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

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Abstract

The long jump has been widely studied in recent years. Two models exist in the literature which define the relationship between selected variables that affect performance. Both models suggest that the critical phase of the long jump event is the touch-down to take-off phase, as it is in this phase that the necessary vertical velocity is generated. Many three dimensional studies of the long jump exist, but the only studies to have reported detailed data on this phase were two-dimensional in nature. In these, the poor relationships obtained between key variables and performance led to the suggestion that there may be some relevant information in data in the third dimension. The aims of this study were to conduct a three-dimensional analysis of the touch-down to take-off phase in the long jump and to explore the interrelationships between key variables. Fourteen male long jumpers were filmed using three-dimensional methods during the finals of the 1994 (n = 8) and 1995 (n = 6) UK National Championships. Various key variables for the long jump were used in a series of correlational and multiple regression analyses. The relationships between key variables when correlated directly one-to-one were generally poor. However, when analysed using a multiple regression approach, a series of variables was identified which supported the general principles outlined in the two models. These variables could be interpreted in terms of speed, technique and strength. We concluded that in the long jump, variables that are important to performance are interdependent and can only be identified by using appropriate statistical techniques. This has implications for a better understanding of the long jump event and it is likely that this finding can be generalized to other technical sports skills.

Keywords: *Long jump, kinematics, models of performance, three-dimensional analysis*

Introduction

The long jump has been widely studied in recent years and much is known about the factors that affect performance. Perhaps the most valuable relationship is that between approach velocity and distance jumped, which is applicable over a wide range of abilities (Hay, 1993). This relationship, though strong, is not perfect and other attempts have been made to introduce and identify variables that provide a deeper understanding of performance, in particular the mechanisms that underpin performance.

Hay and Reid (1988) outlined an approach to associate mechanical variables with a measure of performance. This approach, referred to as a "performance outcome (or deterministic) model", has been applied both to the long (Hay, Miller, & Canterna, 1986) and triple jump (Hay, 1992) events. The specific variables involved in long jump performance are presented in Figure 1. Performance, as measured by distance jumped, is directly related to the height, and vertical and horizontal velocities, of the centre of mass at take-off. Figure 1 further shows that these latter two take-off variables are related to the vertical and horizontal velocities at touch-down and the changes during contact. Hay *et al*. (1986) attempted to identify the relationships that exist within this hierarchical model of performance. They recorded data from national level long jump athletes and although many interrelationships between variables were non-significant, they did find important significant relationships between the successive hierarchical variables of distance, speed at take-off, horizontal velocity at take-off and horizontal approach velocity on the fourth last stride before take-off. These findings provided some support for the model of Hay *et al*. (1986), but the detail of what may be happening between the fourth last stride and take-off (the approach and contact phases) was absent. Despite the attractiveness of this approach to support the choice of key performance variables (Lees, 1999), no further attempts appear to have been made in the

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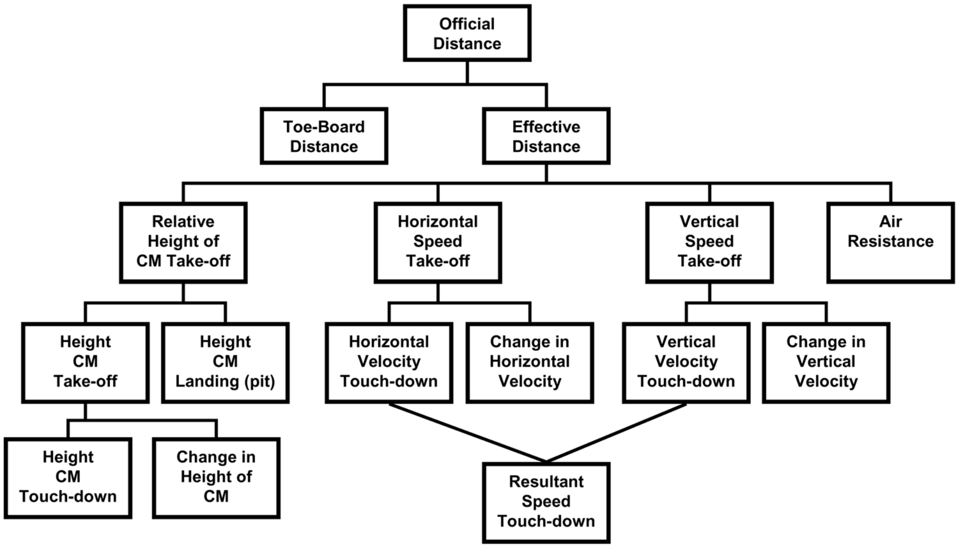

Figure 1. A performance outcome model of the long jump (after Hay *et al.*, 1986). CM = centre of mass.

literature to undertake this type of correlational analysis in athletic jump performance.

An alternative approach to the identification of key performance variables is to use Alexander's (1990) two-segment mathematical model of the touch-down to take-off phase in the long jump. This model showed that the distance jumped was a function of the approach speed, touch-down leg angle with respect to the ground, knee angle and the muscular torque acting about the knee. A more recent development of this approach (Seyfarth, Blickhan, & Van Leeuwen, 2000) has confirmed the importance of approach speed, knee angle and the muscular strength of the knee extensors, but interestingly found that the optimal touch-down leg angle was independent of approach speed. Despite the ambiguity surrounding the importance of the touch-down leg angle, these variables appear to be important in an understanding of how the impulses produced during contact are generated, thus explaining how the changes in horizontal and vertical velocity come about.

In our own studies (Lees, Fowler, & Derby, 1993, Lees, Graham-Smith, & Fowler, 1994), we have tried to quantify the kinematic characteristics of the last stride, touch-down and take-off in the long jump for elite athletes and have shown that the actual centre-of-mass height and touch-down leg angles used by athletes are similar to those predicted by Alexander (1990). Furthermore, these studies have shown that the greatest gain in vertical velocity is during the compression phase (defined as the period from touch-down to when the knee reaches its maximum angle of flexion), which is also associated with a loss of horizontal velocity. The low angle of take-off in long jumping means that any change in vertical velocity has a greater influence on jump distance than an equivalent change of horizontal velocity, and so the mechanisms leading to a gain in vertical velocity and loss of horizontal velocity are of particular interest in long jumping. This led us to propose that the gain in vertical velocity was primarily achieved by the action of the body moving or *pivoting* over the fixed foot of the touch-down leg and being forced upwards, generating vertical velocity at the expense of horizontal velocity. This action has been conceptualized as a "pivot" (Lees *et al.*, 1994), and if acting would imply that there is a relationship between the gain in vertical velocity and the loss of horizontal velocity.

