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Chapter 14

The High Jump

J. DAPENA

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Chapter 14

The High Jump

J. DAPENA

Introduction

This chapter describes the mechanics of the Fosbury-flop style of high jumping, and explains a rationale followed for the evaluation of the techniques used by individual elite high jumpers.

Since 1982, our laboratory has studied the techniques of the best high jumpers in the USA. This work is part of the Scientific Support Services programme sponsored by USATF (USA Track and Field, the governing body for track and field athletics in the USA) at several biomechanics laboratories. The goal of the programme is to give the best US athletes biomechanical information to help improve their performance through changes in technique.

Personnel from our laboratory generally film the top American high jumpers every year at the final of the USATF Championships or at some other major competition. The films are subsequently analysed using three-dimensional biomechanical research

Table 14.1 General information on the analysed jumpers, and meet results.

Athlete	Country	Standing height (m)	Mass (kg)	Personal best mark* (m)	Best height cleared at the meet† (m)
Men					
Gennadiy Avdeyenko	USSR	2.02	82	2.38	2.38 (W87)
Hollis Conway	USA	1.84	68	2.40	2.34 (O92)
Tim Forsyth	Australia	1.97	75	2.34	2.34 (O92)
Igor Paklin	USSR	1.91	72	2.41	2.38 (W87)
Artur Partyka	Poland	1.91	73	2.37	2.34 (O92)
Patrik Sjöberg	Sweden	2.00	82	2.42	2.34 (O92)
Javier Sotomayor	Cuba	1.94	82	2.44	2.34 (O92)
Dwight Stones	USA	1.95	82	2.34	2.34 (T84)
Jan Zvara	Czechoslovakia	1.91	85	2.36	2.34 (W87)
Women					
Amy Acuff	USA	1.88	64	1.98	1.96 (U97)
Galina Astafei	Romania	1.84	65	2.00	2.00 (O92)
Susanne Beyer-Helm	East Germany	1.78	58	2.02	2.02 (W87)
Emilia Dragieva	Bulgaria	1.69	55	2.00	2.00 (W87)
Heike Henkel	Germany	1.82	63	2.07	2.02 (O92)
Stefka Kostadinova	Bulgaria	1.80	60	2.08	2.05 (W87)
Ioamnet Quintero	Cuba	1.80	60	1.98	1.97 (O92)
Coleen Sommer	USA	1.76	58	2.00	1.96 (U87)

* By the end of the meet in which the jumper was analysed.
† T84 = 1984 US Olympic Trials; W87 = 1987 World Indoor Championships; U87 = 1987 USATF Championships; O92 = 1992 Olympic Games; U97 = 1997 USATF Championships.

methods. Reports and videotapes containing mechanical data, computer graphics and interpretations are then prepared, and sent to the coaches and athletes. The reports and videotapes evaluate the advantages and disadvantages of the present techniques of the athletes, and suggest how to correct some of the technique problems. The rationale used for the technique evaluations stems from a comprehensive interpretation of the Fosbury-flop style of high jumping based on the research of Dyatchkov (1968) and Ozolin (1973), on basic research carried out by the author and collaborators (Dapena 1980a,b, 1987, 1995a,b, 1997; Dapena & Chung 1988; Dapena *et al.* 1990, 1997c), and on the experience accumulated through the analysis of US and other high jumpers at our laboratory since 1982 in the course of service work sponsored by USATF, the USOC (United States Olympic Committee), and the IOC (International Olympic Committee) (e.g. Dapena *et al.* 1993a,b, 1997a,b).

The main purpose of this chapter is to describe this interpretation of the Fosbury-flop style of high jumping, and to explain the rationale followed in the reports for the evaluation of technique. The discussions are illustrated with data from the highest jumps by men and women in our database. Table 14.1 shows general information on these athletes, and their results in the analysed competitions. They all used the Fosbury-flop style.

Phases of a high jump

A high jump can be divided into three parts: the run-up phase, the takeoff phase and the flight or bar clearance phase. The purpose of the run-up is to set the appropriate conditions for the beginning of the takeoff phase. During the takeoff phase, the athlete exerts forces that determine the maximum height that the centre of mass (COM) will reach after leaving the ground and the angular momentum (or 'rotary momentum') that the body will have during the bar clearance. The only voluntary movements that can be made after leaving the ground are internal compensatory movements (e.g. one part of the body can be lifted by lowering another part; one part of the body can be made to rotate faster by making another part slow down its rotation).

The run-up serves as a preparation for the takeoff phase, the most important phase of the jump. The actions of the athlete during the bar clearance are less important: Most of the problems found in the bar clearance actually originate in the run-up or takeoff phases.

General characteristics of the run-up

The typical length of the run-up for experienced high jumpers is about 10 steps. In most athletes who

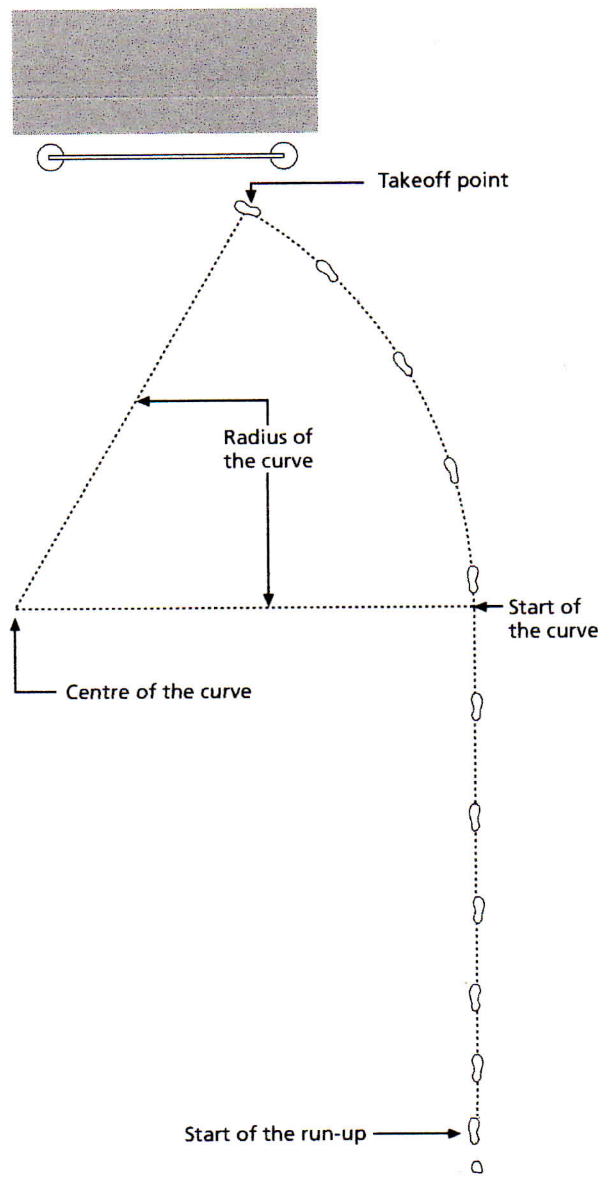

Fig. 14.1 Sketch of the run-up.

use the Fosbury-flop technique, the first part of the run-up usually follows a straight line perpendicular to the plane of the standards, and the last four or five steps follow a curve (Fig. 14.1). One of the main purposes of the curve is to make the jumper lean away from the bar at the start of the takeoff phase. The faster the run-up or the tighter the curve, the greater the lean towards the centre of the curve.

Approach angles

Figure 14.2 shows an overhead view of the footprints and of the COM path during the last two steps of the run-up, the takeoff phase and the airborne phase. Notice that the COM path is initially to the left of the footprints. This is because the athlete is leaning towards the left during the curve. The path then converges with the footprints, and the COM is almost directly over the takeoff foot at the end of the takeoff.

Figure 14.2 also shows angles t_1, p_2, p_1 and p_0: t_1 is the angle between the bar and the line joining the last two footprints; p_2 and p_1 are the angles between the bar and the path of the COM in the airborne phases of the last two steps; p_0 is the angle between the bar and the path of the COM during the airborne phase that follows the takeoff. The angles are smaller in athletes who move more parallel to the bar. The values of these angles are shown in Table 14.2.

Progression of the run-up

To start the run-up, the athlete can either walk a few steps and then start running, or make a standing start. In the early part of the run-up, the athlete should follow a gradual progression in which each step is longer and faster than the previous one. After a few steps, the high jumper will be running rather fast, with long, relaxed steps similar to those of a 400-metre or 800-metre runner. In the last two or three steps of the run-up the athlete should gradually lower the hips. This has to be done without a significant loss of running speed.

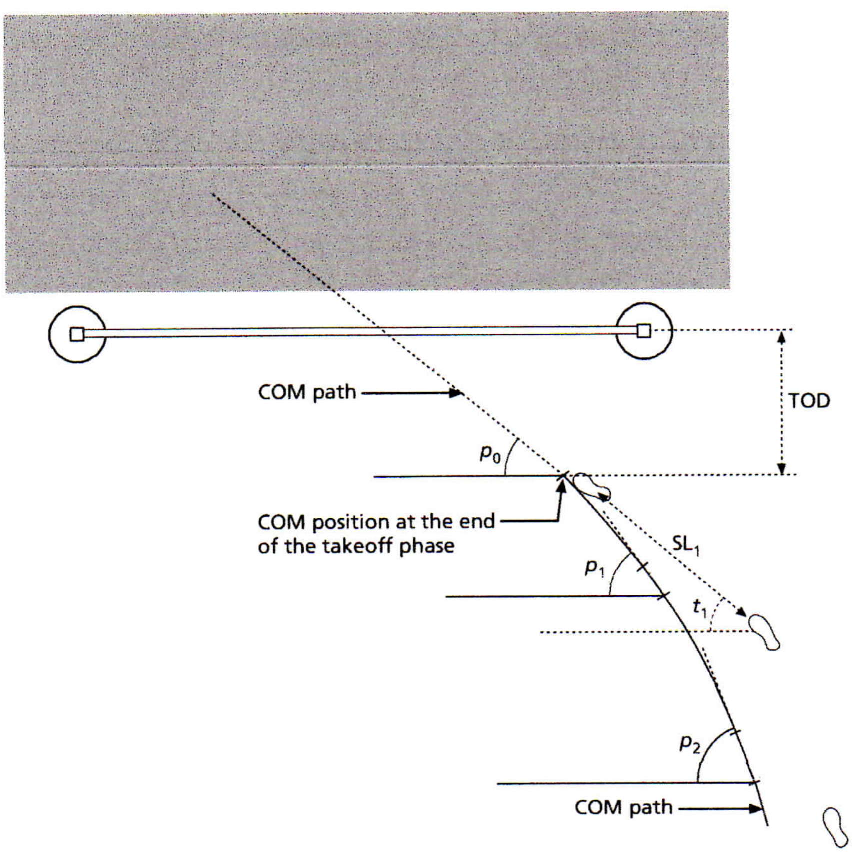

Fig. 14.2 Footprints and centre of mass (COM) path.

Table 14.2 Direction of the footprints of the last step (t_1), direction of the path of the centre of mass (COM) in the last two steps (p_2 and p_1) and after takeoff (p_0), direction of the longitudinal axis of the foot with respect to the bar (e_1), with respect to the final direction of the run-up (e_2) and with respect to the horizontal force made on the ground during the takeoff phase (e_3), length of the last step (SL_1, expressed in metres and also as a percentage of the standing height of the athlete), and takeoff distance (TOD).

Athlete	t_1 (°)	p_2 (°)	p_1 (°)	p_0 (°)	e_1 (°)	e_2 (°)	e_3 (°)	SL_1 (m)	SL_1 (%)	TOD (m)
Men										
Avdeyenko	33	54	44	39	23	21	25	2.27	112	0.96
Conway	15	47	30	34	−9	39	36	2.11	115	0.94
Forsyth	26	46	39	38	17	21	22	2.18	111	0.91
Paklin	32	50	40	33	4	36	43	2.16	113	0.86
Partyka	28	51	41	33	16	25	35	1.83	96	1.01
Sjöberg	26	48	37	29	11	26	35	2.10	105	0.77
Sotomayor	31	–	41	31	11	30	40	2.31	119	0.84
Stones	32	55	44	38	−5	50	56	2.00	102	0.99
Zvara	33	55	43	44	23	20	20	2.11	111	0.67
Women										
Acuff	23	50	36	33	18	18	22	1.69	90	0.53
Astafei	32	–	39	34	21	18	24	2.00	109	0.88
Beyer-Helm	29	50	42	40	24	18	20	1.80	101	1.04
Dragieva	33	47	41	40	31	10	11	1.85	109	0.82
Henkel	30	55	41	38	42	−1	4	1.91	105	0.94
Kostadinova	34	51	43	37	26	16	24	2.06	114	0.98
Quintero	30	51	42	34	27	14	24	1.91	106	0.75
Sommer	23	44	36	33	30	6	11	1.72	98	0.90

Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Horizontal velocity and height of the COM at the end of the run-up

The takeoff phase is defined as the period of time between the instant when the takeoff foot first touches the ground (touchdown) and the instant when it loses contact with the ground (takeoff). During the takeoff phase, the takeoff leg pushes down on the ground. In reaction, the ground pushes up on the body through the takeoff leg with an equal and opposite force. The upward force exerted by the ground on the athlete changes the vertical velocity of the COM from a value that is initially close to zero to a large upward vertical velocity. The vertical velocity of the athlete at the end of the takeoff phase determines how high the COM will go after the athlete leaves the ground, and is therefore of great importance for the result of the jump.

