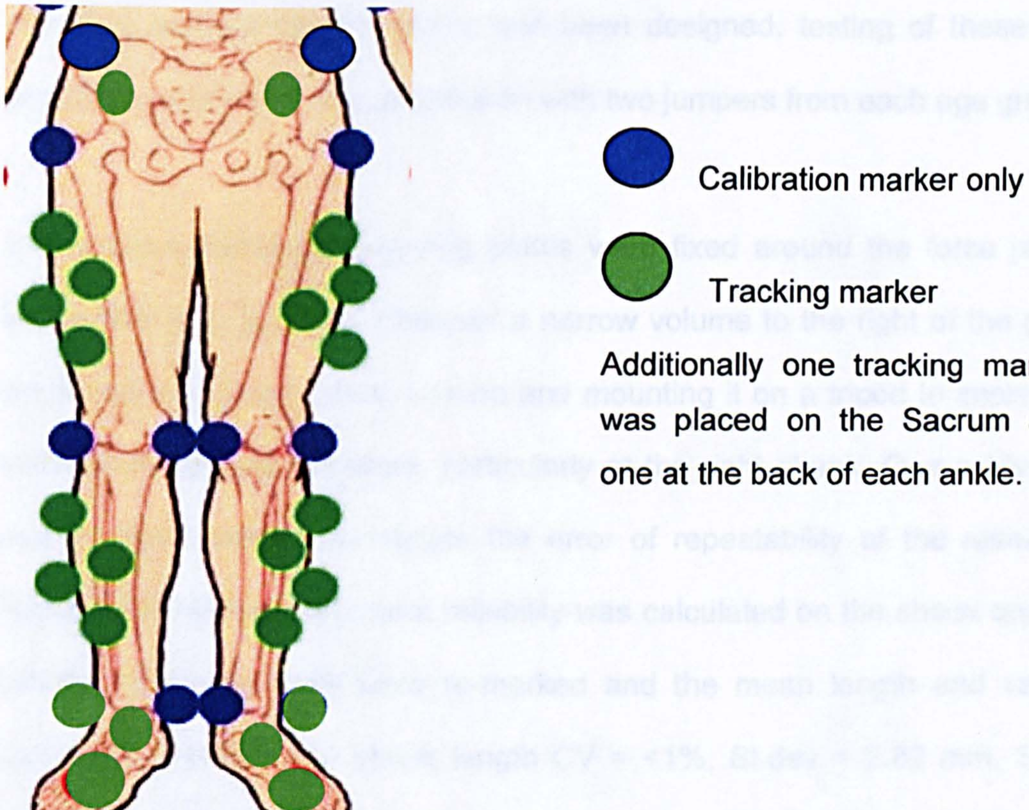
Studies by Manal et al. (2000) have shown that the type of marker fixation is important and they identified distal lateral underwrapped as the most reliable method. However due to the dynamic nature of the long jump (high impact at touchdown) and sand infiltration from landing in the pit, several types of method were trialled. These included underwrapping and overwrapping methods. The underwrapping method was deemed to show movement (particularly at impact) and be particularly unsuitable for use with plates that would be continually placed in sand. The attachment was finalised as a wrap method using elastic and velcro to attach the plate to the leg and shank (see Fig 3.2). Additionally, extra overwrapping was used on the thigh. The thigh plate was fixed laterally and the shank fixed on the front both avoiding the main muscle mass. Initially the elastic was attached on the lateral aspect of the plate passed around the leg and threaded through a long thin hole in the medial aspect and then reversed and velcroed back on to elastic on the leg. The subject was marked for a standing calibration to enable accurate estimation of the joint centres (total markers= 37). Once two calibrations had been collected the anatomical markers (10) were removed leaving only the technical markers (27, including 4 plates) on the subjects thighs, shanks and feet.

Through further trials small additional changes included i) further addition of velcro on the plate front, ii) marking of the subject's leg to view any movement during trials. In conjunction with viewing of the Qualysis (QTM) outputs the plates were made smaller and less intrusive. The velcro straps were attached differently, one on the medial aspect and one on the lateral aspect to provide a counter moment in order to reduce any likely movement. The straps also were extended to wrap around and velcro back onto the front of the plate (see Fig 3.2) for better attachment during the dynamic activity and to overwrap the plates. Legs were marked so that any plate movement could be identified.

It was not possible to use a plate on the foot segment mainly due to the dynamic nature of the activity and the infiltration by sand. Positioning of the tracking markers was dictated by size of the foot, the activity and the marker positions used to identify joint centres. Additional markers were added to the top of the foot and at the back of the ankle (both visible throughout the jump) (Fig 3.2). The four tracking markers were positioned on the heel, 1st metatarsal, top of the foot and the lateral malleolus marker left *in situ* after the standing calibration. To ensure the markers remained in place they were stuck to the shoe, and tape was wrapped around the foot and ankle, to completely overwrap all the marker bases, and reduce the possibility of sand getting under the sticky tape (see Fig 3.3). Subjects were asked to repeatedly jump into the sand to ensure the overwrapping at the foot would not be compromised during the data collection before an adequate method was found.

Figure 3.3 Foot tracking markers (front and side view)

Clothing consisted of tight, short t-shirt/vest, athletic, preferably short lycra bottoms, low cut socks and training shoes or spikes. Marking and viewing the markers was made easier with this clothing. Lycra shorts were allowed to enable attachment to the subject and particularly allowing for greater dignity and comfort (Hazlewood, Hillman, Lawson and Robb, 1997 abstract G&T). Additionally sacrum markers stayed attached for longer on Lycra. In repeated trials, Lycra was deemed to be the most suitable material to attach markers to.



Additionally one tracking marker was placed on the Sacrum and one at the back of each ankle.

Figure 3.4 Marker placement

3.3 Camera layout

In conjunction with the marker plate configuration, the camera layout dictated the ability of the system to pick up the minimum three markers per segment required to acquire the relevant data. The initial testing of the cameras and software took place with the cameras in a fixed position. Familiarity with calibration and software was undertaken using one, and then both legs marked for both right and left leg jumpers. Several parameters within the software settings were changed to identify the best tracking settings to use when executing a jumping action. This actually varied between jumpers and particularly the speed of run up. When the settings had been satisfactorily identified and the marker plates had been designed, testing of these in the laboratory conditions was undertaken with two jumpers from each age group.

The camera positions/ mounting plates were fixed around the force platform and indoor long jump pit. However a narrow volume to the right of the pit was addressed by lowering one camera and mounting it on a tripod to improve the tracking of right foot jumpers, particularly at the right shank. One subject was marked ten times to investigate the error of repeatability of the researcher. Researcher marker placement reliability was calculated on the shank and thigh length. Ten static trials were re-marked and the mean length and variance calculated. Typically for shank length CV = <1%, St.dev = 2.82 mm. System reliability was tested by calibration of the same static marking and comparison of 5 different jumps. Dynamic reliability was calculated by using two different static calibrations on three trials. Application of markers was undertaken solely by the researcher to reduce error. Burkhart, Arthurs and Andrews (2008) point out that measurement differences are smaller and more consistent with one researcher than those associated between researchers.

Data collection took place in an indoor laboratory, the equipment consisted of a long jump pit and run-up (30 m), 3D camera system (8 cameras), force plate (Kistler) and timing lights. The ProReflex system (Qualysis Medical AB, Gothenburg,Sweden) consisting of eight cameras collected data sampling at a rate of 240 Hz. The Kistler force plate (Kistler instruments AG, Winterthur, Switzerland) sampled at 960 Hz and the timing lights were set up to at 11 m, 6 m and 1 m. At least 1 ½ hrs before each session the camera system was calibrated before subject arrived and the timing lights/ force platform checked.

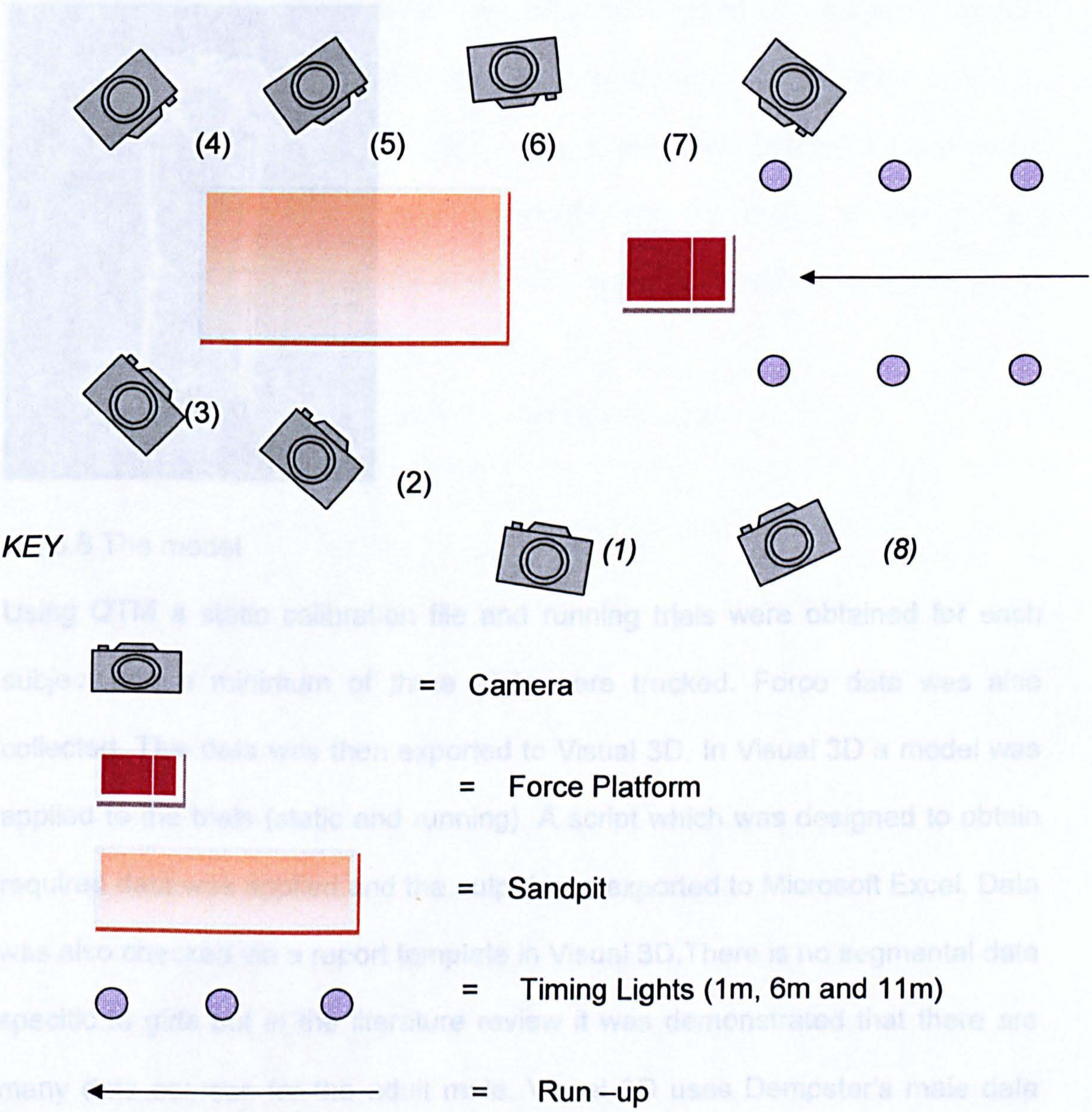


Figure 3.5 Layout of the Laboratory

3.4 Model

The model used was a seven segment anthropometric six degrees of freedom model, based on an elliptical cylinder method (Chester, Tingley and Biden, 2006 Jensen, 1986) (see Fig 3.6). This consisted of i) a pelvis, ii) right and left foot, iii) right and left shank and iv) right and left thigh.

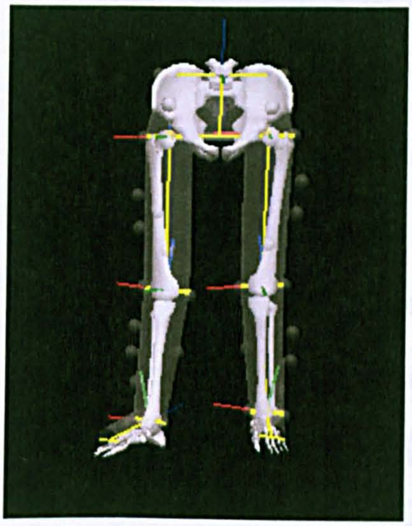


Fig 3.6 The model

Using QTM a static calibration file and running trials were obtained for each subject and a minimum of three trials were tracked. Force data was also collected. This data was then exported to Visual 3D. In Visual 3D a model was applied to the trials (static and running). A script which was designed to obtain required data was applied and the output was exported to Microsoft Excel. Data was also checked via a report template in Visual 3D.There is no segmental data specific to girls but in the literature review it was demonstrated that there are many data sources for the adult male. Visual 3D uses Dempster's male data (default) to build the biomechanical model. As there was very little appropriate female data and little obvious agreement in the literature relating to male or females, the default segmental data were used.

A sensitivity study was carried out to quantify the differences in the data obtained for joint moments and power. This study was undertaken on the most extreme cases of the data categories i.e. two jumpers, the smallest and tallest. As Visual 3D uses Dempster's density ratio and inertial data for use on a geometric model this study used the inertial data based on Caucasian females obtained by Shah and Bonn (2003) for comparison (see Tables 3.2 & 3.3). Within Visual 3D the default mass being taken from Dempster's regression equations and the default mass of inertia and the inertia of the CM are calculated in relation to the segment shape selected. However to change these specific inertial properties can be input.

Table 3.2. Shah and Bonn (2003) inertial values used.

The moments and powers at all joints were compared to observe how the application of differing inertial value would change the data obtained. The output of the same 3 trials of both subjects were processed using Dempster's data, and then using Shah and Bonns (2003) values. The typical error (standard error of measurement) of the means was then calculated (Hopkins, 2000). Typical error was calculated using three trials from each subject and comparing measurements using Dempsters data and Shah and Bonn (2003) data. The typical error is highlighted overleaf in Tables 3.4 and 3.5.

As would be expected the largest error is at the hip (compounded by the calculations). Considering the large power values (1850 W/kg) the values would represent a 2% error @ peak values, which is low. However this would be larger at smaller values, and at the hip particularly.

Table 3.4 Typical error Subject 1 (smallest) (3 trials using two different BSP parameters compared)

Subject 1	Moment			Power (W)		
	Ankle	Knee	Hip	Ankle	Knee	Hip
Typical error (%)						
Trial 1	0.03	1.11	6.48	0.2	8.37	42.35
Trial 2	0.03	0.83	4.15	0.18	6.24	37.16
Trial 3	0.03	0.91	14.65	0.16	8.29	38.18
Mean of 3 above trials	0.03	0.95	8.43	0.18	7.63	39.23
% of peak value	0.02	0.63	6.72	0.02	0.48	9.11

Table 3.5 Typical error Subject 2 (tallest) (3 trials using two different BSP parameters compared)

Subject 2	Moment (Nm)			Power (W)		
	Ankle	Knee	Hip	Ankle	Knee	Hip
Typical error (%)						
Trial 1	0.18	1.22	3.3	0.97	9.1	25.11
Trial 2	0.20	1.07	4.15	1.32	6.27	19.67
Trial 3	0.21	1.15	3.76	1.28	8.8	21.66
Mean of 3 above trials	0.20	1.15	3.74	1.19	8.06	22.15
% of peak value	0.82	0.61	2.00	0.84	0.16	2.08

3.5 Data analysis

Through residual analysis and an inspection of a range of jumps in QTM, from subjects of various abilities, the marker data were filtered with a 4th order Butterworth Filter with cut-off frequency of 15 Hz. Force and Centre of Pressure data were filtered at 40 Hz in Visual 3D.

3.6 Conclusion/summary

The marking system was generally robust and when tracking parameters were adjusted, gave usable data at a variety of run-up speeds. Securing the plates against non-muscle mass and overwrapping ensured limited movement. The plate configuration was easy to track although the right shank was the most likely to have reduced marker tracking. After initial practice, adjustment to the plates occurred quickly. Inevitably, some movement did occur but this was limited and the plates generally maintained their position. Interestingly, sweating under the plates seemed to make them more adhesive to the leg. At TD, vibration of markers did occur particularly at the shank, tracking adjustments helped to minimise the effect of this.

The camera layout was found to be restrictive. Firstly it needed to be adjusted on the right hand side and secondly the inset nature of camera 1 and 8 meant tracking of the support leg was limited before TD of the jump. There was very little that could be done about this however collection of data required to achieve the aims of the study were possible.

Although there is little BSP data for young females, the sensitivity study demonstrated only small error between different inertial values for both young and old subjects. Dempster's data is well established and up to 13 yrs of age male data has been established as applicable to females, so this was then used for the main study. Overall, the methods developed were able to obtain the data.

4.0 Main Study

4.1 Subjects and recruitment

The study was approved by the University's Ethics Committee and an enhanced Criminal Records Bureau clearance was obtained for the author to ensure compliance with ethical procedures. Female subjects were recruited between the ages of 10-16 yrs from the local Southport and Liverpool areas whose parents/guardians gave their informed consent. They were required to volunteer for half a day in order to provide enough time to collect data. Data were collected during the summer period over three years related to the availability of subjects, equipment and resources. Due to the nature of the study and the availability of the equipment, data collection could only take place during summer and subjects were therefore recruited from local schools after Easter in the year of data collection. For ease of recruitment the researcher used,

i) girls from private schools or schools with low percentage free school meal entitlement scores (measures of socio-economic background) for improved parental support in the local area,

ii) girls competing in the local schools' athletic championships and from local athletics clubs.

The nature of the study meant that it was important to identify whether subjects were above or below Tanner's maturational stage 3 (see Appendix G). Therefore, the assistance of Physical Education teachers was required to assist in recruiting female pupils whose jumping could be included (particularly the younger age groups) and therefore time was not wasted with pupils falling outside the categories. Initial contact was made through teachers, coaches or through subjects/parents/teachers at athletic events. Recruitment information sheets were given to all teachers/parents/subject (see Appendix D) and, where relevant, school visits were made to recruit and further inform pupils. Interested pupils then returned the completed consent forms and additional availability forms directly to the researcher or to their Physical Education teacher. Informed consent forms and holiday information/contact details were collected in order to assist organisation of data collection (see Appendices A & B).

The subjects were allowed to be accompanied if required and an observation space for these observers set aside in the research area. Generally two subjects (who knew each other) were tested together as a form of 'reassurance' and to assist in making the subject more comfortable in the experimental area. A minimum of 10 subjects per group were trialled (i.e. 40 girls). A 'private' adjacent area for the collection of height and mass measurements was set aside. Also the sheet for self-identification of Tanner's index was completed in this area (see Appendix C). Testing was completed when 10 subjects per group had been trialled. The groups were divide by age and jump distance (see Fig 4.1 later) into 4 groups, Old Good (OG), Old Poor (OP), Young Good (YG) and Young Poor (YP).

4.2 Subject preparation

Subjects wore gym knickers or lycra shorts (Hazlewood, Hillman, Lawson and Robb, 1997), a short tight fitting top, low cut ankle socks and spikes or training shoes to reduce marker occlusion. All familiarised themselves with the surrounding area (toilets, water etc.), the laboratory and run-up positions were marked.

Subjects warmed up using a combination of aerobic and stretching routines. For the less able this warm up was led by the researcher but the more able had their own routine. The subjects had differing levels of ability some subjects were assisted in identifying a run-up distance marker whilst some already had an established distance. These were checked several times to ensure they could accurately hit the platform. Additionally during the trials, subjects were advised if there was a need to move their run up mark. This was necessary as they adjusted to jumping with the marker sets becoming more familiar with this as they completed more trials.

The subjects were marked as described in the pilot study using the anthropometric landmarks defined by Dempster (1955). The plates were also marked on the leg to ensure no movement had taken place and attached as described in Section 3. Overwrapping was used on the thigh plates and the foot markers were secured in place using insulation tape to stop sand infiltration. The subject was marked for a standing calibration as explained in Chapter 3.

4.3 Data collection and identification

Subjects were instructed to aim for take-off around the middle of the force platform (a line of tape indicated this) to ensure limited error on the force platform and the Centre of Pressure (COP) readings (Middleton, Sinclair and Hatton, 1999). Data were collected for a minimum of at least six, if possible, ten 'good' jumps, which depended on the accuracy of the jumper hitting the board. This was visually checked during the jump and confirmed in the analysis software data window after the jump. Measurements of distance (m) toe-to-board (m) and run-up times were noted on the data collection sheet after each jump (see Appendix C). Any other relevant comments were added onto the data collection sheet. After each jump the marker set was checked to ensure none had been lost and they had maintained their position on the leg. After completion of the jumps, jump length (m) and subject mass (kg) were noted and the subject referred to pictures to self-assess Tanner's stage (Tanner, 1962) (see Appendix G).

4.4 Data Processing

The data (standing and jumping trials) was inspected for any obvious errors and problems before the trials were tracked through the QTM software (Qualysis, Versions :- Beta and 1.9.254). Once this was completed the data was exported and processed through a script in Visual 3D (C-Motion Inc., Rockville MD, USA). The data were inspected and three jumps per subject were processed. Criteria for selection of these was based (in order) on,

1) position on the board,

2) jump distance and

3) repeatability of the trace.

Data were processed using Dempster's segmental data (Visual 3D default). Scripting was developed for both right and left leg trials. The script and report for the 6 degrees of freedom data was processed using Visual 3D (version 3.79) and was written to ensure relevant variables were derived from the kinetic and kinematic data. Through residual analysis and an inspection of a range of jumps from subjects of various abilities, the displacement data was processed using 4th order low-pass Butterworth filter at 15 Hz, with Force and COP data filtered at 40 Hz. Moment and power data were normalised to body mass. Output results were input to an Excel workbook for further processing. The subjects in each age group were subdivided in to 'poor' and 'good' jumpers (identified by jump distance), therefore making the four groups.

4.5 Angle conventions

The laboratory and segment local co-ordinate system (LCS) were defined as as illustrated below in Figure 4.1 (overleaf). The LCs was defined at the proximal joint centre (PJC) for each segment. The foot PJC was located mid-way between the medial and lateral malleolus and its distal joint centre (DJC) was located 0.0035m from the 5th metatarsal, towards the middle of the foot in the plane of the three markers defining the foot. The shank PJC was located between the medial and lateral knee markers, whilst the DJC was at the ankle as defined by the foot. For the thigh, the PJC was located 0.075m from the hip marker towards the middle of the thigh in the plane of the three thigh markers (both knee markers and hip marker). The DJC was at the knee as defined for the shank. The pelvis PJS was located midway between the iliac crest markers and and the DJC was located midway between the thigh proximal centres. For all segments the positive Z (internal/external rotation axis was defined in the direction of distal to proximal joint centres. The positive Y (abduction/adduction) was defined as perpendicular to the Z axis and the plane of the segment (as determined by the three or four markers defining the segment), while the X (flexion/extension) axis was defined as the vector cross product of Y and Z.

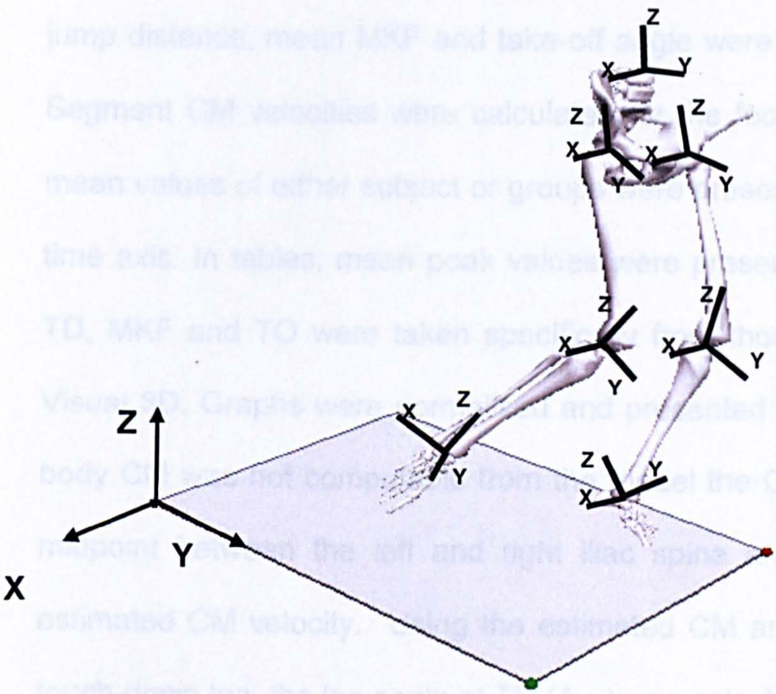


Figure 4.1 Angle convention

4.6 Data analysis

Mean kinematic and kinetic data for the four groups were obtained. In addition the best YG and OG jumper had data collected over two consecutive years in order to track individual changes occurring in the development of their individual technique. Variables were calculated using a script which used displacement and force data to calculate other relevant variables. These included joint angles, linear/angular velocities, joint moment, joint power and work done data for the hip, knee and ankle joints. Work done was calculated in Microsoft Excel using the power data exported from Visual 3D. Normalisation of moment, power and work done was by body weight. All data were collected around the x, y, and z axes in the corresponding planes yz, xz and xy. Initial comparison was made in the sagittal plane with supporting evidence drawn from the frontal and transverse planes. In addition, run-up speed (calculated from timing lights at 11-6 m, 6-1 m and 11-1 m), jump distance, mean MKF and take-off angle were obtained in the sagittal plane. Segment CM velocities were calculated for the foot, shank and thigh. Graphs of mean values of either subject or groups were presented with frames indicating the time axis. In tables, mean peak values were presented from all data but data for TD, MKF and TO were taken specifically from those time points as identified in Visual 3D. Graphs were normalised and presented by frame number. As a whole body CM was not computable from the model the CM was estimated (eCM) as a midpoint between the left and right iliac spine and was used to compare the estimated CM velocity. Using the estimated CM and the lateral malleolus of the touch-down leg, the leg angle at TD (A_{TD}) was calculated.

4.7 Statistical Analysis

Comparisons for each variable at TD, MKF and TO, and the peak values between TD-MKF and MKF-TO (i.e. during peak flexion or extension) across the groups were made using a repeated measures ANOVA (3 trials x 3 events x 4 groups), using Mauchly's test of Sphericity and Greenhouse – Geisser Epsilon correction if appropriate. Bonferroni post–hoc tests were carried out. Significance was established at an alpha level of .05. Normality was tested using Shapiro-Wilks test (SPSS version 16). T-tests of mean run-up velocities, jump distance, height, mass, segment velocity, CM velocities, and joint angle changes were carried out to establish group differences.

4.8 Division of groups

Groups were divided into four groups by age and then by jump distance (as an indicator of ability) in order to investigate differences between the group performances.

i) Old Good (OG), mean age 15.0 ±0.5 yrs, mean jump distance 4.05 ± 0.22 m

ii) Old Poor (OP), mean age 15.2 ± 0.8 yrs, mean jump distance 3.25 ± 0.38 m

iii) Young Good (YG), mean age13.2 ± 0.5 yrs, mean jump distance 4.07 ± 0.3 m

iv) Young Poor (YP), mean age 12.6 ± 0.7 yrs, mean jump distance 3.20 ± 0.3 m

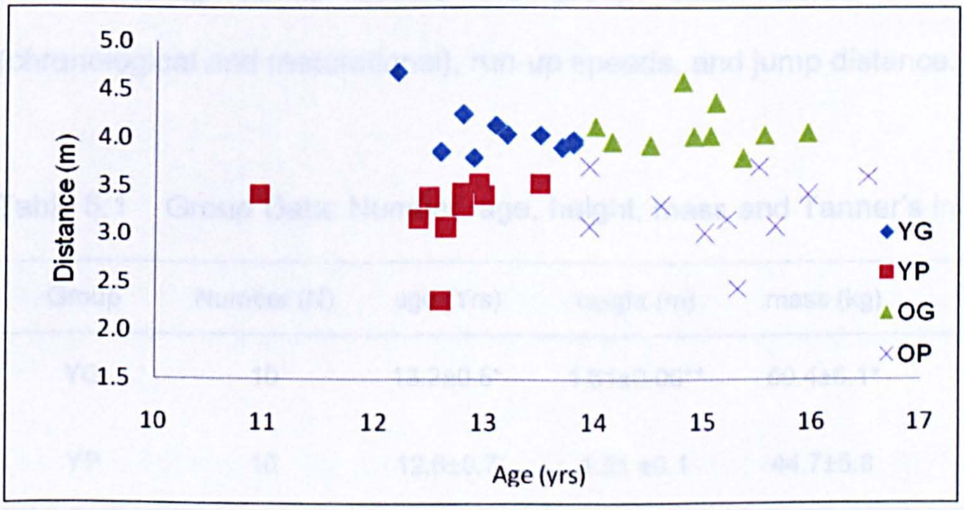


Figure 4.2 Distance jumped related to age: all groups.

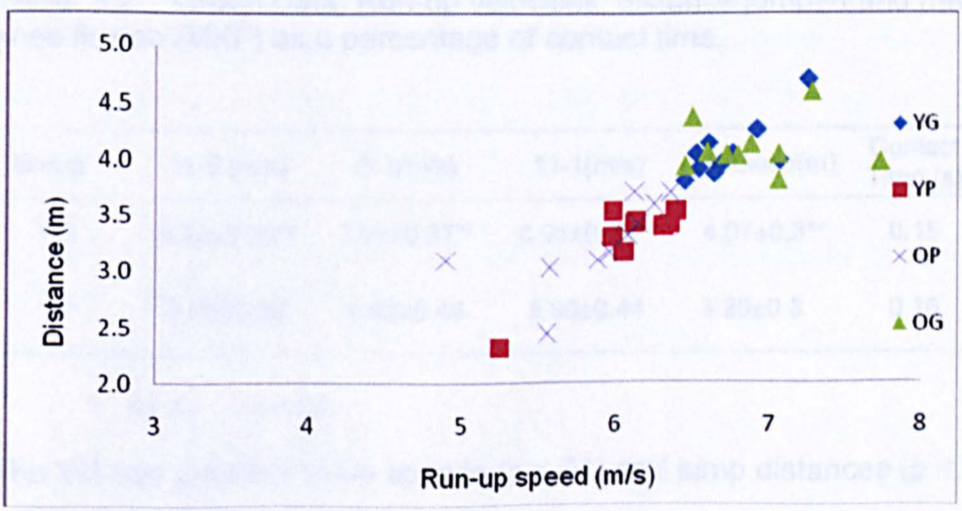


Figure 4.3 Distance jumped and run-up speed: all groups.

5.0 Results and Discussion for the Young Group

The results are divided into sections in the following order. Group data, CM velocities, segment CM velocities, joint angles, segment angles to laboratory, joint angular velocities, moments, powers and work done. This is addressed in the sagittal plane initially using quantative data and then widened to include frontal and transverse plane qualitative data. The good ability group (YG) data are always presented before the poor ability group (YP).

5.1 Group Data

The following tables outline the group data related to development (chronological and maturational), run-up speeds, and jump distance.

Table 5.1 Group Data: Number, age, height, mass and Tanner's index

Group	Number (N)	age (Yrs)	height (m)	mass (kg)	Tanner's
YG	10	13.2±0.5*	1.61±0.06**	50.4±6.1*	2.2±1.0
YP	10	12.6±0.7	1.51 ±0.1	44.7±5.8	1.7±0.5

** p<.01 * p<.05

Table 5.2 Group Data: Run-up velocities, distance jumped and maximum knee flexion (MKF) as a percentage of contact time.

Group	11-6 (m/s)	6-1(m/s)	11-1(m/s)	Distance(m)	Contact Time (s)	MKF (%)
YG	6.24±0.36**	7.25±0.37**	6.91±0.39**	4.07±0.3**	0.15	44.5
YP	5.58±0.30	6.42±0.46	5.90±0.44	3.20±0.3	0.16	45.3

** p<.01 * p<.05

The YG had greater run-up speeds (p <.01) and jump distances (p <.01). They reached MKF slightly earlier in the support period than the YP but this was not significant.