The pivot is a particularly important mechanism for influencing long jump performance. It is implied by the models of both Hay and Reid (1988) and Alexander (1990). The simulation study of Seyfarth *et al.* (2000) has been helpful in providing details of how the pivot might operate. They likened the long jumper to a two-segment mass-spring model and showed that at contact the ground reaction force re-directing the velocity of the centre of mass was also associated with a compression of a "spring" modelled by a muscle–tendon system around the joint between the two segments representing the knee, thus providing the system with an "effective stiffness". During compression energy was absorbed by the muscle and tendon complex, whereas during extension energy was released, although mainly from the tendon, as the energy released by concentric muscular contraction was small. Thus, the force associated with the system compression was responsible for driving the centre of mass vertically and was enhanced by the large force developed at impact such that the greatest vertical impulse was delivered during the compression phase. The release of stored energy during the extension phase (the rebound) provides a means for further enhancement of vertical velocity once the centre of mass has rotated over the point of support such that the pivot can no longer operate. In a previous study, we found that the pivot contributes more than 64% of the vertical velocity at take-off (Lees *et al.*, 1994), confirming that most of the vertical impulse is delivered during the compression phase. The pivot mechanism explains three of the main observations of the touch-down in the long jump, which are that successful jumpers have (a) a high approach speed, (b) a low centre of mass at touch-down and (c) a leg at touch-down which is extended in front of the body by about 60° to the horizontal. The low centre-of-mass position enables the touch-down leg to be flatter to the ground when contact is made, thus creating the conditions for the pivot, while the high approach speed ensures the pivot is functional. Furthermore, the pivot mechanism also explains why the high approach velocity is related to distance jumped. It is the combination of high horizontal velocity (generated through the approach run) and high vertical velocity (generated by the pivot) that enables a greater distance to be jumped.

Because of the importance of the pivot mechanism, attention should be focused on those factors that might influence its effectiveness, which have been identified by Alexander (1990). However, these variables have rarely been reported in experimental studies and so their influence on performance has not been established. To our knowledge, only two studies (Lees *et al.*, 1993, 1994) have tried to examine the interrelationships between these variables for elite (World Student Games) long jumpers. For these athletes, the more general relationships with performance (e.g. between approach speed and distance jumped) were, as expected, confirmed, but the interrelationships relevant to the more detailed aspects of the pivot mechanism were not. The absence of expected relationships led us to suggest (Lees *et al.*, 1994) that two-dimensional sagittal plane analysis may be insufficient to fully describe the pivot in a real three-dimensional long jump and that actions may be occurring in the frontal plane which could only be uncovered with a three-dimensional analysis of the jump. Specifically, joint action at the hip may influence the success of the pivot and this will be influenced by the orientation of the trunk relative to the touch-down leg in both the sagittal and frontal planes.

While three-dimensional analyses of elite long jumping (and, related to this, the triple jump hop take-off) have been presented in the literature (Bober, 1974; Brüggemann, 1990; Fukashiro *et al.*, 1993; Nixdorf and Brüggemann, 1990; Scheirman, Smith, & Dillman, 1989), none have presented data on key variables which describe the touch-down to take-off phase, and in particular none have attempted to use these variables to investigate the detailed characteristics of the interrelationships predicted by existing models of long jump performance, and none have specifically investigated the pivot mechanism. The aims of this study were (1) to report the three-dimensional variables appropriate to the touch-down to take-off phase of long jumping for national long jumpers, and (2) to examine the interrelationships between these variables with reference to established models for the long jump in an attempt to understand better how long jumpers use the pivot mechanism to improve performance.

Methods

Fourteen male long jumpers were assessed for approach speed and technique during the finals of the 1994 ($n = 8$) and 1995 ($n = 6$) AAA Championships in the UK. No data were available for body mass and height. Approach speed was determined using photoelectronic timing devices positioned at 11, 6 and 1 m from the front of the take-off board. Technique was assessed through analysis of film records obtained from two high-speed 16 mm cine-cameras (Locam and Photosonics). The optical axes of the two cameras were approximately 120° apart; one camera was placed in the stand 20 m from the runway and about 10 m behind the take-off board, the second camera was placed 40 m in front and slightly to one side of the landing pit so that a head-on view was obtained. Both cameras were set to record at a frequency of 100 Hz and were checked by recording a millisecond timer. The calibration frame and several control markers were recorded by both cameras. Digitizing equipment included a cine projector (model DF-16c, NAC, Singapore) and a digitizing tablet (model HR48, Terminal Display Systems, Blackburn, UK; resolution 0.025 mm) operating through an Acorn A3000 computer. The best performance of each of the 14 jumpers was digitized using the software developed by Bartlett and Bowen (1993). The three-dimensional volume was reconstructed using the direct linear transformation technique (Abdel-Aziz and Karara, 1971) and the centre of mass was calculated using a 14-segment model defined by 18 points and segmental data proposed by Dempster (1955). The data were smoothed using a Butterworth fourth-order zero-lag filter with padded end-points and a cut-off frequency of 8.33 Hz. This cut-off frequency was selected on the basis of a residual analysis (Winter, 1990) and a qualitative evaluation of the data. Each jump was digitized three times and the average of the processed data taken to reduce errors.

The instants of touch-down, maximum knee flexion and take-off were identified as critical reference points within the take-off phase. Touch-down was defined as the first frame in which the foot had made clear contact with the ground and take-off was defined as the first frame in which the foot had clearly left the ground. The instant of maximum knee flexion was taken to represent the point at which the compression phase ended and the extension phase began (Lees *et al.*, 1993, 1994). The take-off phase represents the time interval between the instants of touch-down and take-off when the foot of the support leg is in contact with the ground.

All data were found to have a normal distribution following skewness and kurtosis tests outlined by Vincent (1995). Relationships were tested using Pearson's product– moment correlation coefficient, the coefficient of determination and the "best subsets" multiple regression analysis (Minitab for Windows, version 13.31, 2000). The coefficient of determination (R^2) was used to assess the association between variables. A maximum of three independent variables was permitted for the multiple regression analyses on the basis of a 5:1 ratio of jumpers to independent variables, as suggested by Vincent (1995).

Results

The accuracy of the three-dimensional reconstruction was determined by the root mean square error of the digitized coordinates and the measured coordinates. Systematic errors of 3.39, 1.92 and 5.20 mm were found for the X, Y and Z directions, respectively. The precision of the digitization was assessed on three repetitions of one randomly selected jump using the mean deviation from the mean of each variable assessed. Typically, displacement measures were precise to 0.4 mm, angles to 1° and velocities to less than 0.1 $m \cdot s^{-1}$.