To maximize the vertical velocity at the end of the takeoff phase, the product of the vertical force exerted by the athlete on the ground and the time during which this force is exerted should be as large as possible. This can be achieved by making a large vertical force while the COM travels through a long vertical range of motion during the takeoff phase.

A fast approach run can help the athlete to exert a larger vertical force on the ground. This can occur in the following way. When the takeoff leg is planted ahead of the body at the end of the run-up, the knee extensor muscles resist the flexion of the leg, but the leg is still forced to flex because of the forward momentum of the jumper. In this process the extensor muscles of the knee of the takeoff leg are stretched. It is believed that this stretching stimulates the muscles, which in turn allows the foot of the takeoff leg to exert a larger force on the ground.

Table 14.3 Height of the centre of mass (COM) at the start of the takeoff phase (h_{TD}, expressed in metres and also as a percentage of the standing height of the athlete), horizontal velocity in the last two steps of the run-up (v_{H2} and v_{H1}), horizontal velocity after takeoff (v_{HTO}), change in horizontal velocity during the takeoff phase (Δv_H), vertical velocity at the start of the takeoff phase (v_{ZTD}), and vertical velocity at the end of the takeoff phase (v_{ZTO}).

	h_{TD}		v_{H2}	v_{H1}	v_{HTO}	Δv_H	v_{ZTD}	v_{ZTO}
Athlete	(m)	(%)	($m \cdot s^{-1}$)	($m \cdot s^{-1}$)	($m \cdot s^{-1}$)	($m \cdot s^{-1}$)	($m \cdot s^{-1}$)	($m \cdot s^{-1}$)
Men								
Avdeyenko	0.92	45.5	8.1	7.9	3.7	−4.2	−0.3	4.50
Conway	0.78	42.5	7.4	7.4	3.4	−4.0	−0.6	4.65
Forsyth	0.95	48.5	7.2	7.3	3.8	−3.4	−0.6	4.55
Paklin	0.85	44.5	8.1	7.7	3.9	−3.9	−0.5	4.55
Partyka	0.93	48.5	7.6	7.4	4.1	−3.3	−0.6	4.50
Sjöberg	0.98	49.0	7.2	7.5	4.0	−3.5	−0.6	4.25
Sotomayor	0.89	46.0	–	8.0	4.0	−4.0	−0.7	4.60
Stones	0.92	47.0	7.0	7.1	3.5	−3.5	−0.4	4.40
Zvara	0.89	46.5	6.9	6.6	2.6	−4.0	−0.6	4.65
Women								
Acuff	0.92	49.0	6.3	6.3	3.5	−2.8	−0.2	3.80
Astafei	0.88	48.0	–	7.2	4.1	−3.1	−0.7	3.95
Beyer-Helm	0.86	48.0	6.9	7.2	3.8	−3.4	−0.5	4.00
Dragieva	0.81	47.5	6.9	7.2	3.5	−3.7	−0.8	4.10
Henkel	0.89	49.0	7.4	7.2	4.3	−2.9	−0.5	3.90
Kostadinova	0.90	50.0	7.5	7.3	4.2	−3.1	−0.5	4.00
Quintero	0.84	46.5	7.3	6.7	3.8	−2.9	−0.8	3.90
Sommer	0.87	49.5	6.9	7.1	4.3	−2.8	−0.6	3.85

Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

In this way, a fast run-up helps to increase the vertical force exerted during the takeoff phase. (For a more extended discussion of the mechanisms that may be involved in the high jump takeoff, see Dapena & Chung 1988.) Table 14.3 shows the values of v_{H2}, the horizontal velocity of the athlete in the next-to-last step of the run-up, and of v_{H1}, the horizontal velocity of the athlete in the last step of the run-up, just before the takeoff foot is planted on the ground. The value of v_{H1} is the important one.

To maximize the vertical range of motion through which force is exerted on the body, the centre of mass needs to be in a low position at the start of the takeoff phase and in a high position at the end of it. The COM of most high jumpers is reasonably high by the end of the takeoff phase, but it is difficult to have the COM in a low position at the start of the takeoff phase. This is because in such a case the body has to be supported by a deeply flexed non-takeoff leg during the next-to-last step of the run-up, which requires a very strong non-takeoff leg; it is also difficult to learn the appropriate neuromuscular patterns that will permit the athlete to pass over the deeply flexed non-takeoff leg without losing speed. Table 14.3 shows the value of h_{TD}, the height of the COM at the instant that the takeoff foot is planted on the ground to start the takeoff phase. It is expressed in metres, but also as a percentage of the standing height of each athlete. The percentage values are more meaningful for comparing athletes.

It is possible to achieve an approach run that is fast and low in the last steps. However, it requires considerable effort and training. If an athlete has learned how to run fast and low, a new problem could occur: The athlete could actually be too fast and too low. If the takeoff leg is not strong enough, it will be forced to flex excessively during the takeoff phase, and then it may not be able to make a forceful

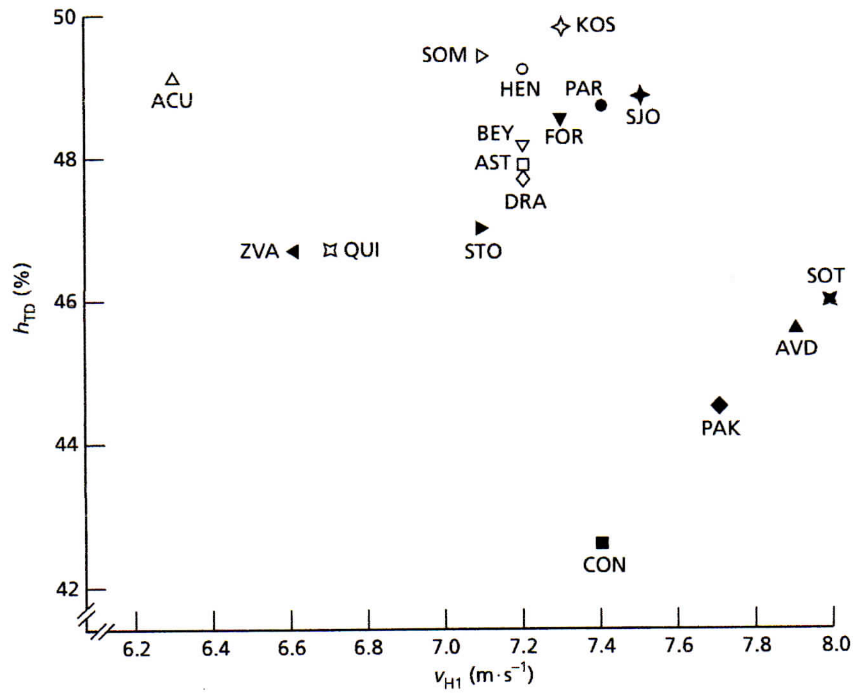

Fig. 14.3 Horizontal velocity at the end of the run-up (v_{H1}) and height (h_{TD}) of the centre of mass (COM) at the end of the run-up.

extension in the final part of the takeoff phase. In other words, the takeoff leg may suffer partial or complete collapse (buckling) under the stress, and the result will be an aborted jump. Therefore, it is important for a high jumper to find the optimum combination of run-up speed and COM height. We will now see how this can be done.

Figure 14.3 shows a plot of h_{TD} vs. v_{H1}. Each point represents one jump by one athlete. (A different symbol has been assigned to each athlete in Fig. 14.3; the same symbol will be used in subsequent graphs.) This kind of graph permits one to visualize simultaneously how fast and how high an athlete was at the end of the run-up. For instance, a point in the upper right part of the graph would indicate a jump with a fast run-up but high COM at the end of the run-up.

Let us consider what would happen if all the athletes shown in Fig. 14.3 had similar dynamic strength in the takeoff leg. In such a case, the athletes in the upper left part of the graph would be far from their limit for buckling, the athletes in the lower right part of the graph would be closest to buckling, and the athletes in the centre, lower left or upper right parts of the graph would be somewhere in between with respect to buckling. Therefore, if all the athletes shown in Fig. 14.3 had similar dynamic strength, we would recommend the athletes in the upper left part of the graph to learn how to run faster and lower, and then experiment with jumps using run-ups that are faster and/or lower than their original ones. Athletes in the centre, lower left and upper right parts of the graph would also be advised to experiment with faster and lower run-ups, possibly emphasizing 'faster' for any jumpers in the lower left part of the graph, and 'lower' for jumpers in the upper right part of the graph. The athletes in the lower right part of the graph would be cautioned against the use of much faster and/or lower run-ups than their present ones, because these athletes would already be closer to buckling than the others.

The procedure just described would make sense if all the jumpers in Fig. 14.3 had similar dynamic strength in the takeoff leg. However, this is unlikely. Some high jumpers will be more powerful than others. Since stronger athletes can handle faster and lower run-ups without buckling, it is possible that an athlete in the upper left part of the graph might be weak, and therefore close to buckling, while an

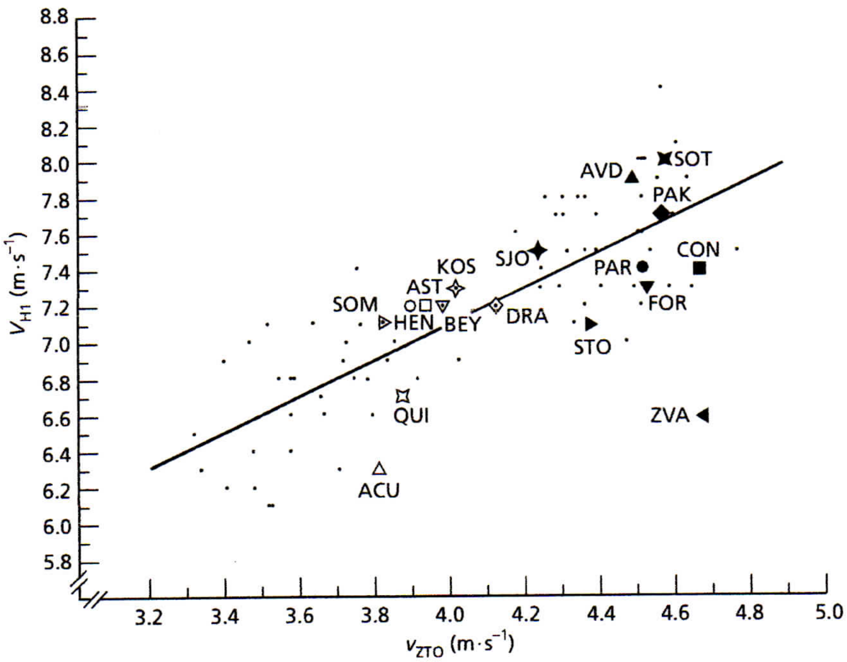

Fig. 14.4 Relationship between the vertical velocity at the end of the takeoff (v_{ZTO}) and the horizontal velocity at the end of the run-up (v_{H1}).

athlete farther down and to the right in the graph might be more powerful, and actually farther from buckling. The optimum combination of run-up speed and COM height will be different for different high jumpers.

High jumpers with greater dynamic strength in the takeoff leg will be able to handle faster and lower run-ups without buckling during the takeoff phase. However, it is not easy to measure the 'dynamic strength' of a high jumper's takeoff leg. The personal record of an athlete in a squat lift or in a vertical jump-and-reach test are not good indicators. This is because these tests do not duplicate closely enough the conditions of the high-jump takeoff. Therefore, we used instead the vertical velocity of the high jumper at the end of the takeoff phase (v_{ZTO}—see below) as a rough indicator of the dynamic strength of the takeoff leg. In other words, we used the capability of a high jumper to generate lift in a high jump as a rough indicator of the athlete's dynamic strength or 'takeoff power'.

To help us predict the optimum horizontal speed at the end of the run-up, we made use of statistical information accumulated through film analyses of male and female high jumpers in the course of Scientific Support Services work in the period 1982–87 (Dapena *et al.* 1990). The athletes involved in these studies were all elite high jumpers filmed at the finals of national and international level competitions (USATF and NCAA Championships, US Olympic Trials, World Indoor Championships).

Each small dot in Fig. 14.4 represents one jump by one of the athletes in our statistical sample. The other symbols show the athletes used here for illustration purposes. The horizontal axis of the graph shows vertical velocity at takeoff (v_{ZTO}): The most powerful high jumpers are those able to generate most lift, and they are to the right in the graph; the weaker jumpers are to the left. The vertical axis shows the final speed of the run-up (v_{H1}). The diagonal 'regression' line shows the trend of the statistical data. The graph agrees with our expectations: The more powerful jumpers, those able to generate more lift (v_{ZTO}), can also handle faster run-ups (v_{H1}) without buckling.