5.2 Sagittal plane data

5.2.1 Estimated CM velocity

Graphs of estimated mean CM horizontal and vertical velocities from TD –TO are given in Fig 5.1 with mean values at TD, MKF and TO given in Table 5.3 and changes TD-MKF, MKF-TO and TD-TO given in Table 5.4

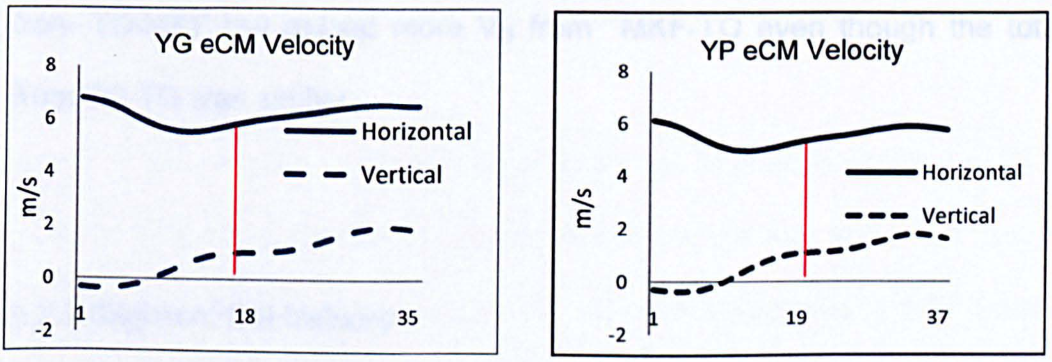


Figure 5.1 Estimated mean CM horizontal and vertical velocities from TD to TO (the vertical line indicates MKF) represented by the midpoint between right and left iliac spine .

Table 5.3 Estimated CM vertical and horizontal velocities (TD, MKF and TO)

	TD		MKF		TO		TO
	V_H (m/s)	V_V (m/s)	V_H (m/s)	V_V (m/s)	V_H (m/s)	V_V (m/s)	angle (^{0})
YG	6.80+/- 0.24**	-0.31+/-0.20	5.81+/-0.45**	1.02+/-0.21	6.39+/- 0.42**	1.65+/- 0.33**	15.0+/- 4.0
YP	6.10+/-0.40	-0.30+/-0.20	5.22+/-0.39	1.00+/-0.21	5.71 +/- 0.48	1.44 +/- 0.30	14.8+/- 3.0

** *p<.01*

Table 5.4 Changes in estimated CM vertical and horizontal velocities between TD-MKF, MKF-TO and TD-TO.

	TD-MKF		MKF-TO		TD-TO	
	V_H (m/s)	V_V (m/s)	V_H (m/s)	V_V (m/s)	V_H (m/s)	V_V (m/s)
YG	-0.99+/- 0.36	1.31+/-0.26	0.58+/-0.33	0.65+/-0.31	-0.41+/- 0.43	1.96+/- 0.46
YP	-0.88+/-0.19	1.29+/-0.25	0.48+/-0.24	0.44+/-0.43	-0.40+/- 0.25	1.73+/- 0.25

The CM velocity profiles are very similar. At TO both groups have a similar take-off angle (NS), and a similar loss in horizontal velocity (NS) but the YG developed a slightly greater vertical (Vv)(NS) and greater horizontal (V_H) ($p<.01$) velocity. The increase in V_V occurred after MKF. The larger horizontal velocity reflected the larger TD horizontal velocity of the YG group. The YG lost the same amount of V_H but had a larger increase in V_V. The YG also lost more V_H from TD-MKF but gained more V_H from MKF-TO even though the total loss from TD-TO was similar.

5.2.2 Segment CM Velocity

Graphs of group mean segment CM velocities (horizontal) from TD–TO are given in Fig 5.2 with mean values at TD, TO and TD-TO given in Table 5.5 Graphs of group mean segment CM velocities (vertical) from TD –TO are given in Fig 5.3. with mean values at TD, TO and TD-TO given in Table 5.6.

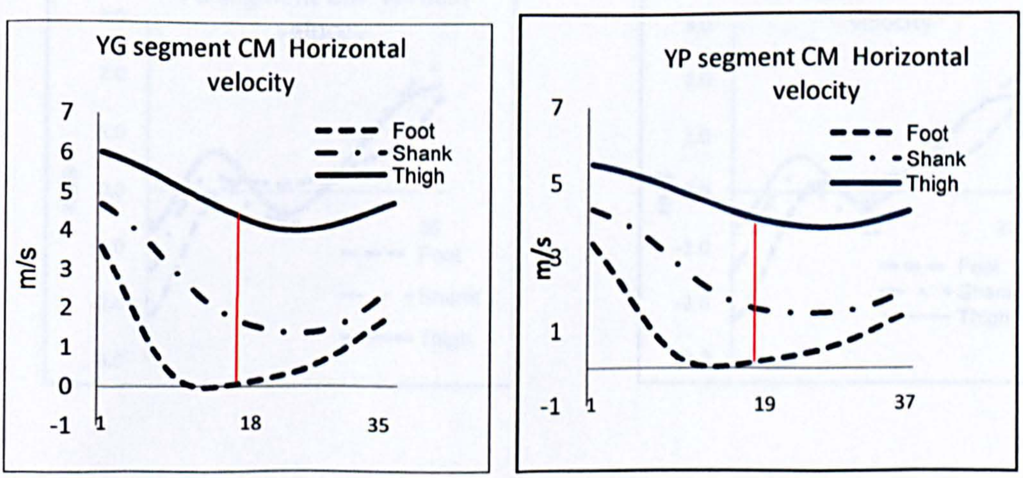


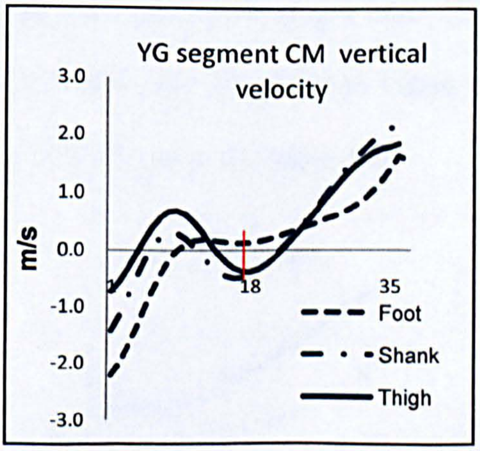
Figure 5.2 Mean segment CM horizontal velocities (V_H) for foot, shank and thigh from TD to TO of the take-off leg (the vertical line indicates MKF).

Table 5.5 Mean segment CM horizontal velocities (V_H) at TD, TO and TD-TO

Segment	YG Velocity (m/s)			YP Velocity (m/s)		
	TD	TO	TD -TO	TD	TO	TD -TO
Foot	3.59	2.31	-1.52	3.35	2.06	-1.29
Shank	4.69**	3.57	-1.06	4.28**	3.20	-1.08
Thigh	6.01**	5.13	-0.92	5.48**	4.69	-0.80

**$p < .01$

The YG had higher horizontal velocities in all segments at TD and TO. From TD-TO. The YG lost more horizontal velocity at the foot and thigh, and less at the shank. Fig 5.2 shows that the YG lost more velocity up to MKF (particularly shank and thigh) but then developed increased horizontal velocity after MKF particularly at the shank and thigh. These observations confirm the general velocity pattern seen above for the eCM.



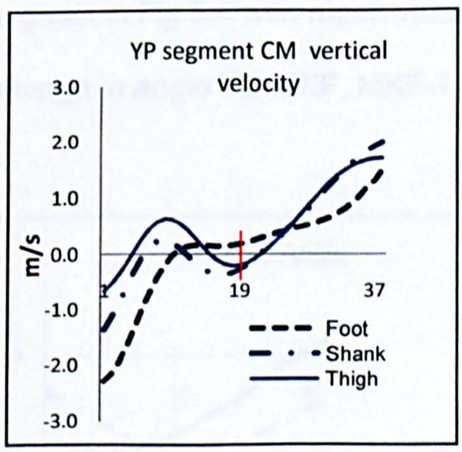


Figure 5.3 Mean segment CM vertical velocities (V_V) for Foot, Shank and Thigh from TD to TO of the take-off leg (the vertical line indicates MKF).

Table 5.6 Segment CM vertical velocities (V_V) at TD, TO and TD-TO

Segment	YG Velocity (m/s)			YP Velocity (m/s)		
	TD	TO	TD -TO	TD	TO	TD - TO
Foot	-2.32	2.2**	4.19	-2.34	1.88*	4.22
Shank	-1.50	2.54**	3.83	-1.36	2.14**	3.50
Thigh	-0.76	1.95*	2.54	-0.67	1.77*	2.44

*p <.05 ** p< .01

The vertical velocity curves are similar however the YG showed an increase in shank velocity after MKF leading to greater vertical velocities in other segments at TO. The YG had greater downward (-ve) shank and thigh velocities at TD and larger upward (+ve) shank velocities at TO. From TD-TO the YG generated a larger change in V_v at the shank and had similar V_v change at the foot and thigh. The greater V_v at the shank in YG is reflected in the eCM V_v previously noted.

5.2.3 Joint angle

Graphs of mean joint angle from TD –TO are given in Fig 5.4 with mean values at TD, MKF and TO given in Table 5.7 and change in angle TD-MKF, MKF-TO and TD-TO given in Table 5.8.

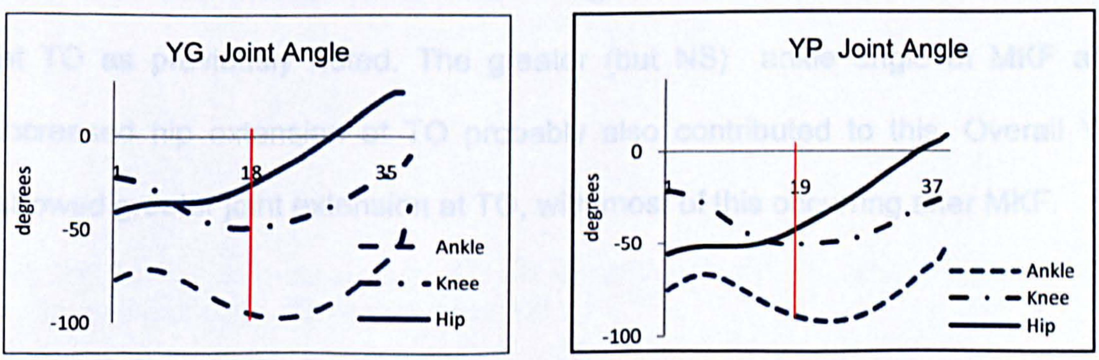


Figure 5.4 Mean joint angle at ankle, knee and hip from TD to TO (the vertical line indicates MKF). All joints flexion (-), extension (+).

Table 5.7 Mean joint angle of ankle, knee and hip at TD, MKF and TO.

.	YG			YP		
	TD	MKF	TO	TD	MKF	TO
Ankle (°)	-77.9	-94.3	-55.2	-75.3	-87.2	-51.5
Knee (°)	-22.1	-50.5	-14.0*	-21.7	-50.7	-22.7*
Hip (°)	-44.5	-33.1	25.2	-55.9	-43.4	9.1

* $p<.05$

Table 5.8 Joint angle changes of ankle, knee and hip between TD-MKF, MKF-TO and TD-TO.

	YG			YP		
	TD-MKF	MKF-TO	TD-TO	TD-MKF	MKF-TO	TD-TO
Ankle (°)	-16.5	39.1	22.7	-11.9	35.7	23.8
Knee (°)	-29.2	36.8	8.1	-29.0	28.0	-1.0
Hip (°)	11.4	58.3	69.7	12.5	52.5	65.0

The graphs for YG and YP are similar in shape with both ankle and knee showing flexion followed by extension and the hip having continuous extension throughout. Differences in hip angle occurred at TD and MKF wih YG having more hip extension at TO. Knee angle was significantly ($p<.05$) straighter in the YG at TO which would contribute to their greater horizontal and vertical velocity at TO as previously noted. The greater (but NS) ankle angle at MKF and increased hip extension at TO probably also contributed to this. Overall YG showed greater joint extension at TO, with most of this occurring after MKF.

5.2.4 Posture

Group mean segment angles relative to Lab from TD –TO are shown in Table 5.9 .

Table 5.9 Segment angles relative to laboratory. Segment moved past vertical (+), behind vertical (-).

	TD		MKF		TO	
	YG	YP	YG	YP	YG	YP
$A_{(PelvLab)}(^{o})$	7.4	12.7	6.4	10.7	-5.3	-1.3
$A_{(ThighLab)}(^{o})$	-41.4	-42.7	-29.7	-32.6	19.4**	13.0**
$A_{(ShankLab)}(^{o})$	-17.6*	-20.7*	23.1	20.8	36.0	36.4
$A_{(FootLab)}(^{o})$	-94.0	-88.6	-69.1	-67.1	-17.5	-15.5
$A_{(TD)}(^{o})$	67.5	68.5				

*p<01 *p<.05

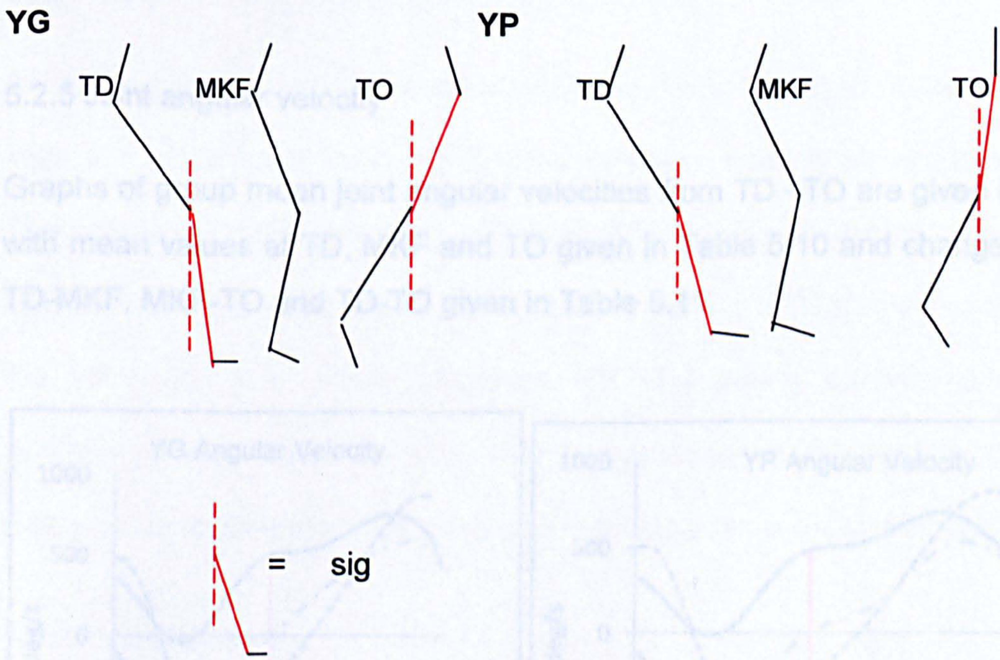


Figure 5.5 Stick diagrams at TD, MKF and TO for YG and YP. Red lines indicate significant differences at p<.05.

There were significant differences in $A_{(ShankLab)}$ at TD and $A_{(ThighLab)}$ at TO and small non-significant difference in the $A_{(PelvLab)}$ at TD and TO. The YG had a more 'upright' pelvis at TD and a more backward tilt at TO. Generally this suggests the YG had their pelvis inclined more backward throughout the jump than the YP. The shank was also more upright at TD in the YG moving through a similar angle and having a greater forward lean at MKF which in combination with the more upright $A_{(ThighLab)}$ suggests the thigh CM had moved further over the foot. The YG also had an increased thigh to vertical angle at TO which along with the backward pelvis tilt explains the increased hip extension at TO noted above. At this point the shank was at a similar angle in both groups therefore knee extension differences at TO are attributable to the increased hip extension in the YG.

5.2.5 Joint angular velocity

Graphs of group mean joint angular velocities from TD –TO are given in Fig 5.6 with mean values at TD, MKF and TO given in Table 5.10 and change in angle TD-MKF, MKF-TO and TD-TO given in Table 5.11.

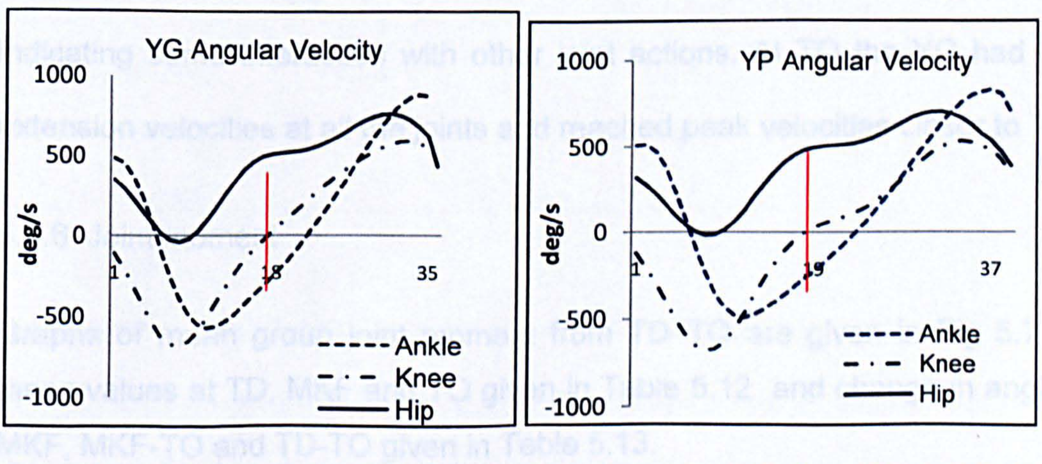


Figure 5.6 Mean angular velocity at ankle, knee and hip from TD to TO (the vertical line indicates MKF). All joint angular velocities flexion (-), extension (+).

Table 5.10 Mean angular joint velocity of ankle, knee and hip at TD, MKF and TO. All joints extension (+), flexion (-).

	YG			YP		
	TD	MKF	TO	TD	MKF	TO
Ankle (deg/s)	518.1	-312.7	824.7	456.7	-216.7	724.0
Knee (deg/s)	-75.7	-22.6	390.8	-138.1	-10.6	301.2
Hip (deg/s)	349.4	423.2	433.6	321.4	500.4	308.9

Table 5.11 Mean peak flexion and extension angular velocities

	YG		YP	
	Peak flex	Peak ext	Peak flex	Peak ext
Ankle (deg/s)	573.0	884.5	462.3	586.8
Knee (deg/s)	-688.7	595.3	-706.8	456.1
Hip (deg/s)	0	766.2	0	480.3

At TD the hip and ankle were extended while the knee flexed. Subsequently the knee and ankle joints flexed and the hip extension velocity slowed to near zero. The hip quickly extended again so that by MKF the hip extension countered the flexion of the knee and ankle. All joints then extend to TO. Knee extension for the YP seemed to plateau between MKF-TO before continuing to extend indicating some interaction with other joint actions. At TO the YG had higher extension velocities at all the joints and reached peak velocities closer to TO.

5.2.6 Joint moment

Graphs of mean group joint moment from TD–TO are given in Fig 5.7 with mean values at TD, MKF and TO given in Table 5.12 and change in angle TD-MKF, MKF-TO and TD-TO given in Table 5.13.

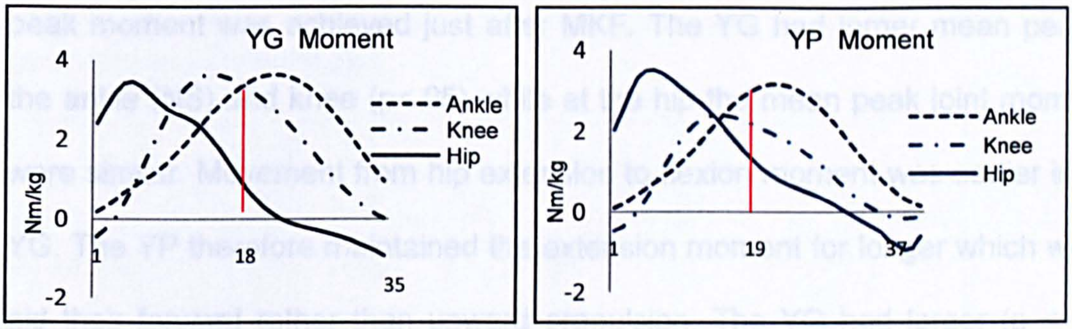


Figure 5.7 Mean joint moment at ankle, knee and hip (normalised to body mass) from TD to TO (the vertical line indicates MKF). All joints moments, extension (+), flexion (-).

Table 5.12 Mean joint moment of ankle, knee and hip at TD, MKF and TO (normalised to body mass).

	YG			YP		
	TD	MKF	TO	TD	MKF	TO
Ankle (Nm/kg)	0.17	3.22	0.07	0.09	2.74	0.05
Knee (Nm/kg)	-0.44	3.40**	-0.23	-0.45	2.26**	-0.14
Hip (Nm/kg)	1.97	1.41	-1.42	1.71	1.47	-1.22

** p<.01

Table 5.13 Mean peak flexion and extension moments (normalised to body mass).

	YG		YP	
	Peak flex	Peak ext	Peak flex	Peak ext
Ankle (Nm/kg)	0.03	3.61	-0.004	3.16
Knee (Nm/kg)	-0.45	3.62*	-0.47	2.40*
Hip (Nm/kg)	1.11	3.44	0.81	3.52

*p<.05

The joints demonstrated mainly extension moments throughout the contact period although after MKF the hip demonstrated a flexion moment and toward TO the knee had a small flexion moment. Peak hip moment was reached slightly after TD. Knee peak moment was achieved just before MKF while ankle peak moment was achieved just after MKF. The YG had larger mean peak at the ankle (NS) and knee (p<.05) while at the hip the mean peak joint moments were similar. Movement from hip extension to flexion moment was earlier in the YG. The YP therefore maintained the extension moment for longer which would aid their forward rather than upward propulsion. The YG had larger (p < .01) knee moments at MKF.

5.2.7 Joint power

Graphs of group mean normalised power from TD –TO are given in Fig 5.8 with mean values at TD, MKF and TO given in Table 5.14 and peak mean power values are given in Table 5.15.

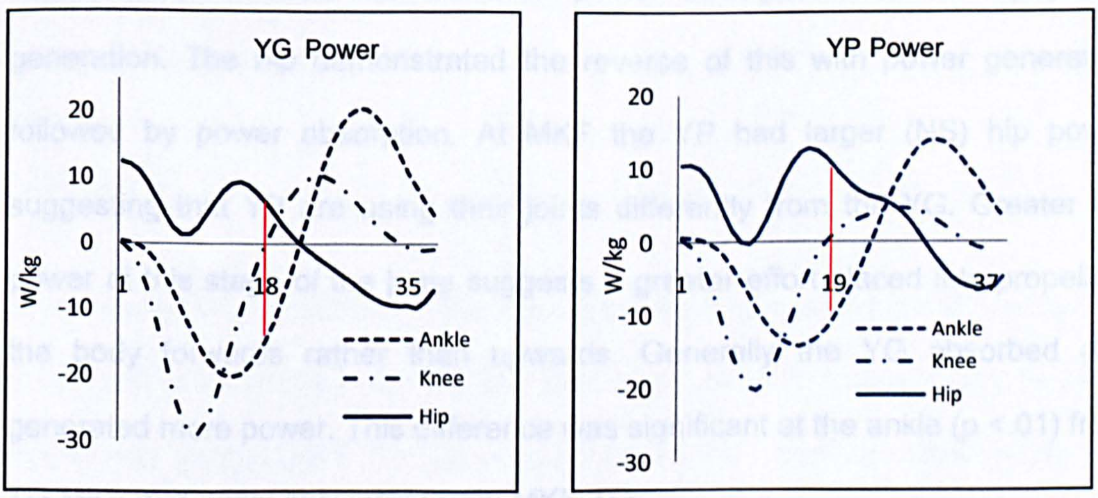


Figure 5.8 Mean joint power at ankle, knee and hip (normalised to body mass) negative = power absorption, positive = power generation from TD to TO (the vertical line indicates MKF).

Table 5.14 Mean joint power of ankle, knee and hip at TD, MKF and TO (normalised to body mass).

	YG			YP		
	TD	MKF	TO	TD	MKF	TO
Ankle (W/kg)	0.3	-13.9	2.2	0.4	-10.0	1.5
Knee (W/kg)	-0.5	-3.2	-1.4	0.4	-0.4	-0.7
Hip (W/kg)	12.3	6.8	-8.2	9.7	11.6	-6.1

Table 5.15 Mean peak absorption and generation power (normalised to body mass)

	YG		YP	
	abs	gen	abs	gen
Ankle (W/kg)	-20.3	20.5*	-14.4	13.8*
Knee (W/kg)	-28.9	10.2	-20.4	4.6
Hip (W/kg)	-9.8	12.4	-6.5	12.6

p<.01

The ankle and knee demonstrated power absorption followed by power generation. The hip demonstrated the reverse of this with power generation followed by power absorption. At MKF the YP had larger (NS) hip power suggesting that YP are using their joints differently from the YG. Greater hip power at this stage of the jump suggests a greater effort placed into propelling the body forwards rather than upwards. Generally the YG absorbed and generated more power. This difference was significant at the ankle (p <.01) from TD-MKF and noticeably larger from MKF-TO.

5.2.8 Work done in the sagittal plane

Graphs of group mean work done (%) contributions from TD –TO are given in Fig 5.9 with mean normalised and % work done values in Table 5.16.

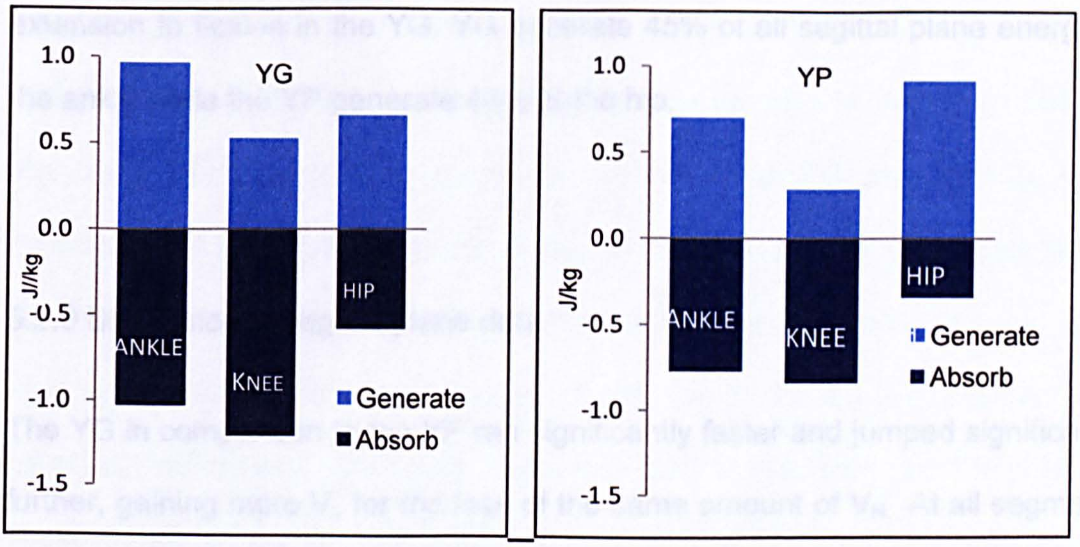


Figure 5.9. Sagittal plane normalised work done contributions.

Table 5.16 Sagittal plane normalised and percentage work done contributions.

	Ankle		Knee		Hip	
	YG	*YP*	*YG*	*YP*	*YG*	*YP*
Absorb (J/kg)	1.03	0.77	1.21	0.84	0.58	0.34
Generate (J/kg)	0.97	0.70	0.53	0.29	0.66	0.91
Absorb %	37.1	39.5	42.8	43.0	30.6	20.1
Generate %	44.6	36.8	24.4	15.2	31.0	48.1

Most energy was absorbed at the knee followed by the ankle. Most energy was generated at the ankle in the YG and the knee in the YP. It should be noted that the energy generated at the hip occured early in the contact period, while that generated at the ankle and knee were in the later contact period. The YG absorbed more energy at all joints. They also generated more at the ankle and knee, but less at the hip compared to the YP group. Increased generation at the knee and ankle seems to be due to an increased extension moment and the decreased generation at the hip due to early change of joint moment from extension to flexion in the YG. YG generate 45% of all sagittal plane energy at the ankle while the YP generate 48% at the hip.

5.2.9 Discussion of sagittal plane data

The YG in comparison to the YP ran significantly faster and jumped significantly further, gaining more V_v for the loss of the same amount of V_H. At all segments they had a higher segment CM horizontal velocity at TD for all segments and maintained this at the shank and thigh at TO. At TD, the YG had a more upright shank, less forward tilt of the pelvis and slightly larger joint angular velocities. From TD-MKF the YG lost more CM V_H but generated this difference after MKF alongside an increased V_v perhaps suggesting increased braking effect TD-MKF and improved concentric muscle extension ability from MKF-TO. Between TD-MKF the YG had increased ankle flexion velocities, slightly smaller peak knee flexion velocity, and significantly increased peak knee moment and ankle power. Both groups absorbed energy at the ankle and knee that in absolute terms was larger in the YG. By MKF the YG had a posture at the thigh, shank and pelvis that suggested a more forward and upright body position with an increased and significant knee joint moment (possibly due to posture and increased ankle flexion velocity) both of which may have contributed to improved extension and CM V_H loss. From MKF-TO the YG developed increased peak angular velocities (achieving these closer to TO), had a smoother knee extension angular velocity curve and increased peak power at the ankle and knee. At TO the knee and hip were more extended. Noticeably, both groups had similar knee angles at TD and MKF. In contrast, hip angles differed at these points and TO. The YG increased their CM Vv which may have been attributable to the shank and ankle segment CM V_v increase at TO. Increased peak powers at ankle and knee in the YG are attributable to increased knee and ankle joint moments alongside larger extension velocities at these joints. In the YG, shorter duration extension joint moment at the hip limits work generated at the hip and together with the increased joint moment and extension velocities at the ankle meant that the YG produced most work at the ankle. In contrast this occurred at the hip in the YP. However with all the outlined previous differences the final take-off angle was similar in both groups.

5.2.10 Overall evaluation

The YG showed some limited pivot characteristics, such as increased run-up velocity and initial V_H loss. A more forward position at MKF alongside increased ankle and knee joint moments assisted joint extension velocities, significantly increasing segment CM V_V at TO and energy generation at the ankle and knee. The YG showed increased knee extension at TO probably accounting for a larger V_H increase at TO. Both groups show limited V_V increase TD-MKF but the YG seem more successful after MKF resulting from either increased strength, greater ankle flexion (leading to increased V_V development after MKF), a more advantageous position at MKF and/or a combination of all.

5.3 Frontal and transverse planes

The analysis was conducted in 3D and so qualitative data available are available for the joint frontal and transverse planes to supplement that described above for the sagittal plane.The sagittal plane graphs are included for comparison.

5.3.1 Joint angle: Frontal and transverse planes

Graphs of group mean joint angles from TD –TO are given in Fig 5.10 (YG) and Fig 5.11 (YP).

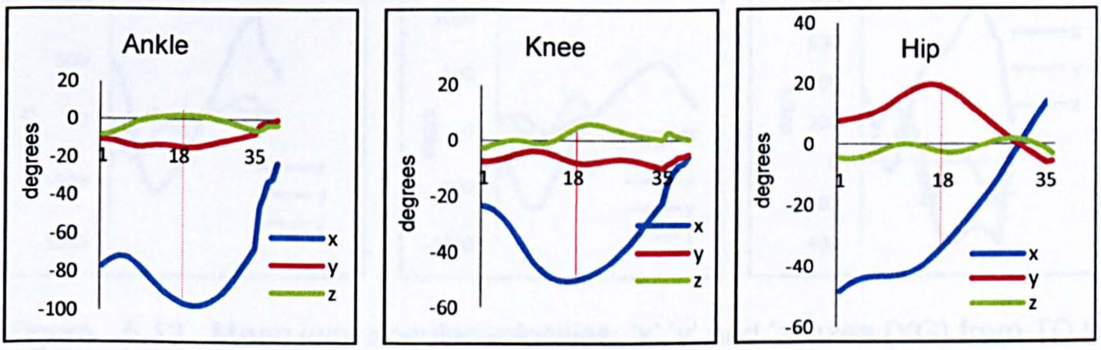


Figure 5.10 Mean joint angles: ‘x’,‘y’ and ‘z’ axes (YG) from TD to TO (the vertical line indicates MKF). All joints, extension (+), adduction (+) and internal rotation (+).