Descriptive analysis

Basic data representing the best performances of the 14 jumpers are presented in Table I, while the values of relevant variables are presented in Table II. The negative velocity at touch-down of the ankle relative to the centre of mass represents backwards movement of the ankle. Such a value indicates an "active" landing, characterized by a backward-sweeping or "pawing" action of the leg at touch-down, which is thought to reduce the loss in horizontal velocity.

The horizontal and vertical velocities are given in Figure 2. As expected, the medio-lateral velocity of

Table I. Basic performance data of the 14 jumpers

Variable	Mean ± *s*	Range
Effective distance (m)	7.45 ± 0.18	7.14 to 7.84
Approach speed, 11 to 1 m ($m \cdot s^{-1}$)	9.95 ± 0.34	9.34 to 10.57
$rV_{(ANKLE)\ TD}$ ($m \cdot s^{-1}$)	−5.56 ± 1.07	−7.34 to − 3.45

Table II. Kinematic data for the instants of touch-down, maximum knee flexion and take-off

Variable	Touch-down	Maximum knee flexion	Take-off
S ($m \cdot s^{-1}$)	9.94 ± 0.37	8.95 ± 0.28	9.20 ± 0.25
VX ($m \cdot s^{-1}$)	9.93 ± 0.37	8.64 ± 0.35	8.55 ± 0.35
VY ($m \cdot s^{-1}$)	−0.18 ± 0.21	2.29 ± 0.32	3.37 ± 0.32
VZ ($m \cdot s^{-1}$)	0.13 ± 0.24	0.10 ± 0.29	0.18 ± 0.32
H (cm)	98 ± 4	104 ± 4	127 ± 4
$D_{(LEG-S)}$ (cm)	55 ± 4	3 ± 5	−44 ± 6
$A_{(LEG-S)}$ (deg)	32.2 ± 2.2	1.8 ± 3.2	−23.6 ± 3.1
$D_{(LEG-F)}$ (cm)	0 ± 3	−3 ± 4	−2 ± 5
$A_{(LEG-F)}$ (deg)	−0.3 ± 1.9	−1.8 ± 2.5	−1.4 ± 2.7
$A_{(TRUNK-S)}$ (deg)	−7.5 ± 3.3	−1.3 ± 3.4	−0.8 ± 5.3
$A_{(TRUNK-F)}$ (deg)	−9.4 ± 6.2	−9.5° ± 3.0	−7.0 ± 3.5
$A_{(HIP-E)}$ (deg)	146.3 ± 5.9	157.3 ± 5.9	201.0 ± 6.2
$A_{(HIP-A)}$ (deg)	91.0 ± 5.4	91.8 ± 6.1	102.5 ± 8.2
$A_{(KNEE)}$ (deg)	166.7 ± 4.7	140.2 ± 4.5	169.3 ± 3.0
$A_{(ANKLE)}$ (deg)	127.0 ± 5.2	99.8 ± 5.9	139.0 ± 6.5
$A_{(HIP-R)}$ (deg)	−15.6 ± 7.2	9.7 ± 8.5	20.1 ± 15.1
$A_{(SHOULDER-R)}$ (deg)	21.6 ± 6.0	4.9 ± 9.0	−17.4 ± 8.4

Note: For variables, see the list of symbols.

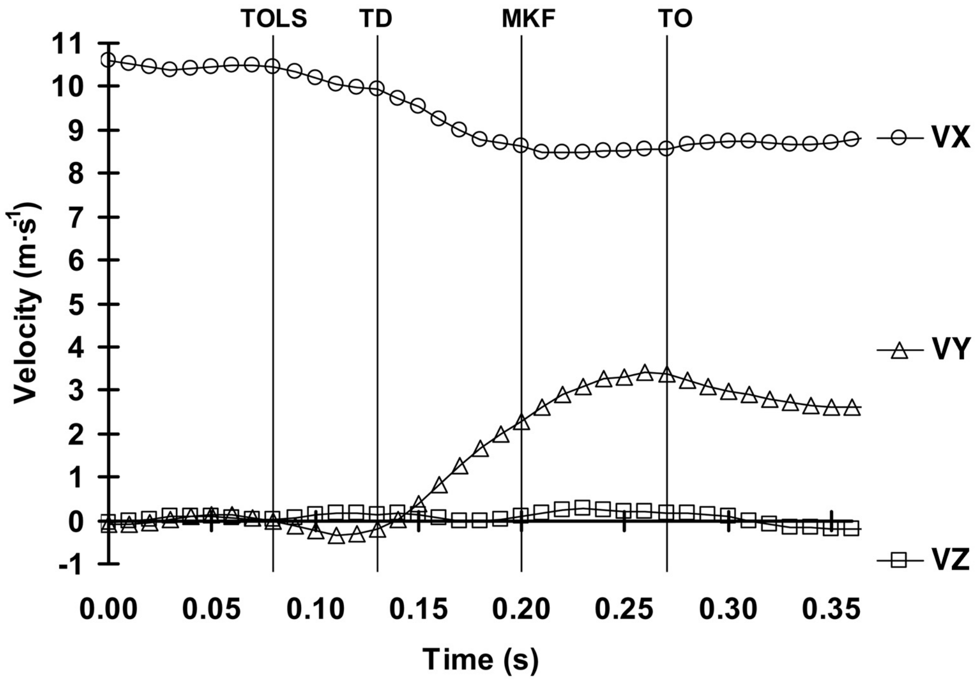

Figure 2. Mean centre of mass velocity profiles (n = 14). TOLS = take-off last stride, TD = touch-down, MKF = maximum knee flexion, TO = take-off, VX = horizontal velocity of the centre of mass, VY = vertical velocity of the centre of mass, VZ = medio-lateral velocity of the centre of mass.

the centre of mass, VZ, produced the smallest values of the three velocity components and these were very close to zero. The total loss of horizontal velocity between touch-down and take-off was $1.38 \pm 0.26\ \text{m} \cdot \text{s}^{-1}$, while the total gain in vertical velocity was $3.54 \pm 0.39\ \text{m} \cdot \text{s}^{-1}$, of which 69.8% was gained by the end of the compression phase, confirming the greater impulse developed during the compression phase (Seyfarth *et al.*, 2000). These changes in horizontal and vertical velocity led to a net loss in resultant speed of $0.74 \pm 0.23\ \text{m} \cdot \text{s}^{-1}$.

The change in the height of the centre of mass between take-off last stride and take-off is shown in Figure 3. The graph depicts an almost flat trajectory between take-off last stride and touch-down, decreasing by only 1 cm, a small increase of 6 ± 2 cm during the compression phase and the greatest gain in height of 23 ± 2 cm occurring during the extension phase. This led to a total gain in height of 29 ± 3 cm between touch-down and take-off. The greater gain during the extension phase is due to the greater velocity at the start of that phase ($2.29\ \text{m} \cdot \text{s}^{-1}$) compared with the start of the compression phase ($-0.18\ \text{m} \cdot \text{s}^{-1}$) for similar durations.