So, what is the optimum run-up speed for a given high jumper? It seems safe to assume that high-jumpers will rarely run so fast that the takeoff leg will buckle. This is because it takes conscious effort to use a fast run-up, and if the athlete feels that the leg has buckled in one jump, an easier (slower) run-up will be used in subsequent jumps. Since partial

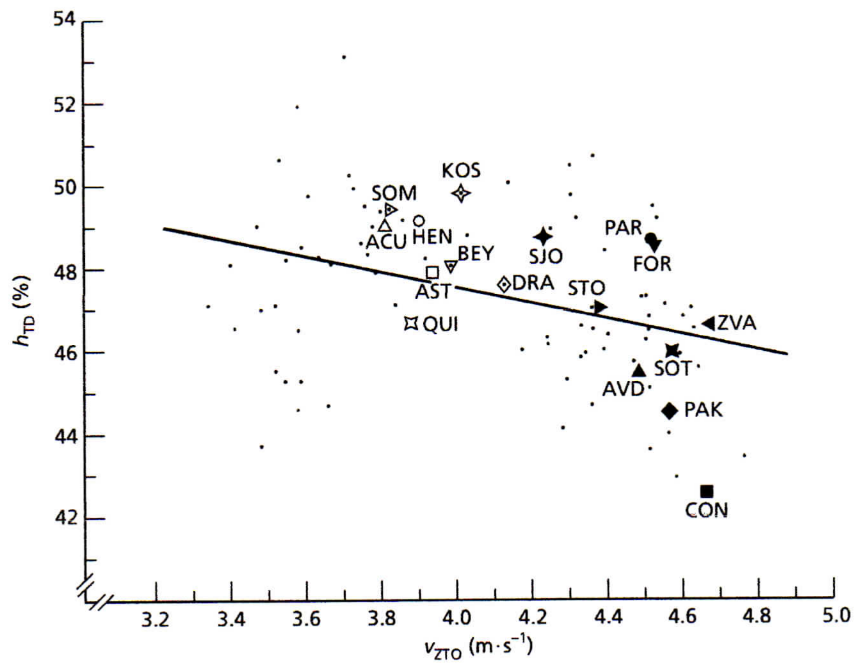

Fig. 14.5 Relationship between the vertical velocity at the end of the takeoff (v_{ZTO}) and the height of the COM at the end of the run-up (h_{TD}, expressed as a percentage of standing height).

buckling will begin to occur at run-up speeds immediately faster than the optimum, few high jumpers would be expected to regularly use run-ups that are faster than their optimum. We should expect a larger number of high jumpers to use run-up speeds that are slower than their optimum. This is because a fair number of high jumpers have not learned to use a fast enough run-up. Therefore, the diagonal regression line which marks the average trend in the graph probably marks speeds that are somewhat slower than the optimum. In summary, although the precise value of the optimum run-up speed is not known for any given value of v_{ZTO}, it is probably faster than the value predicted by the diagonal regression line; athletes near the regression line or below it were probably running too slowly at the end of the run-up.

A similar rationale can be followed with the graph of h_{TD} vs. v_{ZTO}, shown in Fig. 14.5. Each small dot in Fig. 14.5 represents one jump by one of the athletes in our statistical sample. The horizontal axis of the graph again shows vertical velocity at takeoff (v_{ZTO}): the most powerful high jumpers are those able to generate more lift, and they are to the right in the graph; the weaker jumpers are to the left. The vertical axis shows the height of the COM at the start of the takeoff phase (h_{TD}). Although the data are more 'noisy' than in the previous graph (there is a wider 'cloud' around the regression line), the graph in Fig. 14.5 also agrees with our general expectations: The more powerful jumpers (larger v_{ZTO} values) can be lower at the end of the run-up (smaller h_{TD} values) without buckling. In Fig. 14.5, jumpers on the regression line or above it have defective techniques, and the optimum will be somewhere below the regression line.

When Figs 14.4 and 14.5 are used as diagnostic tools, it is necessary to take into consideration the information from both graphs. For instance, if a given athlete is near the regression lines in Figs 14.4 and 14.5, or below the regression line in Fig. 14.4 and above the regression line in Fig. 14.5, we should presume that this athlete is not near the buckling point. Therefore the athlete should be advised to increase the run-up speed and/or to run with lower hips at the end of the run-up. However, if an athlete is slightly below the regression line in Fig. 14.4, but markedly below it in Fig. 14.5, the situation is different. Since the COM was very low during the run-up, maybe the athlete was close to the buckling point, even though the run-up speed was not very fast. In this case, it would not be appropriate to advise an increase in run-up speed, even if the athlete was running somewhat slower than we would expect.

Some caution is needed here. The use of a faster and/or lower run-up will put a greater stress on the takeoff leg, and thus may increase the risk of injury if the leg is not strong enough. Therefore, it is important to use caution in the adoption of a faster and/or lower run-up. If the desired change is very large, it would be advisable to make it gradually, over a period of time. In all cases, it may be wise to further strengthen the takeoff leg, so that it can withstand the increased force of the impact produced when the takeoff leg is planted.

Vertical velocity of the COM at the start of the takeoff phase

The vertical velocity at the end of the takeoff phase, which is of crucial importance for the height of the jump, is determined by the vertical velocity at the start of the takeoff phase and by the change that takes place in its value during the takeoff phase. In normal high jumping, at the end of the run-up (i.e. at the start of the takeoff phase) the athlete is moving fast forwards, and also slightly downwards. In other words, the vertical velocity at the start of the takeoff phase (v_{ZTD}) usually has a small negative value. It is evident that for a given change in vertical velocity during the takeoff phase, the athlete with the smallest amount of negative vertical velocity at touchdown will jump the highest. The values of v_{ZTD} are shown in Table 14.3. The jumpers with the best techniques in this respect are those with the least negative v_{ZTD} values.

In each step of the run-up the COM normally moves up slightly as the athlete takes off from the ground, reaches a maximum height, and then drops down again before the athlete plants the next foot on the ground. In the last step of the run-up, if the takeoff foot is planted on the ground early, the takeoff phase will start before the COM acquires too much downward vertical velocity. To achieve this, the athlete has to try to make the last two foot contacts with the ground very quickly one after the other. In other words, the tempo of the last two foot supports should be very fast.

If the length of the last step is very long, it could contribute to a late planting of the takeoff foot, and therefore to a large negative value for v_{ZTD}. Table 14.2 shows the length of the last step of the run-up (SL_1). This length is expressed in metres, but to facilitate comparisons among athletes it is also expressed as a percentage of the standing height of the athlete.

Another factor that influences the vertical velocity at the start of the takeoff phase is the way in which the COM is lowered in the final part of the run-up. High-jumpers can be classified into three groups, depending on the way in which they lower the COM. Many athletes lower their COM early (two or three steps before the takeoff), and then move more or less flat in the last step. These athletes typically have a moderate amount of downward vertical velocity at the instant that the takeoff phase starts. The second group of athletes keep their hips high until almost the very end of the run-up, and then they lower the COM in the last step. These athletes have a large negative vertical velocity at the start of the takeoff phase, regardless of how early they plant the takeoff foot on the ground. A third group of athletes lower the COM in the same way as the first group, but then raise it again quite a bit as the non-takeoff leg pushes off into the last step. These athletes typically have a very small amount of downward vertical velocity at the start of the takeoff phase, which is good, but they also waste part of their previous lowering of the COM.

The first and the third techniques have both advantages and disadvantages, but the second technique seems to be less sound than the other two, because of the large downward vertical velocity that it produces at the instant of the start of the takeoff phase.

Orientation of the takeoff foot and potential for ankle and foot injuries

At the end of the run-up, the high jumper's COM is moving at an angle p_1 with respect to the bar (see 'Approach angles' above). During the takeoff phase, the athlete pushes on the ground vertically downwards, and also horizontally. The horizontal force that the foot makes on the ground during the takeoff phase points forwards, almost in line with the final

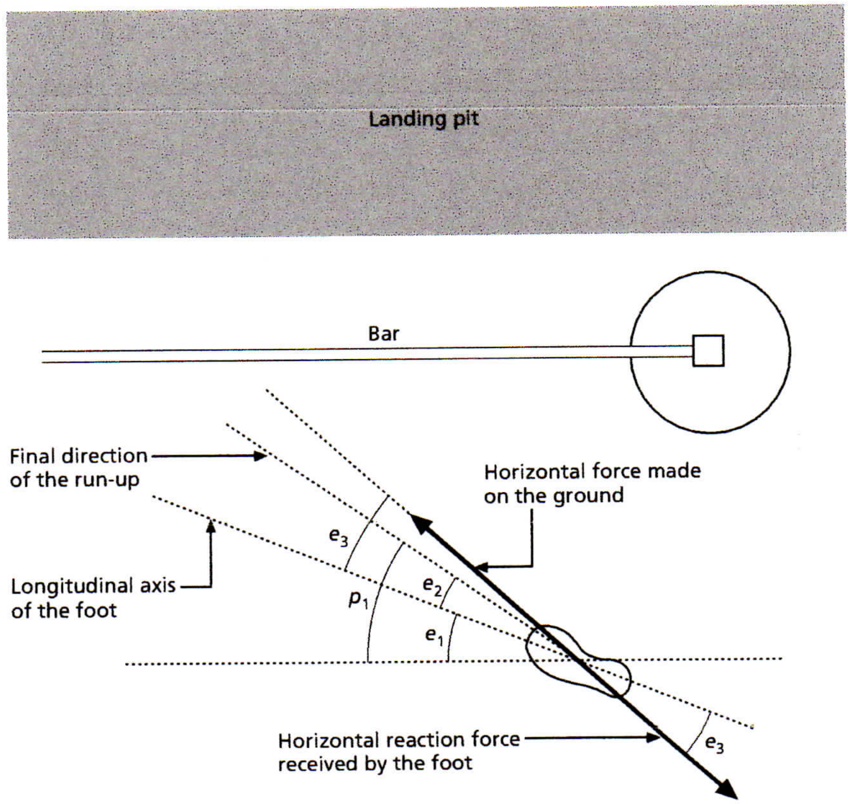

Fig. 14.6 Angles of foot, of run-up direction, and of horizontal force (see text).

direction of the run-up, but usually it is also deviated slightly towards the landing pit (see Fig. 14.6).

Most high jumpers plant the takeoff foot on the ground with its longitudinal axis pointing in a direction that generally is not aligned with the final direction of the run-up nor with the horizontal force that the athlete is about to make on the ground: It is more parallel to the bar than either one of them. Since the horizontal reaction force that the foot receives from the ground is not aligned with the longitudinal axis of the foot, the force tends to make the foot roll inwards. (See the sequence in Fig. 14.7, obtained from a high-speed videotape taken during the 1988 International Golden High Jump Gala competition in Genk, Belgium—courtesy of B. Van Gheluwe.) In anatomical terminology, this rotation is called 'pronation of the ankle joint'. It stretches the medial side of the joint, and produces compression in the lateral side of the joint. If the pronation is very severe, it can lead to injury of the ankle. It also means that the foot becomes supported less by its outside edge, and more by the longitudinal (forward–backward) arch on the medial side of the foot. According to Krahl and Knebel (1979), this can lead to injury of the foot itself.

Pronation of the ankle joint occurs in the takeoffs of many high jumpers. However, it is difficult to see without a very magnified image of the foot. Because of this, pronation of the ankle joint generally is not visible in our standard films or videotapes of high-jumping competitions (and therefore it does not show in our computer graphics sequences either). This does not mean that there is no ankle pronation; we just cannot see it.

In an effort to diagnose the risk of ankle and foot injury for each high jumper, we measure angles e_1 (the angle between the longitudinal axis of the foot and the bar), e_2 (between the longitudinal axis of the foot and the final direction of the run-up) and e_3 (between the longitudinal axis of the foot and the horizontal force) in each jump (see Fig. 14.6). The values of these angles are reported in Table 14.2. For diagnosing the risk of injury, e_3 is the most important angle. Although the safety limit is not known

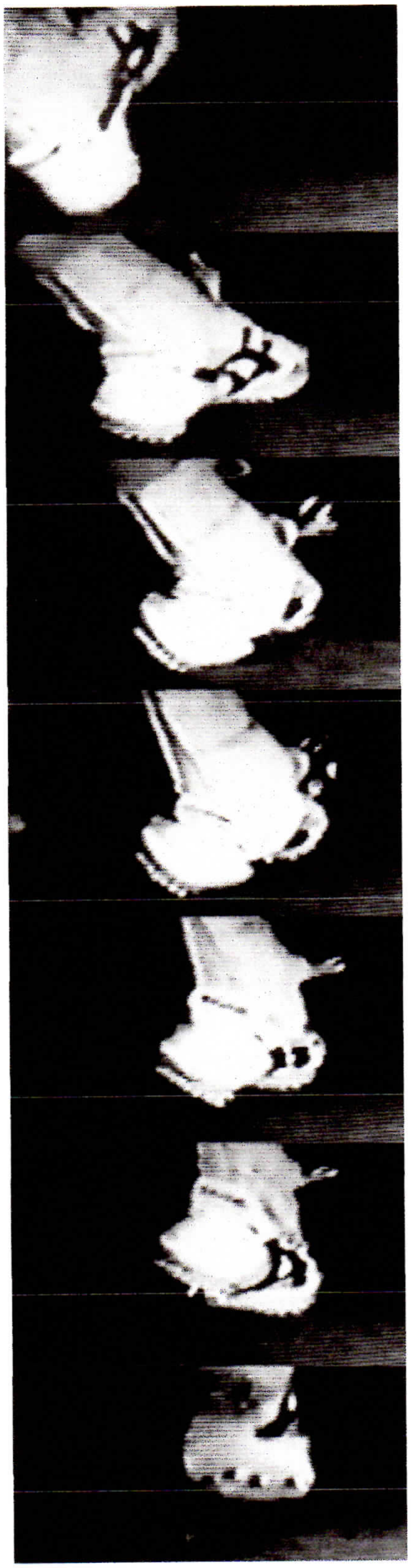

Fig. 14.7 Ankle pronation during the takeoff phase. (Videotape courtesy of B. Van Gheluwe.)

with certainty at this time, anecdotal evidence suggests that e_3 values smaller than 20° are reasonably safe, values between 20 and 25° are somewhat risky, and values larger than 25° are dangerous.

