PREDICTION OF JUMPING DISTANCE USING A SHORT APPROACH MODEL

Sándor Béres[1], Zsolt Csende[2], Adrian Lees[3] and József Tihanyi[2]

[1]*Eszterházy Károly College, Faculty of Natural Sciences, Institute of Physical Education and Sport Sciences, Eger, Hungary*
[2]*Semmelweis University, Faculty of Physical Education and Sport Science, Budapest, Hungary*
[3]*Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, UK*

Original scientific paper
UDC: 796.431.2:796.012.51:001.18

Abstract:

Recent evidence has suggested that relationship between approach speed and distance jumped may not be linear. The aims of this study were (1) to test the hypothesis that using a short approach (6-8-10-12 strides) of increasing length, performance variables will be non-linearly related to distance jumped, (2) to investigate the nature of these relationships for a group of long jumpers and individuals within the group, and (3) to use the regression analysis to determine the optimum number of run-up strides and predict the jumping distance that would be achieved with an optimum length run-up for an individual jumper. Eight male long jumpers with different skill levels (body mass: 75.2±2.2 kg and body height: 188.0±4.2 cm) performed a series of short-approach maximal jumps and the full-length approach in a competition. Kinematic data were collected from video analysis. The relationship between the number of approach strides and velocity, and distance jumped were shown to be best represented by second order polynomial equations. When applied on an individual basis, the predicted jump distances (6.95±.61 m) agreed very well with those found in actual competition (6.96±.58m). As a result, these individual relationships were used to comment on individual optimal approach lengths and to evaluate an individual's potential for performance in the long jump event. It was concluded that the short approach model of performance is a valuable paradigm for investigating long jump behaviour and the performance potential of individuals. The findings also supported the simplified mathematical model proposed in the literature for the study of long jump performance.

Key words: *run-up velocity, take-off velocity, regression analysis, prediction*

Introduction

The relationship between approach speed and distance jumped in the athletic event of long jumping has widely been reported as both linear and highly significant (Brüggemann, Nixdorf, & Erst, 1982; Hay & Nohara, 1990; Nixdorf & Brüggemann, 1990; Lees, Fowler, & Derby, 1994; Madella, 1996; Bridget & Lindthorne, 2005; Linthorne, 2008; Hussain, Khan, & Mohammad, 2011). This in turn has led athletes, coaches and researchers to the opinion that, for an individual athlete, improved performance is likely to be best achieved by increasing approach speed. While advice based on an extrapolation of cross-sectional data typical of the above studies to an individual athlete may seem sensible, the scientific basis for this extrapolation has not been established and in some cases advice based on this may be inappropriate, i.e. an increase in speed may lead to a decrease in performance. There is no *a piori* reason why the relationship between approach speed and distance jumped in the long jump should be linear and evidence to suggest that this relationship may be non-linear comes from various sources. Firstly, in cross-sectional studies, Mikhailov, Yakunin, and Aleshinsky (1981), and Tiupa, Aleshinsky, Primakov, and Pereverzev (1982) investigated a large number of athletes of different ages, sex and skill levels and reported a non-linear relationship between the two variables. Secondly, for an individual, one might expect a non-linear relationship simply on the basis that speed cannot be increased without limit and at some stage the athlete's skill and physical abilities required to convert the approach speed to distance jumped would begin to break down. Thirdly, simulations of long jumping based on individualized two segment (Alexander, 1990; Seyfarth, Blickhan, & Van Leeuwen, 2000) or mass-spring (Seyfarth, Friedrics, Wank, & Blickhan 1999) models demonstrate that jump distance is not a linear function of approach speed. The speed of the centre of mass (CM) at the touch-down is generally sub-maximal and depends upon several factors, such as physical ability and the loss of speed during the last one or two preparatory strides (Popov, 1983; Hay, 1986; Lees, Fowler, & Derby, 1993). It also depends upon the distance of the approach run or the number of strides taken by an athlete. It is known that maximum sprinting speed is attained after about 50-60 metres (Brüggemann & Glad, 1990; Ae, Ito, & Suzuki, 1992), but although the long jump result depends on horizontal speed, elite long jumpers use shorter run-up distances than are needed to attain maximum running speed (Farmer, 1973; Muraki, 1984). Nevertheless, this distance and the number of strides taken is enough to reach 94-99% of the individual maximum running speed (Jarver, 1970; Ballreich & Ernst, 1980; Ae, et al. 1992).

Long jumpers frequently use shortened run-up lengths in training for developing their take-off technique or for preparing for full approach jumps (Lundin & Berg, 1993; Pepin, 1991, Matić, et. al., 2012). Therefore, short approach jumps provide an opportunity to study the relationship between approach velocity and jumping distance in the way different than has occurred to date. A short run-up restricts the approach speed compared to the full length run-up and as a result the jumping distance will be shorter. As the number of run-up strides increases, so does the approach speed of CM and its effect on take-off characteristics and jumping distance. If data from such a short approach model of performance are fitted to the most appropriate non-linear regression equations, the actual jumping distance with a full length run-up could be predicted for individuals. In addition, the optimum number of strides for the run-up could also be determined from this relationship. Such an approach may provide a more appropriate model on which to base individual advice to an athlete than has been used before.