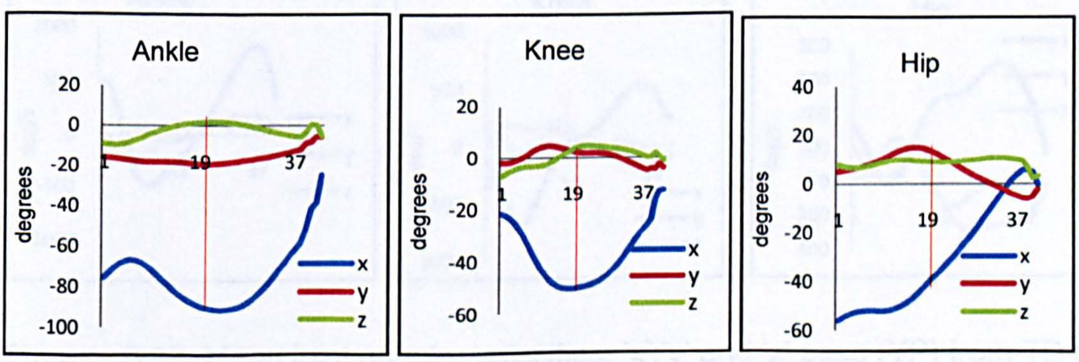


Figure 5.11 Mean joint angles: ‘x’,‘y’ and ‘z’ axes(YP) from TD to TO (the vertical line indicates MKF). All joints, extension (+), adduction (+) and internal rotation (+).

Knee profiles were similar however the YG showed mainly adduction whilst the YP some adduction through the jump. At the hip similar profiles and differing magnitudes occurred as the YG had limited rotation at the hip while the YP showed 10° rotation throughout the contact phase.

5.3.2 Joint angular velocity: Frontal and transverse planes

Graphs of group mean joint angular velocities from TD –TO are given in Fig 5.12 (YG) and Fig 5.13 (YP).

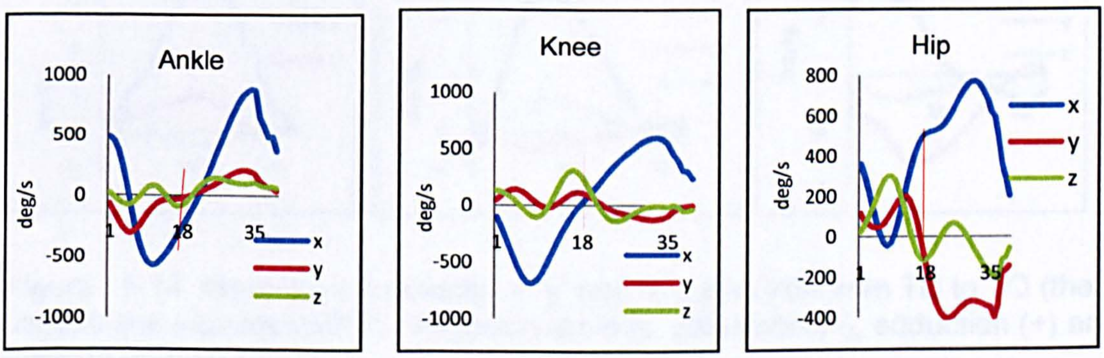


Figure 5.12 Mean joint angular velocities: 'x','y' and 'z' axes (YG) from TD to TO (the vertical line indicates MKF). All joint velocities, extension (+), adduction (+) and internal rotation (+).

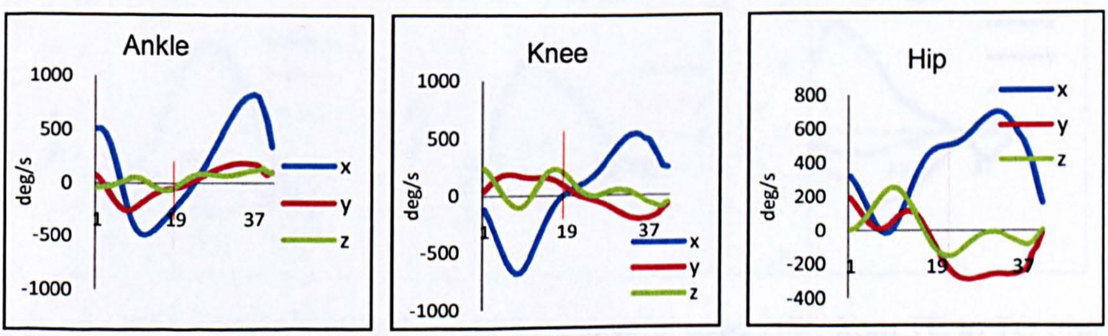


Figure 5.13 Mean joint angular velocities: 'x','y' and 'z' axes (YP) from TD to TO (the vertical line indicates MKF). All joint velocities, extension (+), adduction (+) and internal rotation (+).

At the knee, the YG show a more sustained adduction velocity from TD-MKF and a larger abduction velocity with peaks around 200 deg/s from MKF-TO. The abduction angular velocities were largest at the hip, particularly in the YG where they reach 400 deg/s.

5.3.3 Joint moment : Frontal and transverse planes

Graphs of group mean moment from TD –TO are given in Fig 5.14 (YG) and 5.15 (YP).

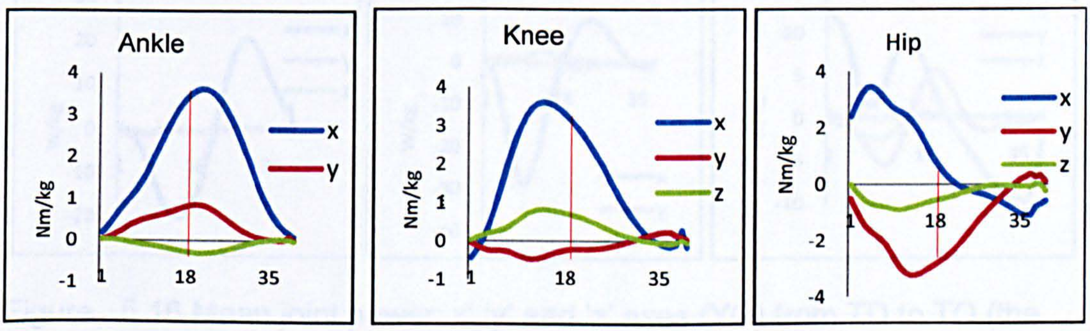


Figure 5.14 Mean joint moments: x','y' and 'z' axes (YG) from TD to TO (the vertical line indicates MKF). All joint moments, extension (+), adduction (+) and internal rotation (+).

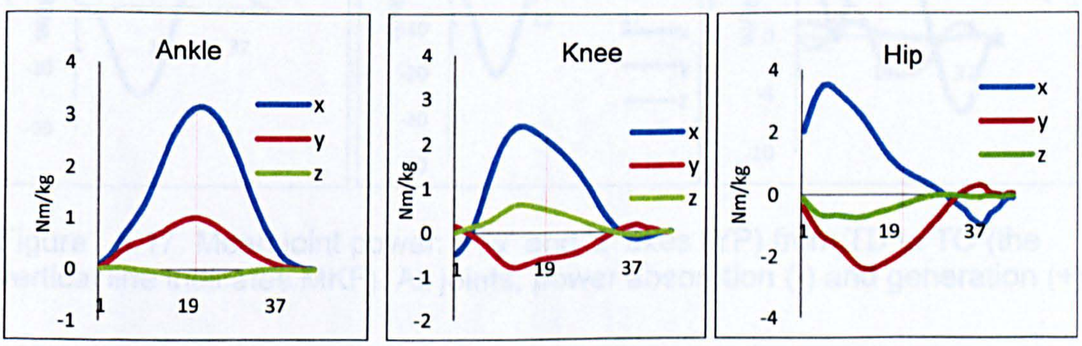


Figure 5.15 Mean joint moments: x','y' and 'z' axes (YP) from TD to TO (the vertical line indicates MKF). All joint moments, extension (+), adduction (+) and internal rotation (+).

At the knee the YG had a smaller peak abduction moment. The YG have an increased abduction moment at the hip, but both groups generate relatively large hip abduction moments.

5.3.4 Joint power : Frontal and transverse planes

Graphs of group mean power from TD –TO are given in Fig 5.16 (YG) and Fig 5 .17 (YP).

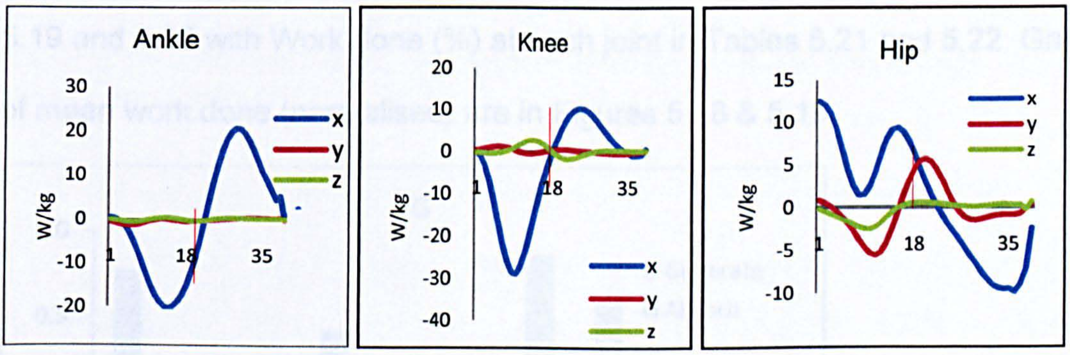


Figure 5.16 Mean joint power: x','y' and 'z' axes (YG) from TD to TO (the vertical line indicates MKF). All joints, power absorption (-) and generation (+).

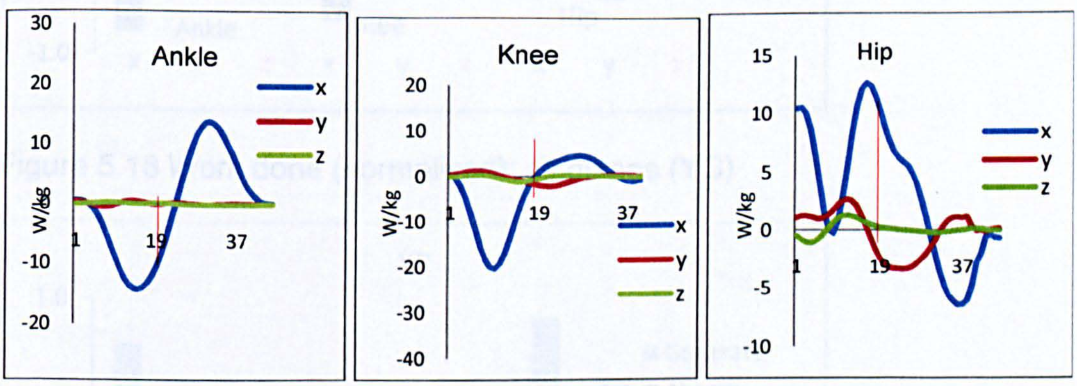


Figure 5.17 Mean joint power: x','y' and 'z' axes (YP) from TD to TO (the vertical line indicates MKF). All joints, power absorption (-) and generation (+).

Most power was generated in the sagittal plane however at the hip, the profile and magnitude of peak hip adduction and abduction differed between the groups. The YG had a negative peak (before MKF) followed by a positive peak (after MKF) which was reversed in the YP. Power differs between the groups mostly in the frontal plane at the hip.

5.3.5 Joint work done: Frontal and transverse planes

Values of group mean % work done and normalised (all planes) are in Tables 5.17 and 5.18. Work done (% and normalised) in each planes are in Tables 5.19 and 5.20 with Work done (%) at each joint in Tables 5.21 and 5.22. Graphs of mean work done (normalised) are in Figures 5.18 & 5.19.

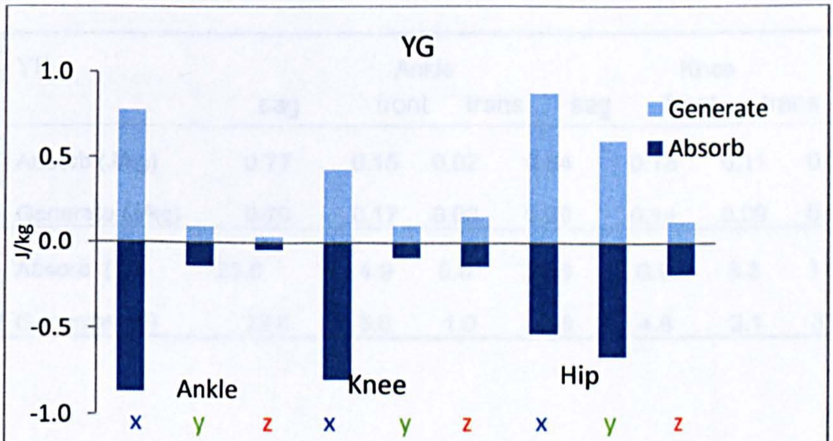


Figure 5.18 Work done (normalised): all planes (YG)

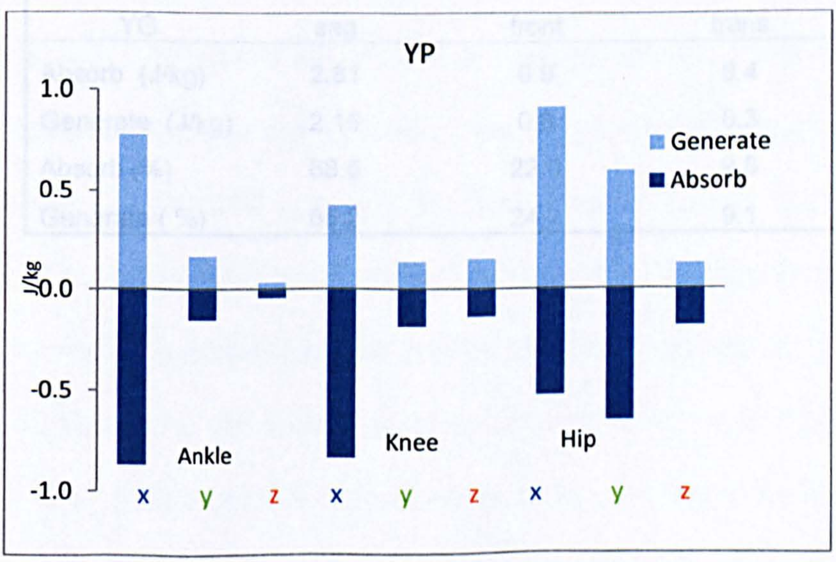


Figure 5.19 Work done (normalised): all planes (YP)

Table 5.17 Joint work done normalised to body mass and percentage: all planes and joints (YG).

YG	Ankle			Knee			Hip		
	sag	front	trans	sag	front	trans	sag	front	trans
Absorb (J/kg)	1.03	0.14	0.04	1.21	0.09	0.14	0.58	0.66	0.18
Generate (J/kg)	0.97	0.09	0.04	0.53	0.10	0.15	0.66	0.60	0.12
Absorb (%)	25.3	3.4	1.3	37.10	2.7	4.2	17.8	20.4	4.9
Generate (%)	29.7	2.8	1.1	16.2	3.0	4.7	20.3	18.4	3.30

Table 5.18 Joint work done normalised to body mass and percentage : all planes and joints (YP).

YP	Ankle			Knee			Hip		
	sag	front	trans	sag	front	trans	sag	front	trans
Absorb (J/kg)	0.77	0.15	0.02	0.84	0.18	0.11	0.34	0.46	0.14
Generate (J/kg)	0.70	0.17	0.03	0.29	0.14	0.09	0.91	0.48	0.13
Absorb (%)	25.6	4.9	0.6	27.8	6.1	3.8	11.3	5.4	4.6
Generate (%)	23.8	5.8	1.0	9.8	4.8	3.1	31.1	16.4	4.4

Table 5.19 Joint work done across all joints: each plane (normalised and percentage) (YG).

YG	sag	front	trans	Total
Absorb (J/kg)	2.81	0.9	0.4	4.1
Generate (J/kg)	2.15	0.8	0.3	3.3
Absorb (%)	68.5	22.0	9.8	
Generate (%)	65.2	24.2	9.1	

Table 5.20 Joint work done across all joints: each plane (normalised and percentage) (YP).

YP	sag	front	trans	Total
Absorb (J/kg)	1.95	0.80	0.27	3.0
Generate (J/kg)	1.90	0.79	0.25	2.9
Absorb (%)	64.7	26.4	8.9	
Generate (%)	64.6	27.0	8.4	

Table 5.21 Joint work done contributions (percentage): each joint, all planes (YG)

YG	Ankle	Knee	Hip
Absorb (%)	29.7	35.2	35.1
Generate (%)	33.6	24.0	42.4

Table 5.22 Joint work done contributions (percentage): each joint, all planes (YP)

YP	Ankle	Knee	Hip
Absorb (%)	31.1	37.6	31.3
Generate (%)	30.5	17.7	51.8

Tables 5.19 and 5.20 show that both groups absorbed more energy than they generated across the 3 planes. The YG generated and absorbed more absolute energy but less % energy in the frontal plane. Tables 5.21 and 5.22 show that the YG generated more and absorbed less % energy at the ankle and knee. At the hip they generated less energy but absorbed slightly more than the YP. The YG showed a net % energy generation at the ankle and hip joint, and a smaller energy deficit (11.2% compared to 19.9%) at the knee. The YP only showed a net % energy generation at the hip joint.

5.3.6 Discussion of frontal and transverse plane data

Most movement during the contact phase is focussed on the sagittal plane. However there are some interesting movements in the other two planes and some subtle differences shown between the groups.

Adduction/abduction (y axes)

At the knee, the YG showed slight fluctuation in adduction whereas in the YP it changed more systematically, after MKF, from adduction to abduction. Peak knee adduction and abduction angular velocities were smaller in the YG, which corresponded to a decreased joint moment and slightly less power absorption in this group. At the hip, a slightly increased adduction angle and increased abduction velocity after MKF was present in the YG. The strategy of power absorption followed by generation in the YG was reversed in the YP where generation was followed by absorption. Both groups generate and absorb 25% of work in the frontal (y) plane.

Rotation (z axes)

The YG generated most % energy in the order knee, hip and ankle, and the YP in the order hip, knee and ankle. Both absorbing small amounts of % energy at each joint in the order of hip, knee and ankle respectively. Comparatively, the YG generated more energy in the knee and less at the ankle and hip. Overall, YG generated and absorbed more energy and had net energy generation at ankle and hip. In contrast, the YP only had this at the hip.

The YG absorbed and generated 4% less energy outside the sagittal plane which shows that more work was done in the plane of the required jump distance and less dissipated outside it implying a more efficient jump.

5.3.7 Overall evaluation

In these planes, with less angular velocity fluctuation the YG seem to show more stability around the joints, had net energy generation at the ankle and an increased % energy generation at the knee.

6.0 Results and discussion for the Old Group

The results are divided into sections in the following order. Group data, CM velocities, segment CM velocities, joint angles, segment angles to laboratory, angular velocities, joint moments, powers and energy. This is addressed in the sagittal plane initially and then widened to include frontal and transverse plane qualitative data. The good ability group (OG) data are always presented before the poor ability group (OP).

6.1 Group Data

The following tables outline the group data related to development (chronological and maturational), jump distance, and run-up speeds.

Table 6.1. Group Data: Number, age, height, mass and Tanner's index

Group	Number (N)	Age (Yrs)	Height (m)	Mass (kg)	*Tanner's*
OG	10	15.0±0.5	1.61±0.1	53.1±4.8	4.3±0.42
OP	10	15.2±0.8	1.65 ±0.1	59.3±56.2	4.2±0.92

Table 6.2 Group Data: Run-up velocities, distance jumped and maximum knee flexion (MKF).

Group	11-6 (m/s)	6-1(m/s)	11-1 (m/s)	Distance	Contact Time	MKF(%)
OG	6.24±0.35	7.34±0.48	6.91±0.39**	4.05 ±-0.22 **	0.15	42.7
OP	5.51±0.36	6.24±0.55	5.88±0.44	3.26±0.38	0.18	43.5

** p>.01

The OG were smaller in height and lower in mass. The OG had greater run-up speeds ($p < .01$) and jump distances ($p < .01$). They reached MKF slightly earlier in the support period than the OP but this was not significant.

6.2 Sagittal plane data

6.2.1 Estimated CM velocity

Graphs of mean CM horizontal and vertical velocities from TD –TO are given in Fig 6.1 with mean values at TD, MKF and TO given in Table 6.3 and changes TD-MKF, MKF-TO and TD-TO given in Table 6.4.

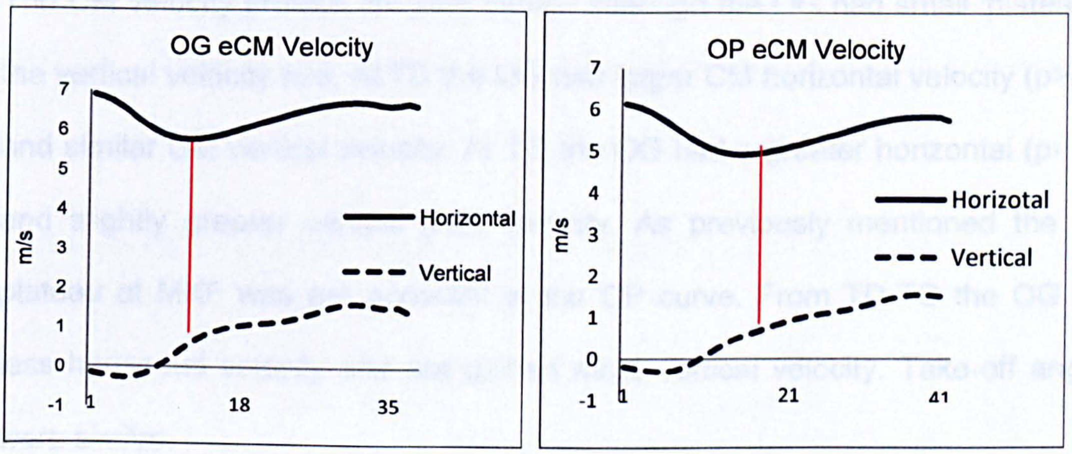


Figure 6.1 Estimated CM horizontal and vertical velocities from TD to TO (the vertical line indicates MKF) represented by the midpoint between right and left iliac spine.

Table 6.3 Estimated CM Vertical and horizontal velocities at TD, MKF and TO

	TD		MKF		TO		TO
	V_H (m/s)	V_V (m/s)	V_H (m/s)	V_V (m/s)	V_H (m/s)	V_V (m/s)	angle (deg)
OG	6.95+/- 0.45*	-0.17+/-0.19	5.90+/-0.26*	0.91+/-0.18	6.60+/- 0.47*	1.36+/- 0.30	11.95+/- 3.29
OP	6.12+/-0.45	-0.19+/-0.19	5.03+/-0.44	0.81+/-0.14	5.70 +/- 0.60	1.26 +/- 0.33	12.88+/- 4.11

* *p<.01*

Table 6.4 Estimated CM Vertical and horizontal velocities changes between TD-MKF, MKF-TO and TD-TO.

	TD-MKF		MKF-TO		TD-TO	
	V_H (m/s)	V_V (m/s)	V_H (m/s)	V_V (m/s)	V_H (m/s)	V_V (m/s)
OG	-1.05+/- 0.21	1.08+/-0.32	0.70+/-0.21	0.49+/-0.35	0.35+/- 0.16	1.57+/- 0.38
OP	-1.09+/-0.16	1.00+/-0.20	0.67+/-0.29	0.45+/-0.28	0.42+/- 0.34	1.45+/- 0.35

The CM velocity profiles are very similar although the OG had small 'plateau in the vertical velocity rise. At TD the OG had larger CM horizontal velocity (p>.01) and similar CM vertical velocity. At TO the OG had a greater horizontal (p>.01) and slightly greater vertical (NS) velocity. As previously mentioned the OG plateau at MKF was not apparent in the OP curve. From TD-TO the OG lost less horizontal velocity and but gained more vertical velocity. Take-off angles were similar.

6.2.2 Segment CM velocities.

Graphs of group mean segment CM velocities (horizontal) from TD –TO are given in Fig 6.2 with mean values at TD, TO and TD-TO given in Table 6.5 Graphs of group mean segment CM velocities (vertical) from TD –TO are given in Fig 6.3. with mean values at TD, TO and TD-TO given in Table 6.6

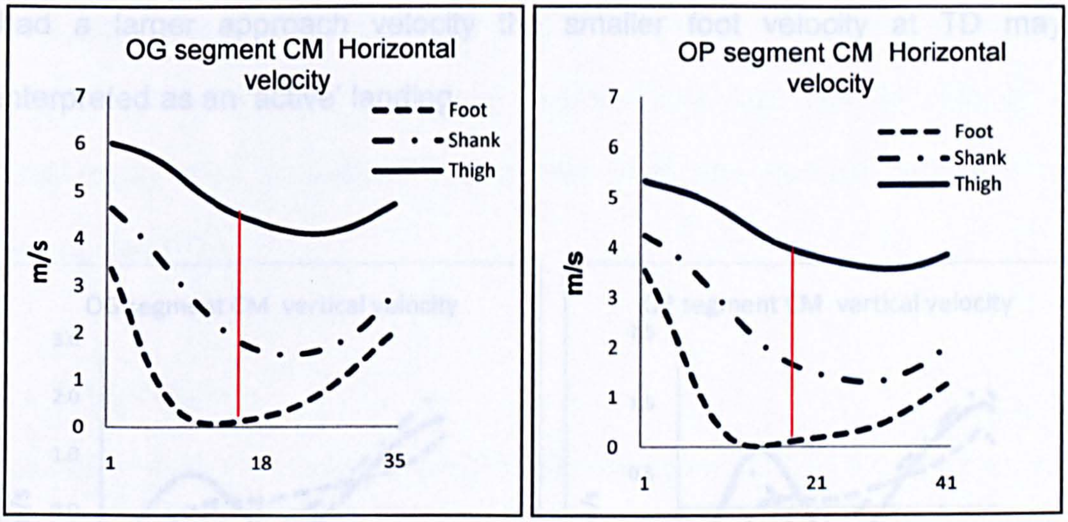


Figure 6.2 Mean segment CM horizontal velocities (V_H) for foot, shank and thigh.

Table 6.5 Mean segment CM horizontal velocities (V_H) at TD, TO and TD-TO.

Segment	OG Velocity (m/s)			OP Velocity (m/s)		
	TD	TO	TD -TO	TD	TO	TD -TO
Foot	3.34	2.44	-0.90	3.55	2.11	-1.44
Shank	4.61*	3.56	-1.05	4.25*	3.29	-0.96
Thigh	5.98**	4.92	-1.06	5.33**	4.59	-0.74

*p < .5 **p <.01

The curves were similar, however after MKF the OG increased their segment velocities at the shank and thigh, more rapidly. With the exception of the $Foot_{TD}$, the segment CM velocity (V_H) was larger in all segments in the OG at both TD and TO. Fig 6.2 shows the OG reached their minimum values earlier particularly at the shank and hip. Additionally from TD-TO shank and thigh lost more velocity in the OG than in the OP. This contrasts the differences in CM horizontal velocities at TO where the OG lost less horizontal velocity. As the OG had a larger approach velocity the smaller foot velocity at TD may be interpreted as an 'active' landing.

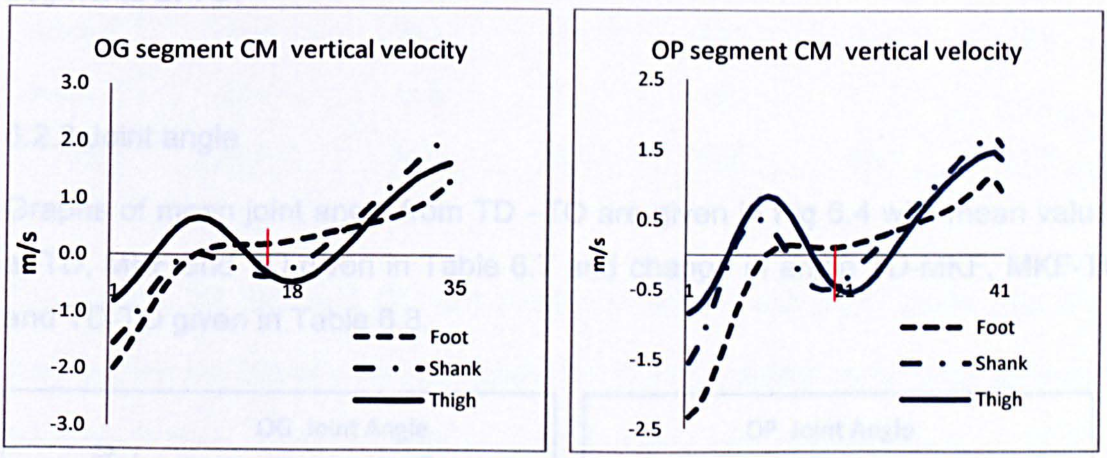


Figure 6 .3 Mean segment CM Vertical velocities (V_v) for foot, shank and thigh from TD to TO (the vertical line indicates MKF).

Table 6.6 Mean Segment CM vertical velocities (V_v) at TD, TO and TD-TO.

Segment	OG Velocity (m/s)			OP Velocity (m/s)		
	TD	TO	TD-TO	TD	TO	TD-TO
Foot	-2.00	2.08	4.08	-2.34	1.78	4.12
Shank	-1.43	2.37*	3.80	-1.55	2.00*	3.55
Thigh	-1.11	1.75	2.86	-0.84	1.49	2.33

*p <.05

The vertical velocity curves are similar but a small difference occurred in the shank CM velocity (see Fig 6.3) which became an upward vertical velocity before MKF in the OP. This did but not in the OG. At TD the downward (-ve) vertical velocities of all segments were smaller in the OG than the OP. The OG developed larger V_v at TO in all segments reflecting the CM vertical velocity increase and CM horizontal difference. The OG also developed larger velocity changes at the shank and thigh from TD-TO. In summary, in all segments the OG had both a larger horizontal velocity loss and vertical velocity gain. Additionally they developed larger horizontal and vertical velocities in all segments at TO.

6.2.3 Joint angle

Graphs of mean joint angle from TD –TO are given in Fig 6.4 with mean values at TD, MKF and TO given in Table 6.7 and change in angle TD-MKF, MKF-TO and TD-TO given in Table 6.8.

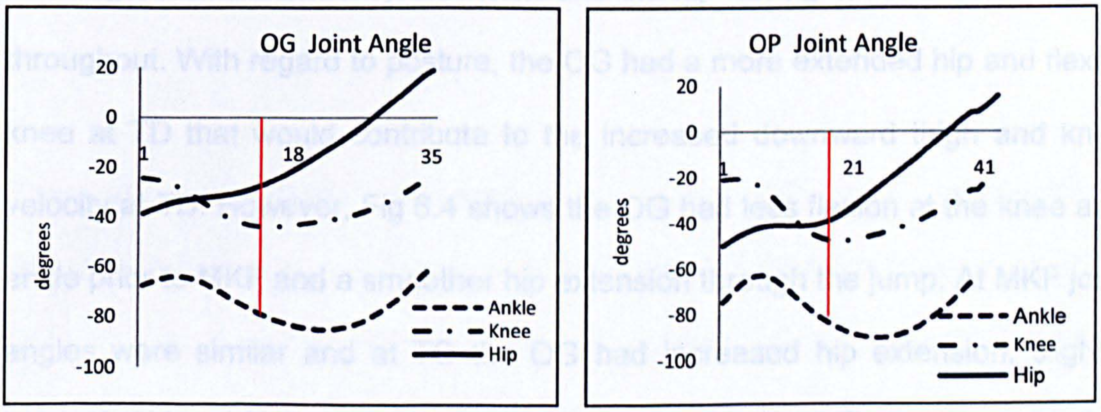


Figure 6.4 Mean joint angle of ankle, knee and hip from TD to TO (the vertical line indicates MKF). All joint angles, extension (+) and flexion (-).