Trunk lean

Figure 14.8 shows BFTD, BFTO, LRTD and LRTO, the backward/forward and left/right angles of lean of the trunk at the start and the end of the takeoff phase, respectively. The values of these angles are given in Table 14.4. The trunk normally has a backward lean at the start of the takeoff phase (BFTD). Then it rotates forwards, and by the end of the takeoff it is close to vertical, and sometimes past the vertical (BFTO). Due to the curved run-up, the trunk normally has also a lateral lean towards the centre of the curve at the start of the takeoff phase (LRTD). During the takeoff phase, the trunk rotates towards the right (towards the left in athletes who take off from the right foot), and by the end of the takeoff it is usually somewhat beyond the vertical (LRTO)—up to 10° beyond the vertical (LRTO = 100°) may be considered normal. Table 14.4 also shows the values of ΔBF and ΔLR. These are the changes that occur during the takeoff phase in the backward/forward and left/right angles of tilt of the trunk, respectively.

Statistical information (Dapena, unpublished observations) shows a relationship of the trunk lean angles with the vertical velocity of the athlete at the end of the takeoff phase, and consequently with the peak height of the COM. If two athletes have similar run-up speed, height of the COM at the end of the run-up and arm actions during the takeoff phase (see below), the athlete with smaller BFTD, ΔBF, LRTD and ΔLR values generally obtains a larger vertical velocity by the end of the takeoff phase. This means that athletes with greater backward lean at the start of the takeoff phase and greater lateral lean towards the centre of the curve at the start of the takeoff phase tend to jump higher. Also, for a given amount of backward lean at the start of the takeoff phase, the athletes who experience smaller changes in this angle during the takeoff phase generally jump higher, and for a given amount of lateral lean at the start of the takeoff phase, the athletes who

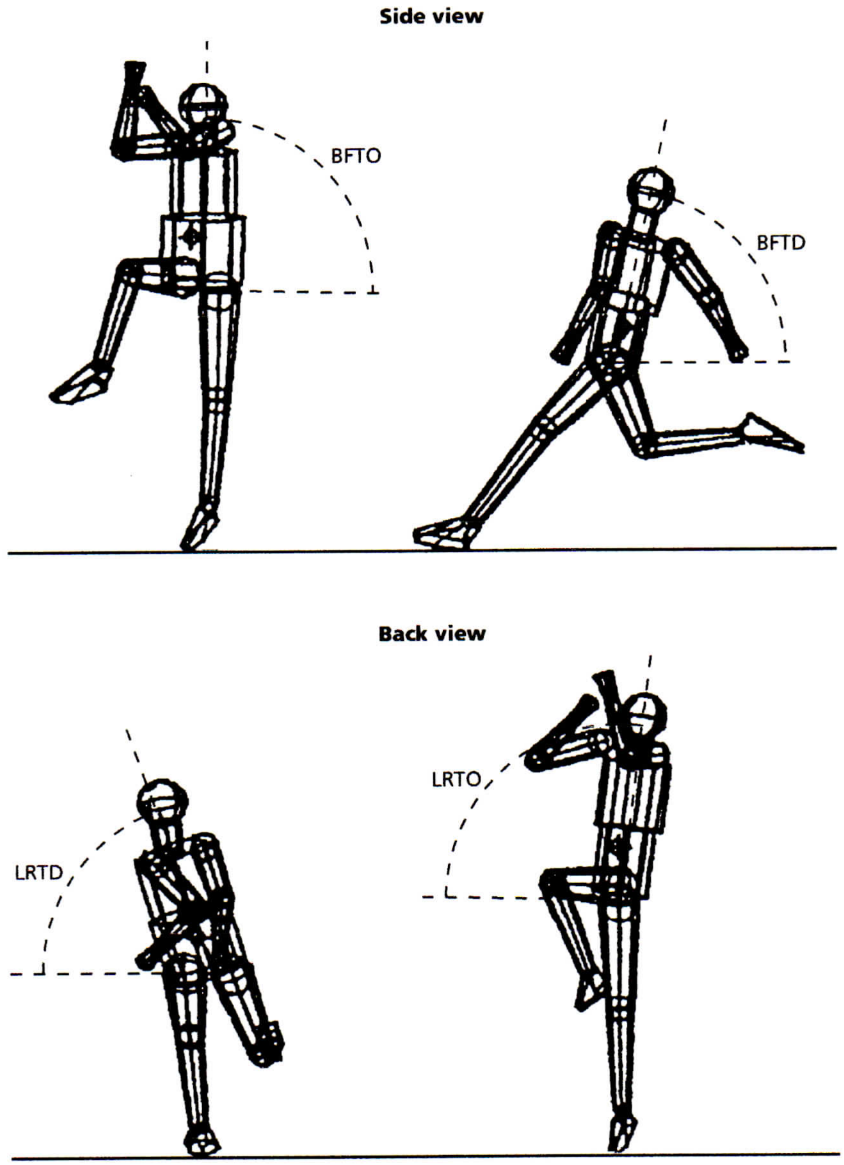

Fig. 14.8 Backward/forward (BF) and left/right (LR) tilt angles of the trunk at the start (TD) and at the end (TO) of the takeoff phase.

experience smaller changes in this angle during the takeoff phase also tend to jump higher.

However, before jumping to conclusions and deciding that all high jumpers should lean backwards and laterally as much as possible at the start of the takeoff phase, and then change those angles of lean as little as possible during the takeoff phase itself, it is necessary to take two points into consideration. Firstly, small values of BFTD, ΔBF, LRTD and ΔLR are not only statistically associated with larger vertical velocities at the end of the takeoff phase (which is good), but also with less angular momentum (see below), and therefore with a less effective rotation during the bar clearance.

Also, we cannot be completely certain that small values of BFTD, ΔBF, LRTD and ΔLR *produce* a takeoff that generates a larger amount of vertical velocity and therefore a higher peak height for the COM We do not understand well the cause–effect mechanisms behind the statistical relationships, and it is possible to offer alternative explanations, such as the following. Weaker athletes are not able to generate much lift, mainly because they are weak. Therefore, they are not able to jump very high. This

Table 14.4 Angles of tilt of the trunk [backward/forward at the start of the takeoff phase (BFTD) and at the end of the takeoff phase (BFTO) and the change in this angle during the takeoff phase (ΔBF); left/right at the start of the takeoff phase (LRTD) and at the end of the takeoff phase (LRTO), and the change in this angle during the takeoff phase (ΔLR)], activeness of the arm nearest to the bar (AAN) and of the arm farthest from the bar (AAF), summed activeness of the two arms (AAT), activeness of the lead leg (LLA), and summed activeness of the three free limbs (FLA).

Athlete	BFTD (°)	BFTO (°)	ΔBF (°)	LRTD (°)	LRTO (°)	ΔLR (°)	AAN ($mm \cdot m^{-1}$)	AAF ($mm \cdot m^{-1}$)	AAT ($mm \cdot m^{-1}$)	LLA ($mm \cdot m^{-1}$)	FLA ($mm \cdot m^{-1}$)
Men											
Avdeyenko	71	92	21	76	104	28	4.3	10.5	14.8	24.0	38.7
Conway	76	83	7	79	95	16	6.7	12.2	18.9	21.2	40.2
Forsyth	71	86	15	76	104	28	10.0	10.7	20.8	24.9	45.6
Paklin	77	81	5	77	99	22	5.3	8.9	14.2	14.1	28.2
Partyka	75	89	14	76	92	16	3.3	7.1	10.4	15.4	25.8
Sjöberg	74	88	15	75	98	23	6.7	10.0	16.7	18.7	35.4
Sotomayor	71	77	5	79	101	22	5.9	10.8	16.7	24.5	41.2
Stones	74	90	16	73	91	19	3.4	8.3	11.7	18.3	30.0
Zvara	68	83	15	77	95	18	9.0	13.3	22.3	41.7	64.0
Women											
Acuff	73	87	14	78	92	14	0.5	7.1	7.5	19.1	26.6
Astafei	77	82	5	84	102	18	3.6	6.6	10.2	13.5	23.7
Beyer-Helm	79	94	15	74	96	23	2.3	7.0	9.3	15.6	24.9
Dragieva	76	82	6	80	92	12	1.3	7.3	8.5	21.8	30.4
Henkel	82	90	8	75	97	22	5.9	8.3	14.2	19.3	33.4
Kostadinova	73	84	12	77	93	17	−0.4	6.2	5.8	21.0	26.8
Quintero	73	91	18	79	104	26	4.4	10.0	14.4	18.2	32.7
Sommer	80	90	10	81	99	18	2.2	4.9	7.1	17.8	24.9

Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

makes them reach the peak of the jump relatively soon after takeoff. Consequently, they will want to rotate faster in the air to reach a normal horizontal layout position at the peak of the jump. For this, they will generate more angular momentum during the takeoff, which in turn will require larger values of BFTD, ΔBF, LRTD and ΔLR. We cannot be sure which interpretation is the correct one: does the trunk tilt affect the height of the jump, or does the weakness of the athlete affect the height of the jump and (indirectly) the trunk tilt? Or are both explanations partly correct? At this point, we do not know for sure.

Arm and lead leg actions

The actions of the arms and of the lead leg during the takeoff phase are important for the outcome of the jump. As these free limbs are accelerated upwards during the takeoff phase, they exert by reaction a compressive force downwards on the trunk. This helps the takeoff leg to exert a larger force on the ground. The increased downward vertical force exerted on the ground evokes by reaction an increased upward vertical force exerted by the ground on the athlete. This produces a larger vertical velocity of the COM of the athlete by the end of the takeoff phase, and consequently a higher jump.

There is no perfect way to measure how active the arms and the lead leg are during the takeoff phase of a high jump. Currently, we express arm activeness as the vertical range of motion of the COM of each arm during the takeoff phase (relative to the upper end of the trunk), multiplied by the fraction of the whole body mass that corresponds to the arm, and divided by the standing height of the subject. The activeness of the lead leg is similarly measured as the vertical range of motion of the COM of the lead leg during the takeoff phase (relative to the lower end of the trunk), multiplied by the fraction of the whole body mass that corresponds to the lead leg, and divided by the standing height of the subject. In effect, this means that the activeness of each free limb is expressed as the number of millimetres contributed by the limb motion to the lifting of the COM of the whole body during the takeoff phase, per metre of standing height. Defined in this way, the activeness of each free limb takes into account the limb's mass, its average vertical velocity during the takeoff phase, and the duration of this vertical motion. It allows the comparison of one jumper with another, and also direct comparison of the lead leg action with the arm actions.

Table 14.4 shows the activeness of the arm nearest to the bar (AAN) and of the arm farthest from the bar (AAF), the summed activeness of the two arms

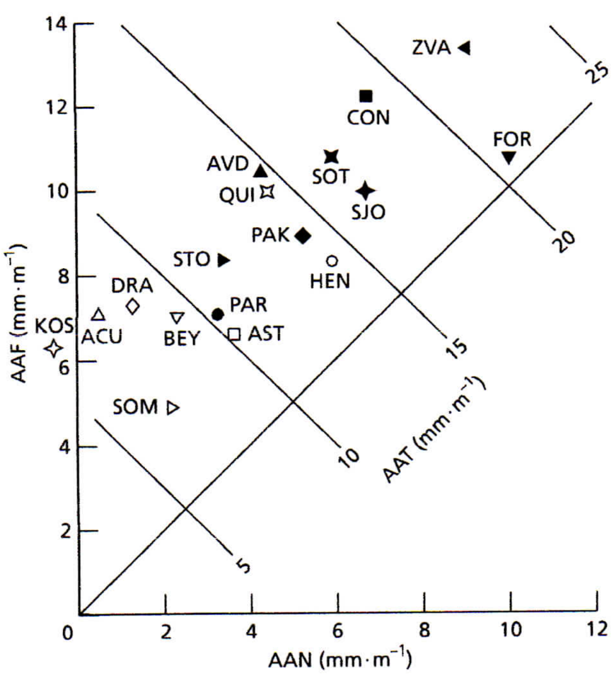

Fig. 14.9 Activeness of the arm nearest to the bar (AAN), of the arm farthest from the bar (AAF), and combined activeness of both arms (AAT).

(AAT), the activeness of the lead leg (LLA) and the combined activeness of all three free limbs (FLA). Larger values indicate greater activeness of the limbs during the takeoff.

Figure 14.9 shows a plot of AAF vs. AAN for the sample jumps. The ideal is to be as far to the right and as high up as possible on the graph, as this gives the largest values for the total arm action, AAT, also shown in the graph.

For a good arm action, both arms should swing strongly forwards and upwards during the takeoff phase. They should not be too flexed at the elbow during the swing—a good elbow angle seems to be somewhere between full extension and 90° of flexion.

The diagonal line going from lower left to upper right in Fig. 14.9 indicates the points for which both arms would have equal activeness. The positions of the points above the diagonal line reflect a well-established fact: high jumpers are generally more active with the arm that is farthest from the bar.

Some high jumpers (including many women) fail to prepare their arms correctly in the last steps of the run-up, and at the beginning of the takeoff phase the arm nearest to the bar is ahead of the body instead of behind it. From this position the arm is not able to swing strongly forwards and upwards during the takeoff, and these jumpers usually end up with small (or even negative) AAN values. These athletes should learn to bring both arms back in the final one or two steps of the run-up, so that both arms can later swing hard forwards and up during the takeoff phase. Learning this kind of arm action will take some time and effort, but it should produce a higher jump. If an athlete is unable to prepare the arms for a double-arm action, the forward arm should be in a low position at the start of the takeoff phase. That way, it can be thrown upwards during the takeoff, although usually not quite as hard as with a double-arm action.