Therefore, the aims of this study were (1) to test the hypothesis that using a short approach model, performance variables will be non-linearly related to the distance jumped, (2) to investigate the nature of these relationships for both the group of long jumpers and individuals within the group, and (3) to use the regression equations obtained (*Matić,* et. al., 2012) to estimate the optimum number of run-up strides and predict the jumping distance that would be achieved with an optimum length run-up for an individual jumper. A further aim was to evaluate how well the short approach model conformed to the simplified mathematical model developed by Seyfarth et al. (2000) for predicting long jump performance.

Methods

Subjects

Eight male long jumpers with different skill levels (age: 22.1±2.4 years, body mass: 75.2±2.2 kg, body height: 1.88±.042 m) were recruited for the study and performed short approach jumps a few days before a scheduled long jump competition. They had at least three years experience of practice and participation in the long jump event. Their personal bests ranged between 6.42m and 8.04m (M: 7.26±66.1m). Prior to testing, the subjects signed an informed consent form approved by the Policy and Review Committee of the Semmelweis University, Budapest.

Experimental protocol and short approach model

The subjects performed their individually selected warm-up, in an indoor sport hall, including jogging, stretching and specific long jump preparatory drills. Thereafter, each of them measured the approach distances for different numbers of strides. The length of the approaches included six (A6), eight (A8), ten (A10) and twelve (A12) strides. The subjects were familiar with these different lengths of approach because they used short approach jumps frequently in their training. Each subject carried out one warm-up jump, followed by three jumps with maximum effort in each randomly selected approach condition. The official jumping distance was measured for each jump. The experiment was carried out four days prior to the competition at which the number of run-up strides and official jump distance were recorded. The best jump of each subject was selected for analysis.

Instrumentation

Three Panasonic video cameras (M10 V-14, NAC Visual system, Woodland Hills, CA) were used to record the reference frame and jumps. Two of them were located perpendicular to the runway and 13 meters from the take-off board so that the last two steps and the take-off could be recorded from two directions. The third camera, located 10 metres from the take-off board, recorded the jumps in the frontal plane. A global reference frame was defined with the x axis parallel to the runway, the y axis was vertical and the z axis was perpendicular to the x-y plane. The 0.0.0 point was on the middle of the jumping line (pit side edge of the jumping board). We used two reference frame cubes (2x2x2m, from high quality aluminium). Placement can be seen in Figure 1. The sampling frequency was a nominal 60Hz. The three cameras were externally synchronized. During competition one camera recorded the foot placed on the board allowing the measurement of the distance from the tip of the shoes to the edge of the board. The estimated dis-

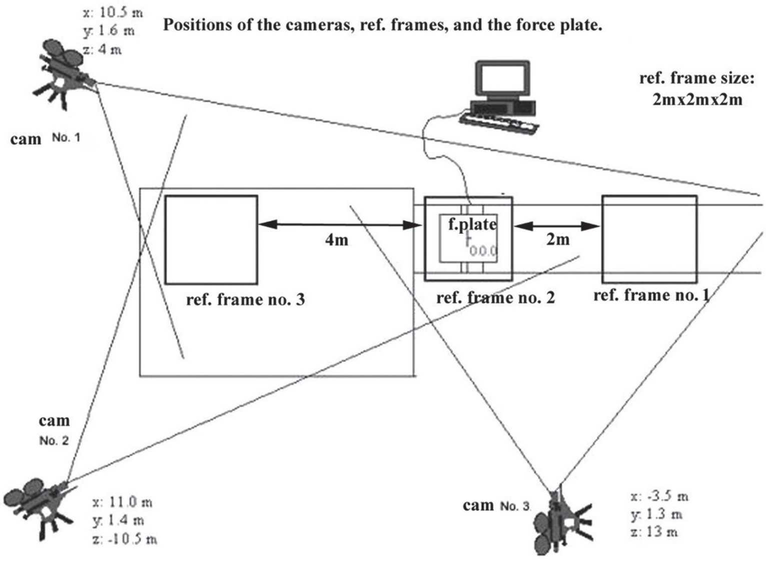

Figure 1. The placing of the reference frames (2x2x2m) and the cameras

tance was added to the official length of the jump to calculate the effective length of the jump for both the short approach and competition trials.

