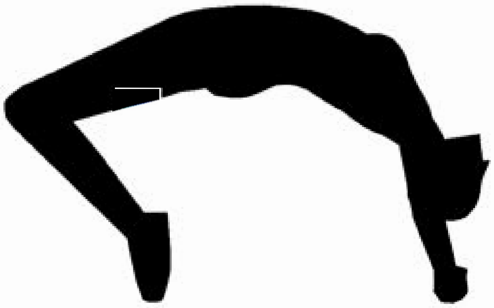
SCIENTIFIC SERVICES PROJECT

(USA Track & Field)

HIGH JUMP
#29
(Women)



Jesús Dapena, Brian J. Gordon
and Benjamin W. Meyer

Biomechanics Laboratory, Dept. of Kinesiology, Indiana University

IMPORTANT INFORMATION FOR THE COACH:

If one of your high jumpers was studied in our project, we hope you will find the information in this report helpful for the coaching of your athlete.

Although the high jump has been one of the most intensely studied events in track and field, knowledge of it is still imperfect, and there is room for doubts and disagreements. We have tried to give you what we believe are the best possible recommendations, based on the biomechanical information that is presently available, but we do not pretend to have all the answers. We hope you do not feel that we are trying to force our ideas on you, because that is definitely not our intent. Use what you like, and ignore what you don't like. If you find any part of this report useful in any way, we will feel that it has served its purpose.

Here is how we suggest that you use the report:

- Read the main text of the report ("Discussion of high jumping technique, and general analysis of results"). Try to follow the logic that we used to arrive at our conclusions.

- If you feel comfortable with our logic, and it fits with your own ideas, try to implement our recommendations as described in "Specific recommendations for individual athletes". Throughout the report, keep in mind that "c.m." stands for "center of mass", a point that represents the average position of the whole body. This point is also called sometimes the "center of gravity".

- If you do not agree with our logic, we still hope that you will find our data useful for reaching your own conclusions.

NOTE FOR PREVIOUS READERS OF THESE AND OTHER REPORTS: The masses or weights of the segments that make up the body of an individual athlete are not known exactly, and neither are the moments of inertia nor other important mechanical characteristics of the segments of the human body. Therefore, researchers have to work with *estimates* of those values, and different researchers work with different estimates. The methods used for the calculation of mechanical information (for instance: three-dimensional coordinates of body landmarks, center of mass position, angular momentum) also vary from one researcher to another. Because of this, *it is often not advisable to compare the data from reports produced by different laboratories.*

Even within our own laboratory, some definitions have changed from one report to another. Also, some of the data are calculated with progressively improved methods which give more accurate values. Therefore, the data in this report may not be strictly comparable with data presented in previous reports. However, all values given in the present report were computed using the same method, because any data for jumps from previous years were re-calculated. Therefore, *all the data presented in this report, including data for jumps made in previous years, are compatible with each other.*

Jesús Dapena

Bloomington, October 2, 2006

Department of Kinesiology
HPER 112
Indiana University
Bloomington, IN 47405
U.S.A.

telephone: (812) 855-8407
email: dapena@indiana.edu

TABLE OF CONTENTS

INTRODUCTION

This report contains a biomechanical analysis of the techniques used by some of the top athletes in the final of the women's high jump event at the 2006 USATF Championships. Data from analyses made in previous years are also shown for some of these athletes.

The report evaluates the advantages and disadvantages of the techniques used by the analyzed athletes, and suggests how to correct some of the technique problems found. The rationale used for the technique evaluations stems from a comprehensive interpretation of the Fosbury-flop style of high jumping that is based on the research of Dyatchkov (1968) and Ozolin (1973), on basic research carried out by the first author of this report (Dapena, 1980a, 1980b, 1987a, 1995a, 1995b; Dapena *et al.*, 1988, 1990, 1997a), and on the experience accumulated through the analysis of American and other high jumpers at Indiana University since 1982 (Dapena, 1987b, 1987c; Dapena *et al.*, 1982, 1983a, 1983b, 1986a, 1986b, 1986c, 1991, 1993a, 1993b, 1993c, 1994a, 1994b, 1995a, 1995b, 1997b, 1997c, 1998a, 1998b, 1999a, 1999b, 2001a, 2001b, 2002a, 2002b, 2003a, 2003b, 2004a, 2004b) in the course of service work sponsored by the United States Olympic Committee, USA Track & Field and/or the International Olympic Committee.

GENERAL METHODOLOGY

Filming and selection of trials

The jumps were filmed simultaneously with two motion picture cameras shooting at 50 frames per second. It was not possible to record all the jumps in the meets. However, it was possible to find for all the athletes presented in this report at least one trial that was representative of the best jumps of the athlete during the competitions. (The best jump of an athlete is not necessarily a successful clearance.)