The position of the centre of mass relative to the supporting foot for a typical touch-down position can be seen in Fgures 4a (sagittal plane) and 4b (frontal plane). The centre of mass was directly above the ankle joint at touch-down in the frontal plane, $0.3 \pm 1.9^\circ$, and this remained within a maximum deviation of 6.8° throughout the take-off. In the sagittal plane, the trunk was observed to be inclined backwards relative to the vertical, $7.5 \pm 3.3^\circ$. In the frontal plane, the trunk was inclined $9.4 \pm 2.8^\circ$ towards the side of support at touch-down and this remained fairly constant throughout the take-off phase (Figure 4d). The former posture would increase joint extension at the hip. Both of these postures would lead to a "straighter" body at touch-down.

No athlete exhibited flexion of the hip during contact. During the last stride the hip began to extend and this continued after touch-down, albeit at a slower angular velocity in the compression phase. This can be seen graphically in Figure 5. During the compression phase, the hip extended through an average of $11.0 \pm 3.5^\circ$ with a minimum extension angular velocity of $1.6 \pm 1.2\ \text{rad} \cdot \text{s}^{-1}$. In the extension phase, the hip extended through a range of $43.6 \pm 5.0^\circ$, reaching a peak extension velocity of $12.7 \pm 1.1\ \text{rad} \cdot \text{s}^{-1}$. As the trunk only moved through a range of $6.7 \pm 5.3^\circ$ between touch-down and take-off, it is clear that the movement of the thigh downwards and backwards had a greater influence on hip extension than the forward rotation of the trunk. The hip joint was observed to adduct by an average of $3.9 \pm 3.6^\circ$ after impact with the board and this generally occurred before the end of the compression phase. The hip then abducted through a range of $15.4 \pm 11.3^\circ$ by take-off.

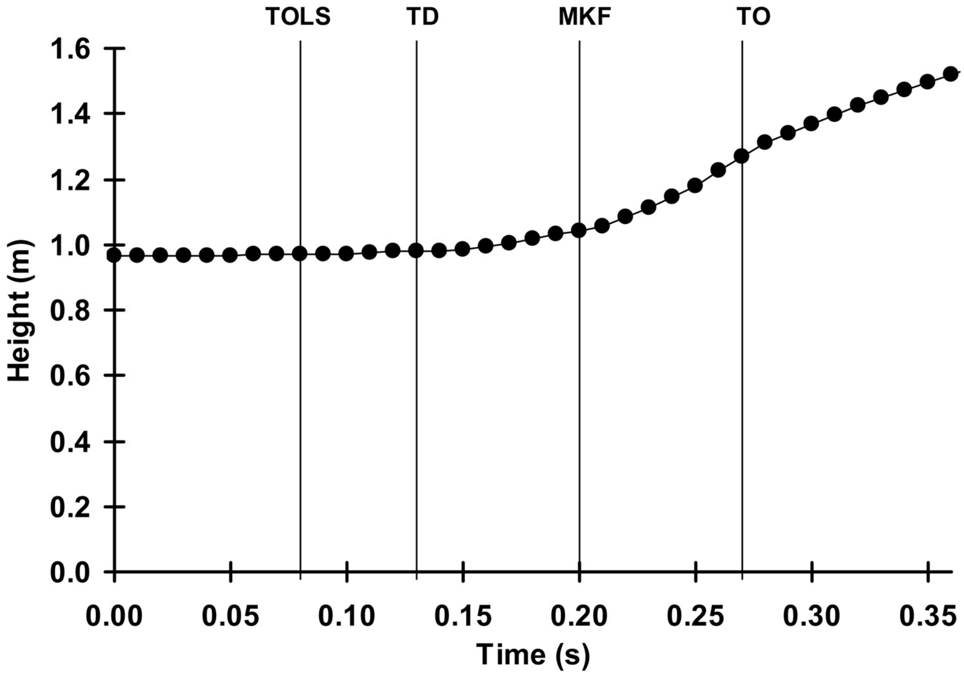

Figure 3. Profile of the mean centre of mass height during the long jump take-off (n = 14). TOLS = take-off last stride, TD = touch-down, MKF = maximum knee flexion, TO = take-off.

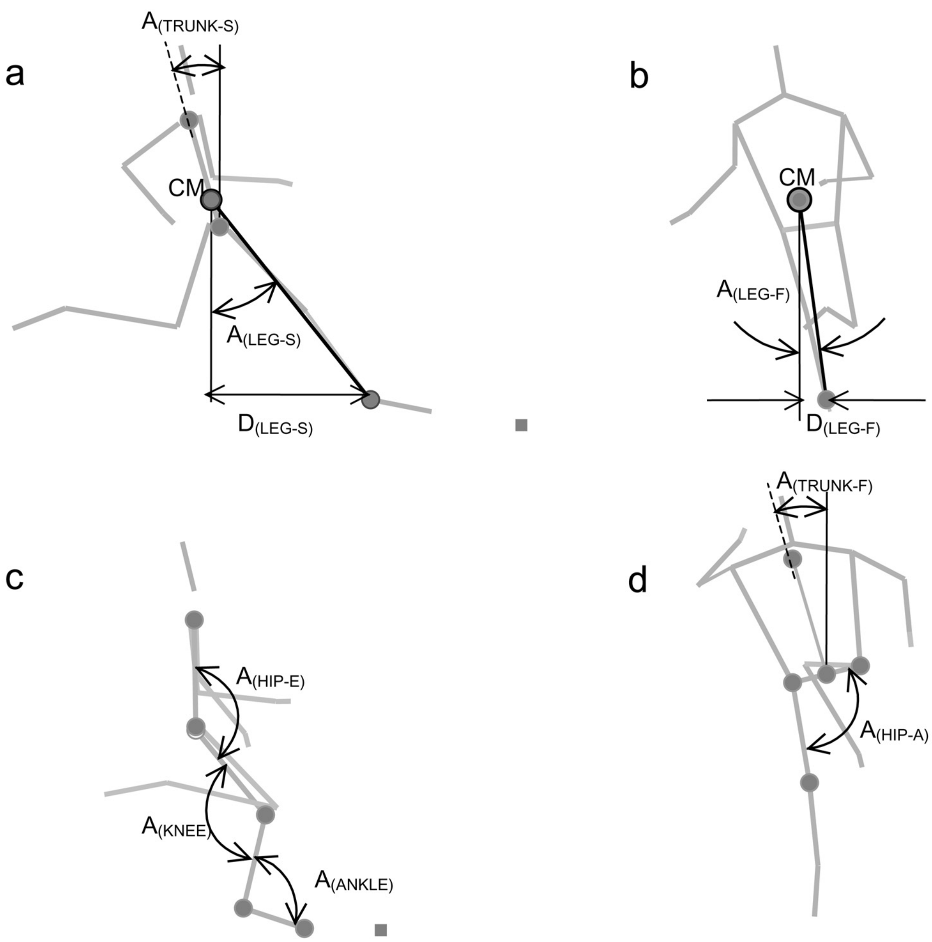

Figure 4. Stick figure representation of variables under investigation. For variables, see list of symbols.