Data collection

Eighteen points were digitized on the body (left and right top of the *phalanx proximalis digiti index; tuber calcanei; malleolus lateralis; condylus lateralis; caput femoris; caput humeri; epycondylus lateralis; os scaphoideum;* base of the third *metacarpus;* top of the *phalanx proximalis digitus medius;* the *protuberantia mentalis;* and the top of the *vertex*) to calculate the position and trajectory of the center of mass (CM) using the Ariel Performance Analysis System (APAS, Englewood, CO) motion analysis software. Segmental data from Dempster (1955) was used for calculation of the location of the segment CM, and hence the location of the whole body CM. The absolute coordinates were low-pass filtered (fourth-order Butterworth) at 12Hz for segment data and 8Hz for the CM location. The following variables were determined: horizontal velocity at the touch-down (Vx_{TD}), horizontal velocity at the take-off (Vx_{TO}), vertical velocity of take-off (Vy_{TO}), resultant velocity of take-off (V_0), projection angle at the take-off (φ), the knee joint angle at the touch-down and (θ), the angle of attack (φ), the angle between the horizontal plane and the straight line connecting the marker located at the ankle joint and the CM, and finally the contact time (CT).

Statistical analysis

Means (M) and standard deviations (SD) were computed for the measured and calculated variables. Because of the limited sample size and according to the requirements of using parametric statistical procedures, all variables were tested with Shapiro-Wilk's W test for normality. The normality test indicated that all variables were normally distributed except φ. Therefore, to test the differences among the four different approach conditions for the eight normally distributed variables repeated measures ANOVA was used, and for φ, non-parametric Friedman's ANOVA was used. Pairs of variables were fitted to different functions (linear, power, exponential, hyperbolic, logarithmic and polynomial) to find the best fit between the criterion and predictor variables. The regression equation, selected for the prediction of jumping distance with full length approach, was that at which the coefficient of determination (r^2) was the greatest. The jumping distances for full length approach obtained by the prediction and in the competition were compared by using two-tailed dependent Student *t*-test. The probability level for statistical significance in all tests was set at $p<.05$.

Results

Comparison of means

In the competition, the athletes performed a mean of 18.5 strides and jumped an actual distance of 6.96±.55m. The jump distance at A6, A8, A10 and A12 was 80.5±2.5, 85.5±3.7, 87.8±3.5 and 90.0±4.8% of the competition distance, respectively (Table 1). The instantaneous horizontal velocity at the touch-down (Vx_{TD}) and at the end of the take-off (Vx_{TO}) increased as a function of the increasing number of approach strides and as a consequence; the effective distance of the jump also increased (Table 1). The horizontal velocity decreased during take-off by 10.2, 12.9, 15.3 and 15.4% determined at A6, A8, A10 and A12, respectively.

The vertical velocity of take-off (Vy_{TO}) was the greatest at A8. It decreased slightly as the stride number increased but the differences between means were not significant, except between A6 and A8. Similarly, the projection angle (φ) decreased as a function of the increasing number of strides when more than six strides were performed, but the differences between means were not significant. The resultant velocity (V_0) increased as a function of the number of strides and differed significantly between all comparisons ($p<.05$). The contact time (CT) ranged between 0.145 and 0.152s with the longest measured at A8 and the shortest at A6, but were not significantly different (Table 1).

Table 1. Means and standard deviations (M, SD) of kinematic and dynamic variables of approach and takeoff

	D	Vx_{TD}	Vx_{TO}	Vy_{TO}	V_0	CT	φ	q	f
	(m)	(m/s)	(m/s)	(m/s)	(m/s)	(s)	(°)	(°)	(°)
A6	5.58 [a]	*7.09 [a]*	6.41 [a]	3.39 [d]	7.26[a]	0.145	27.9	150.3 [a]	75.4[a]
	0.39	*0.39*	0.317	0.48	0.38	0.010	3.8	2.8	2.4
A8	5.93 [b]	*7.52 [b]*	6.70 [e]	3.56	7.58	0.152	27.9	156.7	72.9[e]
	0.46	*0.38*	0.326	0.42	0.41	0.013	2.9	3.1	2.8
A10	6.09 [c]	*7.88 [c]*	6.89 [c]	3.48	7.74[c]	0.150	26.8	157.2	71.0
	0.43	*0.42*	0.262	0.32	0.33	0.010	2.2	5.6	2.5
A12	6.31	*8.21*	7.07	3.46	7.93	0.146	26.2	158.7	69.9
	0.54	*0.46*	0.321	0.33	0.40	0.011	2.1	2.7	2.2

a, significant difference between A6, A8, A10 and A12
b, significant difference between A8, A10 and A12
c, significant difference between A10 and A12
d, significant difference between A6 and A8
e, significant difference between A8 and A12
Legend: D – distance jumped, Vx_{TD} – horizontal CM velocity at the touch down, Vx_{TO} – horizontal CM velocity at the take-off, Vy_{TO} – vertical CM velocity at the take-off, V_0 – resultant CM velocity, CT – contact time, φ – projection angle at the take-off, θ – the knee joint angle at the touch-down, ϕ – the angle of attack, an angle between the horizontal plane and the straight line connecting the marker located at the ankle joint and the CM

Correlation between variables

Pooling all data for each subject from each experimental condition, significant linear relationships were found between jumping distance and Vx_{TD} ($y=0.89x–0.82$, $r^2=.83$), Vx_{TO} ($y=1.1x–1.36$, $r^2=.63$) (Figure 2) and V_0 ($y=1.19x–3.03$, $r^2=.88$). The Vx_{TD} for the full length approach (18.5 strides) was predicted to be 9.33 m/s, and yielded a jump distance of 7.54m which was 0.58m longer than the performance in the competition. The relationship between jumping distance and Vx_{TD} was also significant for each run-up condition ($p<.05$) with linear regression equations of A6: $y=1.06x-1.8$; A8: $y=1.35x-4.2$; A10: $y=1.02x-1.9$: A12: $y=1.3x-4.0$.