Table 6.7 Mean joint angle for ankle, knee and hip at TD, MKF and TO

	OG			OP		
	TD	MKF	TO	TD	MKF	TO
Ankle (°)	-76.5	-92.5	-57.1	-78.7	-90.5	-52.8
Knee (°)	-27.4	-51.1	-18.2	-22.9	-51.2	-19.6
Hip (°)	-46.8	-34.0	20.3	-50.1	-34.7	17.6

Table 6.8 Joint angle range for ankle, knee and hip between TD-MKF, MKF-TO and TD-TO.

	OG			OP		
	TD-MKF	MKF-TO	TD-TO	TD-MKF	MKF-TO	TD-TO
Ankle (°)	-16.0	35.4	19.4	-11.7	37.6	25.9
Knee (°)	-23.7	32.9	9.2	-28.2	31.5	3.3
Hip (°)	12.8	56.3	69.1	15.4	52.3	67.7

The graphs for OG and OP are similar in shape with both ankle and knee showing flexion followed by extension and the hip having continuous extension throughout. With regard to posture, the OG had a more extended hip and flexed knee at TD that would contribute to the increased downward thigh and knee velocity at TD. However, Fig 6.4 shows the OG had less flexion at the knee and ankle prior to MKF and a smoother hip extension through the jump. At MKF joint angles were similar and at TO the OG had increased hip extension, slightly increased knee extension and less ankle extension. The latter probably contributing to the maintenance of vertical velocity and the former two contributing to both the vertical and horizontal velocity increase at TO. The OG showed greater ankle flexion TD- MKF (see Table 6.8) but less (NS) extension at TO. Interestingly, Fig 6.4 shows the OP had more ankle angle movement within (not between) the TD-MKF range. The OG showed increased ankle flexion and less knee flexion occurring TD-MKF whilst differences at the hip increased extension occurred MKF-TO.

6.2.4 Posture

Group segment angles relative to Lab from TD –TO are shown in Table 6.9

Table 6.9 Segment angles relative to laboratory. Segment moved past vertical (+), behind vertical (-).

	TD		MKF		TO	
	OG	OP	OG	OP	OG	OP
$A_{(PelvLab)}{}^{0}$	5.2	7.2	3.5	4.9	-3.6	-2.6
$A_{(ThighLab)}{}^{0}$	-41.9	-41.9	-32.1	-30.1	19.8	16.4
$A_{(ShankLab)}{}^{0}$	-13.9*	-19.9*	19.9	22.5	38.4	35.7
$A_{(FootLab)}{}^{0}$	-90.2	-98.6	-71.0	-69.4	-15.1	-19..2
$A_{(TD)}{}^{0}$	68.9	67.2				

* p>.01

There was a significant difference in $A_{(ShankLab)}$ at TD, small non-significant differences in $A_{(ShankLab)}$ and $A_{(ThighLab)}$ at MKF and TO. Considering posture at TD OG had a more vertical shank and more flexed foot, being virtually horizontal at TD. Relative to the vertical, the groups had similar thigh angles, which, in conjunction with the decreased shank angle of the OG indicate this group had a more upright leg position at TD. By MKF the OG moved their thigh through 2^0 less, shank through 8.5^0 less and pelvis slightly less. This indicates less relative movement of the pelvis, thigh and shank before MKF. After MKF the OG extended the shank and thigh further past the vertical indicating greater extension at TO. The pelvis 'tilt' was similar though the contact phase but more 'backward' in the OG. No difference in $A_{(TD)}$.

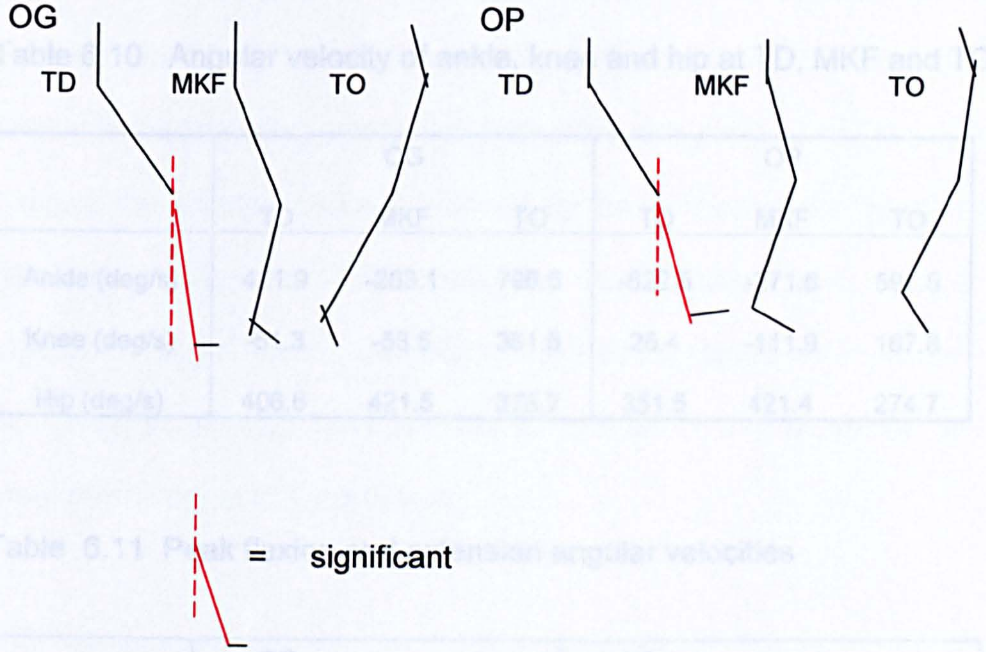


Figure 6.5 Stick diagrams at TD, MKF and TO in OG and OP. Red lines indicate significant differences at p<.01

6.2.5 Angular velocity

Graphs of group mean joint angular velocity from TD –TO are given in Fig 6.6 with mean values at TD, MKF and TO given in Table 6.10 and change in angle TD-MKF, MKF-TO and TD-TO given in Table 6.11.

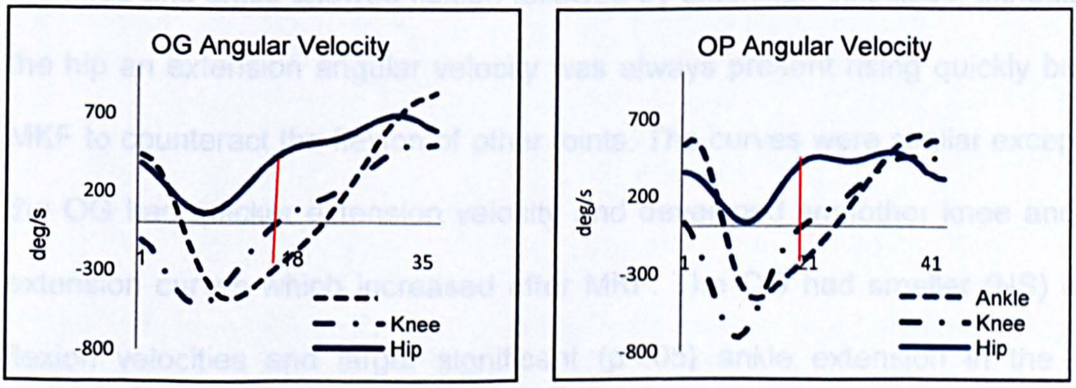


Figure 6.6 Mean angular velocity of ankle, knee and hip from TD-TO (the vertical line indicates MKF). All joint angular velocities, extension (+) and flexion (-).

Table 6.10 Angular velocity of ankle, knee and hip at TD, MKF and TO.

	OG			OP		
	TD	MKF	TO	TD	MKF	TO
Ankle (deg/s)	421.9	-263.1	796.5	-622.5	-271.6	597.5
Knee (deg/s)	-51.3	-53.5	361.5	25.4	-111.9	167.8
Hip (deg/s)	406.6	421.5	373.7	351.5	421.4	274.7

Table 6.11 Peak flexion and extension angular velocities

	OG		OP	
	Peak flex	Peak ext	Peak flex	Peak ext
Ankle (deg/s)	-586.5	1021.9*	-572.0	-872.7*
Knee (deg/s)	-552.4	461.6	-861.9	464.0
Hip (deg/s)	77.5	693.6	23.5	480.3

* $p<.05$

Generally, at TD, the graphs show initial extension velocities at all joints except for the knee in the OG which had a small flexion velocity at TD. Subsequently the knee and ankle showed flexion followed by extension velocities, although at the hip an extension angular velocity was always present rising quickly before MKF to counteract the flexion of other joints. The curves were similar except for the OG had quicker extension velocity and developed smoother knee and hip extension curves which increased after MKF. The OG had smaller (NS) knee flexion velocities and larger significant ($p<.05$) ankle extension in the OG. Preparation for TD by the OP was characterised by an increased ankle extension velocity and a slight extension velocity at the knee, in contrast to the smaller ankle extension velocity and small knee flexion velocity in the OG. Hip extension for the OP seemed to plateau between MKF-TO before continuing to extend indicating some interaction with other joint actions. At TD the OG have a reduced knee flexion which is followed by the development of greater extension velocities at all joints. Additionally the OG achieved peak angular velocity, particularly at the knee, just before TO. This highlights an improved ability of this group to develop (and perhaps co-ordinate) joint extension, alongside a greater resistance to knee flexion.

6.2.6 Joint moment

Graphs of mean group joint moment from TD –TO are given in Fig 6.7 with mean values at TD, MKF and TO given in Table 6.12 and change in angle TD-MKF, MKF-TO and TD-TO given in Table 6.13.

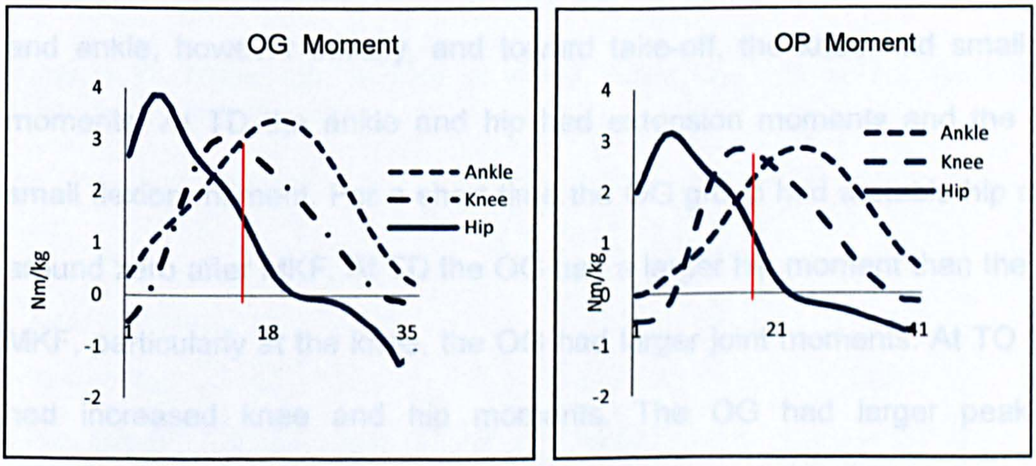


Figure 6.7 Mean joint moments of ankle, knee and hip (normalised to body mass) from TD to TO (the vertical line indicates MKF). All joint moments, extension (+) and flexion (-).

Table 6.12 Mean joint moment of ankle, knee and hip at TD, MKF and TO (normalised to body mass).

	OG			OP		
	TD	MKF	TO	TD	MKF	TO
Ankle (Nm/kg)	0.41	3.06	0.06	-0.08	2.07	0.05
Knee (Nm/kg)	-0.48	3.24	-0.22	-0.50	1.71	-0.11
Hip (Nm/kg)	2.58	1.4	-1.35	2.08	1.11	-0.92

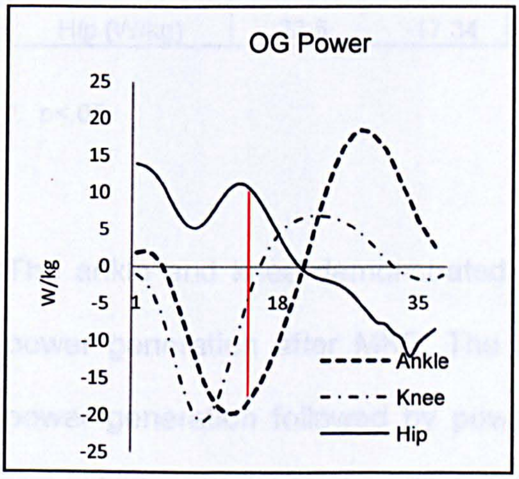
Table 6.13 Mean peak flexion and extension moments (normalised to body mass).

	OG		OP	
	Peak flex	Peak ext	Peak flex	Peak ext
Ankle (Nm/kg)	-0.002	3.5	-0.07	2.9
Knee (Nm/kg)	-0.65	3.17	-0.93	2.8
Hip (Nm/kg)	-1.81	4.05	-1.45	3.32

Throughout the jump the groups had mainly extension moments at the knee and ankle, however initially, and toward take-off, the knee had small flexion moments. At TD the ankle and hip had extension moments and the knee a small flexion moment. For a short time the OG group had a stable hip moment around zero after MKF. At TD the OG had a larger hip moment than the OP. At MKF, particularly at the knee, the OG had larger joint moments. At TO the OG had increased knee and hip moments. The OG had larger peak mean normalised extension moments and smaller peak mean flexion moments at the knee.

6.2.7 Joint power

Graphs of group mean normalised power from TD –TO are given in Fig 6.8 with mean values at TD, MKF and TO given in Table 6.14 and peak mean power values given in Table 6.15



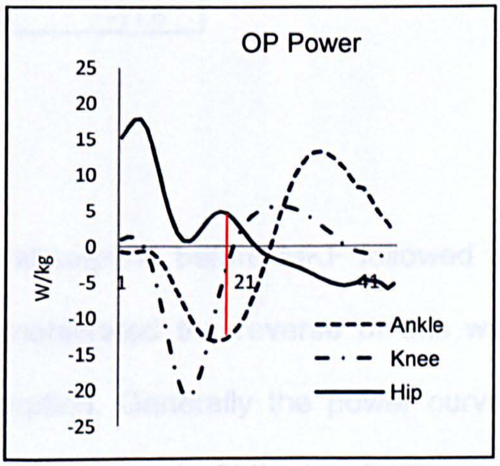


Figure 6.8 Mean joint power at ankle, knee and hip (normalised to body mass) from TD to TO (the vertical line indicates MKF), negative= power absorption- positive = power generation.

Table 6.14 Mean joint power of ankle, knee and hip at TD, MKF and TO (normalised to body mass).

	OG			OP		
	TD	MKF	TO	TD	MKF	TO
Ankle (W/kg)	1.7	-13.9	2.0	-0.5	-12.0	1.0
Knee (W/kg)	-1.5*	-2.6	1.5	0.7*	-4.3	0.6
Hip (W/kg)	16.2	9.3	-11.0*	14.0	3.8	-4.0*

* p<.05

Table 6.15 Mean peak absorption and generation power (normalised to body mass).

	OG		OP	
	gen	abs	gen	abs
Ankle (W/kg)	24.1*	-20.6	16.3*	-16.7
Knee (W/kg)	13.2	-25.1	14.0	-26.2
Hip (W/kg)	22.5	-17.34	17.9	-11.6

* p<.05

The ankle and knee demonstrated power absorption before MKF followed by power generation after MKF. The hip demonstrated the reverse of this with power generation followed by power absorption. Generally the power curves were similar except for the initial hip positive power peak. At the hip, both power graphs showed two initial positive peaks before MKF however the relative magnitude of these differed. There was a significant difference in knee power at TD (p<.05), a noticeable (NS) difference in hip power at MKF and a significant hip power difference (p<.05) at TO. At the ankle the OG had larger positive and negative values. At the knee, similar curves were observed but, in contrast to the ankle, the OP group produced an initial positive peak whilst the OG group did not. The OG had larger mean peak values, at the ankle and hip for both absorption and generation. The OG had significantly increased peak ankle power (generation) between MKF and TO, which reflected the larger angular velocity and joint moment in the OG at the ankle.

6.2.8 Work done in the sagittal plane

Graphs of mean work done (%) contributions are given in Fig 6.9 with mean normalised and % work done values in Table 6.16.

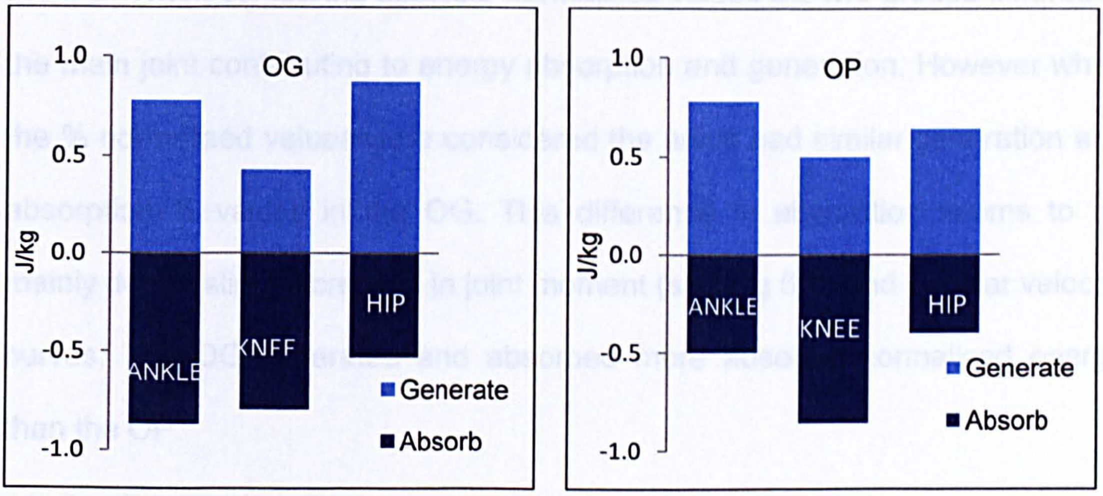


Figure 6.9 Sagittal plane normalised work done contributions (OG and OP).

Table 6.16 Sagittal plane normalised and percentage work done contributions (OG and OP).

	Ankle		Knee		Hip	
	OG	*OP*	*OG*	*OP*	*OG*	*OP*
Absorb (J/kg)	0.87	0.50	0.80	0.86	0.53	0.40
Generate (J/kg)	0.78	0.77	0.40	0.50	0.87	0.64
Absorb (%)	40.1	28.3	36.8	49.1	23.1	22.7
Generate (%)	39.9	40.3	19.5	26.1	40.6	33.6

The graph shows that both groups generated most energy at the ankle and hip, the OG generated most at hip and the OP generated most at the ankle. The OG absorbed most at the ankle, but also a similar amount at the knee and the OP absorbed most energy at the knee. Energy generation at the hip was in the early contact phase and that at the knee and ankle later on in the contact period. Both groups generated similar absolute amounts of energy at the ankle and knee but the OG generated more energy at the hips. The OP had a net positive energy contribution at the ankle and hip, this occurred only at the hip in the OG. When comparing absolute normalised values the two groups differed in the main joint contributing to energy absorption and generation. However when the % normalised values were considered the ankle had similar generation and absorption % values in the OG. This difference in absorption seems to be mainly due to slight increases in joint moment (see Fig 6.7) and angular velocity curves. The OG generated and absorbed more absolute normalised energy than the OP.

6.2.9 Discussion of sagittal plane data

In summary, the OG in comparison to the OP ran significantly faster and jumped significantly further, losing less V_H and , increasing their V_v more which was reflected in larger segment CM horizontal and vertical velocities at TO. At TD the OG had a more vertical shank and appeared to prepare for TD with smaller extension velocities at the ankle and hip, a small knee flexion velocity (extension velocity in the OP), smaller negative vertical CM velocities, larger horizontal CM velocities at the shank and thigh and a smaller horizontal foot velocity most of which could be seen as preparation for TD. From TD-MKF the OG had less knee flexion, smaller ankle and knee flexion velocities, increased work at the hip joint and slightly increased ankle moment assisting control of the shank. A smaller range of shank and thigh movement led to the OG having a different posture at MKF. This corresponds to the OG having a slightly earlier V_V and V_H increase of the segments CM velocity. After MKF the OG generated greater V_V and lost less V_H, had larger hip extension and knee extension TD-TO, moving shank and thigh through larger angles as the ankle developed a significantly increased peak extension velocity. At TO specifically the OG had larger extension velocities at all joints, a significant ankle power difference MKF-TO and a significant difference in hip power at TO. Following the variations outlined, the OG had a net energy balance at the ankle, net energy absorption at the knee and net generation at the hip. In contrast the OP had a net generation at the ankle, a larger deficit at the knee and less generation at the hip.

6.2.10 Overall evaluation

The OG have increased run-up velocities, less knee flexion, better preparation for TD, lose V_H and gain V_V and have a reduced knee flexion velocity (from a more flexed knee at TD). They show pivot characteristics from which, with a significant difference in ankle extension velocity and power they are able to develop a longer jump distance. Larger extension velocities and significant hip and ankle power differences indicate stronger athletes within the OG. The OG were smaller and lighter but probably stronger and had increased technical development (which is particularly apparent in preparation for TD) and improved pivot characteristics.

6.3 Frontal and transverse planes

The analysis was conducted in 3D and so data available are available for the frontal and transverse planes to supplement that described above for the sagittal plane. The sagittal plane graphs are included for comparison.

6.3.1 Joint angles: Frontal and transverse planes

Graphs of group mean joint angles from TD –TO are given in Fig 6.10 for the OG and Fig 6.11 for the OP.

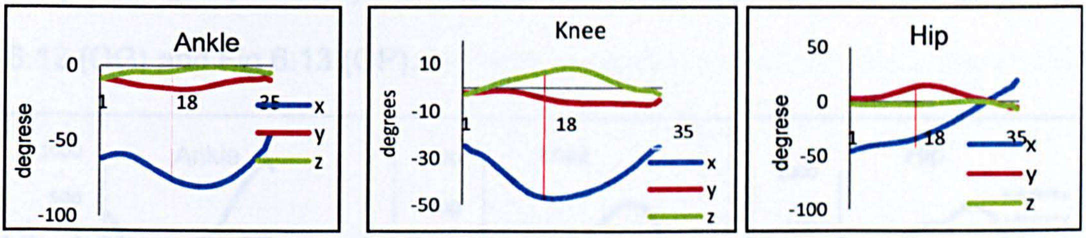


Figure 6.10 Mean joint angles: 'x','y' and 'z' axes (OG) from TD to TO (the vertical line indicates MKF). All joint angles, extension (+), adduction (+) and internal rotation (+).

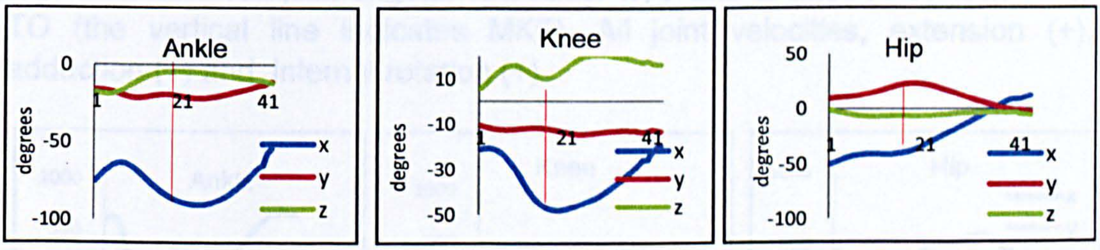


Figure 6.11 Mean joint angles: 'x','y' and 'z' axes (OP) from TD to TO (the vertical line indicates MKF). All joint angles, extension (+), adduction (+) and internal rotation (+).

Generally movement was limited in the 'y' and 'z' planes. However both groups showed both small rotations at all joints and some adduction or abduction that was generally smaller in the OG. The OG had less abduction at the ankle, less internal rotation and abduction at the knee and reduced adduction and external rotation at the hip. The most noticeable difference was the pattern of rotation at the knee. At TD the OG had abduction and adduction values closer to zero and this pattern was maintained through the jump. Similarly rotations, whether internal or external, followed the same pattern. This lack of movement indicated a more stable lower leg.

6.3.2 Joint angular velocity: Frontal and transverse planes

Graphs of group mean joint angular velocities from TD –TO are given in Fig 6.12 (OG) and Fig 6.13 (OP).

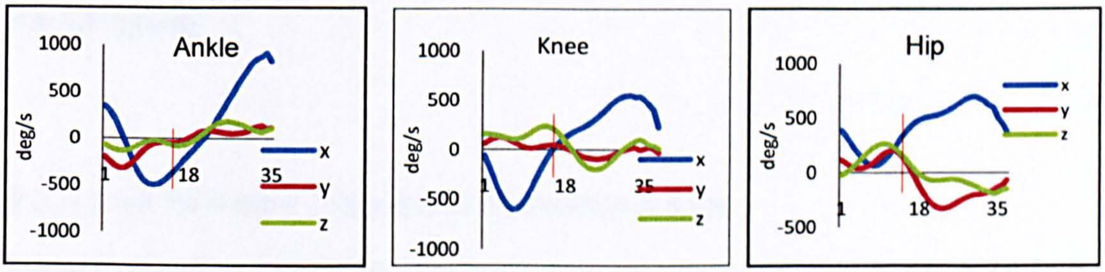


Figure 6.12 Mean joint angular velocities: 'x','y' and 'z' axes (OG) from TD to TO (the vertical line indicates MKF). All joint velocities, extension (+), adduction (+) and internal rotation (+).

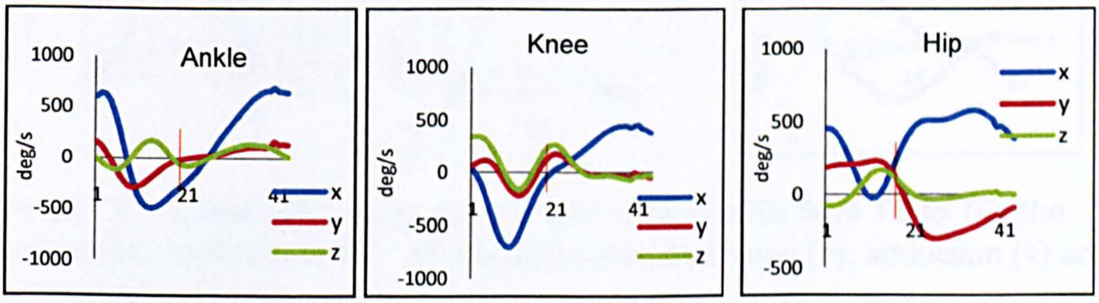


Figure 6.13 Mean joint angular velocities: 'x','y' and 'z' axes (OP) from TD to TO (the vertical line indicates MKF). All joint velocities, extension (+), adduction (+) and internal rotation (+).

In general the joint angular velocity curves were similar with the largest velocities occurring in the sagittal plane, but some large rotational velocities were generated, particularly at the hip. At the ankle mainly abduction velocities moved to toward adduction velocities, and external rotation became internal close to MKF, in both cases less initial fluctuation occurred in the OG. The OG had decreased abduction/adduction and rotational velocities from TD-MKF but increased fluctuation MKF-TO at the knee. At the hip both groups showed adduction moving to abduction close to MKF. The increased values in the OP could link to the increased shank and ankle movement between TD-MKF. At the hip, differences were more noticeable in the sagittal plane although both groups developed large external rotational velocities after MKF. The fluctuations in the knee and ankle curves perhaps support the case for less knee stability in the OP group.

6.3.3 Joint moments: Frontal and transverse planes

Graphs of group mean joint moments from TD –TO are given in Fig 6.14 (OG) and 6.15 (OP).

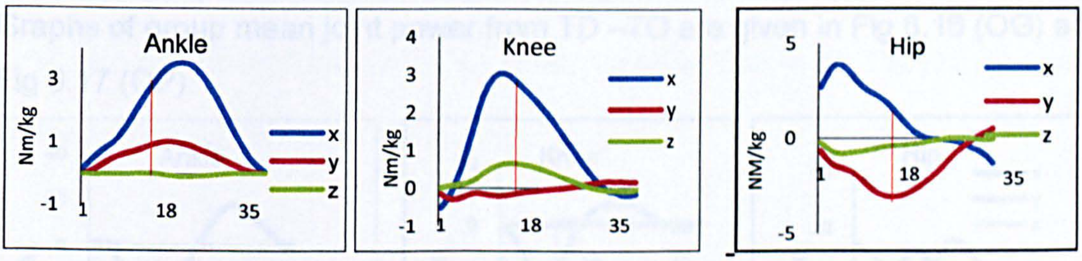


Figure 6.14 Mean joint moment: x','y' and 'z' axes (OG) from TD to TO (the vertical line indicates MKF). All joint moments, extension (+), adduction (+) and internal rotation (+).

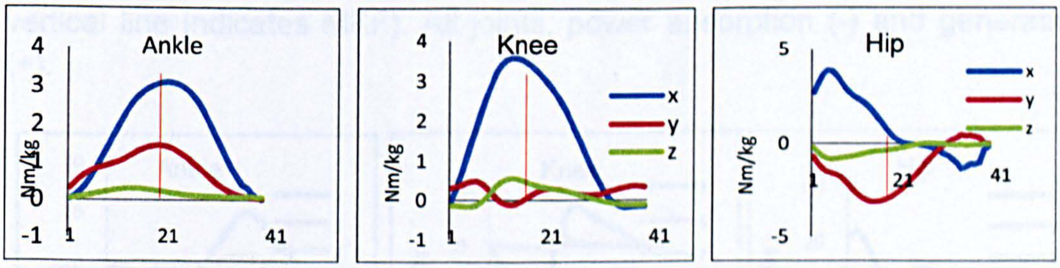


Figure 6.15 Mean joint moment: x','y' and 'z' axes (OP) from TD to TO (the vertical line indicates MKF). All joint moments, extension (+), adduction (+) and internal rotation (+).

The largest moments generally occurred in the sagittal plane with an exception occurring at the hip where the abduction moment was large in both groups. The groups had similar ankle, mainly adduction moment, and knee, mainly internal rotational moments. At the knee, both groups had an adduction moment but the OG had a small external moment moving to internal joint moment, this was vice-versa in the OP. At the hip both groups had large abduction moments comparable (and larger in the OP) to the extension moment. The OG group had a peak abduction joint moment which was smaller than the extension joint moment (3Nm/kg: 4Nm/kg respectively). In contrast the OP group had a larger abduction joint moment to extension moment (3.25 Nm/kg: 3.1 Nm/kg respectively).

6.3.4 Joint power: Frontal and transverse planes

Graphs of group mean joint power from TD –TO are given in Fig 6.16 (OG) and Fig 6.17 (OP).

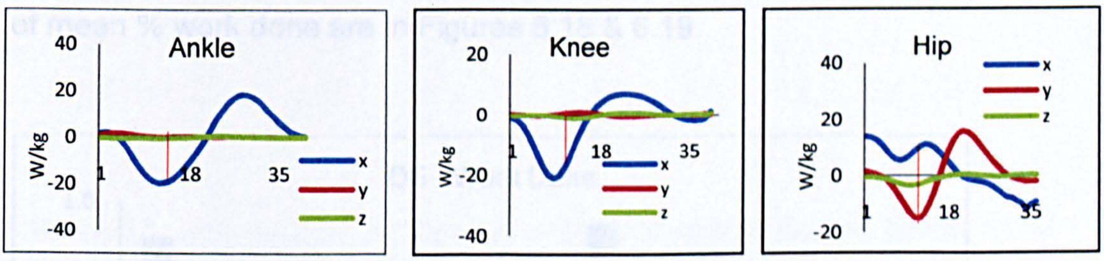


Figure 6.16 Mean joint power: x','y' and 'z' axes (OG) from TD to TO (the vertical line indicates MKF). All joints, power absorption (-) and generation (+).