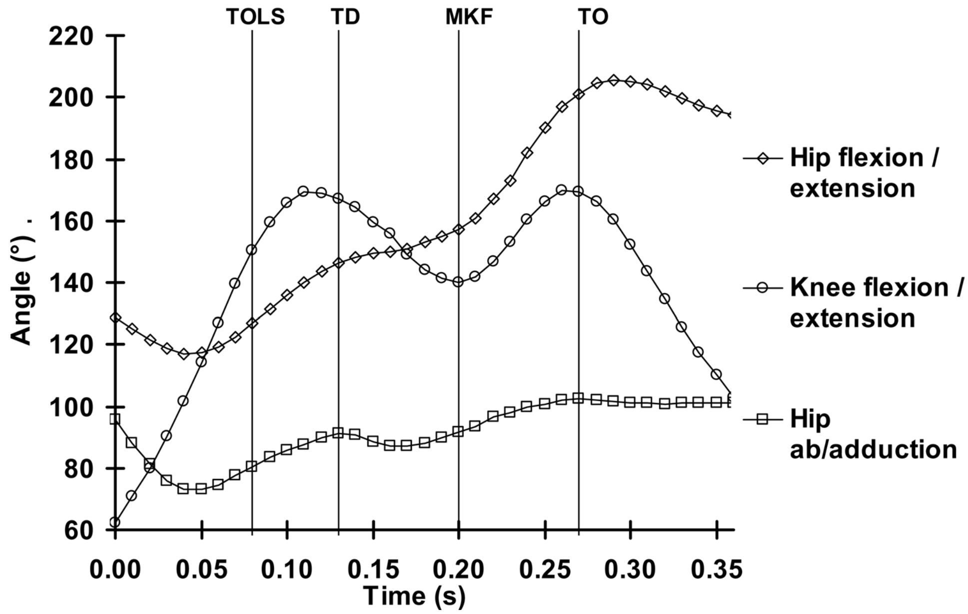

Figure 5. Mean profiles of the hip, knee and ankle joint angles in the long jump take-off (n = 14). TOLS = take-off last stride, TD = touch-down, MKF = maximum knee flexion, TO = take-off. Increasing trends relate to joint extension or abduction; decreasing trends relate to joint flexion or adduction.

It can be seen in Figure 5 that the knee extends throughout the last stride reaching an angle of $167.0 \pm 4.7^{\circ}$ at touch-down. Following contact with the board there was a marked flexion of the knee of $26.5 \pm 5.2^{\circ}$, followed by an extension of $29.1 \pm 3.6^{\circ}$. A slightly greater range of knee extension than knee flexion indicates that the knee was not fully extended at touch-down. Peak knee flexion velocity was observed to be 10.1 ± 1.3 rad $\cdot$ s^{-1} and peak knee extension velocity 11.2 ± 1.1 rad $\cdot$ s^{-1}.

Correlation analysis

The relationship between approach velocity and effective distance jumped was non-significant ($r = 0.496$, $P > 0.05$), contrary to expectations. The failure to observe such a relationship, which has been widely reported elsewhere, is interpreted as an indication of the relatively high variability in the measured variables in relation to the range over which these quantities are spread. This is not an unusual finding when dealing with elite and relatively homogeneous groups of athletes and may reduce the likelihood of finding other meaningful relationships. Further relationships between measured variables are investigated on the basis of the performance outcome model of Hay *et al.* (1986) and Alexander's (1990) simulation model. These models provide a rationale for expecting relationships between variables (i.e. eliminates chance) and so corrections for the multiple use of data sets have not been made.

With regard to the relationships predicted by the performance outcome model (Figure 1), the official distance correlated significantly ($r = 0.911$, $P < 0.001$) with effective distance, but effective distance did not correlate significantly with the three projection variables of height ($r = -0.083$, $P > 0.05$), vertical ($r = 0.279$, $P > 0.05$) and horizontal ($r = 0.215$, $P > 0.05$) velocity of take-off, or speed of take-off ($r = 0.403$, $P > 0.05$). These findings are not in general agreement with the relationships reported by Hay *et al.* (1986), in which a significant relationship between jump distance and take-off speed was reported. The failure to find expected relationships is, as suggested above, probably due to the variability in relation to the range for each variable. For deeper layers in the hierarchical performance outcome model, the height of take-off did not correlate with any other variable. However, the vertical velocity at take-off correlated inversely with the horizontal velocity at take-off ($r = -0.736$, $P < 0.01$), confirming the relationship expected from the action of the pivot. In particular, the loss in horizontal velocity by the instant of maximum knee flexion was significantly related to the gain in vertical velocity by the instant of maximum knee flexion ($r = -0.694$, $P < 0.01$), suggesting that the overall velocity changes are the result of the events occurring during the compression phase. As a consequence of this, the projection angle was related to the vertical velocity at take-off ($r = 0.975$, $P < 0.001$) and inversely related to the horizontal velocity at take-off ($r = -0.869$, $P < 0.001$). The loss in speed from touch-down to take-off was significantly related to the loss in horizontal velocity ($r = 0.838$, $P < 0.001$), but not related to the gain in vertical velocity ($r = -0.067$, $P > 0.05$). It is worth noting that had a correction been made for the multiple use of data sets, all of the significant relationships identified above would still be significant at the chosen level of significance ($P < 0.05$).