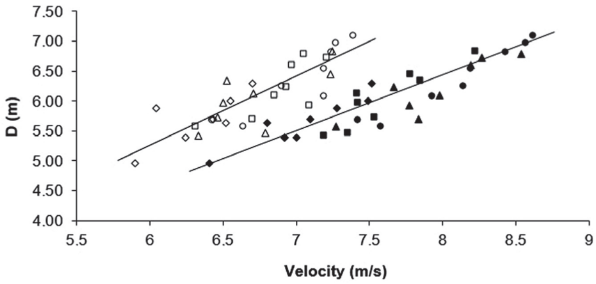

Figure 2. Relationship between jumping distance (D) and horizontal velocity at the touch-down (filled symbols) and horizontal velocity at the end of take-off (open symbols). Symbols are as follows: ◊-A6, □–A8, Δ-A10, ○–A12.

Data fitting using non-linear analysis

The group mean data were fitted to polynomial equations ($y=ax^2+bx+c$) which were found to produce the highest coefficients of determination (r^2) ranging between .98 and .99. Table 2 shows the relationships between the predictor and dependent variables and the regression equations. By applying equation 1, the calculated jump distance was 6.58 m at 18.5 strides (the average number of strides used in the competition) which was 0.38 m shorter than the mean actual jumping distance in the competition. When the number of strides' influence on the run-up speed was studied (equation 2), the velocity of CM was 8.86 m/s for the full length approach. To calculate the effect of run-up speed on the jumping distance this velocity was substituted in equation 3. The predicted jumping distance was 6.57 m which is similar to that calculated from equation 1, but still 0.39 m shorter than the actual jumping distance accomplished in the competition.

Table 2. Polynomial regression equations for predictions using group mean data. D and N denote the effective jumping distance and number of strides, respectively

Variables			
Predictor	Dependent	Equations	
N	D	$y=-0.007x^2+.25x+4.35$	(1)
N	V_{xTD}	$y=-0.006x^2+.29x+5.54$	(2)
V_{xTD}	D	$y=0.123x^2+2.54x-6.28$	(3)

The mean approach speed obtained from linear regression equations (see above) and distance jumped for each condition was used to form a further regression equation ($y=-0.123x^2+2.54x-6.28$). This improved the prediction of jumping distance, but was still only 6.71 m, that is 0.25 m shorter than the jumping distance in the competition. The relationships between Vx_{TD} and Vx_{TO}, Vx_{TD} and V_0, Vx_{TO} and V_0 were also non-linear and the data fitted to polynomial regression equations were $y=-0.09x^2+2.0x-3.1$, $y=-0.11x^2+2.2x-2.2$ and $y=-0.06x^2+1.75x-1.6$, respectively.

Table 3. Polynomial regression equations for each subject used for the prediction of individual jumping distance (y and D_p) in terms of the number of strides (x) used in competition

	Regression equation	x	D_p
Sub1	$y=-0.0037x^2+0.21x+4.91$	18	7.49
Sub2	$y=-0.0081x^2+0.26x+4.1$	16	6.19
Sub3	$y=-0.0094x^2+0.36x+4.1$	19	7.55
Sub4	$y=-0.0037x^2+0.18x+4.7$	20	6.82
Sub5	$y=-0.0037x^2+0.196x+4.0$	15	6.11
Sub6	$y=-0.0056x^2+0.26x+4.8$	20	7.76
Sub7	$y=-0.0012x^2+0.09x+4.9$	18	6.13
Sub8	$y=-0.005x^2+0.27x+4.0$	22	7.26
Mean		18.5	6.91
SD		2.3	.69

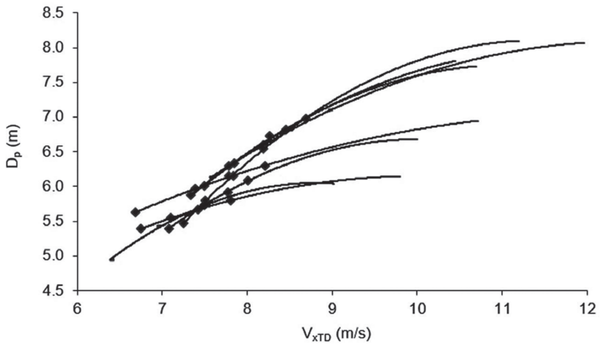

Figure 3. Relationship between jumping distance (D) and horizontal velocity at the touch-down (VxTD) for each subject. The regression lines are extended as far as that velocity value when no further increase occurs.