A number was assigned to each trial. This number simply indicated the order of appearance of that jump in our films, and it is used here for identification purposes.

Film analysis

The locations of 21 body landmarks were measured ("digitized") in the images obtained by the two cameras. Computer programs were then used to calculate the three-dimensional (3D) coordinates of the body landmarks from the final part of the run-up through the takeoff phase and the bar clearance. Another program used these 3D coordinates to calculate the location of the center of mass (c.m.) (also called the center of gravity, c.g.), speed of the run-up, step lengths, and other information.

Sequences

Computer graphics were used to produce several motion sequences for each jump. They are inserted in this report immediately after the individual analysis of each athlete. There are three pages of sequences for each trial.

The first page is labeled "Run-up", and it shows a double sequence of the end of the run-up and the takeoff phase. The top of the page shows a side view; the bottom of the page shows a back view. The back view is the one that would be seen by a hypothetical observer following the athlete along the curved path of the run-up; the side view is the one that would be seen by an observer standing at the center of the run-up curve. The numbers at the bottom of the page indicate time, in seconds. To facilitate the comparison of one jump with another, the value t = 10.00 seconds was arbitrarily assigned in all trials to the instant when the takeoff foot first made contact with the ground to start the takeoff phase.

The next page of computer plots (labeled "Takeoff Phase") shows side and back views of a detailed sequence of the takeoff phase. (The sequence usually extends somewhat beyond the loss of contact of the takeoff foot with the ground.)

The third page (labeled "Bar Clearance") shows a double sequence of the bar clearance. The top of the page shows the view along the bar; the bottom of the page shows the view perpendicular to the plane of the bar and the standards.

Subject characteristics and meet results

Table 1 shows general information on the analyzed athletes, and their results in the competitions. All the jumpers used the Fosbury-flop style.

DISCUSSION OF HIGH JUMPING TECHNIQUE, AND GENERAL ANALYSIS OF RESULTS

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 c.m. will reach after leaving the ground and the angular momentum (also called "rotary momentum") that the body will have during the bar clearance. The only active movements that can be made after leaving the ground are internal compensatory movements (for instance, one part of the body can be

Table 1

General information on the analyzed jumpers, and meet results.

Athlete	Standing height (m)	Weight (Kg)	Personal best mark (*) (m)	Best heights cleared at meets (**) (m)
Amy ACUFF	1.88	64	2.01	1.89 (N94); 1.95 (U95); 1.96 (U97); 1.94 (U98); 1.93 (U99); 1.88 (U01); 1.90 (U02); 1.95 (U03); 1.95 (T04); 1.92 (U06)
Sheena GORDON	1.79	70	1.91	1.84 (T04); 1.78 (U06)
Destinee HOOKER	1.91	70	1.92	1.86 (U06)
Chaunte HOWARD	1.77	59	2.01	1.89 (U03); 1.95 (T04); 2.01 (U06)
Christine SPENCE	1.77	61	1.88	1.83 (U06)
Kaylene WAGNER	1.85	65	1.92	1.84 (U03); 1.84 (T04); 1.83 (U06)

(*) by the end of the last meet in which the jumper was analyzed

(**) N94 = 1994 NCAA Championships; T04 = 2004 U.S. Olympic Trials; U95 = 1995 USATF Ch.; U97 = 1997 USATF Ch.; U98 = 1998 USATF Ch.; U99 = 1999 USATF Ch.; U01 = 2001 USATF Ch.; U02 = 2002 USATF Ch.; U03 = 2003 USATF Ch; U06 = 2006 USATF Ch.

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 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 (Figure 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 or the tighter the curve, the greater the lean toward the center of the curve. (For more details on the shape of the run-up, see Appendix 4.)