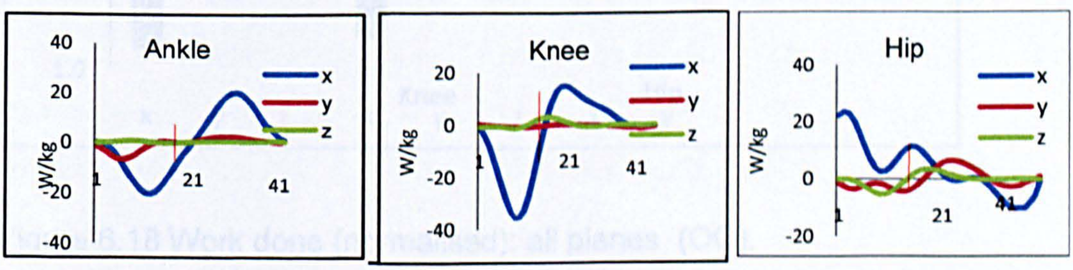


Figure 6.17 Mean joint power: x','y' and 'z' axes (OP) from TD to TO (the vertical line indicates MKF). All joints, power absorption (-) and generation (+).

Most power was generated in the sagittal plane with small contributions from the 'y' and 'z' planes. At the ankle and knee there was little difference between the groups and limited power generation in the 'y' and 'z' planes. At the hip alongside differences in sagittal power there was a noticeable difference in the peak adduction/abduction curves. At the hip the OG had much larger adduction and abduction power peaks. Power differs in the frontal plane and sagittal planes at the hip.

6.3.5 Joint work done

Values of group mean % work done and normalised (all planes) are in Tables 6.17 and 6.18. Work done (% and normalised) in each planes are in Tables 6.19 and 6.20 with Work done (%) at each joint in Tables 6.21 and 6.22.Graphs of mean % work done are in Figures 6.18 & 6.19

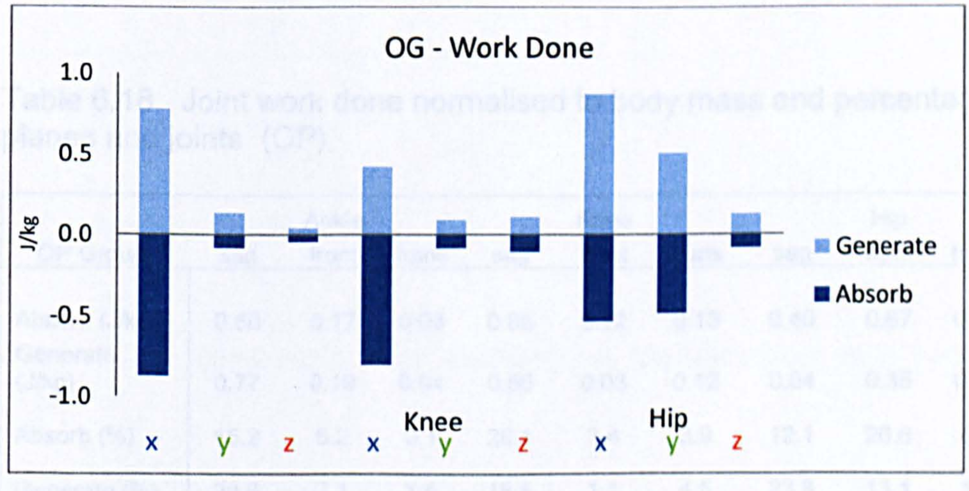


Figure 6.18 Work done (normalised): all planes (OG).

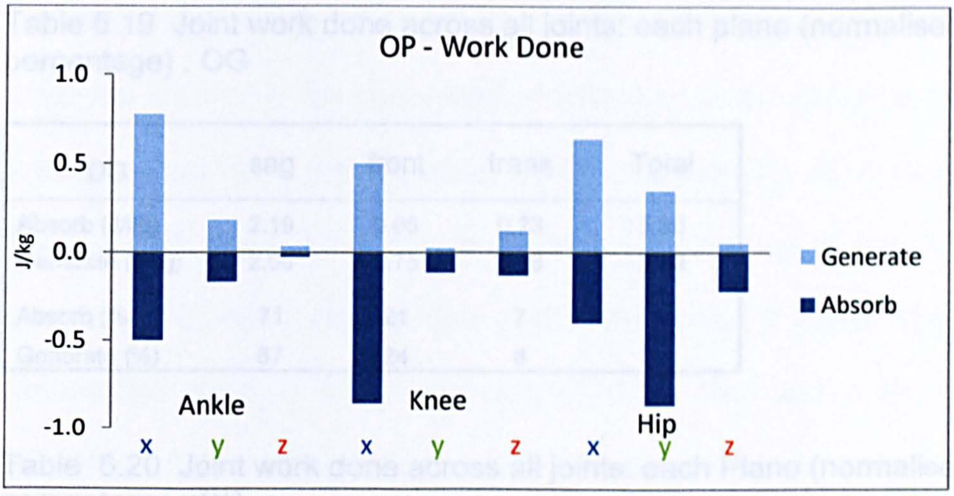


Figure 6.19 Work done (normalised): all planes (OP).

Table 6.17 Joint work done normalised to body mass and percentage : all planes and joints (OG).

	Ankle			Knee			Hip			Total
OG Group	sag	front	trans	sag	front	trans	sag	front	trans	
Absorb (J/kg)	0.87	0.08	0.04	0.80	0.08	0.10	0.53	0.48	0.08	3.06
Generate (J/kg)	0.78	0.14	0.04	0.43	0.10	0.11	0.87	0.51	0.13	3.11
Absorb (%)	28.3	2.6	1.4	25.9	2.7	3.4	17.3	15.8	2.7	
Generate (%)	25.1	4.5	1.4	13.7	3.2	3.7	28.0	16.3	4.2	

Table 6.18 Joint work done normalised to body mass and percentage : all planes and joints (OP).

	Ankle			Knee			Hip			
OP Group	sag	front	trans	sag	front	trans	sag	front	trans	Total
Absorb (J/kg)	0.50	0.17	0.03	0.86	0.12	0.13	0.40	0.87	0.22	3.30
Generate (J/kg)	0.77	0.19	0.04	0.50	0.03	0.12	0.64	0.35	0.05	2.69
Absorb (%)	15.2	5.2	0.1	26.1	3.4	3.9	12.1	26.6	6.7	
Generate (%)	28.6	7.1	1.5	18.6	1.1	4.5	23.8	13.1	1.9	

Table 6.19 Joint work done across all joints: each plane (normalised and percentage) : OG

OG	sag	front	trans	Total
Absorb (J/kg)	2.19	0.65	0.23	3.30
Generate (J/kg)	2.08	0.75	0.28	2.69
Absorb (%)	71	21	7	
Generate (%)	67	24	8	

Table 6.20 Joint work done across all joints: each Plane (normalised and percentage) : OP.

OP	sag	front	trans	Total
Absorb (J/kg)	1.76	1.16	0.38	3.30
Generate (J/kg)	1.91	0.57	0.21	2.69
Absorb (%)	72	16	12	
Generate (%)	77	13	10	

Table 6.21 Joint work done contributions (percentage): each joint, all planes (OG)

OG	Ankle	Knee	Hip
Absorb (J/kg)	32.3	32.0	35.7
Generate (J/kg)	30.9	20.6	48.5

Table 6.22 Joint work done contributions (percentage): each joint, all planes (OP)

OP	Ankle	Knee	Hip
Absorb (J/kg)	20.4	33.4	45.2
Generate (J/kg)	37.2	24.2	38.6

Overall the net energy absorption/generation was similar in the OG (3.1: 3.07 J/kg) but showed a net absorption of 0.61 J/kg in the OP. The OG had a net energy generation at the hip, whilst the OP has a energy absorption at the ankle (Tables 6.21 and 6.22). When comparing work across all the planes the OG generate and absorb slightly more work in the frontal 'y' plane. At the ankle both groups generate in the frontal plane, 0.14 J/kg and 0.19 J/kg (OG:OP respectively), and both also generated and absorbed substantial energies at the hip. In the frontal plane the OG had a net energy balance at the hip but the OP had a net absorption of 0.52 J/kg. Looking at % energy contributions, in each plane both groups absorb and generate similar amounts, however the OG utilised the frontal plane 'y' to generate 24% of the energy compared to 13% generated by the OP.

6.3.6 Discussion of frontal and transverse plane data.

Generally the sagittal plane was the main contributor to movement in the jumps however there were some differences in the frontal and transverse planes that are of interest.

Abduction/adduction

At the knee the OG had no abduction at TD but gradually moved to 10^{o} at MKF, in contrast, the OP had 10^{o} knee abduction throughout the contact phase. At the hip, the OG had a smaller adduction angle throughout the contact phase. At the knee these differences led to increased angular velocity fluctuations, particularly before MKF. At the knee the joint moment in the OG moved from abduction to adduction midway through contact whilst the OP demonstrated the opposite. At the hip, the OG had increased hip power generation and absorption. Following this, the OG generated more absolute work, particularly at the hip, but absorbed much less. Both groups generated and absorbed substantial energies at the hip in the frontal plane but the OG had a small net %energy deficit while the OP had a larger net energy absorption.

Rotation

The OG had smaller internal rotation of the knee, less external rotation of the hip and less initial external rotation at the ankle. At the ankle and knee the OG had smaller fluctuation in velocities before MKF implying greater stability and control. Moments and powers were generally similar in these groups, however, before MKF at the hip, the OG had power absorption whereas the OP had a small power generation. The OG also absorbed less and generated more work at the hip in the transverse plane. As both a percentage and absolute in energy terms the OP had a deficit whilst the OG had a net energy gain. Contextually, the OG absorbed and generated more actual and percentage energy in the frontal plane.

6.3.7 Overall evaluation

In the frontal plane both groups have relatively large energy exchange occuring at the hip. The OG show less energy absorption and more energy generation than the OP at the hip who have a energy deficit. The OG have a net generation at the hip which shows a difference in the technique and highlights the possibility of hip 'collapse' in the frontal plane in the OP (Fig 6.19). This increased absorption is reflected in the initial hip adduction velocity of the OP and a possible lack of strength further highlighted by increased knee abductive and rotational velocity fluctuations in the group.

7.0 Case study for one younger athlete

This section compares data for one young athlete one year apart. It is sub-divided into 2 sections on subject data and posture followed by a chronological overview from touch-down to take-off encompassing biomechanical variables that are relevant to the pivot model.

7. 1 Subject Data

The following tables outline the subject data (mean of three trials) related to development (chronological and maturational), jump distance, and run-up speeds.

Table 7.1 Subject Data: Age, height, mass and Tanner's index

Year	Age (Yrs)	Height (m)	Mass(kg)	*Tanner's*
Yr 1	12.2	1.66	52.0	2
Yr 2	13.1	1.66	53.9	2

7.2 Results

Table 7.2 Subject Data: Run-up velocities, distance jumped and maximum knee flexion (MKF) as a percentage of contact time.

Year	11-6 (m/s)	6-1 (m/s)	11-1 (m/s)	Distance(m)	Contact time	MKF%
Yr 1	6.64±0.16	7.05±0.14	7.25±0.10	4.68±0.08	0.15	52
Yr 2	6.29±-0.13	6.42±0.39	6.67±0.13	4.26±0.10	0.13	40

From Yr 1 to Yr 2 there was no change in height and a small increase in mass. However run-up speed and jump distance were reduced. MKF was reached earlier in Yr 2.

The following results compare Yr 1 to Yr 2. Graphs of mean CM horizontal and vertical velocities from TD-TO are given in Fig 7.1 and changes TD-MKF, MKF-TO and TD-TO given in Table 7.3. Table 7.4 and 7.5 highlights subject mean joint angle and posture at TD, MKF and TO. Stick diagrams at TD, MKF and TO are in Fig 7.2. Fig 7.3 shows posture at MKF. Mean joint angle change TD-MKF, MKF-TO and TD-TO are given in Table 7.6. Graphs of mean joint angles ('x', 'y' and 'z') axes from TD –TO are given in Fig 7.3 for the OG and Fig 7.4 for the OP. Graphs of group mean joint angular velocity from TD –TO are given in Fig 7.5. Mean joint moments (normalised) in all planes are shown in Figure 7.8. Graphs of mean work done (%) contributions are given in Fig 7.9 with graphs of work done % (normalised to body mass) in all planes in Fig 7.10.

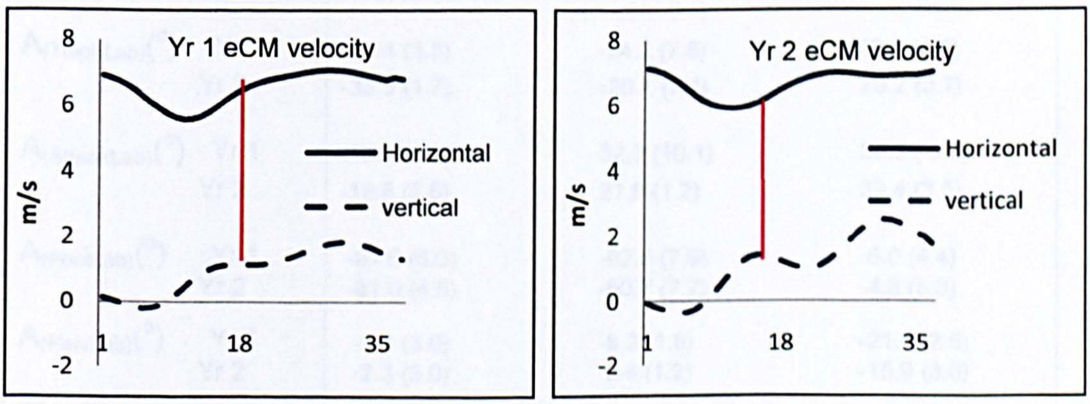


Figure 7.1 Estimated mean CM horizontal and vertical velocities (vertical line indicates MKF) between TD and TO represented by the midpoint between right and left iliac spine (Yr1 and Yr 2).

Table 7.3. eCM vertical and horizontal velocities (TD-MKF, MKF-TO and TD-TO)

	TD-MKF VH (m/s)	TD-MKF VV (m/s)	MKF-TO VH (m/s)	MKF-TO VV (m/s)	TD-TO VH (m/s)	TD-TO VV (m/s)	TO angle (°)
Yr 1	-0.40	0.99	0.24	0.23	-0.16	1.22	11.59
Yr 2	-0.89	1.3	0.65	0.66	-0.24	1.96	15.72

Table 7.4 Mean joint angle of ankle, knee and hip at TD, MKF and TO.

	TD		MKF		TO	
	Yr 1	Yr 2	Yr 1	Yr 2	Yr 1	Yr 2
Ankle (°)	-75.0	-64.9	-86.4	-91.8	-47.8	-45.4
Knee (°)	-22.7	-13.7	-56.3	-41.2	-15.9	-10.4
Hip (°)	-41.0	-32.7	-15.2	-17.7	37.7	44.8

Table 7.5 Segment angles relative to laboratory. Segment moved past vertical (+), behind vertical (-).

		TD	MKF	TO
$A_{(ThighLab)}$(°)	Yr 1	-42.4 (3.5)	-24.2 (7.8)	20.3 (1.7)
	Yr 2	-33.9 (1.7)	-20.1 (7.4)	29.2 (3.7)
$A_{(ShankLab)}$(°)	Yr 1	-19.4 (1.4)	32.7 (10.1)	39.3 (3.7)
	Yr 2	-19.8 (3.6)	21.6 (1.2)	39.4 (3.5)
$A_{(FootLab)}$(°)	Yr 1	-91.6 (6.0)	-62.0 (7.9)	-6.0 (4.4)
	Yr 2	-81.0 (4.5)	-60.7 (7.2)	-4.8 (5.3)
$A_{(PelvLab)}$(°)	Yr 1	-1.2 (3.0)	-8.9 (1.8)	-21.4 (2.5)
	Yr 2	-2.3 (3.0)	0.4 (1.2)	-15.9 (3.6)
$A_{(TD)}$(°)	Yr 1	67.8		
	Yr 2	68.8		

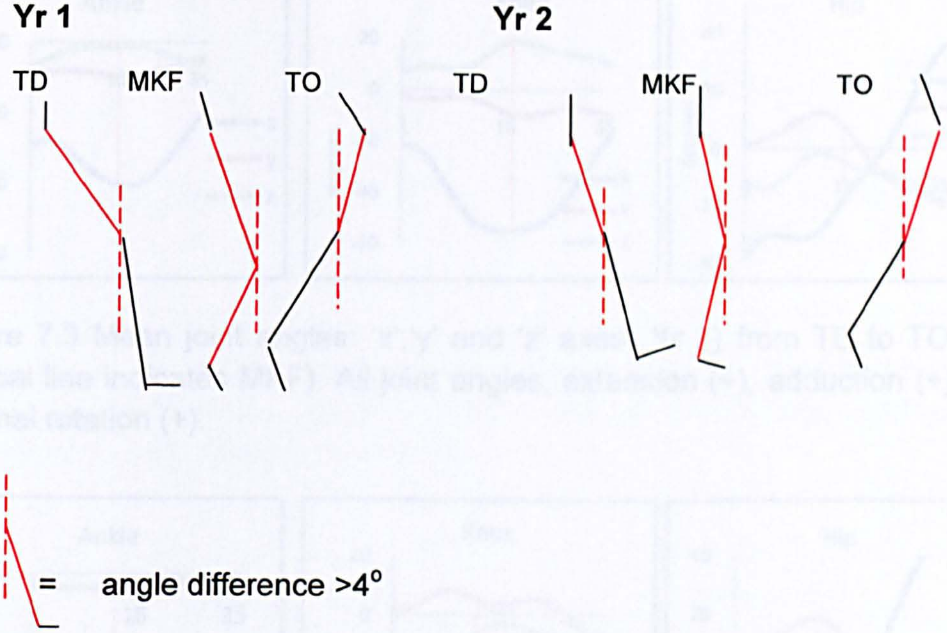


Figure 7.2 Stick diagrams at TD, MKF and TO in Yr 1 and Yr 2. Red lines indicate differences. Red lines indicate differences > 4°.

Table 7.6 Joint angle changes at ankle, knee and hip between TD-MKF, MKF-TO and TD-TO.

	TD-MKF		MKF-TO		TD-TO	
	Yr 1	Yr 2	Yr 1	Yr 2	Yr 1	Yr 2
Ankle (°)	-11.4	-26.9	52.7	46.6	27.2	19.5
Knee (°)	-33.6	-27.5	40.6	30.8	6.8	3.3
Hip (°)	25.8	15.0	52.8	62.5	78.6	77.5

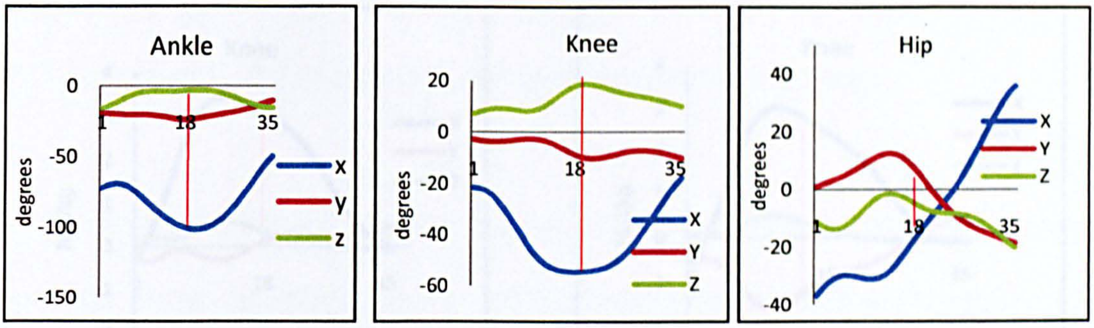


Figure 7.3 Mean joint angles: 'x','y' and 'z' axes(Yr 1) from TD to TO (the vertical line indicates MKF). All joint angles, extension (+), adduction (+) and internal rotation (+).

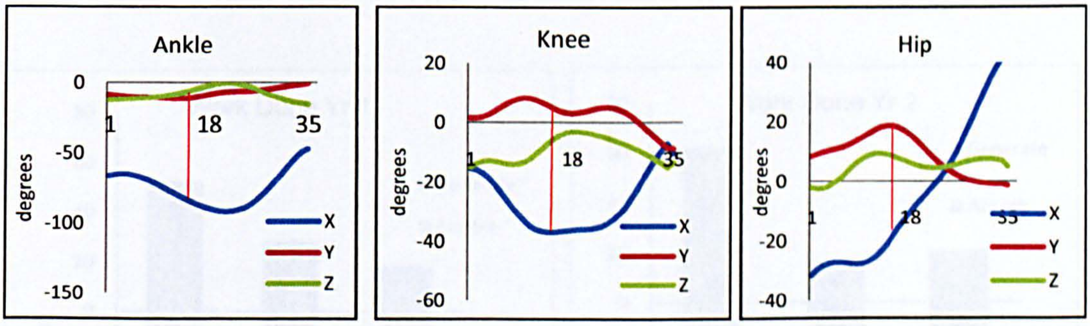


Figure 7.4 Mean joint angles: 'x','y' and 'z' axes (Yr 2) from TD to TO (the vertical line indicates MKF). All joint angles, extension (+), adduction (+) and internal rotation (+).

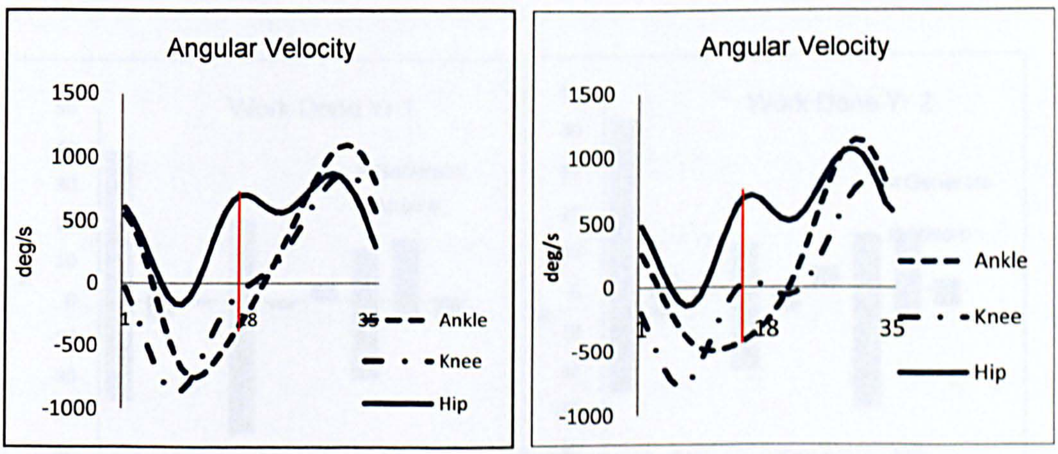


Figure 7.5 Mean angular velocity at ankle, knee and hip from TD to TO in Yr 1 and Yr 2 (the vertical line indicates MKF). All joint angular velocities flexion (-) and extension (+).

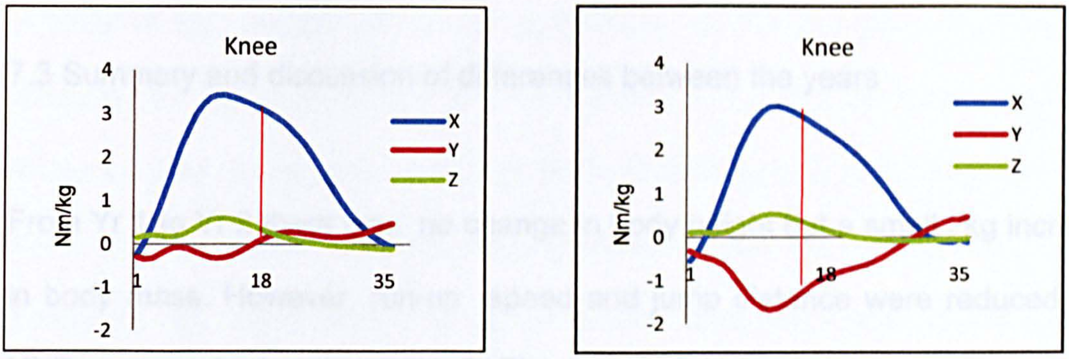


Figure 7.6 Mean joint moment: x','y' and 'z' axes (Yr 1 & 2 normalised) from TD to TO (the vertical line indicates MKF). All joint moments, extension (+), adduction (+) and internal rotation (+).

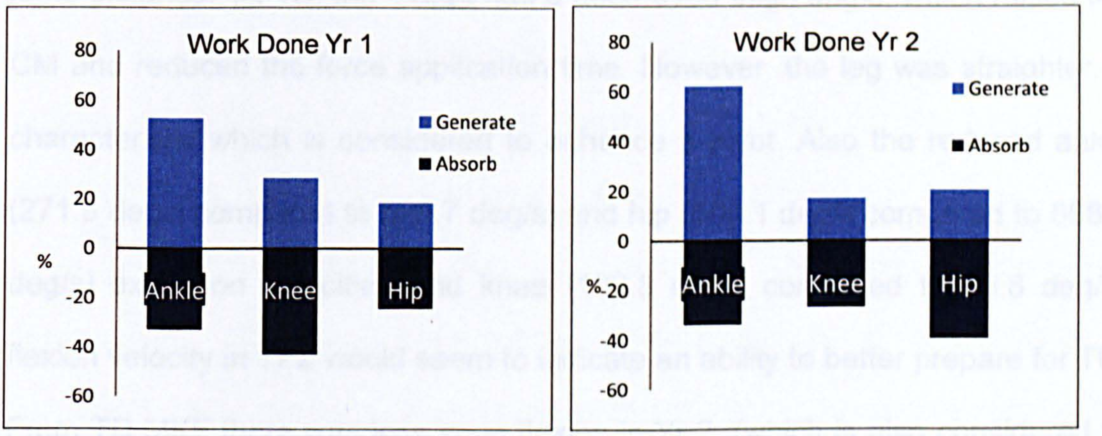


Figure 7.7 Sagittal plane (only) percentage work done contributions in Yr 1 and Yr 2

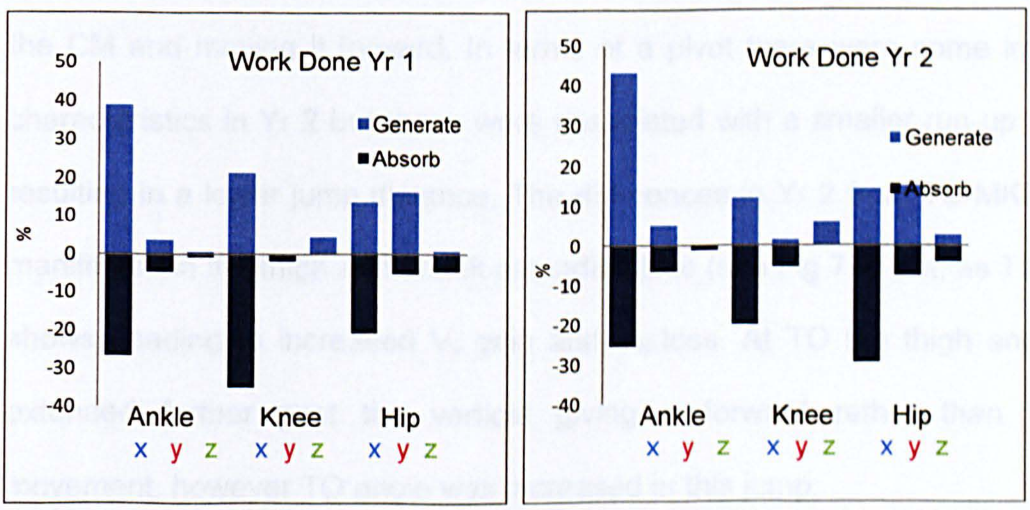


Figure 7.8 Work done (percentage) normalised to body mass: all planes and all joints in Yr 1 and Yr 2.

7.3 Summary and discussion of differences between the years

From Yr 1 to Yr 2 there was no change in body height but a small 2kg increase in body mass. However, run-up speed and jump distance were reduced and MKF was reached earlier in Yr 2. The relationship between run-up speed and distance jumped is the most basic within the long jump and these findings reflect this accepted relationship with a smaller run-up velocity giving a smaller jump distance. At TD, the YG_{case} had a decreased thigh angle, which raised the CM and reduced the force application time. However, the leg was straighter, a characteristic which is considered to enhance a pivot. Also the reduced ankle (271.5 deg/s compared to 520.7 deg/s) and hip (508.1 deg/s compared to 608.1 deg/s) extension velocities and knee (199.8 deg/s compared to 85.8 deg/s) flexion velocity in Yr 2 would seem to indicate an ability to better prepare for TD. From TD-MKF there was less knee flexion in Yr 2, (which is also considered to enhance a pivot) and increased ankle flexion. At MKF, the thigh (backward inclination) and shank angles (forward inclination) decreased therefore raising the CM and moving it forward. In terms of a pivot there were some improved characteristics in Yr 2 but these were associated with a smaller run-up velocity resulting in a lower jump distance. The differences in Yr 2 from TD-MKF were manifested in the thigh and shank extending less (see Fig 7.2) but, as Table 7.3 shows, leading to increased V_V gain and V_H loss. At TO the thigh angle had extended further past the vertical giving a forward rather than upward movement, however TO angle was increased in this jump.

Outside of the sagittal plane the differences at the hip (in adduction and rotation) can be seen clearly in Figs 7.3 & 7.4. In Yr 2 an increased knee abduction joint moment occurs before MKF. Overall, in Yr 2 in the sagittal plane, there was increased ankle energy generation and hip energy absorption alongside decreased knee energy generation and absorption. In the frontal plane there was increased absorption at the knee and hip.

When considering the possible implications of the differences between the two years it is important to acknowledge that some differences may be due to subject variability and inter-session repeatability needs to be considered. However, from viewing the individual data it does seem clear that there are some noticeable differences that may assist in understanding technique development. There are several indicators that point to an increased ability to plan for TD, and velocities changes are apparent within both segment and eCM data. In addition, the posture at TD, MKF and TO indicate there are differences in strategies between the years that lead to increased energy generated at the ankle and energy absorption at the hip in Year 2.

Continued repetition of the activity seems to have assisted the development of some pivot actions and the preparation for TD. The straighter leg shows some technical development but may also reflect an increase in strength. In Yr 2 the posture difference at MKF could be seen to be advantageous however the increased V_H loss, reduced run-up speed and $A_{(ThighLab)}$ at take-off ensured a smaller jump distance with what could be argued was an improved TD technique. This demonstrates the importance of run-up speed but also highlights the complexity of jumping, as an upright position at MKF, although advantageous does not lead to a larger jump distance. The implications for strength (both concentric and eccentric muscle) development are also interesting in Yr 2 as although the YG_{case} was able to generate a larger V_v it could not be maintained at the eCM. After the initial 'pivot' and rise in vertical velocity knee angular velocity was not maintained and dropped before a further increase (Fig 7.1). This suggests either a lack of concentric strength to continue extension, poor timing of extension or a difficult position to extend from. Additionally, it may be that the more extended knee angle at MKF limits the concentric contraction at the knee in Yr 2. It is likely that although the YG_{case} is developing an improved technique the influence of limited strength may impact on this, particularly at this point in her development. She perhaps has to compromise in her technique due to the lack of strength related to her age and maturity. For this particular subject the reduced jump distance may influence any continued participation as, whilst she shows some improvement in technique and seeks to 'jump' better (more V_V), strength (a 2kg weight increase) seems to be more influential.

8.0 Case study for one old athlete

This section compares data for one older athlete one year apart. It is sub-divided into 2 sections on subject data and posture followed by a chronological overview from touch-down to take-off encompassing biomechanical variables that are relevant to the pivot model.

8.1 Subject data

The following tables outline the subject data related to development (chronological and maturational), jump distance, and run-up speeds.

Table 8.1 Subject Data: Age, height, mass and Tanner's index

Year	Age (Yrs)	Height (m)	Mass(kg)	*Tanner's*
Yr 1	14.2	1.65	45.6	4
Yr 2	15.1	1.67	49.5	5

8.2 Results

Table 8.2 Subject Data: Run-up velocities, distance jumped and MKF

Year	11-6 (m/s)	6-1(m/s)	11-1	Distance	MKF%
Yr 1	7.17±0.11	8.29±0.08	7.73±0.02	3.97±0.18	32
Yr 2	7.64±0.07	8.51±0.15	8.07±0.08	4.37±0.06	53

The subject increased in mass, height and Tanner's index over the year. From Yr 1 to Yr 2 subject run-up speed, and distance jump all increased. The timing of MKF was later in Yr 2.