Table 4. Polynomial regression equations for each subject used for the prediction of jumping distance (y and D_p) with full-length run-up by applying horizontal velocity (V_{xTD}) calculated by the equations presented in Table 3

	Regression equation	V_{xTD}	D_p	D_c	D_p-D_c
Sub1	$y=-0.113x^2+2.64x-7.4$	9.48	7.47	7.47	0
Sub2	$y=-0.147x^2+2.96x-8.15$	8.41	6.35	6.30	.05
Sub3	$y=-0.13x^2+2.93x-8.6$	9.53	7.51	7.51	0
Sub4	$y=-0.045x^2+1.12x+0.317$	8.90	6.72	6.81	-.09
Sub5	$y=-0.21x^2+3.68x-9.8$	8.46	6.30	6.21	.09
Sub6	$y=-0.058x^2+1.63x-2.85$	10.13	7.71	7.79	-.08
Sub7	$y=-0.39x^2+6.64x-21.9$	7.97	6.24	6.35	-.11
Sub8	$y=-0.15x^2+3.5x-11.8$	8.69	7.28	7.21	0.07
Mean			6.95	6.96	
SD			0.61	0.58	

Legend: y – jumping distance, Dp – jumping distance, VxTD – horizontal velocity, Dc – actual jumping distance accomplished in the competition, Dp-Dc – the difference between the predicted and the performed jumping distance.

The data for each individual were fitted to a polynomial regression equation, and the equations differed between individuals. For the number of run-up strides used, the regression equations predicted an average jumping distance of 6.91±0.66 m, which was just 0.05 m shorter than the actual jumping distance achieved in the competition. Similarly, the effect of number of strides on Vx_{TD} (Table 4) predicted a mean velocity at the touch-down for a full-length run-up to be 8.95±0.71m/s. Using the individual speeds, the jumping distance was again predicted (Table 3 and Figure 3) yielding an average distance of 6.90±0.65 m, which was just 0.06 m shorter than the jumping distance measured in the competition. The differences between both predicted distances and the actual jump distance from the competition were not significant.

Discussion and conclusions

The short approach model of performance has provided an opportunity to study long jump behaviour as approach speed increases. It has been shown that relationships between performance variables are best represented by non-linear functions, and in particular by a second order polynomial. This has enabled individualized relationships to be determined which have been found to be better predictors of jump distance than group mean data based on non-linear relationships, or either individual or group data based on linear relationships. Consequently, this has provided a means for predicting individual maximal performance in the long jump event based on sub-maximal performance and enables an insight into an individual's performance not previously reported.

The individualized non-linear relationships have practical value within an applied setting. The length of the approach run and the speed that an athlete is able to achieve from it are two variables that determined long jump performance. One might assume that athletes judge their run-up lengths optimally for performance, but the question arises whether they might have some advantage in changing that length. The individualized data suggests that as an athlete increases his/her number of strides, performance increases but the benefits begin to reduce as the curve reaches a plateau. The same conclusions can be drawn from the predicted horizontal velocity and jump distance. The good agreement between the predicted jump distance and actual jump distance (Tables 4) suggests that an individual's maximal performance can be accurately predicted from his/her sub-maximal performance. This in turn suggests that the short approach model is of value for evaluating an individual's jumping potential and will be of interest to those working in an applied setting.

The question of why the athletes in this study are not able to perform as well as those at, for example, the Olympic Games, can also be addressed by these data. The posture of an athlete at the touch-down and the mechanisms operating during the touch-down to take-off phase ensure that there is a reduction in horizontal velocity with a related increase in vertical velocity. The 15.4% reduction of horizontal velocity at A12 approximates the value (16.1%) that was reported for top-class long jumpers by Nixdorf and Brüggemann (1990). It could be assumed that if the number of strides had been increased, then a further reduction in horizontal velocity would have occurred. Testing this assumption, we fitted our values to a polynomial equation ($y=-.16x^2+3.8x-7.0$, where y is the reduction in horizontal velocity and x is the number of strides) and found that the reduction of horizontal velocity as a percentage decreased rather than increased. It seems that this may be one of the limiting factors which prevented the long jumpers in our study from performing similar jumping distances as top-class jumpers. In contrast, the vertical velocity at the take-off reduced with an increasing number of strides from A8 to A12, and at A12 was 3.46 m/s, which is considerably greater than that reported by Nixdorf and Brüggemann (1990) for top-class male jumpers in competition (3.22m/s). If the number of strides had been increased, it might be assumed that the vertical velocity would have decreased further to reach the normal value for a full-length run-up jump. Fitting the data of A8, A10 and A12 to polynomial regression equation ($y=.002x^2-.08x+4.05$, where y denotes the vertical velocity and x represents the number of strides), we found that the vertical velocity did decrease further, but showed a value of 3.34m/s at the mean number of strides (18.5), still higher than the vertical take-off velocity of top-class athletes.