The second model used to predict relationships is Alexander's (1990) simulation model. The leg angle at touch-down ($A_{(LEG\text{-}S)\ TD}$) is related to the touch-down distance ($D_{(LEG\text{-}S)\ TD}$) ($r = 0.850$, $P < 0.001$), which would be expected on geometrical grounds, but not with the vertical velocity gained by the instant of maximum knee flexion ($r = 0.275$, $P > 0.05$) or by the instant of take-off ($r = 0.335$, $P > 0.05$), or with the knee angle at the instant of touch-down on the board ($r = 0.007$, $P > 0.05$). However, greater leg angles at touch-down are related to greater losses in horizontal velocity ($r = -0.562$, $P < 0.05$), supporting the findings of Koh and Hay (1990). A second variable identified in Alexander's model is the knee angle at the instant of touch-down on the board ($A_{(KNEE)\ TD}$), which is related to vertical velocity gained from the instant of touch-down on the board to the instant of maximum knee flexion ($r = 0.740$, $P < 0.01$), confirming the importance of an extended knee at the instant of touch-down on the board, which increases the mechanical advantage of the leg and promotes the pivot. Interestingly, the knee angle at the instant of touch-down on the board is also correlated with hip flexion angle in the sagittal plane ($r = 0.751$, $P < 0.01$), and inversely related with the (negative) trunk angle in the sagittal plane ($r = -0.563$, $P < 0.05$). This is interpreted as the body becoming straighter as the knee and hip angles increase (providing a better posture to increase the effective "spring" stiffness and so resist the high forces of impact), and so the trunk leans back more with the body inclined along the line of the leg. It might be assumed that a summation of the knee and hip angles would be a better predictor of pivot effectiveness in terms of vertical velocity gain by the instant of maximum knee flexion, but the correlation, although significant, reduced to $r = 0.558$ ($P < 0.05$). A third variable suggested by Alexander's model is the peak knee flexion angular velocity ($pAV_{(KNEE)}$) at touch-down, which is a consequence of muscle strength of the knee extensors such that for a given situation the stronger the knee extensors the smaller the knee flexion velocity. No significant relationship was found between peak knee flexion velocity and the gain in vertical velocity from the instant of touch-down on the board to the instant of maximum knee flexion ($r = -0.103$, $P > 0.05$), or from the instant of touch-down on the board to the instant of take-off ($r = 0.197$, $P > 0.05$). However, there was a strong relationship between peak knee flexion angular velocity and the range of knee flexion from the instant of touch-down on the board to the instant of maximum knee flexion ($r = 0.835$, $P < 0.01$), suggesting that an ability to control the speed of knee flexion would help to reduce the "collapse" of the knee and keep the pivot strong. Interestingly, athletes who extended the knee more at touch-down exhibited less knee flexion ($r = -0.598$, $P < 0.05$) and generated more vertical velocity ($r = 0.584$, $P < 0.05$), again emphasizing the importance of a straighter knee at touch-down.

Regression analysis

A third approach to the examination of relationships between variables characterizing long jump performance is to use these within a regression analysis. Thirteen variables were selected to represent long jump performance (Table III). Four of these reflect variables outlined by the performance outcome model of Hay *et al.* (1986); three were selected based on Alexander's (1990) pivot model and the remaining six reflect other characteristic joint positions and movements of the hip, knee and trunk during the take-off phase. The rationale for their inclusion is based on observations made earlier and comments made by Lees *et al.* (1994), who suggested that the effectiveness of the pivot mechanism could be impaired by significant compression of the support leg, which may occur in both the sagittal and frontal planes. The variables were entered into a "best subsets" multiple regression analysis (Minitab, version 13.31, 2000) to determine their relationship with (1) the effective distance and the two main velocity change variables, (2) the gain in vertical velocity ($VY_{TD\text{-}TO}$) and (3) loss in horizontal velocity ($VX_{TD\text{-}TO}$) between the instant of touch-down on the board and the instant of take-off, but for these analyses the speed variable ($S_{TD\text{-}TO}$) was omitted to avoid overlap between variables. The statistical significance of the multiple regression analyses is shown in Table IV.

(i) The regression equation determined for effective distance was:

effective distance (m) = 1.396 + 0.485 S_{TD} ($m \cdot s^{-1}$) + 5.836 $H_{TD\text{-}TO}$ (m) - 0.655 $S_{TD\text{-}TO}$ ($m \cdot s^{-1}$)

The first of these variables is related to speed. The latter two variables are related to technique (leg placement to reduce touch-down height and actions to minimize loss of horizontal speed) and so the theory that elite long jumpers

Table III. Key performance variables in the long jump as used in the regression analyses

Variable	Description
Hay and colleagues' (1986) model	
S_{TD}	Resultant velocity of the centre of mass at touch-down
H_{TD}	Height of the centre of mass at touch-down – the centre of mass is in its lowest vertical position at the instant of touch-down
$H_{TD\text{-}TO}$	Change in height during the take-off phase
$S_{TD\text{-}TO}$	Change (loss) in speed during the take-off phase (expressed as an absolute value)
Alexander's (1990) model	
$A_{(LEG\text{-}S)\ TD}$	Leg inclination angle (sagittal) at touch-down
$A_{(KNEE)\ TD}$	Knee joint angle at touch-down
$pAV_{(KNEE)}$	Peak knee flexion velocity (expressed as an absolute value)
Kinematic observations of joint movements	
$A_{(HIP\text{-}E)\ TD}$	Hip extension angle (sagittal) at touch-down
$A_{(HIP\text{-}E)\ TD\text{-}TO}$	Range of hip joint extension throughout the take-off phase
$A_{(KNEE)\ TD\text{-}MKF}$	Range of knee joint flexion in the compression phase (expressed as an absolute value)
$A_{(HIP\text{-}A)\ TD\text{-}MHA}$	Range of hip adduction (frontal) from touch-down to its minimum hip adduction angle (expressed as an absolute value)
$rV_{(ANKLE)\ TD}$	Horizontal velocity of ankle relative to the horizontal velocity of the centre of mass at touch-down
$A_{(TRUNK\text{-}F)\ TD}$	Inclination angle of the trunk in the frontal plane at touch-down

Table IV. Summary of multiple regression statistics (coefficient of variation, R^2; standard error, SEe; ANOVA statistic, F; and the significance value, P)

	R^2 (%)	SEe	F	P
Effective distance (m)	65.5	0.107	9.2	0.003
Gain in vertical velocity from the instants of touch-down to take-off ($m \cdot s^{-1}$)	78.8	0.178	17.1	0.000
Loss in horizontal velocity from the instants of touch-down to take-off ($m \cdot s^{-1}$)	84.5	0.101	24.7	0.000

require good take-off technique in addition to a fast approach run is supported by this analysis. The relationship between the speed of touch-down and the effective jump distance was earlier reported as non-significant with a coefficient of determination (R^2) of 24.6%. By taking into account variables related to technique, the coefficient of determination increased to an R^2(adj) value of 65.5%. Longer effective distances are associated with a greater approach speed and a technique that encourages the greatest possible gain in height and a smaller loss in speed of the centre of mass. To have a large increase in height, the centre of mass must adopt a low position at touch-down and a high upright position at take-off related to good arm and leg lift. To maintain horizontal speed, the horizontal velocity lost during the take-off phase must be compensated for, and this could be associated with the active landing.