Graphs of mean CM horizontal and vertical velocities from TD - TO are given in Fig 8.1, with mean values at TD, MKF and TO given in Table 8.3 and changes TD-MKF, MKF-TO and TD-TO given in Table 8.4. Graphs of mean joint angle from TD –TO are given in Fig 8.2 and change in angle TD-MKF, MKF-TO and TD-TO given in Table 8.5. Table 8.6 highlights the different postures of the subject at TD, MKF and TO from Yr 1 to Yr 2. Fig 8.3 shows stick figures at TD, MKF and TO. Table 8.7 shows the peak flexion and extension angular velocities whilst mean angular velocities are shown in Fig 8.4. Graphs of mean group joint moment from TD –TO are given in Fig 8.5. Table 8.8 gives mean peak absorption and generation power (normalised to body mass). Fig 8.6 and Fig 8.7 show mean joint angular velocities from TD-TO. Graphs of mean work done (%) contributions are given in Fig 8.7 with graphs of mean work done (%) contributions in all planes in Fig 8.8.

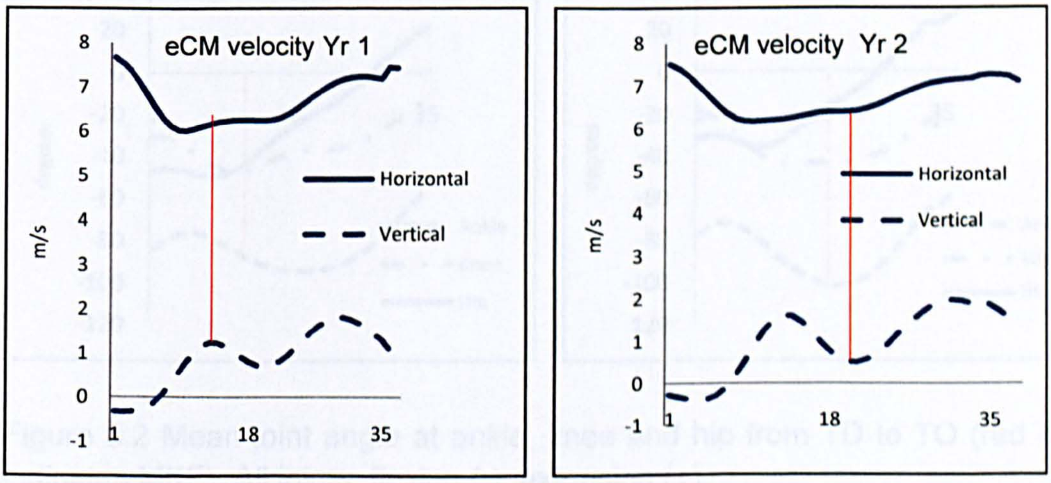


Figure 8.1 Estimated mean CM horizontal and vertical velocities (vertical line indicates MKF) (represented by the midpoint between right and left iliac spine).

Table 8.3 eCM Vertical and horizontal velocities at TD, MKF and TO

	TD		MKF		TO		TO
	VH (m/s)	VV (m/s)	VH (m/s)	VV (m/s)	VH (m/s)	VV (m/s)	angle (°)
Yr 1	7.66+/-0.15	-0.32+/-0.17	6.24+/-0.38	1.17+/-0.53	7.19+/- 0.36	1.23+/- 0.32	9.78
Yr 2	7.51+/-0.08	-0.27+/-0.06	6.31+/-0.01	0.89+/-0.61	7.16 +/- 0.11	1.50 +/- 0.12	12.04

Table 8.4 eCM vertical and horizontal velocities changes between (TD-MKF, MKF-TO and TD-TO).

	TD-MKF		MKF-TO		TD-TO	
	VH (m/s)	VV (m/s)	VH (m/s)	VV (m/s)	VH (m/s)	VV (m/s)
Yr 1	-1.42	1.49	0.95	0.06	-0.47	1.55
Yr 2	-1.20	1.16	0.85	0.62	-0.35	1.77

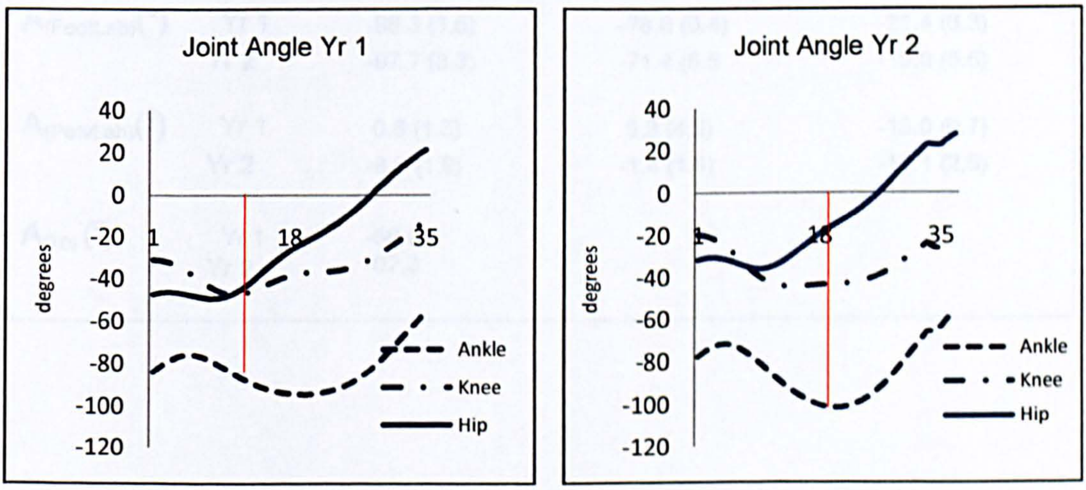


Figure 8.2 Mean joint angle at ankle, knee and hip from TD to TO (red line indicates MKF). All joints flexion (-), extension (+).

Table 8.5 Joint angle range: ankle, knee and hip from TD-MKF, MKF-TO and TD-TO.

	TD-MKF		MKF-TO		TD-TO	
	Yr 1	Yr 2	Yr 1	Yr 2	Yr 1	Yr 2
Ankle (°)	-1.8	-11.5	30.6	29.7	28.8	18.2
Knee (°)	-17.2	-15.1	24.5	20.4	7.3	5.3
Hip (°)	0.7	13.6	59.7	48.9	60.4	62.5

Table 8.6 Segment angles relative to laboratory. Segment moved past vertical (+), behind vertical (-).

		TD	MKF	TO
$A_{(ThighLab)}$(°)	Yr 1	-37.8 (0.5)	-29.6 (5.0)	21.8 (1.7)
	Yr 2	-38.1 (2.8)	-20.4 (6.3)	19.7 (3.9)
$A_{(ShankLab)}$(°)	Yr 1	-14.5 (3.3)	7.2 (6.1)	34.1 (8.7)
	Yr 2	-18.8 (2.4)	25.8 (10.8)	35.7 (5.3)
$A_{(FootLab)}$(°)	Yr 1	-98.3 (1.6)	-78.0 (0.4)	-21.4 (6.3)
	Yr 2	-97.7 (3.3)	-71.4 (5.5	-19.0 (5.5)
$A_{(PelvLab)}$(°)	Yr 1	0.6 (1.3)	5.3 (4.2)	-13.0 (0.7)
	Yr 2	-6.6 (1.9)	-1.4 (1.4)	-12.1 (2.5)
$A_{(TD)}$ (°)	Yr 1	-66.9		
	Yr 2	-67.3		

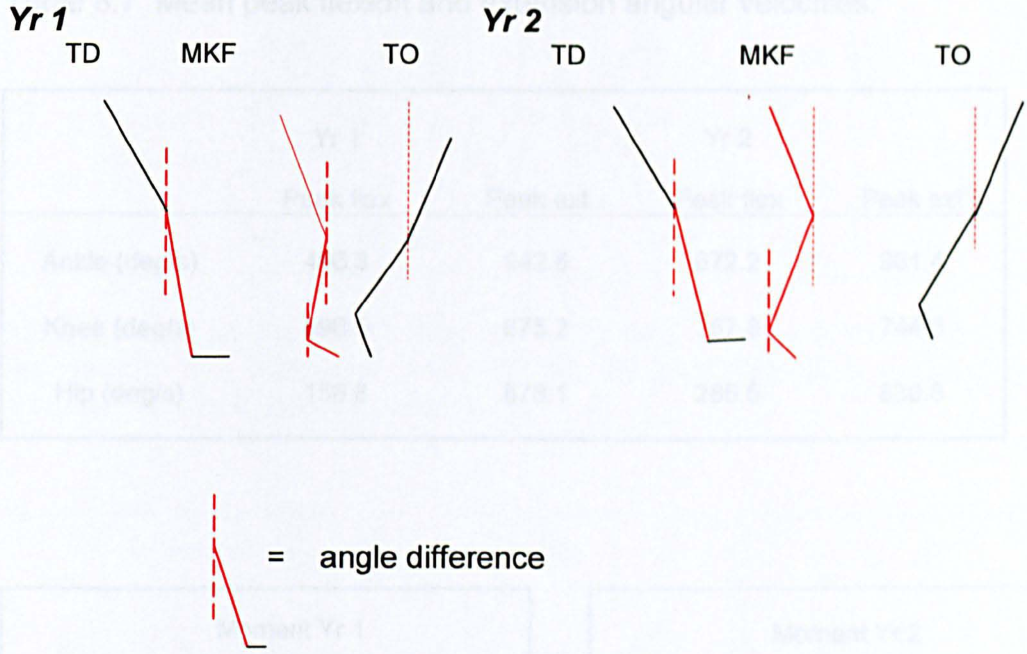


Fig 8.3 Stick diagrams at TD,MKF and TO in Yr 1 and Yr 2. Red lines indicate differences > 4°.

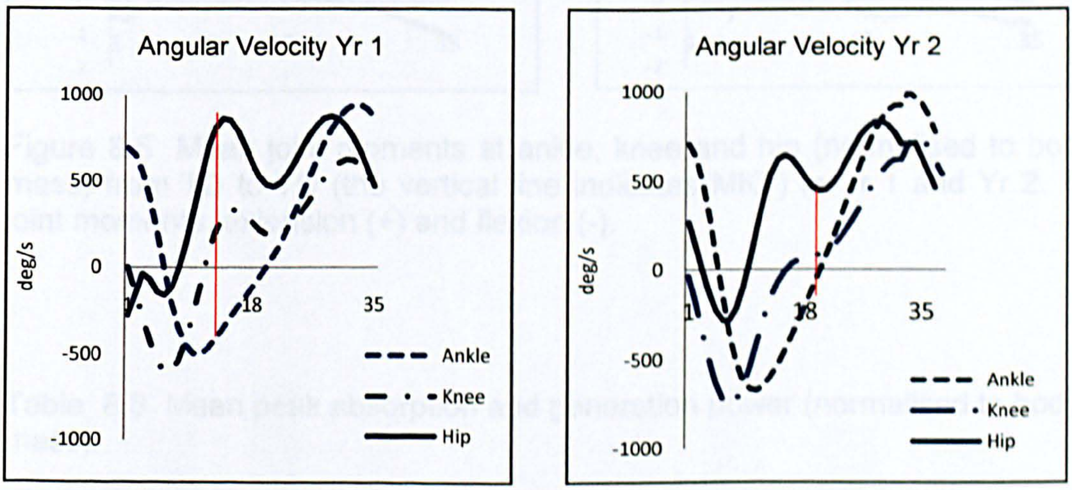


Figure 8.4 Mean angular velocity at ankle, knee and hip from TD-TO (the vertical line indicates MKF) in Yr 1 and Yr 2. All joint angular velocities flexion (-) and extension (+).

Table 8.7 Mean peak flexion and extension angular velocities.

	Yr 1		Yr 2	
	Peak flex	Peak ext	Peak flex	Peak ext
Ankle (deg/s)	496.3	942.6	672.2	961.4
Knee (deg/s)	596.5	675.2	757.8	744.3
Hip (deg/s)	156.8	878.1	285.5	830.8

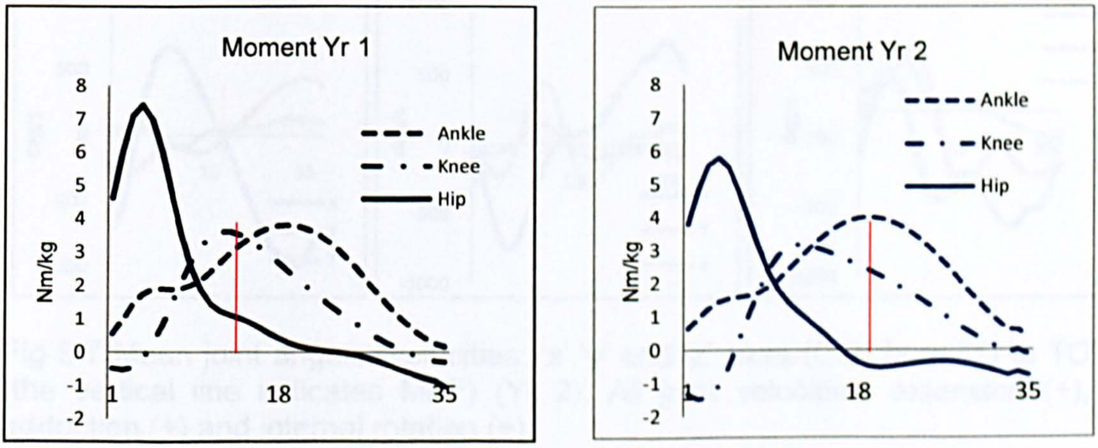


Figure 8.5 Mean joint moments at ankle, knee and hip (normalised to body mass) from TD to TO (the vertical line indicates MKF) in Yr 1 and Yr 2. All joint moments, extension (+) and flexion (-).

Table 8.8 Mean peak absorption and generation power (normalised to body mass).

	Yr 1		Yr 2	
	Gen	Abs	Gen	Abs
Ankle (W/kg)	20.94	19.57	23.4	23.4
Knee (W/kg)	17.0	10.21	5.98	20.87
Hip (W/kg)	27.3	14.4	9.05	15.36

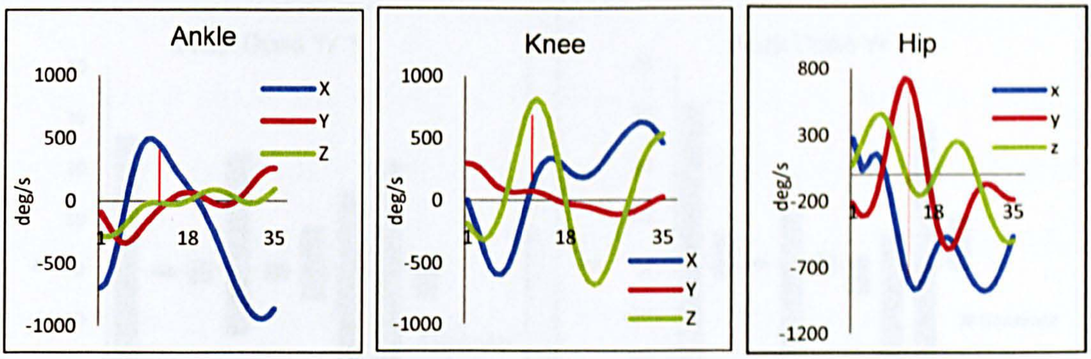


Fig 8.6 Mean joint angular velocities: 'x','y' and 'z' axes from TD to TO (the red vertical line indicates MKF) (Yr 1). All joint velocities, extension (+), adduction (+) and internal rotation (+).

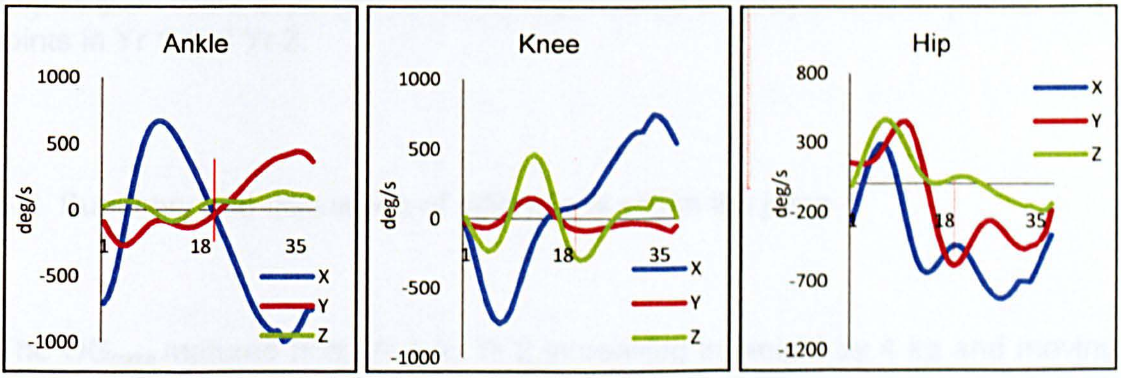


Fig 8.7 Mean joint angular velocities: 'x','y' and 'z' axes (OG) from TD to TO (the vertical line indicates MKF) (Yr 2). All joint velocities, extension (+), adduction (+) and internal rotation (+).

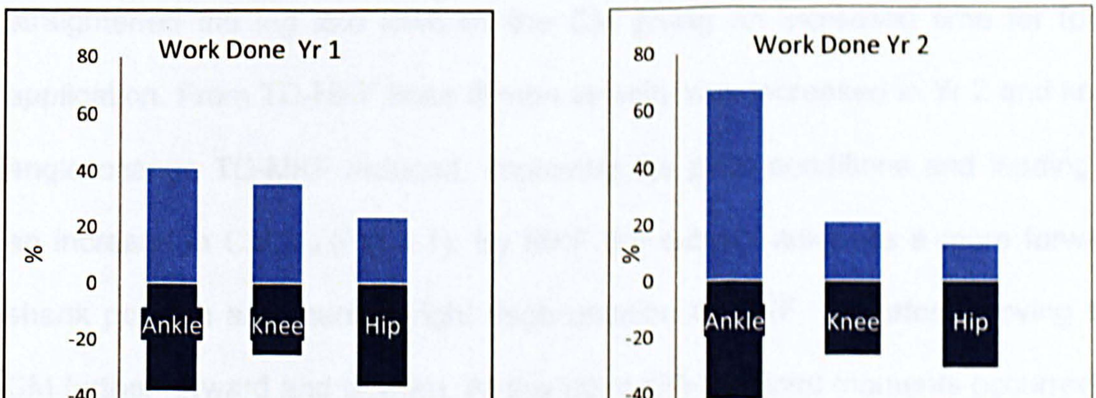
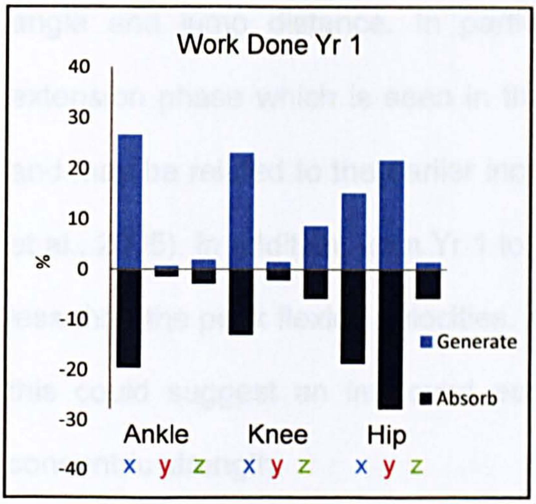


Figure 8.8 Sagittal plane (only) percentage work done contributions at all joints in Yr 1 and Yr 2.



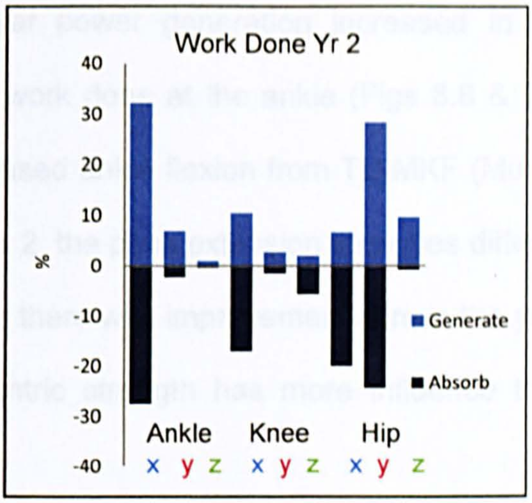


Figure 8.9 Work done (percentage) (normalised to body mass) all planes at all joints in Yr 1 and Yr 2.

8.3 Summary and discussion of differences within the jump

The OG_{case} matured from Yr 1 to Yr 2 increasing in weight by 4 kg and moving from 4 to 5 on the Tanners index. In addition she increased her run-up speed (improving the pivot conditions) and jump distance. At TD in Yr 2 the shank angle was increased backward and as the thigh angle was similar this straightened the leg and lowered the CM giving an increased time for force application. From TD-MKF knee flexion velocity was increased in Yr 2 and knee angle change TD-MKF reduced, improving the pivot conditions and leading to an increase in CM V_V (Fig 8.1). By MKF the subject achieves a more forward shank position and more upright thigh position at MKF, therefore moving the CM further forward and upward. At this point different joint moments occurred at all joints. From MKF, small increases in ankle and knee velocities led to consistently increasing knee and ankle velocity extension curves and at TO this led to similar CM $V_{H.}$ However, CM V_V increased in Yr 2 giving an increased TO angle and jump distance. In particular power generation increased in the extension phase which is seen in the work done at the ankle (Figs 8.8 & 8.9) and may be related to the earlier increased ankle flexion from TD-MKF (Muraki et al., 2005). In addition, from Yr 1 to Yr 2, the peak extension velocities differed less than the peak flexion velocities. As there was improvement across the year this could suggest an improved eccentric strength has more influence than concentric strength.

Outside the sagittal plane there seems to be more stability particularly at the knee and hip joints which can be seen in the angular velocity curves, and there is increased work generation at the hip in both frontal and transverse planes

OG_{case} demonstrated improved run-up velocity, a straighter leg, less knee flexion, lowered CM and increased V_V generation, all of which improve the quality of a pivot. She resisted knee flexion at higher run-up speeds and showed more consistent knee extension which implies better eccentric, and possibly, concentric strength. Take-off angle and jump distance improved as she utilised the ankle more in the sagittal plane, hip more in the frontal plane and improved the opportunity to jump 'upward'. During compression pivot qualities were demonstrated, and after MKF she has improved ability to extend quickly, either through increased strength, technique or both. It may still be argued that the increased run-up speed is responsible for the improvement in jump distance but noticeable differences in jump technique, moving toward more elite technique and a more effective pivot, suggest that this is a factor.

Research (Stephanshyn and Nigg,1998; and Graham-Smith and Lees, 2005) has highlighted that ankle work and hip adduction are important to long jump performances it is likely that the increased hip work in the frontal plane and ankle work in the sagittal plane are part of an improving and evolving technique. It is possible that increased strength and later stages of maturation allow the subject to move toward more mature 'elite' technique. Utilising the hip in the frontal plane and ankle to extend and act on all body segments may be of increased importance if jumping

9.0 Discussion

This section will be divided into several sections and compares the findings to literature, relates them to the pivot model, explores the case study finding, points of detail and practical application.

9.1 Comparison to findings in the literature

Long jump performance is characterised by approach speed, take-off velocities and jump distance. Most studies of the long jump have been concerned with elite mature athletes with fewer studies concerned with junior athletes. Nevertheless, data from this study compares favourably with those fewer studies using similar subject groups. In this section unless otherwise stated comparison to elite findings is made using OG data. In order to contextualise the OG comparison group differences (relative to the OG) are highlighted.

9.1.1 Kinematics

The mean approach speeds for the young and old good jumpers were 5.9 m/s and 6.9 m/s respectively with both good and poor jumpers having similar run-up speeds. In this study speeds were comparable to those obtained by Glize and Laurent (1997) for 'skilled' (6.7 m/s) and unskilled (5.4m/s) jumpers. In this study the YG and OG had jump distances of 4.0 m while the YP jumped 3.0 m and the OP achieved a mean of 3.3 m. The English Schools Athletic Association school standards award a gold to a 4m jump and silver to a 3.3m to girls at Key Stage 3 (aged 11-14 yrs) and a 4m jump is a merit at Key Stage 4 (aged 15-16 yrs) level. This shows that the good jumpers are better than most jumpers for their age. In addition, the English Secondary Schools (2009/2010) county standards (minimum) are 4.65 m for junior girls ((U'15) and 4.80 m for intermediate girls (U'17). This also highlights the limited progress observed in young girls between the ages of 14-16 yrs that partially explains the similar mean jump distance (4m) and run-up velocities (6.9 m/s) for the good groups.

From touch-down to take-off the long jump is characterised by changes in horizontal and vertical velocity. Within this study the data (profile) generally reflected that of elite athletes although some differences were observed. For ease, the OG are used for comparison unless otherwise stated. The OG lost horizontal velocity of around 0.4 m/s. This was smaller than the 1.07 m/s quoted by Berg and Greer (1995) and the 1.20 m/s reported by Lees et al., (1993). In addition, the 1.57 m/s gain in vertical velocity found in this study was roughly half the 3.07 m/s reported by Lees et al. (1993) for elite athletes. The loss in horizontal velocity and gain in vertical velocity during the compression phase is indicative of the use of a pivot mechanism for jumping. The lower loss of horizontal velocity and lower gain of vertical velocity demonstrated by the subjects in this study may reflect the lower approach speed, but may also reflect a difference in the effective use of the pivot mechanism. In addition the model used was only a lower body model therefore the upper body was not factored in the calculation of the CM. As the arms are elevated to aid take-off they would not be considered, potentially lowering the calculated vertical velocity at take-off.

The values for vertical velocity generation obtained in this study are, as expected, smaller than elite values, but increase constantly through the contact phase as they do the elite jumpers. The pattern of change for horizontal velocities between TD and MKF is similar between subjects in this study and elite jumpers but there was a velocity increase from MKF-TO found in this study, in contrast to that of Lees et al. (1993) where horizontal velocity did not increase after MKF. This indicates a compromised ability to continue to drive upward after MKF. Specifically in this study the vertical velocity values at TD, MKF and TO were -0.17, 0.91 to 1.36 which were smaller than those of -0.03, 1.98 and 3.05 m/s generated by elite female athletes (Lees et al., 1993). The horizontal velocities in this study were 6.95, 5.9 and 6.60 m/s at TD, MKF and TO which differs from the 8.75, 7.73 and 7.75 m/s pattern reported in the Lees et al. (1993) study. The clear horizontal velocity *increase* in the extension phase of the jump for the subjects in this study demonstrates a difference in technique after MKF that increases horizontal velocity and contributes to their lower TO angle.

When comparing this study to Lees et al. (1993) there is a larger relative foot velocity at TD (3.34: 2.15 m/s), smaller knee flexion velocity (9.64 : 12.1 $rads^{-1}$), and increased knee flexion (23.7 ° : 21.6 °) from TD-MKF. This suggests less of a 'pawing' action and reduced preparation for TD alongside limited pivot ability due to a more flexed rather than straight leg. In addition, from TD-MKF they showed less ability to resist the forces occurring after TD showing more knee flexion. Interestingly, a reduced knee flexion velocity should reduce the knee flexion TD-MKF however this is not the case implying a reduced strength. These differences, alongside those relating to CM velocities and a lack of strength seem to indicate a difference in technique.

From MKF jumping is typified by extension of all joints this enables the continued development of CM vertical velocity and suitable take-off angle. In this study peak ankle extension velocity was 17.9 rads^{-1} although no comparative values could be found. However, knee extension was similar to the 8 rads^{-1} reported by Lees et al. (1993) but smaller than the 11-12 rads^{-1} quoted in the studies of Graham-Smith and Lees (2005) and Muraki et al. (2008). At the hip, mean peak extension was 12.2 rads^{-1}, similar to the 12.7 rads^{-1} reported by Graham-Smith and Lees (2005). It would seem that the subjects in this study were less able to extend the knee quickly after MKF. This observation could explain the dip in vertical velocity generation that elite athletes do not exhibit (see Fig 2.8), however this may also be due to differences in sampling frequency or CM calculations (lack of trunk and free limbs in this study). Following the velocity differences it is unsurprising the take-off angles of 12° are much lower than reported values of 22° - 22.5° (Lees et al.,1993; Lees et al.,1994).

As expected, the young females had lower run-up speeds and jump distances, which in turn led to lower V_V gains and V_H losses. The development of vertical velocity is important in the jump for distance. However, all the subjects were able to increase their vertical velocity but their level of success was different, as was the way in which the distance was achieved. The young jumpers showed preparation for TD similar to elite athletes but this was less marked. Larger shank inclinations led to increased knee flexion TD-MKF and smaller inclinations led to a more flexed leg at TD in the young jumpers. In general, the young jumpers were less able to show eccentric and concentric strength leading to increased knee flexion and a consequent dip in the CM vertical velocity development curve. This is also demonstrated in their increase in V_H after MKF which is not seen in elite jumpers. These young jumpers show some preparation for jumping, with better jumpers having less shank inclination at TD but they all seem to lack the strength required to mirror elite jump technique.

Group kinematic differences

The good group had jump distances of 4 m compared to 3.2 m in the poor group, and comparative run-up velocities of 6.9 m/s compared to 5.9 m/s. In preparation for TD the OG had a smaller backward inclination of the thigh (13.9 ° compared to 17.8 ° - 20.7 °), moving the CM further forward and in preparation for TD, along with the YG and YP demonstrated a knee flexion velocity. However, the OG had a more flexed rather than straight leg at TD (27 ° compared to 22 ° in the other groups) enabling an increased time for the application of force and assist an increase in the CM vertical velocity after MKF. The OG were also more able to resist knee flexion (with a more flexed leg) having a decreased knee flexion velocity (552 m/s compared to a range of 688 – 862 m/s), improving the conditions for the pivot. Interestingly both good groups had larger peak ankle extensions (20% more than the relative poor group) perhaps indicating this as a developmental factor in the jump. This is further demonstrated in the OG having increased V_H and V_V at the ankle segment, alongside both good groups developing larger shank and thigh segment CM V_H. The importance of the ankle is further highlighted as both good groups show increased ankle dorsiflexion before MKF.

The OG have a more vertical shank and increased knee flexion at TD, and less knee flexion and increased ankle flexion during the compression period. From this they develop increased peak ankle extension velocities. The OG therefore have increased eccentric strength, ensuring less knee flexion from a more disadvantageous position and also utilizes the ankle most effectively (implying either concentric strength or better use of the stretch shorten cycle) to aid extension after MKF. This is further demonstrated in the OG having increased V_H and V_V at the ankle segment, and along with the ability both good groups show in maintaining larger shank and thigh segment CM V_H at TO which aids jump distance.

However the OG demonstrated smaller extension velocities at the knee and hip than the YG they produced a similar jump distance with a different shank and knee angle at TD, and with less knee flexion. In addition they produced smaller angular velocities but developed similar joint moments, perhaps highlighting, that different strategies can produce similar jump distances. All groups showed a limited ability to gain vertical velocity and jumped flatter than elite jumpers indicating a more running than jumping style of jump.

9.1.2 Kinetics

Recently, Stephanshyn and Nigg (1998) and Muraki et al. (2005) have investigated the running long jump and provided details of joint moments, powers and energy in adult male subjects, As this study was investigating young 11-16 yr old females it would be expected they would develop smaller joint moments than older elite male athletes. The peak joint moments developed at the hip 4.05 Nm/kg, knee 3.17 Nm/kg and ankle 3.5 Nm/kg were approximately half the values obtained by Muraki et al. (2005) and Stephanshyn and Nigg (1999). The joint moment curves were similar in shape although in this study there was not a late extension moment at the hip. Mean peak power was similarly reduced although at the knee power generation was a third of the elite values which may highlight either strength or technique differences relating to knee extension. This in turn was reflected in hip power curves that differed from Muraki et al. (2005) and Stephanshyn and Nigg (1998), having power absorption rather than power generation very close to take-off. However, Muraki et al. (2005) indicate that any hip work in the extension phase is important as it correlates with CM V_V increase. All the groups in this study were unable to do this due to the lack of a hip extension moment at the end of the jump. In terms of energy generation the OG generated energy in the order hip (0.87 J/kg), ankle (0.78 J/kg) and knee (0.40 J/kg). Stephanshyn and Nigg (1999) found generation in the order ankle (103.9 J), hip (55.8 J) and knee (52.0 J), whilst contrastingly, Muraki et al. (2005) found this to be in the order ankle, knee and hip. Both these studies clearly show the ankle as the main energy generator, The OG hip power curves reflected a double extension peak similar to Muraki et al. (2005) differing from the near single peak reported by Stephanshyn and Nigg (2005). The increased second peak in their hip power curve alongside the lack of an extension moment at TO could perhaps be partially explained by the hip being the main energy generator in the group. The sensitivity study showed that the moment errors were limited and the maximum power error (<10%) occurred at the hip. These would be deemed acceptable errors but clearly highlight that hip power has the most error associated with it. The BSP changes used in the sensitivity study suggest that using different BSP will impact on kinetic variables but within acceptable parameters.