The vertical velocity with the corresponding horizontal velocity at the take-off determines the take-off angle that was predicted to be higher for the athletes used in this study (21.1°) than the average of elite athletes (19.0 and 19.8°; Lees, et al., 1994; Nixdorf & Brüggemann, 1990). It seems that the long jumpers we studied cannot reach the same horizontal velocity at the touch-down and take-off, and despite their ability to generate high vertical velocity at the take-off, giving them a better angle of projection, they still were not able to achieve similar jumping distances to those of top-class long jumpers. This may be due to several reasons, such as lower technical skills and/or weaker physical abilities.

It is possible to speculate on the mechanisms underpinning the individual non-linear relationships between approach speed and jump distance. The influence of technique and physical ability on performance in long jump has recently been determined using a simulation based on the two-segment model with a realistic knee extensor muscle (Seyfarth, et al., 2000). With regard to technique, these authors determined that in addition to approach speed, the body posture at the touch-down, defined by the knee angle and the angle of attack, influenced performance. With regard to physical abilities, muscle strength and the eccentric/isometric strength ratio were the factors influencing performance as approach speed increased. Other factors investigated – such as tendon compliance, muscle shortening speed, relative length of fibres and tendon, and ratio of muscle fibre to tendon cross-sectional areas – all had an influence on performance but were found to be insensitive to approach speed. As for technique, the data in Table 1 indicate that the angle of attack decreased, while the knee angle increased as approach speed increased from A6 to A12. The decrease in the angle of attack is exactly as predicted by the simulation executed by Seyfarth et al. (2000). The straightening of the leg at knee joint increases leg stiffness and provides for a more effective pivot (Lees, 1994), thus enabling a greater loss of horizontal velocity and a corresponding benefit to the vertical velocity during the compression phase. This re-direction of the jumper's CM velocity is further influenced by a change in the mechanisms used during the propulsion phase. Seyfarth et al. (2000) have shown that for the touch-down at high speed the impact force generated during the compression phase causes a considerable amount of energy to be stored in the tendon, and while some of this is recovered during the propulsion phase, only a small amount of energy comes from the contracting muscle. It is likely that the contribution of concentric muscle contraction is more important at low approach speeds where the knee has a greater flexion enabling it to do more muscular work during extension, and where the severity of the touch-down is lower, producing a lower storage of energy in the tendon for recovery during recoil. As speed increases, the concentric muscle contribution reduces, while the tendon recoil energy increases leading to a progressive change in the source of energy used to generate vertical velocity in the propulsion phase. As the mechanisms for generating vertical velocity are several and complex, it is not surprising that underlying relationships are non-linear.

The data in Table 1 generally support the view of the operational mechanisms as described above and provide good support for the simplified two-segment model of Seyfarth et al. (2000). For the range of approach speeds (7.09 to 8.21m/s) and angles of attack (75.4 to 69.9°) obtained for A6 to A12, Seyfarth et al. (2000) predict jumping distances of approximately 5.10 to 6.20m compared to the actual values of 5.58-6.31m, a remarkably good agreement. Similar agreement is seen in the touch-down to take-off energy ratio which is greater than 100% (an energy gain) for the combinations of low approach speed and high angle of attack. This corresponds to condition A6 where the take-off vector velocity is substantially greater than the touch-down velocity (the vertical touch-down velocity is close to zero) suggesting that there is an energy gain at this approach speed. This energy gain must come from muscle contraction. As approach speed increases, the take-off velocity vector becomes smaller than the touch-down horizontal velocity, indicating energy loss, more typical for long jumping, and in agreement with the predictions of Seyfarth et al. (2000). The predictions for the take-off angle are less successful, as for the conditions from A6 to A12. Seyfarth et al. (2000) predict a range of approximately 19 to 18°, while it was actually found to be 27.9 to 26.2° in this study. This and other small discrepancies could be ascribed to the slightly larger values for the angle of attack in this study compared to the others, likely to be due to the influence of the lower frame rate used in this study. A small shift in the angle of attack to lower values would improve the agreements mentioned above, providing even stronger support for the Seyfarth et al. (2000) model.

It is also worth commenting specifically on condition A6. This condition is unusual in that it produces a high force of impact and, as suggested above, is normally associated with higher leg stiffness which would lead to a larger storage of elastic energy. Arampatzis, Brüggemann, and Matzler (1999) have demonstrated that in running (between 2.5 and 6.5m/s) leg stiffness increases with speed, so a lower speed approach would be expected to be associated with a lower leg stiffness and a lower impact force. The large flexion of the knee noted at the A6 speed is indicative of a reduced leg stiffness so it is likely that the high force is not related to a greater energy storage and hence energy recoil of the tendon. This, together with its greater potential for generating muscular energy through a greater range of knee extension, and the energy gain at the take-off as noted above, all suggest that the A6 condition is a somewhat different from the other approach conditions. Consequently, the inclusion of speeds lower than those generated from a 6-stride approach would probably not benefit the predictive ability of the regression equations and is also not suitable to practice the technique of the jump.