(ii) The regression equation determined for the gain in vertical velocity from the instant of touch-down on the board to the instant of take-off was:

$$VY_{TD\text{-}TO}\ (m \cdot s^{-1}) = -3.283 - 5.591\ H_{TD}\ (m) + 0.0851\ A_{(KNEE)\ TD}\ (^\circ) - 0.188\ pAV_{(KNEE)}\ (rad \cdot s^{-1})$$

The predictive equation indicates that the greatest gains in vertical velocity from the instant of touch-down on the board to the instant of take-off are associated with a technique that exhibits a low centre of mass, a larger (i.e. more extended) knee joint at touch-down, combined with a low peak knee flexion velocity (which is associated with the ability to resist knee flexion). The combination of these three variables explains 78.8% of the variance in the gain in vertical velocity from the instant of touch-down on the board to the instant of take-off. The theory that a pivot mechanism operates during the long jump take-off, and that its effectiveness is influenced by the athlete's ability to resist joint compression, appears to be supported by these results.

(iii) The regression equation determined for the loss in horizontal velocity (expressed as an absolute value) was:

$VX_{TD\text{-}TO}$ ($m \cdot s^{-1}$) = 0.370 + 4.40 $H_{TD\text{-}TO}$ (m) + 0.041 $A_{(HIP\text{-}A)\ TD\text{-}MHA}$ (°) − 0.008 $A_{(HIP\text{-}E)\ TD\text{-}TO}$ (°)

The predictive equation indicates that greater loss in horizontal velocity during the take-off phase is related to a large change in height, large range of hip adduction and a small range of hip extension. These three variables explain 84.5% of the variance in the change in horizontal velocity. The large change in height is a characteristic of the pivot, so losses in horizontal velocity can be minimized by minimizing hip adduction and maximizing hip extension. The former may be achieved by strengthening of the hip abductor muscles, while the latter may be achieved by emphasizing the extension of the hip joint at take-off and would be enhanced by greater extension flexibility in this joint. The height of the centre of mass at the instant of touch-down on the board serves both to increase vertical velocity gain but also to increase horizontal velocity loss. This would imply that this variable has an optimal value: if too low, it would lead to greater losses in horizontal velocity; if too high, it would compromise the gain in vertical velocity.

The three multiple regression equations were checked for validity on the second best performance of seven of the athletes. Validity was checked between actual and predicted values using three methods (Table V). The coefficients of determination were smaller than for the original data, but were all sufficiently large to explain between 52% and 76% of the variance in the independent variables. The limits of agreement found only small differences between the predicted and actual measurements, none of which were significant. The gain in vertical velocity was overestimated by 0.01 $m \cdot s^{-1}$, the loss in horizontal velocity was overestimated by 0.12 $m \cdot s^{-1}$, and the effective distance was overestimated by 7 cm. These differences and the 95% error limits are reasonable for the variables being analysed. The three regression equations can therefore be regarded as valid.

Discussion

Some three-dimensional characteristics of the long jump take-off for national level athletes have been presented. These form normative data for this event and include variables representative of the touch-down to take-off phase, which has been identified as the most critical phase, and also frontal plane variables not previously reported for this event.

The main use of the data was to test experimentally the applicability of two models of long jump performance presented in the literature by examining the interrelationships between the measured variables. Two quite different models have been proposed in the literature. The model of Hay *et al.* (1986) attempts to relate performance to a series of whole-body variables, while Alexander's (1990) model introduces segment and joint angle variables for the touch-down leg which relate to the pivot mechanism operating during the contact phase. In both models, the links between the specified variables have a well-established mechanical basis. With the exception of the work of Hay *et al.* (1986), no attempt appears to have been made to verify these models on an experimental basis. Our attempt to use correlational analysis was not very successful. We found that for the group of jumpers investigated, some expected interrelationships were missing. In particular, one of the more enduring relationships reported for the long jump, that between approach speed and distance jumped, was non-significant. While some expected interrelationships were confirmed, these did not provide strong support for either of the two models. There are two reasons why this might be so.

The first reason is to do with the measurement error associated with each variable in relation to the range over which the variable changes (i.e. signal-to-noise ratio). The error estimates reported above are within normal tolerance levels for the type of kinematic data reported in this study, but the range of values associated with each variable is narrow due to the homogeneous nature of the group of athletes used. If this were the case, then there is a fundamental

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

	Actual mean ± s	Predicted mean ± s	R^2 (%)	t	P	Limits of agreement
Effective distance (m)	7.41 ± 0.18	7.48 ± 0.17	60.1	−1.63	NS	0.07 ± 0.23
Gain in vertical velocity from the instants of touch-down to take-off ($m \cdot s^{-1}$)	3.52 ± 0.26	3.51 ± 0.27	76.5	0.18	NS	0.01 ± 0.26
Loss in horizontal velocity from the instants of touch-down to take-off ($m \cdot s^{-1}$)	−1.30 ± 0.23	−1.42 ± 0.26	51.9	−1.65	NS	−0.12 ± 0.37

limit to the value of data from competition-based kinematic analyses. Data quality will always be compromised to a greater or lesser extent by the demands of competition in which the experimenter has no control of such factors as clothing worn by athletes and location of cameras. Furthermore, within an event, competitors will inevitably be homogeneous in their performance level and so improving the signal-to-noise ratio may be difficult. Investigating the validity of the two models referred to above would require a different analytical strategy, which would involve the pooling of data from different standards of competition. To date this approach has not been undertaken.

The second reason why expected interrelationships were not found is that the variables recorded are not truly independent and have some interaction. For example, as approach speed increases, the angle of touch-down of the support leg may be expected to decrease because of the high forces produced on contact of the support leg with the ground. The jumper's response is to reduce these forces by reducing the angle of touch-down of the support leg. Such an interaction between variables will not negate the basic mechanical features of the two models detailed above, but it does imply that attempts to validate the models using simple correlations between selected variables will have severe limitations. This has wider implications for the identification of key variables in other sports where biomechanical techniques are used to provide support to performers.

It is because of the likely interaction between selected variables that we chose to analyse the data by regression analysis. The scope of the analysis was limited due to the small number of participants, although the regression analysis was found to be valid from our validity checks. The regression analysis was considered a successful approach in that it identified co-variables that allowed a more refined understanding of long jump performance. Specifically, the relationship between approach speed and distance jumped was not initially found to be significant through simple correlation, but the regression analysis suggested an interaction with two other variables which when added made its predictive ability highly significant. In particular, these other variables can be interpreted as "technique" variables and so it is evident that performance in the long jump is dependent not only on speed but also on technique. This is a particularly satisfying outcome as support for technique variables in relation to performance has not been widespread in the literature.