Group kinetic differences

Generally, the both good groups had increased joint moments at TD (OG) and MKF (YG), the OG group had the largest mean peak flexion moments, and the YG the largest mean peak extension moments. At TD, the OG had the largest power values and at TO the good groups had higher values (absorption or generation) at all joints. The OG were the only group to have the ankle as the main absorber. Peak power generation at the ankle was larger in the good groups (20.5 -24.1 W/kg compared to 13.8-16.3 W/kg in the poor) and peak ankle absorption was larger in the good group at the ankle (20.3-20.6 W/kg compared to 16.7-14.4 W/kg). Interestingly, the OG absorbed a similar absolute amount of energy at the hip as the YG but less at both the ankle and knee.

At TD the OG had a larger ankle extension moment that in turn increased ankle power generation. From TD-MKF the good groups produced larger peak knee and ankle moments, and at MKF increased moments at all joints. The good groups seemed more able to resist larger forces at TD, whilst controlling knee and ankle flexion even at their greater run-up speeds. After MKF, their increased extension moments aided the extension particularly at the ankle as the good groups were able to generate significantly larger peak ankle powers at TO. This occurred at TO alongside larger knee flexion moments (perhaps in order to avoid over extension and injury at these joints), and slightly increased hip flexion moments that do not reflect the extension moments seen in the elite literature. The increased ankle flexion (and limited knee flexion) in the OG ensured they had more energy absorption at the ankle not the knee as in the other groups.

The good groups both generate larger moments and powers than the poor groups and the OG demonstrate more kinematic rather than kinetic differences. This may be due to different techniques as it seems that the OG had developed different characteristics that move them toward the elite technique. Both kinematically and kinetically the good groups show improvements around the ankle. When studying the standing long jump, Horita et al. (1991) found that although 6 yr olds had developed similar joint patterns they do not contribute similar amounts of work at the ankle, perhaps highlighting the importance of the ankle in jump technique development. Strength and extension around the ankle may influence the whole of the bodies' vertical velocity generation and may be seen as crucial in long jumping. As the long jump is a more complex action than standing long jump it is possible that these young athletes are later developing the 'mature' pattern of technique, particularly around the ankle, although the good jumpers do show development
around it.

9.2 Pivot model

The pivot model of long jumping is characterised by i) a high approach speed, ii) lowering of the body's CM during the last few strides and iii) placement of the contact foot well in front of the CM at TD. The movement from TD to MKF can be termed a pivot, a mechanical mechanism that has been found to generate over 65% of the vertical velocity within the jump (Lees et al.,1993). This is further aided by, upward arm movement, use of stored elastic energy (eccentric contraction), and the release of stored muscle chemical energy (concentric contraction) (Lees et al., 1994). As previously explained, the short time span of foot contact and the interaction of these 3 characteristics is complex, being a balance between vertical velocity gain and horizontal velocity loss, and particularly difficult for young developing females to execute considering the large forces operating on comparatively weak young females as seen below.

9.2.1 Young Groups

At TD, the YG were more upright than the YP however at MKF both groups had developed similar CM V_V and, the YG achieve a greater CM V_v at TO and thus appear to produce a more effective jump,. The kinematic and kinetic data also highlight the function of the knee in the pivot. The YG flex through the same angle as the YP but have a slightly lower knee flexion velocity (688.7 $rads^{-1}$ compared to 706.8 $rads^{-1}$) therefore they appear to control knee flexion even with their increased run-up velocity. This perhaps explains why, with a higher CM position at TD they are able to develop a similar CM V_V at MKF. They also generated a significantly larger knee extension joint moment at MKF to resist this flexion. Both of these observations indicate greater strength in the YG. The greater approach speed placed increased stress on the knee, but was controlled by the greater strength of the knee in the YG. Generally it seems the pivot is not effectively performed, strength seems to be the important factor in the success of the YG.

At MKF, due to a more upright thigh and pelvis the YG have a different posture that moves their CM further over the foot. The YG have at this point lost slightly more CM $V_{H,}$. From this more upright forward position they are able to develop larger peak extension velocities toward TO. Although this group have an increased shank CM V_V this is not seen in the thigh CM V_V probably due to its' significantly increased forward inclination. As the groups have similar knee flexion and flexion velocities it is likely that some increase in CM V_V at TO was due to the strength previously identified and the increased ankle extension velocity (884.5 rads^{-1} compared to 586.8 rads^{-1}) which contributed to the significantly increased ankle power. This suggests that they are 'jumping'. The increased ankle power would have contributed to the increase in shank and thigh CM velocities. This was then reflected in main energy generation that occurred at the ankle in the YG and hip in the YP. Throughout the jump the YG absorbed more energy due to increased ankle flexion velocity, and larger knee and hip moments, but also generated more energy (3.3 J/kg compared to 2.9 J/kg) mainly due to increased extension velocities at all joints and an increased knee joint moment. The increased absorption could indicate the opportunity to use the stretch shorten cycle to improve generation particularly at the ankle. In addition in the 'y' and 'z' planes the YG show less fluctuation in angular velocities and joint moments particularly TD-MKF which indicates a more stable lower leg supporting the notion of increased leg strength in this group. Across all planes, the YG generate and absorb more energy (% and absolute). The YG are able (after MKF) to develop an increased CM V_V at TO, perhaps due to an improved position at MKF, but the relevance of the pivot is not clearly established. In fact, in this case, at this age, the pivot conditions do not appear to produce a better jump distance and speed seems to be the dominant feature.

9.2.2 Old Groups

At TD the OG had a more flexed knee but a more upright shank increasing their CM height. They also had an increased run-up speed aiding a pivot but a higher rather than lower CM position (aided by a significantly different shank angle) which would provide less opportunity to develop vertical velocity via a pivot. At TD they had a higher CM which is less effective for a pivot but had reduced joint angular velocities the knee, better preparation for TD. The increased knee angle and less straight leg are not signs of an effective pivot, however contrastingly, from TD-MKF, they had less knee flexion and less knee flexion velocity demonstrating an improved strength and ability to control the knee at a more disadvantageous position, improving the pivot. This is aided at MKF by increased joint moments at all the joints. By MKF they had a slightly larger CM V_V and a better position to increase in CM height than the OP.

In the compression phase the OG seem to prepare better for TD having a reduced foot velocity, increasing the 'pawing' effect and indicating improved technique. In addition they had reduced ankle angular velocity (-421.9:-622.5 deg/s) alongside a knee flexion (-51.3: 25.4 deg/s) rather than extension velocity. After contrasting positions at TD, a similar position at MKF indicates less shank movement, and aiding a pivot the OG show increased knee strength as they flex the ankle through 4.0° more providing an improved opportunity for later use of the stretch shorten cycle at the joint.

The larger joint extension moments of the OG enabled the generation of larger peak extension velocities at the ankle and hip. Peak ankle moment and velocity were both significant and unsurprisingly led to significantly increased ankle power that would act on the shank and thigh segments. At TO the OG had increased V_V at all segments inferring a more 'upward'/ jumping style, which would follow from greater ankle power and the larger ankle angle (-57.1 ° : -52.8 °) at TO. At all segments the OG had increased vertical and horizontal velocity that (at these small velocities) would, in combination, correspond to a longer jump distance.

In the rotational and transverse planes the OG exhibited less movement / velocity fluctuation before MKF (see figs 6.12 & 6.13) indicating more stability than the OP. In all planes the OG generated more and absorbed less energy, giving a net energy balance overall whereas the OP had a 'net' energy absorption mainly at the hip which was related to increased adduction velocities and abduction moments. In the frontal plane the OG had 'net' energy generation at the hip in contrast to the OP who had a 'net' energy deficit.

In summary, the OG show several indications of the improved strength, a more effective ability to provide a pivot and increased technical ability (pawing). At increased run-up speeds they resisted knee flexion and even with a higher CM and greater ankle flexion are able to increase their V_V slightly more by MKF. The knee angular velocity at TD combined with lower flexion TD-MKF reflected the findings of Graham-Smith and Lees (2005) in 'elite' performances. There are some indications that the OG are stronger, jump with greater stability and produce a more effective pivot than the OP. In addition they demonstrate an improved ability to use the ankle to develop vertical velocity during extension.

9.2.3 Young Good to Old Good comparison

Whilst the mean jump distance and run-up speed were similar, the manner in which the distance was achieved differed between the young and old good jumpers. At TD the OG had more knee flexion (NS) , a less inclined shank and higher CM. From TD-MKF they had less knee flexion (5.5°) and peak flexion velocity at the knee was smaller, demonstrating improved strength and control in the group further demonstrated by increased ankle and knee power at TD. The OG demonstrated some more effective pivot characteristics whilst being 4kg heavier, however they did have a less extended leg and therefore a more upright position which is not a reflection of elite athletes. This different posture contributed to differences from TD-MKF as the OG had less shank movement (33.8° compared to 40.7 °) and similar thigh movement (11.7compared to 9.8 °) which in turn indicates a more rigid lower leg and a more pivot type action.

After MKF the OG had a smaller peak extension moment and angular velocity at the knee but increased peak ankle extension velocity. At TO the OG generated larger horizontal and vertical CM velocities at the foot and as both good groups had a significantly larger peak ankle power in the extension phase, highlighting the ankle's importance within the jump. In addition the OG show less pelvis movement from TD-TO (18.8° compared to 12.8°). Interestingly, the OG generated less absolute power and absorbed less, except at the hip. Overall the OG were more energy efficient generating and absorbing less energy. Whilst both good groups showed less angular velocity fluctuation outside the sagittal plane, at the knee, the OG had less rotational fluctuation, perhaps due to increased strength. In addition, this group did less work in the 'y' and 'x' planes generally having a more efficient technique.

These findings suggest different strategies can obtain similar distances and confirms the complexity of long jumping. A less backward inclined shank angle develops with age and ability, perhaps as a learnt technique, as an adaptation from a running to jumping style approach or, in part due to an increased (4kg) body weight. This position would allow the OG more movement of the thigh around the knee from TD-MKF, which interestingly does not occur as they have a more rigid lower leg. Also an increased power at TD suggests that the increased eccentric resistance aids performance reducing knee flexion and aiding a 'pivot'. After MKF the YG showed increased extension velocities but this was not apparent in the older jumpers where knee extension timing and peak ankle extension seemed more important. This, in conjunction with the ankle extension, contributed to increased foot CM V_V and V_H in the older jumpers. Both groups have similar thigh angles but differing shank movement through the jump and the OG also have less pelvis (suggesting less trunk) movement. Overall, the OG are more energy effective generating and absorbing less energy. This reflects the work of Anderson and Pandy (1993) who found pre-stretching (knee at TD and ankle TD-MKF) leads to a more efficient rather than significantly higher vertical jump.

Although performance similarities between the groups are acknowledged they clearly differ in their ability to resist knee flexion and have differences at TD and TD-MKF. At this point the shank angle seems to be a contributing factor.

Fluctuations in the frontal and transverse planes may reduce effectiveness of the jump and it seems that strength development, alongside weight increase, may influence the technique adopted i.e. whilst moving gradually from a running to jumping style. In terms of development, the importance of ankle power is highlighted in both groups, and knee eccentric strength is seen in the OG. In terms of a pivot action the OG do show improved pivot variable related to strength and they clearly pivot over the ankle using a more rigid lower leg segment. To generate good jump distance training to improve ankle power and knee eccentric strength, preferably under jump conditions, could aid development. Perhaps strangely, under similar conditions, less energy is used to propel the OG the same distance as the YG. Seyfarth et al. (2000) identified that jump distance is sensitive to eccentric force enhancement and muscle strength. From observation, in relation to young female jumpers, elite jumpers show limited joint movement within a jump which is reflected in the reduced shank and pelvis movement Of the OG compared to the YG. .This may raise the possibility that traditional mechanical energy investigations only partially explain the energy expenditure and within a jump.

Although similarities between the groups are acknowledged they clearly differ in their ability to resist knee flexion and have differences at TD and TD-MKF At this point the shank seems to be an influential factor. Fluctuations in the frontal and transverse planes may reduce effectiveness of the jump and it seems that strength development may influence the technique adopted ie moving gradually from a running to jumping style. In terms of development, the importance of ankle power is highlighted in both groups, and knee eccentric strength is seen in the OG. In terms of a pivot action the OG do show improved pivot variable related to strength and they clearly pivot over the ankle using a more rigid lower leg segment. To generate good jump distance training to improve ankle power and knee eccentric strength, preferably under jump conditions, could aid development. Perhaps strangely, under similar conditions, less energy is used to propel the OG the same distance as the YG. Seyfarth et al. (2000) identified that jump distance is sensitive to eccentric force enhancement and muscle strength. From observation, in relation to young female jumpers, elite jumpers show limited joint movement within a jump. This may raise the possibility that traditional mechanical energy investigations only partially explain the energy expenditure and within a jump.

9.3 Case studies

These are two case studies, one young and one old good jumper carried out in two consecutive years with data collected in the athletics season roughly 1 year apart.

9.3.1 YG_{Case}

There are several indicators that point to an increased ability to plan for TD and velocities changes are apparent within both segment and CM data. In addition the differences in posture at TD, MKF and TO indicate there are differences in strategies between the years that lead to increased ankle work in Year 2 (fig 9.1 below). This is further supported by viewing the pelvis angle difference at MKF from Yr 1 to Yr 2.

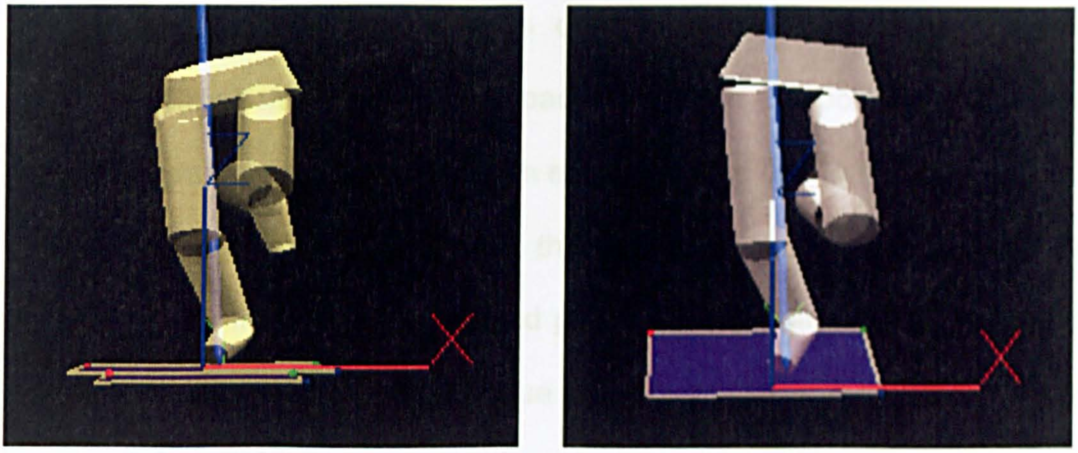


Figure 9.1 Posture at MKF in Yr 1 (left) and Yr 2 (right) for the YG_{case}.

Continued repetition of the activity seems to have assisted the development of some pivot actions and the preparation for TD. The straighter leg action shows technical development and the reduced knee flexion is possibly a reflection of this but may also reflect an older stronger subject. Interestingly a lowering of run-up velocity may have been an aid to develop technique i.e. solely to develop a 'jumping' rather than running action in Yr 2. In Yr 2 the posture difference at MKF could be seen to be advantageous however the increased V_H loss, reduced run-up speed and $A_{(ThighLab)}$ at take-off ensured a smaller jump distance with what could be argued was an improved initial technique. This demonstrates the importance of run-up speed but also highlights the complexity of jumping, as an upright position at MKF, although advantageous does not lead to a larger jump distance. The implications for strength (concentric muscle) development are also interesting as in Yr 2 as although the YG_{sub} was able to generate larger V_v this was not maintained at the CM after the initial 'pivot' and was reflected in knee angular velocity curves. This perhaps being explained by the age-related angle specificity identified by Rousanoglou and Boudolos (2008) in 13-19 yrs females, and relating to more extended or flexed knee angles. It is likely that although the YG_{case} has developed an improved technique the influence of maturation limits the impact this has at this point in development. They perhaps have to compromise on elite technique due to the lack of strength due to their age and maturity. For this particular subject the reduced jump distance may influence any continued participation as, at this point, whilst they show some improvement in technique and 'jump' better, maturation seems to be more influential.

It is clear that concentric strength development, at specific and related knee angles (straighter leg angle) may benefit and aid technique development and jump distance. Using this case study approach, although qualitative, has allowed a clear view of data change from Yr 1 to Yr 2 without the masking effect that can occur in 'pooled' data. Differences have been shown to occur in both basic technique variables (run-up velocity) and more complex variables (knee flexion velocity and pelvis angles) giving the opportunity to comment on possible subtle changes as a young female develops their technique.

9.3.2 OG_{case}

Clearly the OG_{case} improves from Yr 1 to Yr 2 possibly due to increased run-up speed. However there are indications that there is a difference in technique which allows for increased generation of CM V_v initially, which may indicate a more effective pivot, and also during the extension phase after MKF. Generally the subject seems to be more biomechanically effective within the jump. At TD a she has a straighter leg and more upright position, moving to provide a MKF position which allows upward velocity generation at the segments and have moved the CM forward therefore reducing the braking effect on the body and losing less V_H. The differences in posture at MKF seem to be highlighted by the different moments at all joints.

Her ability to resist knee flexion at increased flexion velocities, alongside their faster approach and increased shank angle suggests increased eccentric strength enhances technique. Her are also able to generate a larger peak knee angular velocity and are able to maintain a more consistent knee extension velocity which could indicate better technique, increased concentric strength or a combination of both. The technique used seems to generate more vertical velocity throughout the jump although there is still a difference (when compared to elite profiles) in the ability to maintain a smooth CM vertical velocity increase. It may still be argued that the increased run-up speed is responsible for the improvement in jump distance but noticeable differences in jump technique, moving toward more elite technique, suggest that, in contrast to the YG_{case}, she are able to use an increased speed with an improved technique. This could be a combination of improved strength, increased practice and repetition of the long jump and also a consistent body weight as she matured. These factors either assisting performance, developing ability or helping to maintain interest.

9.4 Details within the study

9.4.1 Three dimensions

This type of 3D analysis has been used mainly with less dynamic and more cyclic movements eg gait, walking and running. Application to such a dynamic activity posed problems that have to be acknowledged but also help to improve and develop understanding of the long jump. Certainly the influence of the hip and individual differences (particularly in the case studies) can be more clearly observed using 3D analysis.

Utilising 3D analysis has ensured a wealth of data that has previously not been easily used and calculated. In this study some benefit was gained from using the segment CM data, moments, powers and energy data and the angle, angular velocities, available because of the 3D nature of the study. Care however was taken when using the frontal and transverse plane data and generally they were used in a supportive role due to the previously identified errors particularly associated with the variables in the transverse and rotational planes (Reinschmidt, Van der Bogert, Nigg, Lundberg and Murphy, 1997). However, they did provide useful information about trends of movement and on inspection of individual data, did reflect patterns within individuals.

9.4.2 Variables

As research has developed in sport, and particularly the long jump, knowledge has improved and the variables used for analysis and comparison have 'evolved' and changed. Additionally, the definition of terms has differed slightly promoting confusion as to what actually is being measured. Using 3D technology may add to this by introducing more and different options but may also lead to difficulty in the comparison of studies. However it also allows easy access to more variables that *may* enhance any research but 3D non-sagittal data in dynamic activities should be used carefully. In this research it has been beneficial by allowing easy access to, i) segment CM velocities assisting a more detailed exploration of segment movement, ii) detailed kinetic and energy data

iii) both segment orientated and lab orientated data therefore giving a more detailed picture of the jumper and their pose. However it also creates the possibility for data 'overload', therefore requiring good planning, and in the case of long jumping, specifics need to be regarded carefully due to errors. In this study this could be further compounded by intra-subject variability particularly in poorer performers.

As stated, comparison to previous data is not always easy with differing methods and in this study whole body CM was difficult to calculate (not appropriate for the method) so comparison to previous data was difficult. This, although useful, has to be interpreted carefully as it may be influenced by the leg swing of the non-support leg and any related technique differences between subjects. This would then have an influence on CM height and CM velocities at the specific time points that are of great relevance to the pivot mechanism. In addition, as previous studies have not been carried out in 3D, nor on young athletes, comparison of some variables for junior athletes was not possible.

9.4.3 Methodology

Under the specific conditions the methods were optimised as to provide the most accurate reliable data however this was complicated by subject's ages, gender and the ability to recruit willing female subjects. Initially the problem of obtaining relevant BSPs was identified but as yet a reliable source for 13-16 yr old females has not been found although research into the younger age group has generally concluded that limited difference in actual moment and power values occur using 'male' data (Ganley and Powers, 2004). Therefore, the same parameters were used across both age ranges, which, it could be argued in the case of the OG was acceptable due to the comparative stature (observed and measured) to the YG. However, this is less likely in the case of the OP.

The recruitment of young female subjects prepared to spend a half day in a University laboratory, in athletic clothes and with an unknown researcher is quite difficult and influenced the subject recruitment. The ability of the YP jumpers although less than the YG, was, in some case 'not bad' for their age group. At an older age, recruitment was hindered by fewer participants in long jumping, alongside club involvement and maturation making subjects less willing to take part. The jump distance of the two good groups was similar and could perhaps be viewed sceptically. However, to put this in to context at the National schools championships 2010 the Junior girls winner (13-15 yrs) jumped only 10 cm less than the Senior Girls (17+ yrs) winner. Overall, ideally the subjects could have been 'better spread', however given the constraints they did reflect different abilities within their age group. Additionally the laboratory space made a difference to the 'ideal' tracking of right foot jumpers. However the changes made to the marker set-up did not have a detrimental effect, as four not the minimum three markers were used for each segment.

9.5 Practical Applications

Findings indicate that generally jumpers tend to run rather than 'jump' having a low angle of take-off and much smaller vertical velocity generation than elite jumpers. Differences between the young groups were limited, but included some significant technique (angles, angular velocities) and performance (moments, powers) variables. The role of the pivot was not clear. As YG_{case} hip angle differences also occurred from Yr 1 to Yr 2 particularly in the frontal plane (see Fig 7.7) it is possible that jumping technique is still evolving. However, the YG had less knee flexion, larger knee moments, increased ankle power and increased CM V_v at TO. The inter-dependence of these variables is difficult to quantify but YG do employ a technique which absorbs and produces more energy, has increased extension velocities and extension at some joints. The OG had developed characteristics of the pivot and some aspects of technique demonstrated by elite athletes eg extended leg, less knee flexion, preparation for TD, larger extension velocities and a more efficient jump. The OG_{case} seemed to show development across the two years reflecting jump characteristics of elite athletes, and improved jump distance whilst producing less energy ie being more effective..

9.5.1 Implications for teaching/coaching

Development of jumping performance is complicated and due to maturation it is difficult to clearly detail time related differences in performance but the clear improvement of the OG_{case} alongside the differences in the OG performance may suggest that it takes time for jumpers to develop a 'good' technique. However it is clear that within their development the subjects show increased eccentric (older) and concentric strength (younger) within their jumps. Better jumpers seem to modify their ankle/leg position to improve performance. It also seems likely that 'quicker' movement of the shank past the vertical can enhance performance by reducing the time of the braking force and moving the body to a mechanically advantageous position. At the hip, larger extension velocities occur in the good jumpers and the OG_{case} shows clear differences in their hip strategy outside the sagittal plane and the OG_{case} shows more 'elite' type characteristics indicating improved preparation for TD. In addition, this group do less work in the 'y' and 'x' planes generally having a more efficient technique.

In teaching and developing long jump the characteristics highlighted need to be addressed. Clearly maturation and chronological development will influence all children and cannot be changed. Research demonstrates that late maturing children tend not to compete in elite level competition as the process of maturation and factors that develop around this lead to 'drop out' from physical activity (Malina et al., 2004). From a performance point of view in order to develop and maintain long jumper's interest in the activity both technique and performance need to be addressed. From a performance perspective exercises to improve ankle muscles (which assist the propulsion of the whole body upward), knee muscles (both concentric and eccentric) and in all planes, alongside hip muscles (particularly abductors and extensors) should assist in improving young performers. As research has found that muscle strength should be specific to task (Nielsen, Nielsen, Behrendt and Asmussen, 1980) it is clear eccentric knee strength should be improved at knee extensions close to maximum (straight leg), hip strength under loaded conditions (i.e. reflecting touch-down conditions) and ankle extension, particularly following soleus contraction.

Improving these areas will support the athlete in developing the ideal technique but as has been seen, a lot of good jumpers manage to attain some characteristics of this without specific teaching or coaching input. As in most activities a combination of 'natural'ability, hard work and will power are essential to produce an excellent performance. However, working to reproduce certain key features in drills may improve performances. From a technique perspective, drills utilising upward (following flexion) ankle extension, running and jumping from a beat board and hopping with a sideways element may all be helpful. Ultimately long jumpers have developed with little reference to, or knowledge of the pivot and it is likely that only continued and maintained practice, having previously developed the attributes highlighted, that will ensure improved performance.

As previously acknowledged maturity, mass and self-concept influence all aspects of physical activity, and, at a young age can eliminate many young females from athletics. From both data and observation all those who continued to perform well at an older age are generally lighter and smaller than their counterparts at a similar stage of maturation. Although lighter they appeared to be more muscular and therefore more likely to have a larger strength to weight ratio. The question arises, 'which influences first? Maturation seems to reduce female's willingness to participate and therefore few participate and practice, which in turn helps the development of a 'better' technique. From a teaching perspective all athletic activities show reduced female interest early in secondary school as maturation occurs, and from experience few early maturing females choose to participate in voluntary activities. It seems important that for young females to achieve, they need to develop continual participation from a young age which as they develop and practice allows them to develop a more 'elite'type jumping technique. Early participation (and physical competence and improved motor ability related to increased participation in general physical activity that alongside longer limbs, is advantageous at this age. However, as age increases more technique dominated individuals are likely to succeed due to continued practice, continued physical exercise, delayed maturity and therefore an improved stature. Supporting this it is noticeable that the OG_{sub} highlights observable (and measurable) improvements in technique and pivot related characteristics at 15 yrs.

9.6 Conclusion

Development of long jump technique is understandably complex, particularly around puberty, when maturation prompts changes in the body in the specifically relevant areas of strength and body mass. Young jumpers reflect the general principle that speed is important for developing a longer jump distance, however, they do show some preparation for the jump in areas associated with models of jumping and good technique. The OG show improved pivot characteristics particularly the strength related reduced knee flexion and knee flexion velocity alongside a more rigid lower leg. They also improve the timing (rather than magnitude) of their extension velocities. There are also indications from both good groups that ankle power and extension is important and the rigid lower leg and reduced shank movement could indicate that the shank has an important role to play in the jump.

There is not a clear technical developmental pathway and adjustments are made as young females continue to participate, certainly some of which seem influenced by strength (concentric, eccentric and isometric). It would be difficult to improve technique directly and seems more likely that influencing the strength of specific muscles under 'jump' conditions, also aiming to develop vertical velocity, is likely to be the most advantageous approach to developing jumping ability in young females.

Limitations

It would perhaps have been helpful to have the ability to change certain parameters within QTM at certain frames as unlike gait, the long jump has a large deceleration at TD. This should improve the tracking within QTM.

As only a lower body model was used the eCM did not take into account the free limbs and trunk. Excluding these and using the centre point between iliac spine would influence the eCM height, eCM velocity (particularly the vertical velocity dip after MKF) and possibly the interpretation of the pivot.

The lack of BSP for young females was a limitation but the results of the sensitivity study suggest that those used may not have exceeded acceptable errors. However either using specific young female data or deriving data (for the subjects used) from another method dual-emission X-ray absorptiometry (DEXA) would have improved the study.

It would also have been useful to have larger differences between the sample populations, particularly the young subjects and also the time (and their patience) to collect perhaps 10 trials per individual.

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APPENDIX A

Availability and Contact Information

Please fill in your daughters' availability on the following table.
√ = available
X = not available

I hope to conduct most testing in the mornings although I realise some schools will not allow pupils to take time off school and therefore their testing may take place late afternoon/early evening.

Week Beginnin	Mon	Tue	Wed	Thurs	Fri
19th June					
26th June					
3th July					
10th July					
17th July					
24th July					
31st July					
7th August					
14th August					
21nd Augus					

Contact details:

Name____________________________

Home number____________________________

Mobile Number____________________________

Any Further Information (medical etc)____________________________

APPENDIX B

LIVERPOOL JOHN MOORES UNIVERSITY

FORM OF CONSENT (B) (CARER)

Title of project/procedure:- *The Development of Long Jump performance with Respect to Distance Jumped in Young Females*

CONSENT FORM A To be completed by parent / guardian

Please delete as applicable

I *agree/ do not agree* for my child……………………………………………………………………………

To participate in the research project named above concerning Long Jump performance and physical development. The protocol being as outlined in the letter provided.

I have had the opportunity to discuss the experimental procedures and understand that not all those who volunteer will complete the whole experiment due to random selection. I understand that my child will self assess for biological maturity.

I understand that the filming will take place at John Moores University in Liverpool, with a time commitment of approximately half a day.

***Signed**………………………………………………………(Parent/Guardian)*

***Date**…………………………………………………………………*

CONSENT FORM (B) To be completed by child

I……………………………………………………………*agree/do not agree* to participate in the study described above, the nature of which has been clearly explained to me. I understand the scope of my involvement in the project and that am free to withdraw froom the project at any time

Signed…………………………………………………………………………………………(Child Subject).

Date………………………………………………………………………………………………

Form (if applicable)…………………………………………………………………………

APPENDIX C
DATA COLLECTION SHEET

NAME:...

AGE:..

DOB:................. DATE.......................................

SCHOOL...

HEIGHT:.......................

WEIGHT......................

TANNERS............

JUMP	FOOT (TO)	DISTANCE (m)	T-B (m)	TIMING1 (sec)	TIMING2 (sec)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

OTHER COMMENTS

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....

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APPENDIX D

Dear Parent/Guardian,

Having recently completed a M.Phil. degree which investigated biomechanical characteristics of novice female long jumpers I am now involved in Ph.D. research project which is designed to gain more detailed information about young female jumpers and the way that jumping develops This involves the use several cameras and a force platform which will provide information for 3D analysis and also identify the forces involved at take-off.

As the study will be looking at the development of the long jump and therefore varying ages, the process of biological maturation will need to be considered. Therefore part of this study will involve a biological maturation self assessment by each child participant. Basically this involves a common protocol whereby each participant views a set of simple line drawings that relate to the advancing stages of physical growth. After carefully considering each drawing the participant records which one most closely relates to themself. This process is done in strict confidence and the results remain totally anonymous. Some subjects will be randomly selected to participate in long jump filming, however if your daughter is not selected they will not be placed at a disadvantage.

Taking part involves a half day commitment when the long jumping and filming will take place. This will be done at a research laboratory (with an indoor long jump pit) at John Moore's University in Liverpool This half day involves:

1) A warm up
2) The application of small circular markers to joint centres (knee, ankle, hip). These are removed but a shin and thigh marker cluster are left in place whilst jumping takes place.
3) Approximately 10 jumps
4) Height and weight will be discretely measured

I am confident that this research will be of significant value to the furthering of knowledge into the development of long jump technique and it will be an interesting and educative experience for those who participate I hope that you are willing to allow your child take part. Enclosed is a consent form, please return it to...............................

If you have any queries regarding this study please do not hesitate to contact me.