Seyfarth et al. (2000) have suggested that as well as postural influences, muscle strength and eccentric/isometric strength ratio are important factors of performance. These two factors relate to physical abilities that are susceptible to training. The relatively poorer performance of athletes in this study, when compared to the top-class performers, is likely to be due to these physical abilities. A greater strength enables a greater ground reaction force which acts to re-direct the jumper upwards. If strength is insufficient, the knee will flex, maintaining horizontal speed and limiting the ability to create vertical velocity. The athletes in our study chose to reduce their approach speed, and hence the severity of contact, in order to preserve their ability to gain vertical velocity. This is sensible, as jump distance is very sensitive to vertical velocity. On the other hand, to improve jump performance, these athletes would need to be able to sustain forces associated with greater approach speeds and to do so would require greater strength. As the vertical velocity is primarily produced during the compression phase of contact (Lees, et al., 1994), eccentric strength and the eccentric/isometric strength ratio are important factors. Although other factors are likely to be influential in actual long jumping performance, such as arm swing and movements in the frontal plane (Graham-Smith & Lees, 2005), the simplified model of Seyfarth et al. (2000) provides valuable insights into the musculoskeletal mechanisms that may be operating during long jump performance and an underpinning rationale for the individualized non-linear relationships identified.

In conclusion, as it was hypothesized using the short approach model, the run-up and take-off variables selected related to the length of the jumps non-linearly, and these relationships were shown to be best represented by the second order polynomial equations. When applied on an individual basis, the predicted jump distances agreed very well with those found in the actual competition. The result of this study may suggest that the short approach model of performance is a valuable paradigm for investigations into long jump behaviour and performance potential of individuals, and supports the simplified mathematical model proposed by Seyfarth, et al. (2000) for the study of long jump performance.

References

Ae, M., Ito A., & Suzuki M. (1992). The men's 100 metres. *New Studies in Athletics*, *7*, 47-52.

Aleshinski, S.I., Tiupa, V.V., Ter-Ovenesian, I.A., & Pereverzev, A.P. (1980). *Biomechanical aspects of the long jump technique.* Moscow: State Central Institute of Physical Culture.

Alexander, R.M. (1990). Optimum take-off techniques for high and long jumps. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 329*(1252), 3-10.

Arampatzis, A., Brüggemann, G-P., & Metzler, V. (1999). The effect of speed on leg stiffness and joint kinetics in human running. *Journal of Biomechanics, 32*, 1349-1353.

Ballreich, R., & Ernst, H. (1980). Biomechanischen Individual Analysen. [Biomechanical individual analyses.] In R. Ballreich & A. Kuhlow (Eds.), *Beiträge zur Biomechanik des Sport* (pp. 71-74). Schorndorf: Verlag Karl Hofmann.

Bridgett, L.A. & Linthorne, N.P. (2005). Biomechnaical analysis of two long jump take-off techniques. In Quing Wang (Ed.), *23rd International Symposium on Biomechanics in Sports 2005* (pp. 276-279). Beijing.

Brüggemann, G.P., & Glad, B. (1990). Time analysis of sprint events. In G.P Brüggemann & B. Glad (Eds.), *Scientific research project at the Games of the XXIVth Olympiad – Seoul 1988* (pp. 11-99). Monaco: International Athletic Federation.

Brüggemann, G-P., Nixdorf, E., & Ernst, H. (1982). Biomechanischen Untersuchungen beim Weitsprung. [Biomechanical investigations in long jump.] *Lehre Leichtathletic*, *40*, 1635-1636, 1641-1642.

Dempster, W.T. (1955). *Space requirements of the seated operator (WADCTR 55-159).* Wright-Petterson Air Force Base, OH:Aerospace Medical Research Laboratory.

Farmer, D. (1973). Guidelines for the long jump. *Scholastic Coach, 42*(52), 7-9.

Graham-Smith, P., & Lees, A. (2005). A three-dimensional kinematic analysis of the long jump take-off. *Journal of Sports Sciences, 23*(9), 891-903.

Hay, J.G. (1986). The biomechanics of long jump. *Exercise and Sport Science Review, 19,* 855-866.

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

Hussain, I., Khan, A., & Mohammad, A. (2011). Analysis of selected kinematical parameters of two different level male long jumpers. *International Journal of Sports Science and Engineering, 5*(4), 213-218.

Jarver, J. (1970). The long jump. In F. Wilt & T. Ecker (Eds.), *International Track and Field Encyclopedia* (pp. 166-198). West Nyack, New York: Parker Publishing.

Karras, V.L, Susanka, P., Otohal, S., & Morakova, E. (1983). Aktuelle Probleme in der biomechanischen Forschung für Sportlokomotion. [Contemporary problems in biomechanical research of sport-related locomotion.] In W. Baumann (Ed.), *Biomechanik und sportliche Leistung* (pp. 41-51). Schorndorf: Verlag Karl Hoffman.