The regression analysis was extended to consider other aspects of the models of long jump performance. Of major interest to us was the concept of the pivot, which explains how the horizontal velocity can be used to gain vertical velocity and thus greater distance jumped; the second regression analysis investigated the factors that contributed to the change in vertical velocity. It was satisfying to see that knee angle and angular velocity were identified as co-variables, both of which were implied by Alexander's (1990) model but were not individually significantly related to gain in vertical velocity. The third regression investigated the loss in horizontal velocity. The change in height of the centre of mass was a main factor but this was enhanced by action at the hip joint, specifically hip adduction, and reduced by hip extension. It would appear that hip action is critical to the maintenance of horizontal velocity and so both technique and strength are implicated. This is supported by the observation that the hip did not flex following touch-down, but rather continued to extend throughout the take-off. It would appear that activation of the hip extensor muscles before touch-down not only helps to produce an "active" leg placement, but also strengthens the pivot by keeping the leg and trunk more rigid, and therefore increasing the effective leg or pivot length. Thus the regression analysis has identified variables that can be classified as being related to speed, technique and strength.

Touch-down leg angle did not specifically enter into any of the correlational or regression analyses and was not found to be related to change in vertical velocities in our earlier studies (Lees *et al*., 1993, 1994). The role of the touch-down leg angle has been clarified by recent simulation studies. Contrary to the suggestion of Alexander (1990), Seyfarth *et al*. (2000) have shown both theoretically and experimentally that the distance jumped is independent of touch-down leg angle at jumping speeds greater than $6\ m \cdot s^{-1}$. This finding results from a more realistic muscle and tendon model than used by Alexander in his two-dimensional two-segment model of the jumper and occurs because of the effect that a greater or lesser leg angle has on the muscular dynamics at high stretching velocities. It helps to explain our failure to find the relationships postulated. The simulation study of Seyfarth *et al.* also provides further insight into long jump performance, although not all variables associated with real jumping performance were studied. They found that jump performance was enhanced by a high approach speed, a high knee angle at touch-down and high (concentric and eccentric) muscle strength. Factors which did not have a great influence on jump distance were tendon compliance, muscle fibre contraction speed and some aspects of muscle architecture. Thus it appears that the important factors identified can also be clearly related to speed, technique and strength, and are closely related to those identified from the present regression analysis.

These findings have several implications. One is that the reason for failing to find expected relationships appears not to be the quality of the data, or the low signal-to-noise ratio in the data (although undoubtedly the main relationships defining performance are more likely to be established with larger ranges of performance), but the interaction between key performance variables. The present regression analysis assumed that the interaction between these variables is linear, although this assumption may be an oversimplification. Recently, Greig and Yeadon (2000) have shown that for high jumping, some key performance variables for an individual athlete interact in a non-liner way as performance varies. It may be that the results of this study can be further improved with a non-linear regression analysis.

A second implication is that performance in the long jump can specifically be related to speed, strength and technique variables. This conceptualization of long jumping – as requiring speed, strength and technique – is convenient, but it has not been possible until now to introduce variables that relate to all three aspects. The regression analysis has not only enabled these to be identified, but also some order of importance can be suggested. Speed dominates as it is the most important variable related to distance jumped. Technique and strength come next and, in combination, the position of the touch-down leg enables the pivot to occur but only if the athlete has sufficient strength will the pivot be effective. Strength is required in the knee extensors, but also in the hip abductors and extensors. This insight will be of value to coaches who should ensure that as an athlete develops, attention is paid to not just the development of speed but also to the development of technique and strength. Graham-Smith and Lees (2000) presented evidence indicating that approach speed and performance develop in a stepwise manner – that is, increases in approach speed do not necessarily lead to an immediate improvement in jump distance. It was suggested that the benefits of the increased speed are not realized until the athlete improves technically and develops sufficient strength to deal with the increased forces at take-off. The findings of the present study support the view that a balance must exist between speed, strength and technical requirements.

A third implication is more general in its application. Biomechanists attempt to identify key variables that relate to performance which they can measure (Lees, 1999). It is clear that this task is considerably more complex than has hitherto been considered. The likely interaction between key variables means that to give suitable advice to high-level performers, details of this interaction should be known. This then implies that more sophisticated analyses must be undertaken to obtain a deeper understanding of the factors and the interactions between factors that affect performance.

In summary, normative data for national level long jumpers have been presented which focus on the touch-down to take-off phase of the event. Two models that define performance of the long jump were examined in terms of the interrelationships between key variables. The individual relationship between these variables was generally poor. However, when analysed using a multiple regression approach, a series of variables was identified which supported the general principles outlined in the two models. These variables could be interpreted in terms of speed, technique and strength. We conclude that in the long jump event, several variables are important to performance but these are interdependent and are only apparent through the use of appropriate statistical techniques. It is likely that this finding can be generalized to other technical sports.

List of symbols

Key reference points and phases

TOLS	instant of take-off into the last stride
TD	instant of touch-down on the board
MKF	instant of maximum knee flexion
MHA	instant of minimum hip adduction
TO	instant of take-off
TOLS-TD	flight phase of the last stride
TD-TO	take-off phase
TD-MKF	compression phase of the take-off
MKF-TO	extension phase of the take-off

Kinematic variables

$A_{(LEG-S)}$	Angle of leg placement in the sagittal plane (angle made to the downward vertical of the line connecting the centre of mass to the ankle joint)
$A_{(LEG-F)}$	Angle of leg placement in the frontal plane (angle made to the downward vertical of the line connecting the centre of mass to the ankle joint)
$D_{(LEG-S)}$	Touch-down distance of the ankle relative to centre of mass in the sagittal plane (horizontal distance between the centre of mass and the ankle joint)
$D_{(LEG-F)}$	Touch-down distance of the ankle relative to centre of mass in the frontal plane (horizontal distance between the centre of mass and the ankle joint)
H	Height of the centre of mass
$A_{(ANKLE)}$	Ankle angle
$A_{(TRUNK-S)}$	Trunk angle in the sagittal plane

$A_{(TRUNK-F)}$	Trunk angle in the frontal plane
$A_{(KNEE)}$	Knee angle
$A_{(HIP-E)}$	Hip extension angle
$A_{(HIP-A)}$	Hip abduction/adduction angle
$A_{(HIP-R)}$	Hip rotation angle
$A_{(SHOULDER-R)}$	Shoulder rotation angle
$pAV_{(KNEE)}$	Peak knee flexion velocity
$pAV_{(HIP-E)}$	Peak hip extension velocity
S	Speed/resultant velocity of the centre of mass
VX	Horizontal velocity of the centre of mass
VY	Vertical velocity of the centre of mass
VZ	Medio-lateral velocity of the centre of mass
$rV_{(ANKLE)}$	Horizontal velocity of the ankle relative to the horizontal velocity of the centre of mass (VX)

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