Figure 14.10 shows a plot of LLA vs. AAT for the trials in the sample. The ideal is to be as far to the right and as high up as possible on the graph, as this gives the largest values for the total free limb action, FLA, also shown in the graph.

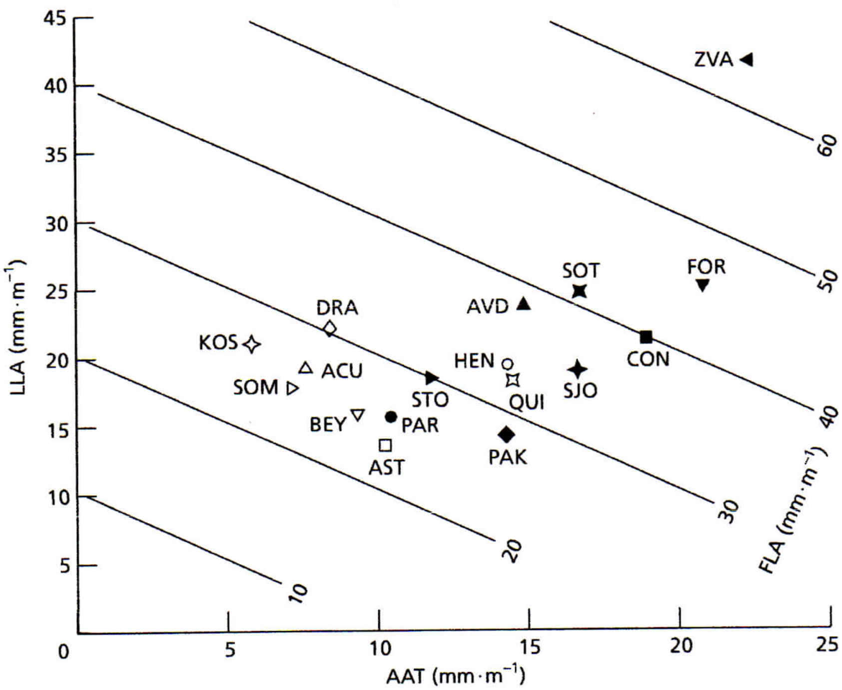

Fig. 14.10 Combined activeness of both arms (AAT), activeness of the lead leg (LLA), and total activeness of the free limbs (FLA).

Takeoff time

The duration of the takeoff phase (T_{TO}) is shown in Table 14.5. (Due to the slow camera speeds used, the value of T_{TO} can easily be in error by 0.01 s, and sometimes by as much as 0.02 s.) This 'takeoff time' is influenced by a series of factors. Some of them are beneficial for the jump; others are detrimental. Short takeoff times go together with a strong action of the takeoff leg (good), but also with weak arm actions and with a high COM position at the start of the takeoff phase (bad). In summary, takeoff times are informative, but the length of the takeoff time by itself does not necessarily indicate good or bad technique.

Change in horizontal velocity during the takeoff phase

It was explained before that the athlete should have a large horizontal velocity at the instant immediately before the takeoff foot is planted on the ground to start the takeoff phase, and that therefore no horizontal velocity should be lost before that instant. However, the horizontal velocity should be reduced considerably during the takeoff phase itself. The losses of horizontal velocity that all high jumpers experience during the takeoff phase (see Δv_H in Table 14.3) are due to the fact that the jumper pushes forwards on the ground during the takeoff phase, and therefore receives a backward reaction force from the ground. These losses of horizontal velocity during the takeoff phase are an intrinsic part of the takeoff process, and they are associated with the generation of vertical velocity. If an athlete does not lose much horizontal velocity during the takeoff phase, this may be a sign that the athlete is not making good use of the horizontal velocity obtained during the run-up. We could say that the athlete should produce a lot of horizontal velocity during the run-up so that it can then be lost during the takeoff phase while the athlete obtains vertical velocity. If not enough horizontal velocity is produced during the run-up, or not enough is lost during the takeoff, the run-up is not being used appropriately to help the athlete to jump higher.

Table 14.5 Takeoff time (T_{TO}), height of the bar (h_{BAR}), maximum height of the centre of mass (COM) (h_{PK}), clearance height in the plane of the standards (h_{CLS}), absolute clearance height (h_{CLA}), effectiveness of the bar clearance in the plane of the standards (Δh_{CLS}), and absolute effectiveness of the bar clearance (Δh_{CLA}); twisting angular momentum (H_T), forward somersaulting angular momentum (H_F), lateral somersaulting angular momentum (H_L) and total somersaulting angular momentum (H_S) during the airborne phase.

Athlete	T_{TO} (s)	h_{BAR} (m)	h_{PK} (m)	h_{CLS} (m)	h_{CLA} (m)	Δh_{CLS} (m)	Δh_{CLA} (m)	H_T (*)	H_F (*)	H_L (*)	H_S (*)
Men											
Avdeyenko	0.21	2.38	2.46	2.41	2.42	−0.05	−0.04	40	75	80	110
Conway	0.18	2.34	2.41	2.33	2.35	−0.08	−0.06	45	40	85	90
Forsyth	0.17	2.34	2.44	2.35	2.39	−0.09	−0.05	45	60	80	100
Paklin	0.20	2.38	2.41	2.40	2.41	−0.01	0.00	45	75	80	110
Partyka	0.15	2.34	2.39	2.36	2.36	−0.03	−0.03	40	80	90	120
Sjöberg	0.16	2.34	2.33	2.35	2.35	0.02	0.02	40	70	85	110
Sotomayor	0.17	2.34	2.44	2.36	2.39	−0.08	−0.05	60	5	100	100
Stones	0.17	2.34	2.36	2.29	2.29	−0.07	−0.07	35	60	85	105
Zvara	0.23	2.34	2.46	2.36	2.36	−0.10	−0.10	75	50	80	95
Women											
Acuff	0.18	1.96	2.07	1.97	1.97	−0.10	−0.10	30	95	80	125
Astafei	0.15	2.00	2.09	2.00	2.01	−0.09	−0.08	50	35	90	100
Beyer-Helm	0.16	1.97	2.06	2.00	2.03	−0.06	−0.03	45	80	85	115
Dragieva	0.15	2.00	2.06	2.00	2.00	−0.06	−0.06	40	95	70	115
Henkel	0.14	2.02	2.06	2.05	2.05	−0.01	−0.01	45	80	85	120
Kostadinova	0.14	2.05	2.09	2.09	2.09	0.00	0.00	60	90	100	135
Quintero	0.17	1.97	2.04	1.97	1.97	−0.07	−0.07	40	55	90	105
Sommer	0.14	1.96	1.99	1.94	1.95	−0.05	−0.04	45	105	85	130

Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.
* Angular momentum units: $s^{-1} \times 10^{-3}$.

Height and vertical velocity of the COM at the end of the takeoff phase

The peak height that the COM will reach over the bar is completely determined by the end of the takeoff phase. It is determined by the height and the vertical velocity of the COM at the end of the takeoff phase.

At the instant that the takeoff foot loses contact with the ground, the COM of a high jumper is usually at a height somewhere between 68% and 73% of the standing height of the athlete. This means that tall high jumpers have a built-in advantage: their centres of gravity will generally be higher at the instant that they leave the ground.

The vertical velocity of the COM at the end of the takeoff phase (v_{ZTO}, shown in Table 14.3) determines how much higher the COM will travel beyond the takeoff height after the athlete leaves the ground.

Height of the bar, peak height of the COM, and clearance height

The height of the bar (h_{BAR}) and the maximum height reached by the COM (h_{PK}) are shown in Table 14.5. All of the jumps shown here were successful clearances.

The true value of a high jump generally is not known: If the bar is knocked down, the jump is ruled a foul and the athlete gets zero credit, even though a hypothetical bar set at a lower height would have been cleared successfully; if the bar stays up, the athlete is credited with the height at which the bar was set, ignoring whether the jumper

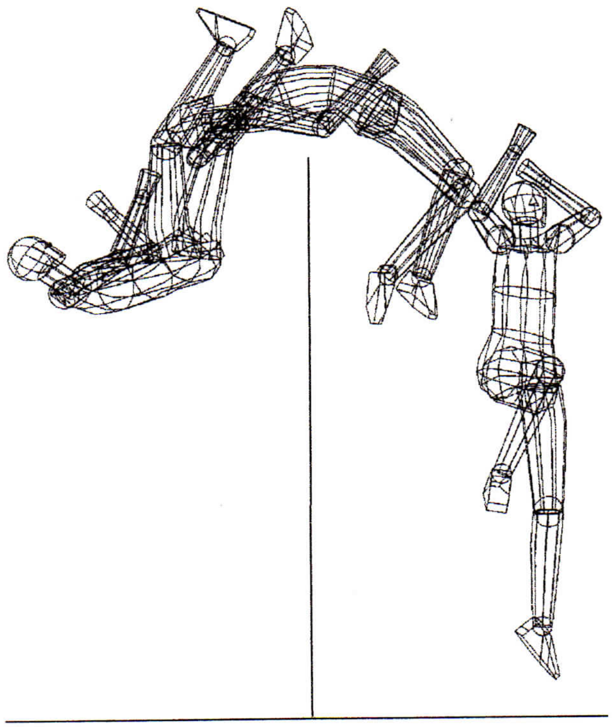

Fig. 14.11 Three images of a bar clearance.

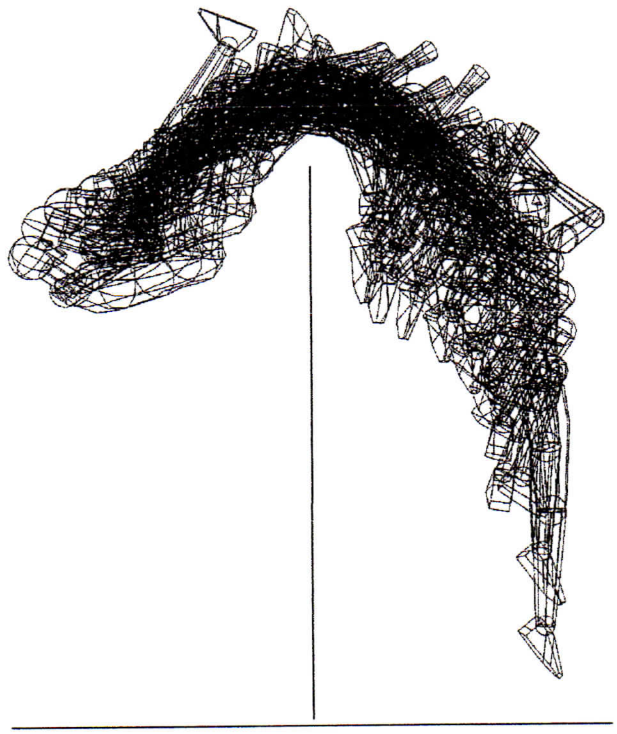

Fig. 14.12 All the images of a bar clearance available from film analysis.

had room to spare over it or whether the jumper depressed the bar during the clearance.

Using computer modelling and graphics, it is possible to estimate the approximate maximum height that an athlete would have been able to clear cleanly without touching the bar in a given jump ('clearance height'), regardless of whether the actual jump was officially a valid clearance or a foul. Figure 14.11 shows three images of a high jumper's clearance of a bar set at 2.25 m. Figure 14.12 shows all the images obtained through film analysis of the bar clearance. In Fig. 14.13 the drawing has been saturated with intermediate positions of the high jumper, calculated through a process called curvilinear interpolation. The scale in the 'saturation drawing' shows that in this jump the athlete would have been able to clear a bar set in the plane of the standards at a height of 2.34 m (h_{CLS}) without touching it. A closer examination of Fig. 14.13 also shows that the maximum height of the 'hollow' area below the body was not perfectly centred over the bar: If this athlete had taken off closer to the plane of the standards, he would have been able to clear a bar set at an absolute maximum height of 2.35 m (h_{CLA}) without touching it.

Due to errors in the measurements taken from the films or videotapes, in the thicknesses of the various body segments of the computer graphics model and in the degree of curvature of the trunk in the drawings, the value of the clearance height in the plane of the standards (h_{CLS}) and the value of the absolute clearance height (h_{CLA}) obtained using this method are not perfectly accurate. A test showed that the true value of h_{CLS} will be over- or underestimated on average by between 0.02 m and 0.03 m. Therefore, the calculated clearance height values should be considered only rough estimates. Another point to consider is that high jumpers can generally depress the fibreglass bar by about 0.02 m (and sometimes by as much as 0.04 or even 0.06 m) without knocking it down.