Lees, A., Fowler, N., & Derby, D. (1993). A biomechanical analysis of the last stride, touchdown and takeoff characteristics of the women's long jump. *Journal of Sport Sciences, 11,* 303-314.

Lees, A., Fowler, N., & Derby, D. (1994). A biomechanical analysis of the last stride, touchdown and takeoff characteristics of the men's long jump. *Journal of Applied Biomechanics, 10,* 61-78.

Linthorne, N.P. (2008). Biomechanics of the long jump. In Y. Hong & R. Bartlet (Eds.), *Handbook of biomechanics and human movement science* (pp. 340-354). Oxon & New York: Routledge.

Lundin, P., & Berg, W. (1993). Developing the approach in the jumps. *New Studies of Athletics, 8*, 40-50.

Madella, A. (1996). Speed in the horizontal jumps: Muscular properties or cognitive treatment? *New Studies in Athletic, 11,* 127-133.

Matić, M., Mrdaković, V., Janković, N., Ilić, D., Stefanović, Đ., & Kostić, S. (2012). Active landing and take-off kinematics of the long jump. *Facta Universitatis Series: Physical Education and Sport, 10*(3), 243–256.

Mikhailov, N.G., Yakunin, N.A., & Aleshinsky, S.Y. (1981). Biomehanicseszkaja ocenka ottalkuvanyija v prizskoh v dlinu. [Biomechanical assessment of take-off in long jump.] *Teoria i Praktika Fizicheskoi Kulturi, 5*, 11-13.

Muraki, Y. (1984). Fundamentals of approach running and takeoff. *Track Technique, 89*, 2843-2845.

Nixdorf, E., & Brüggemann, G-P. (1990). Biomechanical analysis of the long jump. In G.P Brüggemann & B. Glad (Eds.), *Scientific research project at the Games of the XXIVth Olympiad – Seoul 1988* (pp. 263-301). Monaco: International Athletic Federation.

Pepin, G. (1991). Developing a long jump approach. *Track & Field Quarterly, 4*, 12-13.

Popov, V.B. (1983). The long jump run up. *Track Technique, 85*, 2708-2709.

Seyfarth, A., Friedrichs, A., Wank, V., & Blickhan, R. (1999). Dynamics of the long jump. *Journal of Biomechanics, 32*, 1259-1267.

Tiupa, V.V., Aleshinsky, S.I., Primakov, I.N., & Pereverzev, A.P. (1982). The biomechanics of the movement of the body's general centre of mass during the long jump. *Theoria i Praktika Fizicheskoi Kulturi, 5*, 21-32.

PREDVIĐANJE DALJINE SKOKA KORIŠTENJEM MODELA KRATKOG ZALETA

Nedavni dokazi sugeriraju da odnos brzine zaleta i daljine skoka ne mora biti linearna. Ciljevi ovog istraživanja su (1) testirati hipotezu da se korištenjem kratkog zaleta (6-8-10-12 koraka) kojem se povećava duljina, varijable izvedbe skoka nelinearno povezuju s daljinom skoka, (2) istražiti prirodu tih odnosa u grupi skakača udalj i pojedinaca unutar grupe te (3) korištenjem regresijske analize utvrditi optimalan broj koraka zaleta i predvidjeti daljinu skoka koja bi bila postignuta dužinom zaleta optimalnom za određenog skakača. Osam skakača udalj različite razine tehničke pripremljenosti (tjelesna masa: 75,2±2,2 kg; tjelesna visina: 188,0±4,2 cm) izvela je seriju maksimalnih skokova udalj s kratkim zaletom te s cjelovitim zaletom na natjecanju. Kinematički parametri prikupljeni su video analizom. Pokazalo se da odnos između broja koraka zaleta, brzine zaleta i dužine skoka može se najbolje objasniti korištenjem poliniminalnih jednadžba drugog reda. Kada su se jednadžbe koristile za izračunavanje dužine skoka za svakog pojedinca, predviđena duljina skoka (6,95±0,61) bila je vrlo bliska duljinama zabilježenima na natjecanjima (6,96±0,58). Kao rezultat, ti su individualni odnosi korišteni za definiranje individualne optimalne duljine zaleta te za procjenjivanje potencijala skakača za nastup na skakačkim natjecanjima. Zaključeno je da je model kratkog zaleta vrijedna paradigma za istraživanje parametara skoka udalj kao i potencijala pojedinaca za tu disciplinu. Rezultati istraživanja podupiru pojednostavljeni matematički model predložen u literaturi za proučavanje izvedbe skoka udalj.

Ključne riječi: *brzina zaleta, brzina odraza, regresijska analiza, predviđanje*

Submitted: May 8, 2013
Accepted: April 4, 2014

Correspondence to:
Prof. József Tihanyi, Ph.D.
Professor of Biomechanics
Department of Biomechanics, Kinesiology and Informatics, Faculty of Physical Education and Sport Science, Semmelweis University, Budapest
Alkotás u. 44, 1123 Budapest, Hungary
Phone: +36 1 4879205
E-mail: tihanyi@tf.hu