Yours faithfully

Miss G Griffiths

Appendix E

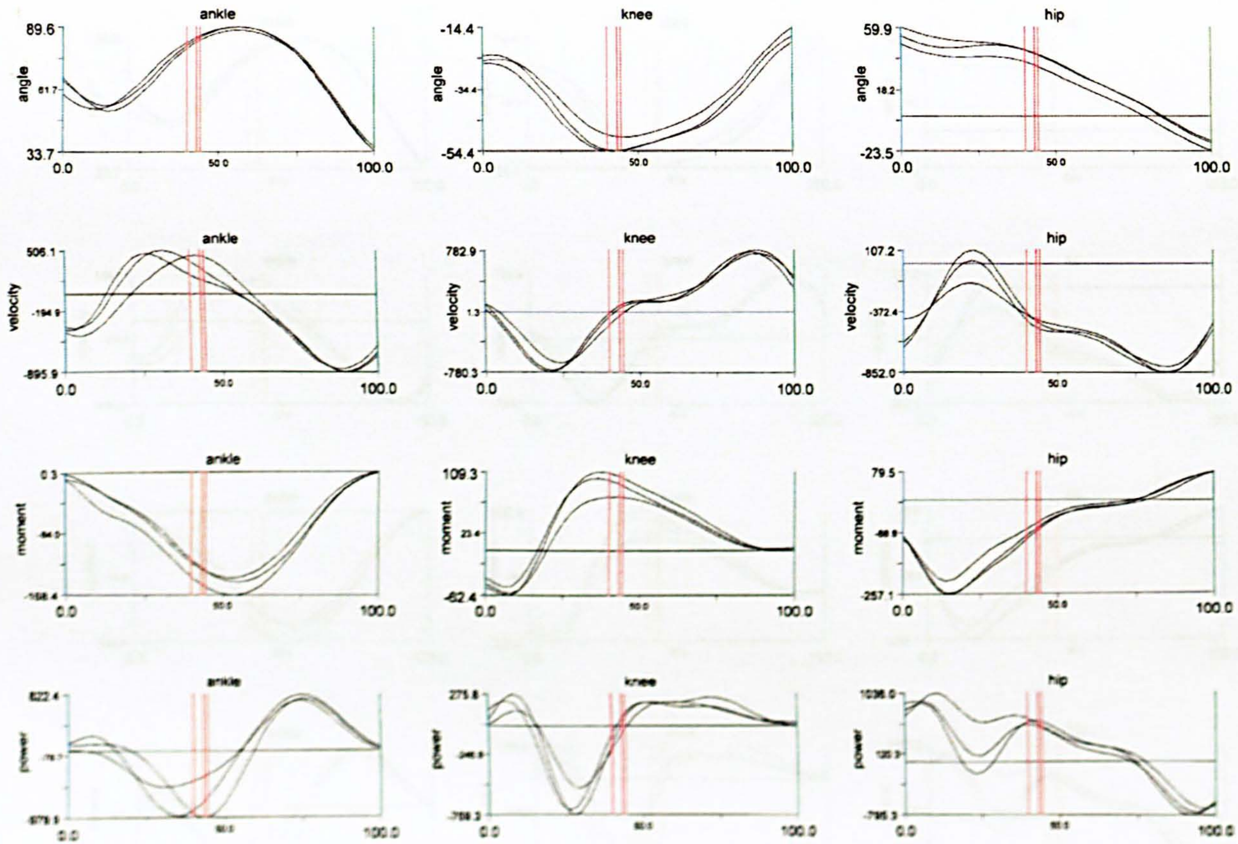
Group and subject variability

Angle		Ankle				Knee				Hip			
Group	Time	mean	Group SD	Ind max	Ind min	mean	Group SD	Ind max	Ind min	mean	Group SD	Ind max	Ind min
YG	TD	77.8	8.3	7.8	5.7	-24.0	4.7	5.6	1.0	48.1	10.8	6.2	0.1
	MKF	94.3	4.5	5.7	0.8	-50.5	4.5	5.4	1.7	33.1	15.0	7.5	1.1
	TO	55.2	6.7	3.4	0.4	-14.0	4.7	5.5	1.2	25.2	9.9	11.2	1.6
YP	TD	75.3	10.2	4.3	0.0	-21.7	8.1	7.6	4.0	55.9	7.0	4.3	1.7
	MKF	87.2	10.7	8.8	0.8	50.7	8.5	5.2	1.3	43.4	11.1	10.8	2.8
	TO	51.5	10.7	7.6	4.0	-22.7	6.8	7.6	2.3	-9.1	5.8	7.6	0.8
OG	TD	76.5	6.2	3.2	0.3	-27.4	3.8	6.8	0.8	46.8	8.4	5.2	0.6
	MKF	92.5	7.1	7.9	1.6	-51.1	8.2	9.1	0.9	34.0	12.0	7.6	0.8
	TO	57.1	7.4	7.5	2.0	-18.2	6.5	7.0	1.8	-20.3	9.2	8.5	1.1
OP	TD	78.7	3.2	4.4	1.2	-22.9	6.5	9.1	0.5	50.1	7.1	8.9	0.5
	MKF	90.5	7.2	8.4	1.2	-51.2	9.4	15.4	2.2	34.7	10.2	11.1	2.6
	TO	52.8	8.1	4.8	1.2	-19.6	10.2	10.0	2.2	-17.6	7.2	6.7	1.0

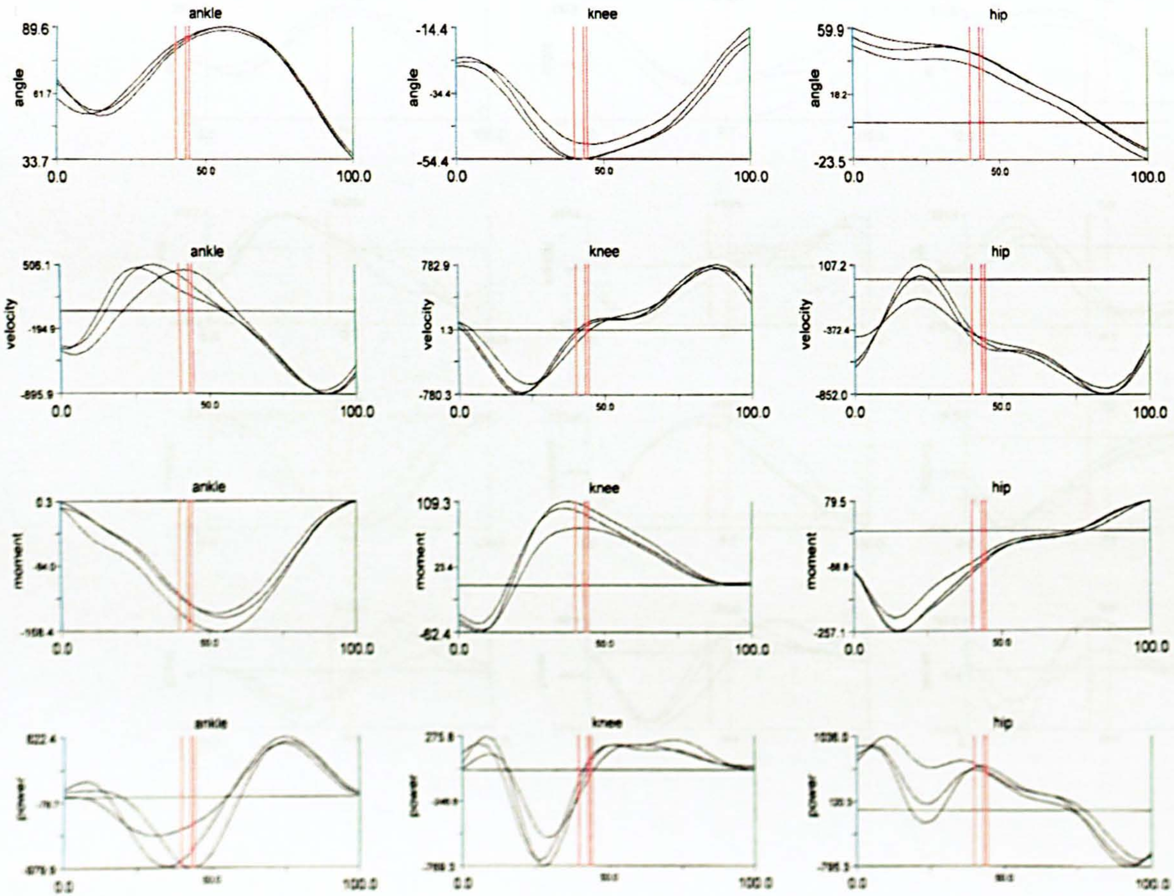
One subject graphs (sagittal plane) from V3D report from each group follow in the order,

i. YG
ii. YP
iii. OG
iv. OP
v. YG_{CASE} Yr 1
vi. YG_{CASE} Yr 2

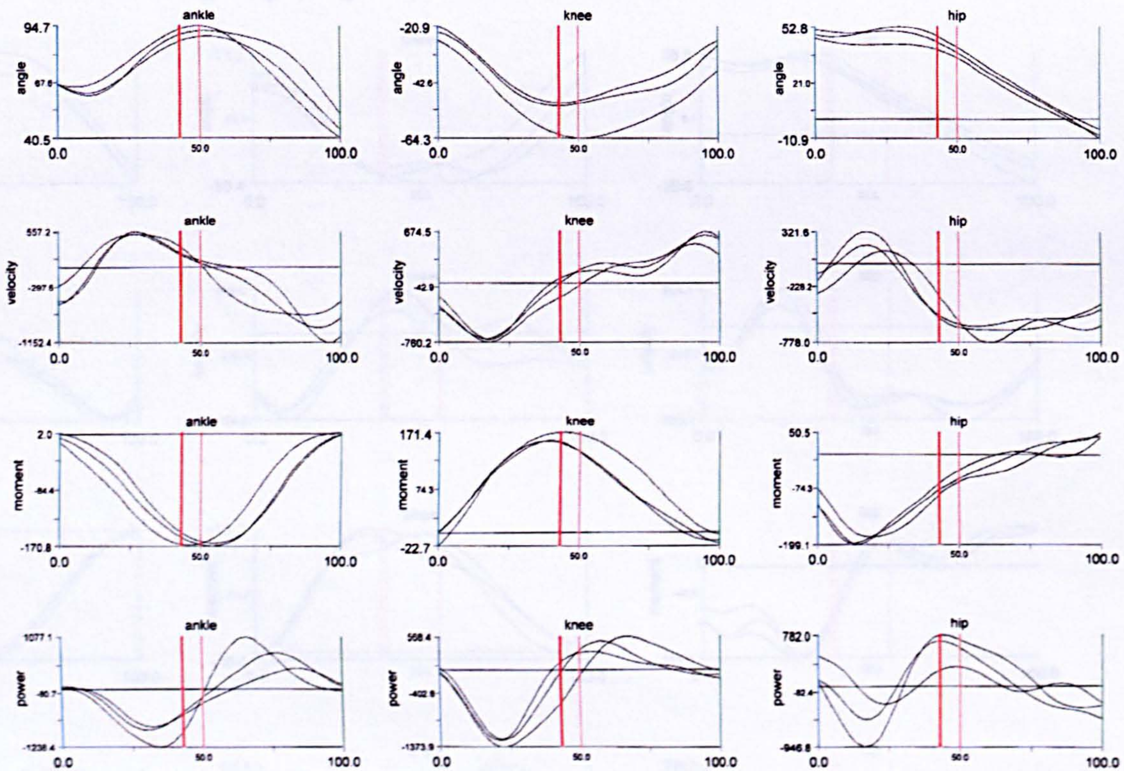
Landing leg flexion/extension



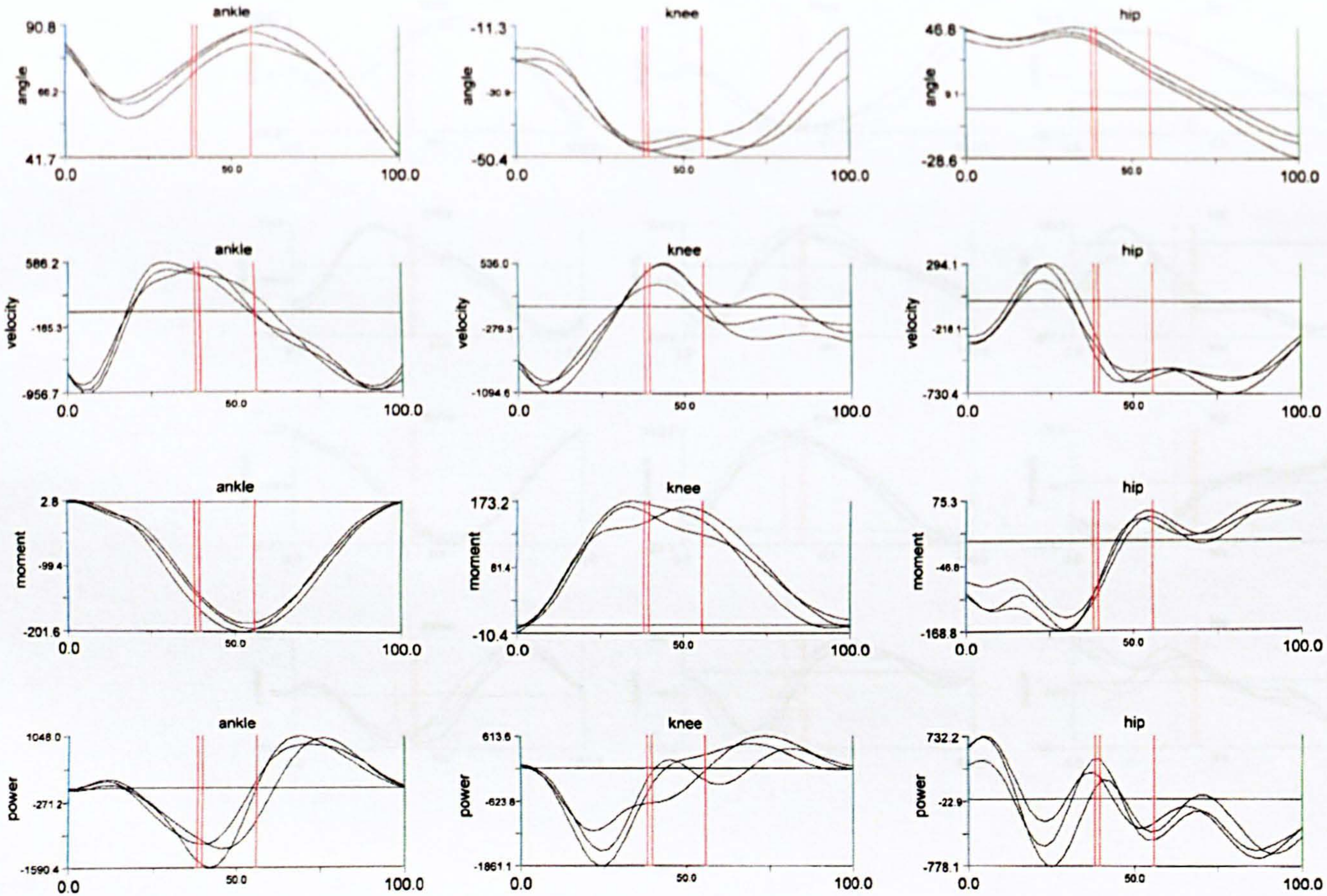
Landing leg flexion/extension



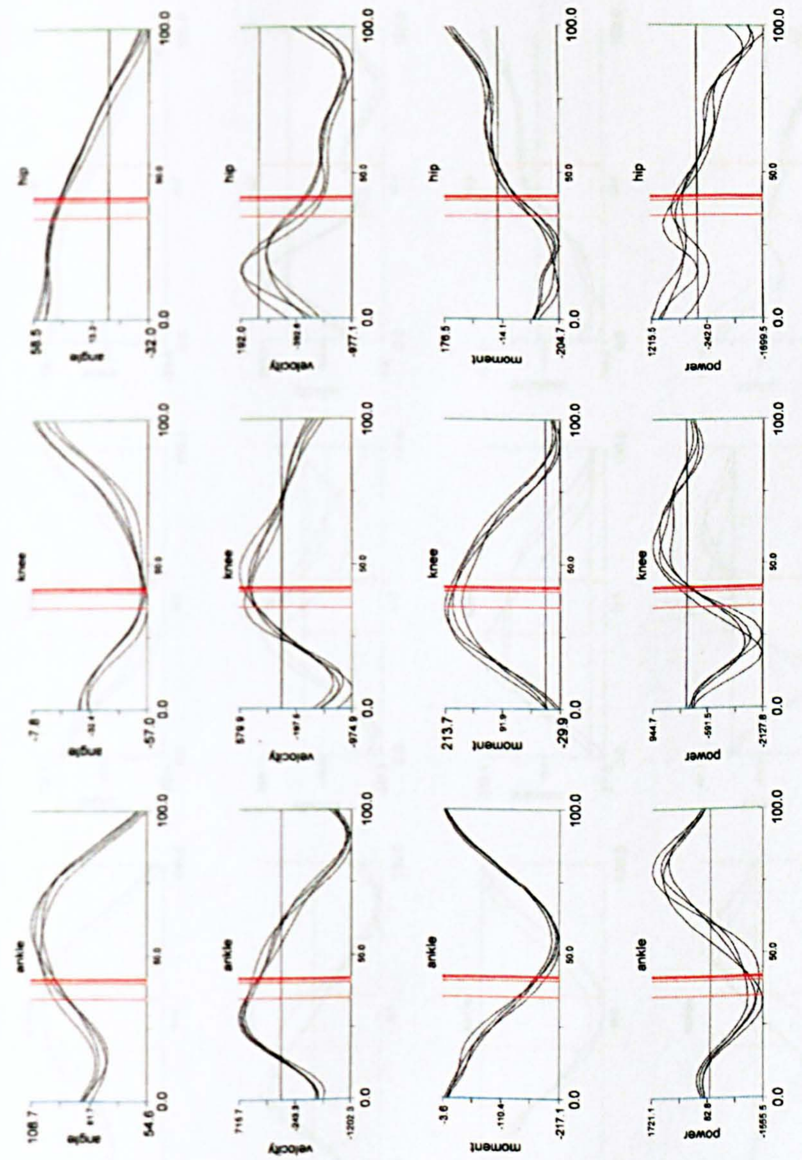
Landing Leg (sagittal) flexion/extension



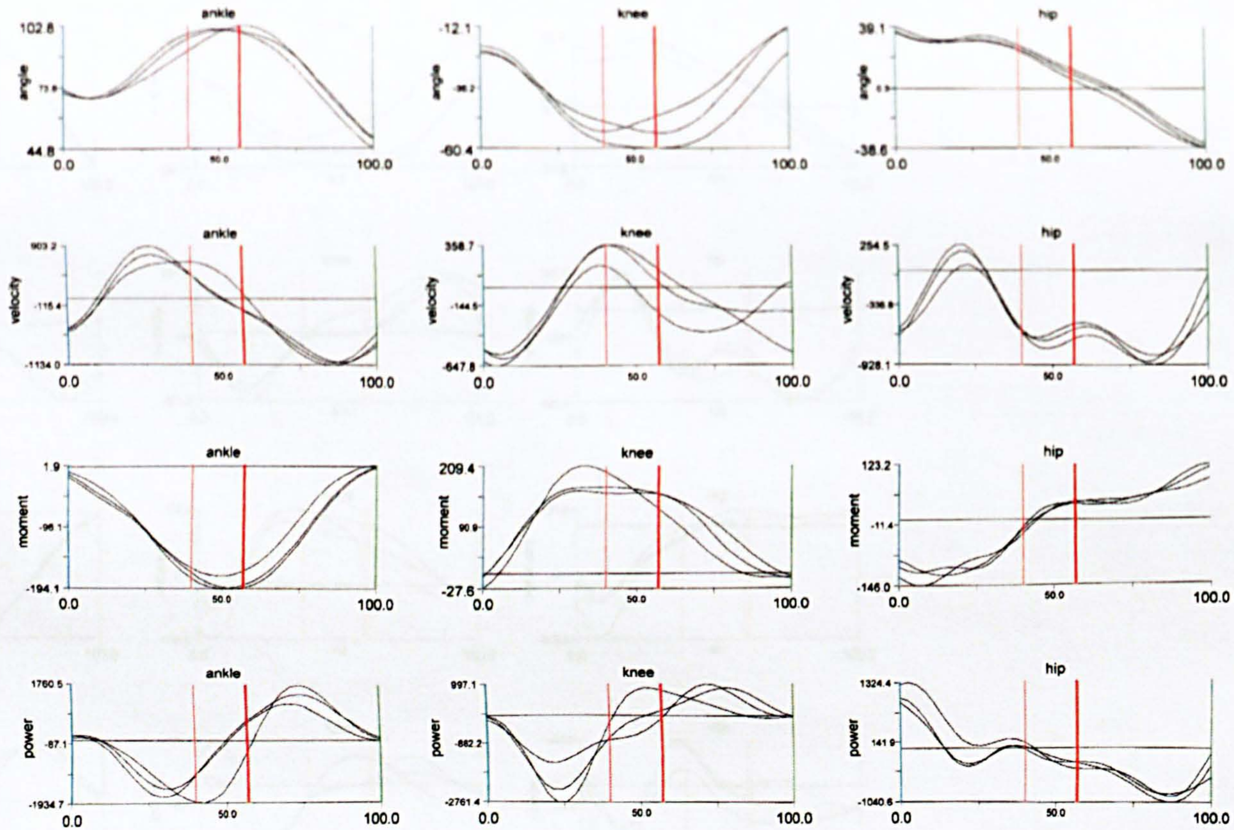
Landing Leg (sagittal) flexion/extension

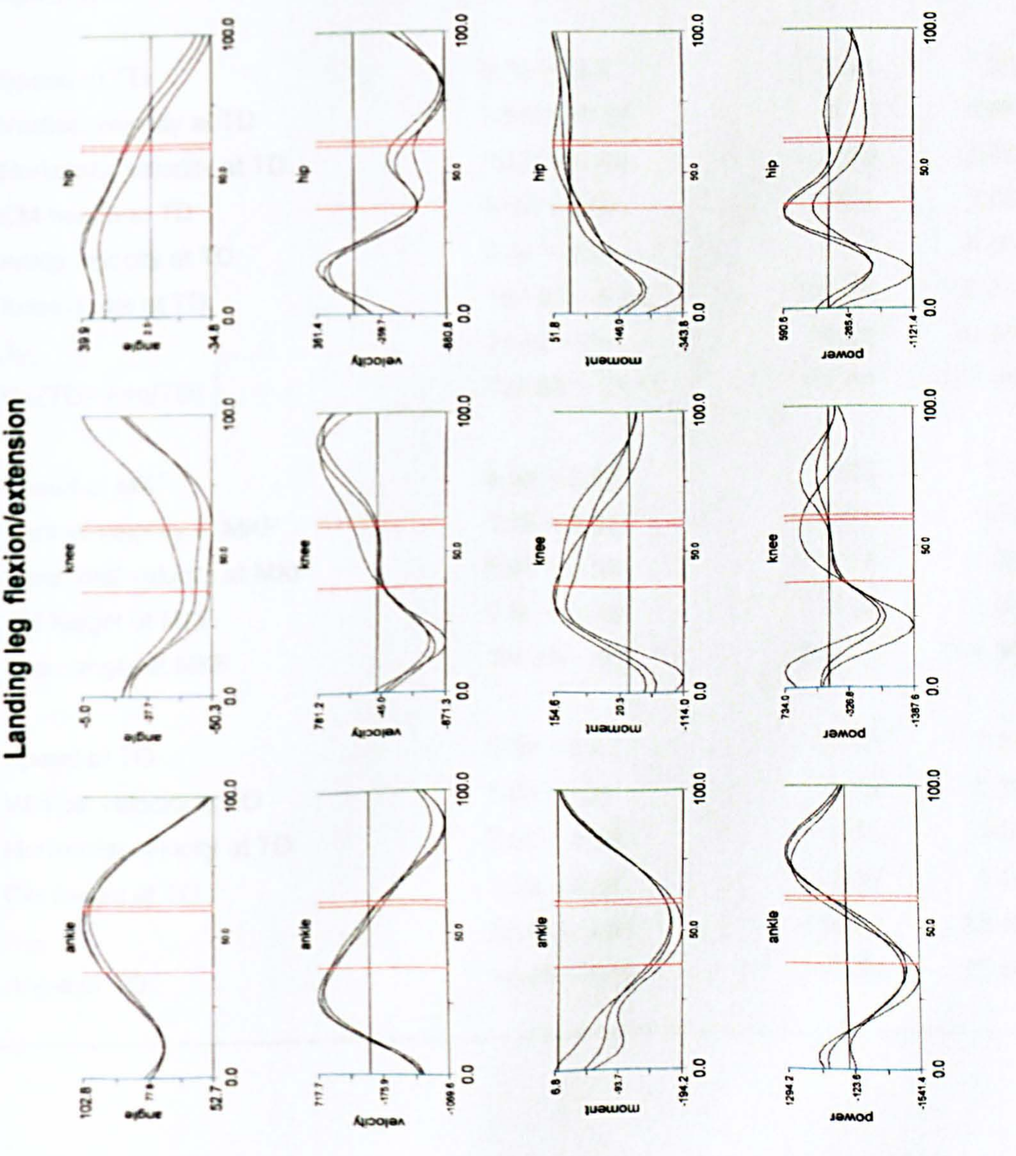


Landing Leg (sagittal) flexion/extension



Landing Leg (sagittal) flexion/extension




Landing leg flexion/extension
ankle
knee
hip
angle
velocity
moment
power
102.8
52.7
-5.0
-50.3
39.9
-34.8
717.7
-1069.6
781.2
-871.3
361.4
-880.8
6.8
-194.2
154.6
-114.0
51.8
-343.8
1294.2
-1541.4
734.0
-1387.6
590.6
-1121.4
0.0
100.0

Appendix F

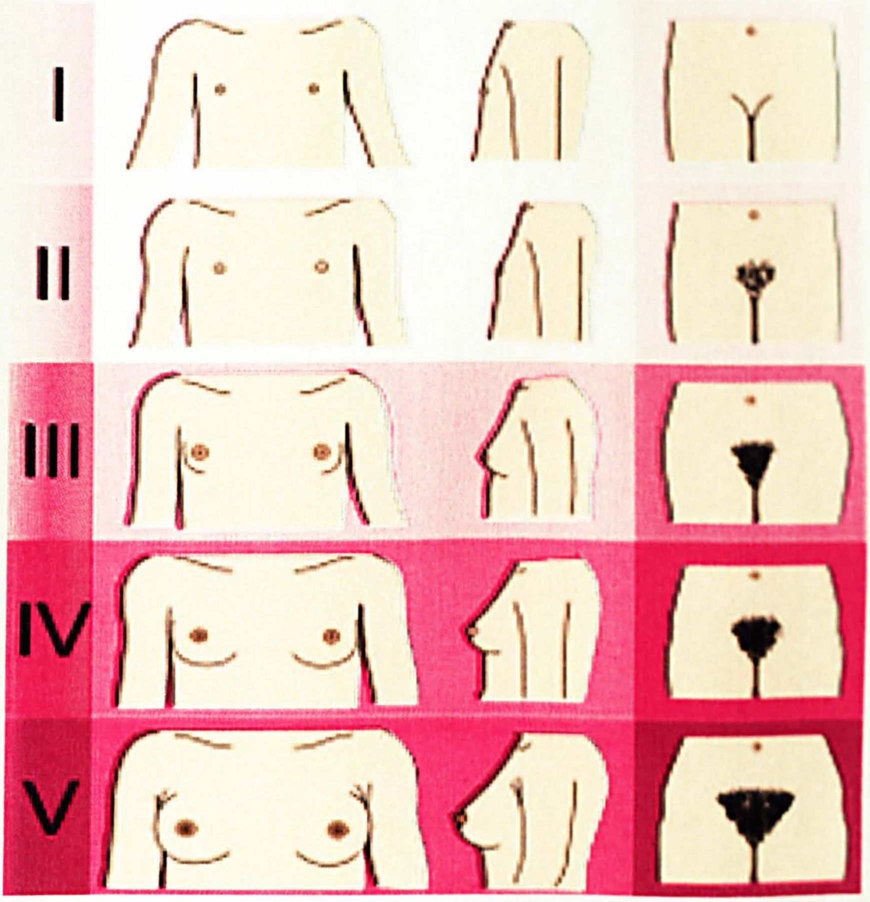
Best results from Griffiths (2000)

Variable	BEST X S.Dev	Minimum	Maximum
Distance jumped	3.98~0.26	3 70	4 07
Age(yrs)	13.83~0.94	14 7	11 25
Speed at TD	6.38 ~0.43	5 93	7 32
Vertical velocity at TD	!-0.02 ~ 0.31	-0 78	0 46
Horizontal velocity at TD	-6.37 ~ 0.43	5 93	7 32
CM height at TD	0.96 ~ 0.04	0 9	1 05
Ankle velocity at TD	3.14 ~ 1.04	1 2	4 46
Knee angle at TD	157.02 ~ 6.84	147 68	169 51
A_{TD}	21.62 ~ 3.9	16 06	32 91
Vel(TD)*Ang(TD)	137.63 ~ 25.11	102 84	197 36
Speed at MKF	5.96 ~ 0.52	5 29	7 1
Vertical velocity at MKF	1.05 ~ 0.35	0 64	1 62
Horizontal velocity at MKF	5.85 ~ 0.54	5 15	7 04
CM height at MKF	0.99 ~ 0.05	0 92	1 09
Knee angle at MKF	146.25 ~ 6.9	132 67	159 94
Speed at TO	6.29 ~ 0.47	5 72	7 26
Vertical velocity at TO	1.64 ~0.31	1 19	2 38
Horizontal velocity at TO	6.06 ~ 0.46	5 72	7 26
CM height at TO	1.12 ~ 0.04	1 03	1 19
A_{TD}	23.91 ~ 3.81	16 31	32 18
Angle of TO	15.45 ~ 3.08	11 25	22 54

Appendix F

Worst results from Griffiths (2000)

Variable	WORST X S.Dev	Minimum	Maxmum
Distance jumped	3.10 ~0.38	3 42	2 46
Age (yrs)	13.03~0.91	11 83	14 58
Speed at TD	5.69 ~ 0.43	4.67	6 4
Vertical velocity at TD	-0.16 ~ 0.23	-0.65	0 3
Horizontal velocity at TD	5.67 ~ 0.43	4.66	6 37
CM height at TD	09.3 ~ 0.05	0.78	1
Ankle velocity at TD	3.09 ~ 0.71	1.85	4 57
Knee angle at TD	157.96 ~ 5.87	144.86	173 67
A_{TD}	19.93 ~ 3.19	13.48	28 46
Vel(TD)/Ang(TD)	114.84 ~ 22.56	72 6	168 31
Speed at MKF	5.43 # 0.57	4 28	6 83
Vertical velocity at MKF	1.03 ~ 0.34	0 44	1 62
Horizontal velocity at MKF	5.38 ~0 .57	4 19	6 8
CM height at MKF	0.97 ~ 0.06	0 83	1 07
Knee angle at MKF	141.33 ~7.13	131 83	161 57
Speed at TO	5.55 ~ 0.42	4 58	6 27
Vertical velocity at TO	1.42 ~ 0.41	0 77	2 6
Horizontal velocity at TO	45.36 ~ 0.42	4 33	6 14
CM height at TO	1.09 ~ 0.06	0 97	1 19
A_{TD}	22.76 ~3.84	17 99	30 4
Angle of TO	15.22 ~ 4.64	7 06	28 00



Breasts (female)

Tanner I
no glandular tissue: areola follows the skin contours of the chest (prepubertal) [typically age 10 and younger]

Tanner II
breast bud forms, with small area of surrounding glandular tissue; areola begins to widen [10-11.5]

Tanner III
breast begins to become more elevated, and extends beyond the borders of the areola, which continues to widen but remains in contour with surrounding breast [11.5-13]

Tanner IV
increased breast size and elevation; areola and papilla form a secondary mound projecting from the contour of the surrounding breast [13-15]

Tanner V
breast reaches final adult size; areola returns to contour of the surrounding breast, with a projecting central papilla. [15+]

Self-assessment done in private area and the investigator informed or subject enters on to own trials sheet.