Table 14.5 shows the maximum height that the athlete would have been able to clear without touching the bar in the plane of the standards (h_{CLS})

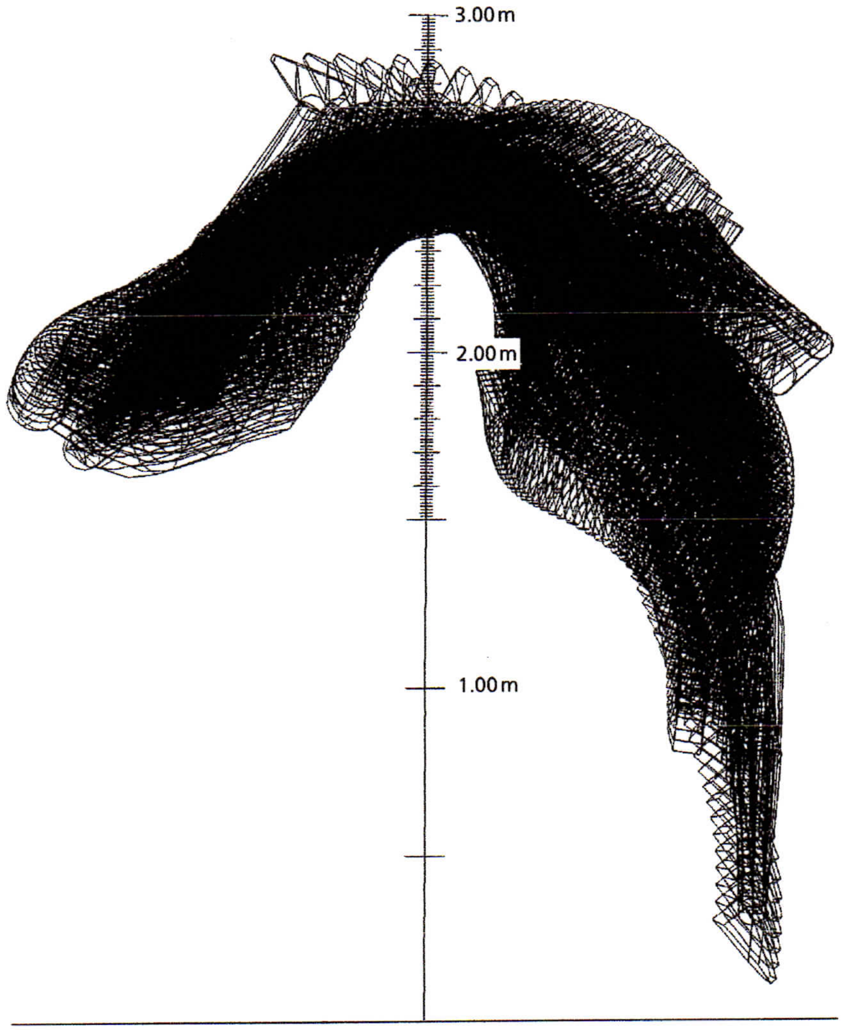

Fig. 14.13 Graph of a bar clearance produced through saturation with interpolated images.

and the absolute maximum height that the athlete would have been able to clear without touching the bar (h_{CLA}).

The differences between the clearance heights and the peak height of the COM indicate the effectiveness of the bar clearance in the plane of the standards ($\Delta h_{CLS} = h_{CLS} - h_{PK}$) and the absolute effectiveness of the bar clearance ($\Delta h_{CLA} = h_{CLA} - h_{PK}$). Table 14.5 shows their values in the sample trials. Larger negative numbers indicate less effective bar clearances.

The main reasons for an ineffective bar clearance are: taking off too close or too far from the bar, insufficient amount of somersaulting angular momentum, insufficient twist rotation, poor arching, and bad timing of the arching/un-arching process. These aspects of high jumping technique will be discussed next.

Takeoff distance

The distance between the toe of the takeoff foot and the plane of the bar and the standards is called the 'takeoff distance' (TOD in Fig. 14.2). The value of this distance is shown in Table 14.2, and it is important because it determines the position of the peak of the jump relative to the bar: If an athlete takes off too far from the bar, the COM will reach its maximum height before crossing the plane of the standards, and the jumper will probably fall on the bar; if the athlete takes off too close to the bar, there will be a large risk of hitting the bar while the COM is on the way up, before reaching its maximum height. Different athletes usually need different takeoff distances. The optimum value for the takeoff distance of each athlete is the one that will make the COM of the jumper reach its maximum height more or less directly over the bar, and it will depend primarily on the final direction of the run-up and on the amount of residual horizontal velocity that the athlete has left after the completion of the takeoff phase.

In general, athletes who travel more perpendicular to the bar in the final steps of the run-up (indicated by large p_2 and p_1 angles in Table 14.2) will also travel more perpendicular to the bar after the completion of the takeoff phase (indicated by large p_0 angles in Table 14.2), and they will need to take off farther from the bar. In general, athletes who run faster in the final steps of the run-up (indicated by large values of v_{H2} and v_{H1} in Table 14.3) will also have more horizontal velocity left after takeoff (indicated by large values of v_{HTO} in Table 14.3); thus, they will travel through larger horizontal distances after the completion of the takeoff than slower jumpers, and they will also need to take off farther from the bar in order for the COM to reach its maximum height more or less directly over the bar.

High jumpers need to be able to judge after a miss whether the takeoff point might have been too close or too far from the bar. This can be done by paying attention to the time when the bar was hit. If the bar was hit a long time after the takeoff, this probably means that the bar was hit as the athlete was coming down from the peak of the jump, implying that the athlete took off too far from the bar, and in that case the athlete should move the starting point of the run-up slightly closer to the bar; if the bar was hit very soon after takeoff, this probably means that the bar was hit while the athlete was still on the way up towards the peak of the jump, implying that the takeoff point was too close to the bar, and in that case the athlete should move the starting point of the run-up slightly farther from the bar.

Angular momentum

Angular momentum (or 'rotary momentum') is a mechanical factor that makes the athlete rotate. High jumpers need the right amount of angular momentum to make in the air the rotations necessary for a proper bar clearance. The athlete obtains the angular momentum during the takeoff phase, through the forces that the takeoff foot makes on the ground; the angular momentum cannot be changed after the athlete leaves the ground.

The bar clearance technique of a Fosbury-flop can be described roughly as a twisting somersault. To a great extent, the twist rotation (which makes the athlete turn his or her back to the bar during the ascending part of the flight path) is generated by swinging the lead leg up and somewhat away from the bar during the takeoff, and also by actively turning the shoulders and arms during the takeoff in the desired direction of the twist. These actions create angular momentum about a vertical axis. This is called the twisting angular momentum, H_T. The H_T values of the analysed athletes are shown in Table 14.5. (To facilitate comparisons among athletes, the angular momentum values have been normalized for the mass and standing height of each athlete.) Most high jumpers have no difficulty obtaining an appropriate amount of H_T. (However, we will see later that the actions that the athlete makes in the air, as well as other factors, can also significantly affect whether the high jumper will be perfectly face-up at the peak of the jump, or tilted to one side with one hip lower than the other.)

The somersault rotation, which will make the shoulders go down while the knees go up, results from two components: a forward somersaulting component and a lateral somersaulting component.

Forward somersaulting angular momentum (H_F)

During the takeoff phase, the athlete produces angular momentum about a horizontal axis perpendicular to the final direction of the run-up (see Fig. 14.14a and the sequence at the top of Fig. 14.15). This forward rotation is similar to the one produced when a person hops off from a moving bus facing the direction of motion of the bus: After the feet hit the ground, the tendency is to rotate forward and fall flat on one's face. It can be described as angular momentum produced by the checking of a linear motion.

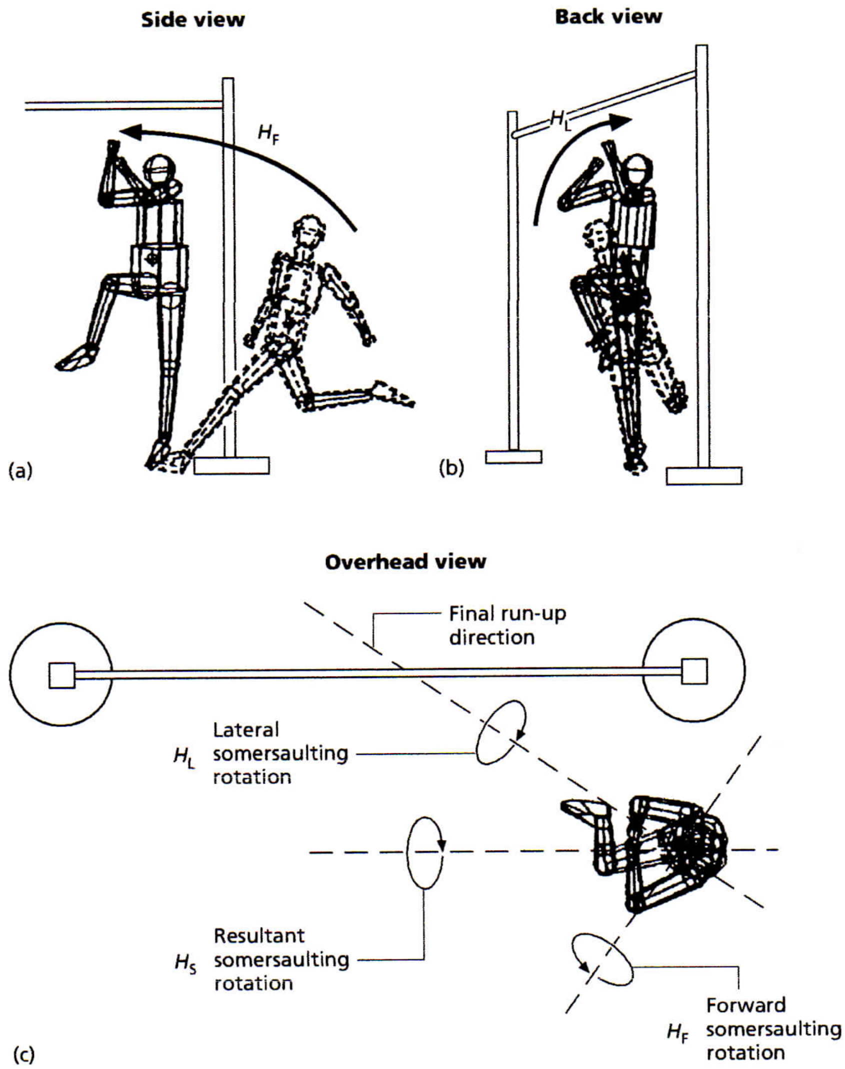

Fig. 14.14 (a) Forward somersaulting angular momentum; (b) lateral somersaulting angular momentum; (c) resultant somersaulting angular momentum.

The tilt angles of the trunk at the start and at the end of the takeoff phase (see 'Trunk lean' above) are statistically related to the angular momentum obtained by the athlete (J. Dapena, unpublished observations). Large changes of the trunk tilt from a backward position towards vertical during the takeoff phase are associated with a larger amount of forward somersaulting angular momentum. This makes sense, because athletes with a large amount of forward somersaulting angular momentum at the end of the takeoff phase should also be expected to have a large amount of it already during the takeoff phase, and this should contribute to a larger forward rotation of the body in general and of the trunk during the takeoff phase.

Statistics show that jumpers with a very large backward lean at the start of the takeoff phase (small BFTD angles) do not get quite as much forward somersaulting angular momentum as other jumpers. The reasons for this are not completely clear.

The forward somersaulting angular momentum can also be affected by the actions of the arms and lead leg. Wide swings of the arms and of the lead leg during the takeoff can help the athlete to jump higher (see 'Arm and lead leg actions' above). However, in a view from the side (top sequence in Fig. 14.16) they also imply backward (clockwise) rotations of these limbs, which can reduce the total forward somersaulting angular momentum of the body.

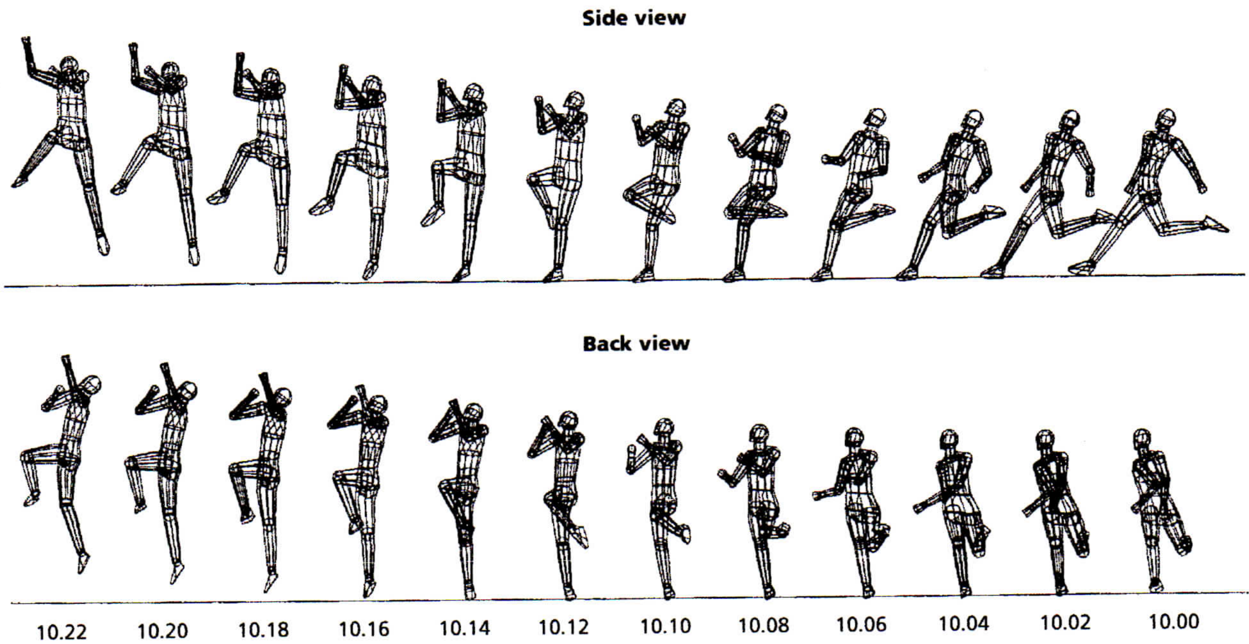

Fig. 14.15 Side and back views of the takeoff of a standard jump. To facilitate the comparison of one jump with another, the value $t = 10.00$ s is arbitrarily assigned in all jumps to the instant at which the takeoff foot first makes contact with the ground to start the takeoff phase.

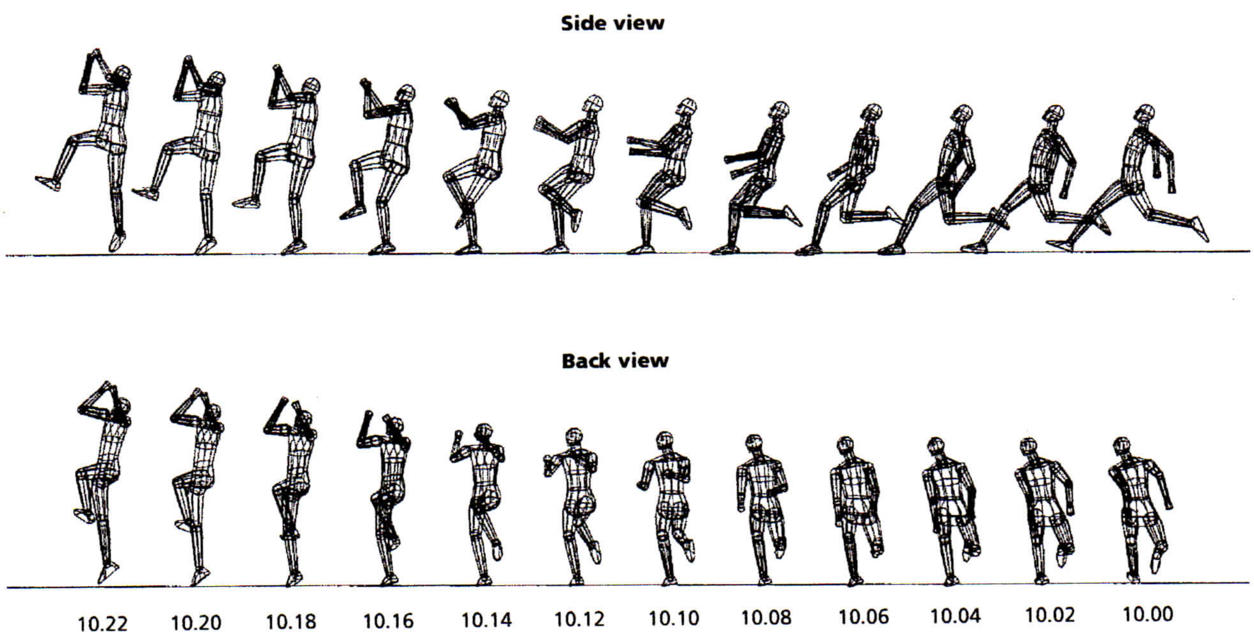

Fig. 14.16 Side and back views of the takeoff of a jump with direct forward arm swing.

To lessen this problem, some high jumpers turn their back partly towards the bar in the last step of the run-up, and then swing the arms diagonally forwards and away from the bar during the takeoff phase (see Fig. 14.17). Since this diagonal arm swing is not a perfect backward rotation, it interferes less with the generation of forward somersaulting angular momentum.

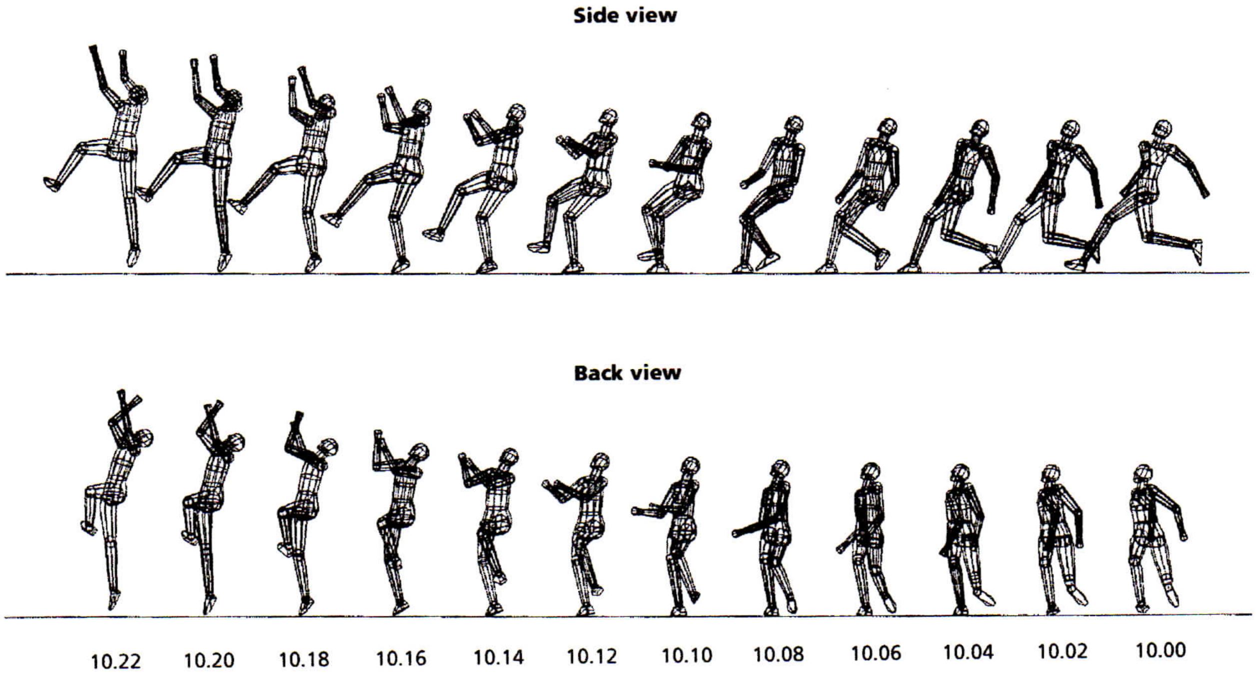

Fig. 14.17 Side and back views of the takeoff of a jump with diagonal arm swing.

Lateral somersaulting angular momentum (H_L)

During the takeoff phase, angular momentum is also produced about a horizontal axis in line with the final direction of the run-up (see Fig. 14.14b and the bottom sequence in Fig. 14.15). In a rear view of an athlete who takes off from the left leg, this angular momentum component appears as a clockwise rotation.

If the jumper made use of a straight run-up, in a rear view the athlete would be upright at touchdown, and leaning towards the bar at the end of the takeoff. Since a leaning position would result in a lower height of the COM at the end of the takeoff phase, the production of angular momentum would thus cause a reduction in the vertical range of motion of the COM during the takeoff phase. However, if the athlete uses a curved run-up, the initial lean of the athlete to the left at the end of the approach run may allow the athlete to be upright at the end of the takeoff phase (see Fig. 14.14b and the bottom sequence in Fig. 14.15). The final upright position contributes to a higher COM position at the end of the takeoff phase. Also, the initial lateral tilt contributes to a lower COM position at the start of the takeoff phase. Therefore the curved run-up, together with the generation of lateral somersaulting angular momentum, contributes to increase the vertical range of motion of the COM during the takeoff phase, and thus permits greater lift than if a straight run-up were used. (However, some caution is necessary here, since statistical information suggests that jumpers with an excessive lean towards the centre of the curve at the start of the takeoff phase tend to generate a smaller amount of lateral somersaulting angular momentum than jumpers with a more moderate lean. The reasons for this are not clear.)

There is some statistical association between large changes in the left/right tilt angle of the trunk during the takeoff phase and large amounts of lateral somersaulting angular momentum at the end of the takeoff phase (J. Dapena, unpublished observations). This makes sense, because athletes with a large amount of lateral somersaulting angular momentum at the end of the takeoff phase should also be expected to have a large amount of it already during the takeoff phase, which should contribute to a larger rotation of the trunk during the takeoff phase from its initial lateral tilted position toward the vertical.

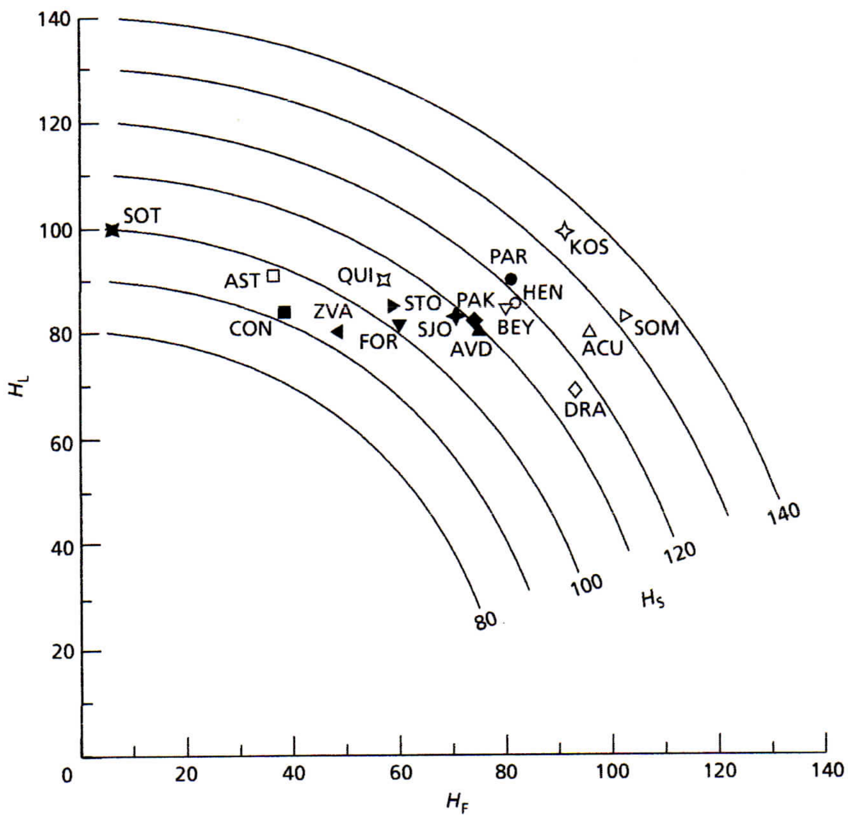

Fig. 14.18 Forward (H_F), lateral (H_L) and total (H_S) somersaulting angular momentum.

The reader should be reminded at this point that although large changes in tilt during the takeoff phase and, to a certain extent, small backward and lateral leans of the trunk at the start of the takeoff phase (i.e. large BFTD and LRTD values) are associated with increased angular momentum, they are also statistically associated with reduced vertical velocity at the end of the takeoff phase, and therefore with a reduced maximum height of the COM at the peak of the jump. This supports the intuitive feeling of high jumpers that it is necessary to seek a compromise between the generation of lift and the generation of rotation.

The bottom sequence in Fig. 14.17 shows that in an athlete who takes off from the left leg a diagonal arm swing is associated with a clockwise motion of the arms in a view from the back, and therefore it contributes to the generation of lateral somersaulting angular momentum.

High jumpers usually have more lateral than forward somersaulting angular momentum. The sum of these two angular momentum components adds up to the required total (or 'resultant') somersaulting angular momentum, H_S (Fig. 14.14c).

The forward (H_F), lateral (H_L) and total (H_S) somersaulting angular momentum values of the analysed athletes are shown in Table 14.5, and in graphical form in Fig. 14.18. In general, athletes with more angular momentum tend to rotate faster.

Female high jumpers tend to acquire more angular momentum than male high jumpers. This is because the women do not jump quite as high, and therefore they need to rotate faster to compensate for the smaller amount of time available between the takeoff and the peak of the jump.

Adjustments in the air

After the takeoff is completed, the path of the COM is totally determined, and there is nothing that the athlete can do to change it. However, this does not mean that the paths of all parts of the body are determined. What cannot be changed is the path of the point that represents the average position of all the

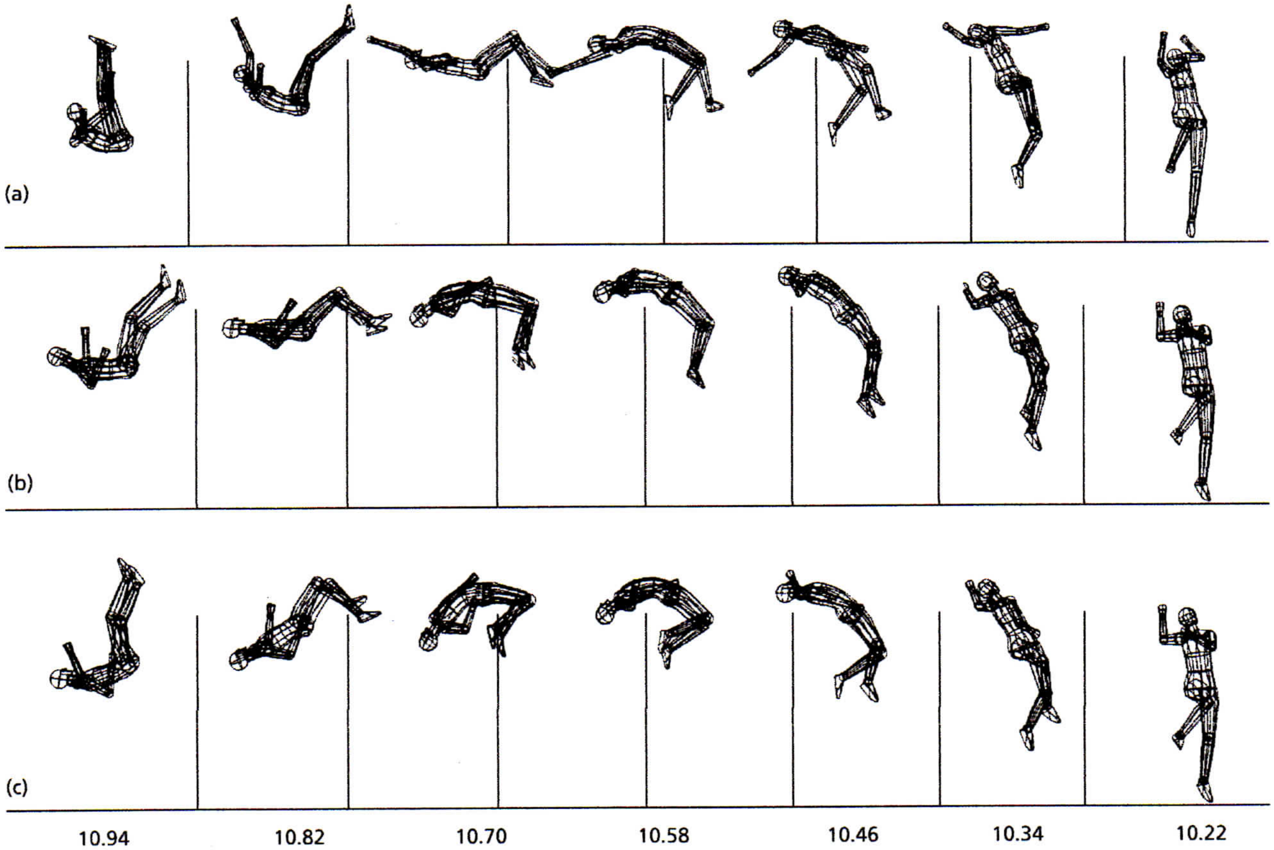

Fig. 14.19 Bar clearance sequences of three jumps (see text).

body parts (the COM), but it is possible to move one part of the body in one direction if other parts are moved in the opposite direction. Using this principle, after the shoulders pass over the bar the high jumper can raise the hips by lowering the head and the legs. For a given position of the COM, the farther the head and the legs are lowered, the higher the hips will be lifted. This is the reason for the arched position on top of the bar.

To a great extent, the rotation of the high jumper in the air is also determined once the takeoff phase is completed, because the angular momentum cannot be changed during the airborne phase. However, some alterations of the rotation are still possible. By slowing down the rotations of some parts of the body, other parts of the body will speed up as a compensation, and vice versa. For instance, the athlete shown in Fig. 14.19a slowed down (and even reversed) the counterclockwise rotation of the takeoff leg shortly after the takeoff phase was completed, by flexing at the knee and extending at the hip ($t = 10.34$–10.58 s). In reaction, this helped the trunk to rotate faster counterclockwise, and therefore contributed to produce the horizontal position of the trunk at $t = 10.58$ s. Later, from $t = 10.58$ to $t = 10.82$ s, the athlete slowed down the counterclockwise rotation of the trunk, and even reversed it into a clockwise rotation; in reaction, the legs simultaneously increased their speed of rotation counterclockwise, and thus cleared the bar ($t = 10.58$–10.82 s).

The principles of action and reaction just described both for translation and rotation result in the typical arching and un-arching actions of high jumpers over the bar. The athlete needs to arch in order to lift the hips, and then to un-arch in order to speed up the rotation of the legs. As the body un-arches, the legs go up, but the hips go down.

Therefore, timing is critical: If the body un-arches too late, the calves will knock the bar down; if the body un-arches too early, the athlete will 'sit' on the bar and will also knock it down.

Another way in which rotation can be changed is by altering the 'moment of inertia'. The moment of inertia is a number that indicates whether the various parts that make up the body are close to the axis of rotation or far from it. When many parts of the body are far from the axis of rotation, the moment of inertia of the body is large, and this decreases the speed of turning about the axis of rotation. Vice versa, if most parts of the body are kept close to the axis of rotation, the moment of inertia is small, and the speed of rotation increases. This is what happens to figure skaters in a view from overhead when they spin: as they bring their arms closer to the vertical axis of rotation, they spin faster about the vertical axis. In high jumping, rotation about a horizontal axis parallel to the bar (i.e. the somersault) is generally more important than rotation about the vertical axis, but the same principle is at work. The jumps shown in Fig. 14.19b and c both had the same amount of somersaulting angular momentum. However, the athlete in Fig. 14.19c somersaulted faster: both jumpers had the same tilt at $t = 10.22$ s, but at $t = 10.94$ s the athlete in Fig. 14.19c had a more backward-rotated position than the athlete in Fig. 14.19b. The faster speed of rotation of the jumper in Fig. 14.19c was due to a more compact body configuration in the period between $t = 10.46$ s and $t = 10.70$ s. It was achieved mainly through a greater flexion of the knees. This configuration of the body reduced the athlete's moment of inertia about an axis parallel to the bar, and made him somersault faster. (The jumps shown in Fig. 14.19b and c were artificial jumps generated using computer simulation. This ensured that the athlete had exactly the same position at takeoff and the same amount of angular momentum in both jumps.)

The technique used by the athlete in Fig. 14.19c can be very helpful for high jumpers with low or moderate amounts of somersaulting angular momentum. Both jumps shown in Fig. 14.19b and c had the same amount of angular momentum ($H_S = 110 \cdot 10^{-3}\ s^{-1}$), and the centre of mass reached a peak height 0.07 m higher than the bar in both jumps. While the athlete in Fig. 14.19b hit the bar with his calves ($t = 10.82$ s), the faster somersault rotation of the athlete in Fig. 14.19c helped him to pass all parts of the body over the bar with some room to spare.

In the rare cases in which a high jumper has a very large amount of angular momentum, the technique shown in Fig. 14.19c could be a liability, because it might accelerate the rotation so much that the shoulders would hit the bar on the way up. For athletes with a very large amount of somersaulting angular momentum, it would be better to keep the legs more extended on the way up to the bar, following the body configuration pattern shown in Fig. 14.19b. This will temporarily slow down the backward somersault, and thus prevent the athlete from hitting the bar with the shoulders on the way up to the bar. (Of course, the athlete will still need to arch and un-arch with good timing over the bar.)

The twist rotation: problems in its execution

It was pointed out earlier that the twist rotation in high jumping is produced to a great extent by the twisting component of angular momentum, H_T. But it was also mentioned that other factors could affect whether the jumper would be perfectly face-up at the peak of the jump, or rotated to one side with one hip lower than the other. One of the most important of these factors is the relative sizes of the forward and lateral components of the somersaulting angular momentum. We will now see how this works.

Figure 14.20 shows sketches of a hypothetical high jumper at the end of the takeoff phase and after three pure somersault rotations in different directions (with no twist), all viewed from overhead. For simplicity, we have assumed that the final direction of the run-up was at a 45° angle with respect to the bar. A normal combination of forward and lateral components of somersaulting angular momentum would produce at the peak of the jump the position shown in Fig. 14.20b, which would require in addition 90° of twist rotation to generate a face-up orientation. If instead an athlete generated only

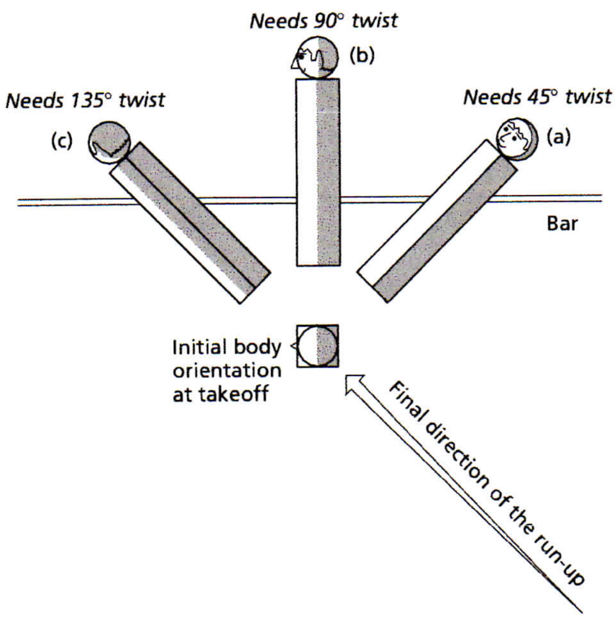

Fig. 14.20 Sketch showing the relationship between the direction of the somersaulting rotation and the amount of twist rotation needed to reach a face-up position at the peak of the jump.

lateral somersaulting angular momentum, the result would be the position shown in Fig. 14.20a, which would require only about 45° of twist rotation to achieve a face-up orientation; if the athlete generated only forward somersaulting angular momentum, the result would be the position shown in Fig. 14.20c, which would require about 135° of twist rotation to achieve a face-up orientation. It is very unusual for high jumpers to have only lateral or forward somersaulting angular momentum, but many jumpers have much larger amounts of one than the other. The example shows that jumpers with particularly large amounts of forward somersaulting angular momentum and small amounts of lateral somersaulting angular momentum will need to twist more in the air if the athlete is to be face-up at the peak of the jump. Otherwise, the body will be tilted, with the hip of the lead leg lower than the hip of the takeoff leg. Conversely, jumpers with particularly large amounts of lateral somersaulting angular momentum and small amounts of forward somersaulting angular momentum will need to twist less in the air than other jumpers in order to be perfectly face-up at the peak of the jump. Otherwise, the body will be tilted, with the hip of the takeoff leg lower than the hip of the lead leg.

Another point that needs to be taken into account is that, while the twisting component of angular momentum (H_T) is a major factor in the generation of the twist rotation in high jumping, it is generally not enough to produce the necessary face-up position on top of the bar. In addition, the athlete also needs to use rotational action and reaction about the longitudinal axis of the body to increase the amount of twist rotation that occurs in the air. In a normal high jump, the athlete needs to achieve about 90° of twist rotation between takeoff and the peak of the jump (see Fig. 14.20b). Approximately half of it (about 45°) is produced by the twisting angular momentum; the other half (roughly another 45°) needs to be produced through rotational action and reaction. Rotational action and reaction is sometimes called 'catting' because cats dropped from an upside-down position with no angular momentum use a mechanism of this kind to land on their feet.

The catting that takes place in the twist rotation of a high jump is difficult to see, because it is obscured by the somersault and twist rotations produced by the angular momentum. If we could 'hide' the somersault and twist rotations produced by the angular momentum, we would be able to isolate the catting rotation, and see it clearly. To achieve that, we would need to look at the high jumper from the viewpoint of a rotating camera. The camera would need to somersault with the athlete, staying aligned with the athlete's longitudinal axis. The camera would also need to twist with the athlete, just fast enough to keep up with the portion of the twist rotation produced by the twisting component of angular momentum. That way, all that would be left would be the rotation produced by the catting, and this rotation is what would be visible in the camera's view. It is impossible to make a real camera rotate in such a way, but we can use a computer to calculate how the jump would have appeared in the images of such a camera if it had existed. This is what is shown in Fig. 14.21. The sequence in Fig. 14.21 covers the period between takeoff and the peak of the jump, and progresses from left to right. All the images are viewed from a direction aligned with the

Fig. 14.21 Catting: use of clockwise rotations of the right leg and arm to produce counterclockwise twist rotation of the rest of the body (see text).

longitudinal axis of the athlete. (The head is the part of the athlete nearest to the 'camera'.) As the jump progressed, the camera *somersaulted* with the athlete, so it stayed aligned with the athlete's longitudinal axis. The camera also *twisted* counterclockwise with the athlete, just fast enough to keep up with the portion of the twist rotation produced by the twisting component of angular momentum. Figure 14.21 shows a clear counterclockwise rotation of the hips (about 45°) between the beginning and the end of the sequence. This implies that the athlete rotated counterclockwise faster than the camera, i.e. faster than the part of the twist rotation produced by the twisting component of angular momentum. The counterclockwise rotation of the hips visible in the sequence is the amount of twist rotation produced through catting. It occurred mainly as a reaction to the clockwise motions of the right leg, which moved towards the right, and then backwards. (These actions of the right leg are subtle, but nevertheless visible in the sequence.) In part, the counterclockwise catting rotation of the hips was also a reaction to the clockwise rotation of the right arm. Without the catting, the twist rotation of this athlete would have been reduced by an amount equivalent to the approximately 45° of counterclockwise rotation visible in the sequence of Fig. 14.21.

Some jumpers emphasize the twisting angular momentum more; others tend to emphasize the catting more. If not enough twisting angular momentum is generated during the takeoff phase, or if the athlete does not do enough catting in the air, the athlete will not twist enough in the air, which will make the body adopt a tilted position at the peak of the jump, with the hip of the lead leg lower than the hip of the takeoff leg. This will put the hip of the lead leg (i.e. the low hip) in danger of hitting the bar.

There are other ways in which problems can occur in the twist rotation. If at the end of the takeoff phase an athlete is tilting backwards too far, or is tilting too far towards the right (too far towards the left in the case of a jumper who takes off from the right foot), or if the lead leg is lowered too soon after takeoff, the twist rotation will be slower. This is due to interactions between the somersault and twist rotations which are too complex to explain here; for more details see Dapena (1997).

According to the previous discussion, a tilted position at the peak of the jump in which the hip of the lead leg is lower than the hip of the takeoff leg can be due to a variety of causes: an insufficient amount of twisting angular momentum; a much larger amount of forward than lateral somersaulting angular momentum; insufficient catting in the air; a backwards tilted position of the body at the end of the takeoff phase; a position that is too tilted towards the right at the end of the takeoff phase (towards the left in the case of jumpers taking off from the right foot); and premature lowering of the lead leg soon after takeoff.

When this kind of problem occurs, it is necessary to check the cause of the problem in each individual case, and then decide the easiest way to correct it.

Acknowledgements

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