Approach angles

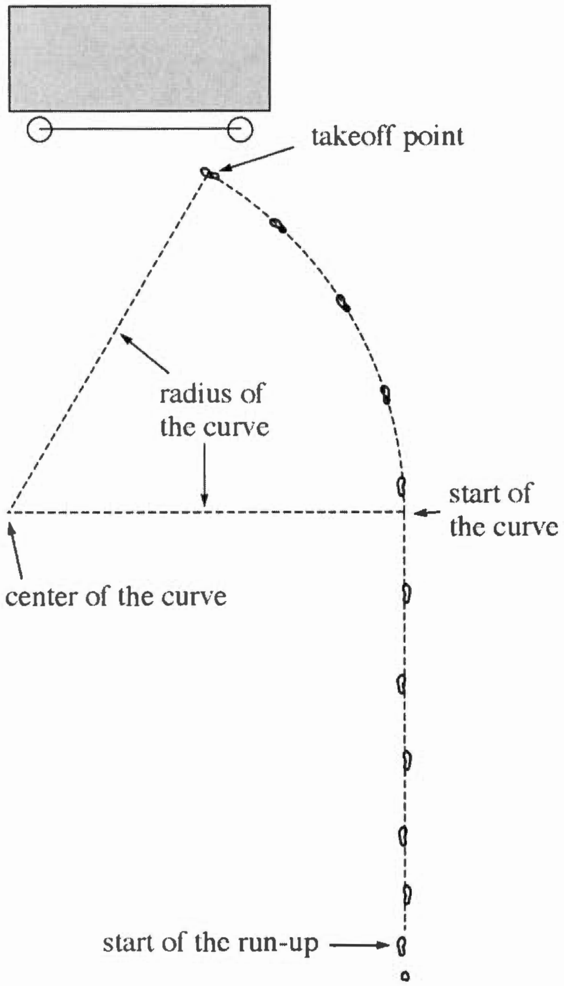
Figure 2 shows an overhead view of the last two steps of the run-up, the takeoff phase and the airborne phase. Notice that the c.m. (c.g.) path is initially to the left of the footprints. This is because the athlete is leaning toward the left during the curve. The path then converges with the footprints, and the c.m. is pretty much directly over the takeoff foot at the end of the takeoff.

Figure 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 c.m. in the airborne phases of the last two steps; p_0 is the angle between the bar and the path of the c.m. 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 2.

Progression of the run-up

To start the run-up, the athlete can either take a few walking steps and then start running, or make a standing start. In the early part of the run-up the athlete needs to follow a gradual progression in which each step is a little bit longer and faster than the previous one. After a few steps, the high jumper will be running pretty fast, with long, relaxed steps, very similar to those of a 400-meter or 800-meter runner. In the last two or three steps of the run-up the athlete should gradually lower the hips. It must be stressed here that this lowering of the hips has to be achieved without incurring a significant loss of running speed.

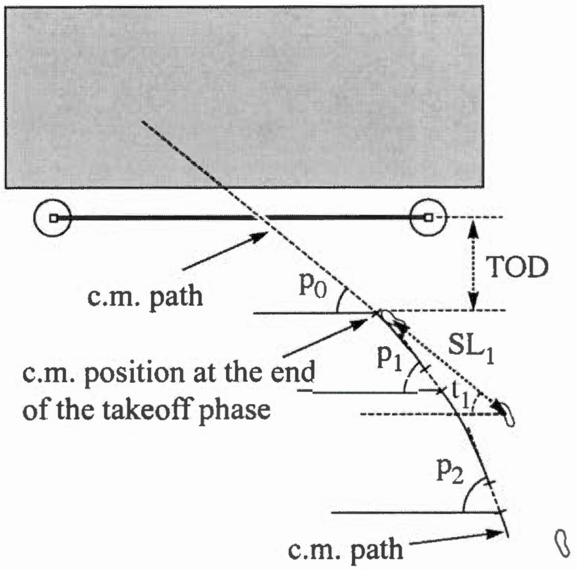
Figure 1



Horizontal velocity and height of the c.m. 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 c.m. 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 c.m. will go after the athlete leaves the ground, and is therefore of great importance for the result of the jump.

Figure 2



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 the vertical force as large as possible and the vertical range of motion through which the c.m. travels during the takeoff phase as long as possible.

A fast approach run can help the athlete to exert a larger vertical force on the ground. This can happen 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 (quadriceps) resist against the flexion of the leg, but the leg is forced to flex anyway, 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 produces a stimulation of the muscles, which in turn allows the foot of the takeoff leg to exert a larger force on the ground. 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 and Chung, 1988.) Table 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.

Table 2

Direction of the footprints of the last step (t_1), direction of the path of the c.m. 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 meters and also as a percent of the standing height of the corresponding athlete), and takeoff distance (TOD). Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	t_1	p_2	p_1	p_0	e_1	e_2	e_3	SL_1		TOD
		(°)	(°)	(°)	(°)	(°)	(°)	(°)	(m)	(%)	(m)
Acuff	15 N94	28	44	36	28	13	23	31	1.83	97	0.49
	77 U95	29	48	38	35	5	33	36	1.90	101	0.57
	57 U97	23	50	36	33	18	18	22	1.69	90	0.53
	45 U98	21	39	31	27	16	16	21	1.70	90	0.54
	43 U99	33	54	44	40	14	30	36	1.82	97	0.76
	32 U01	32	56	46	46	17	29	29	1.77	94	0.97
	19 U02	31	56	44	41	5	38	43	1.85	98	0.83
	58 U03	32	58	44	40	6	39	44	1.88	100	0.84
	47 T04	33	58	46	44	12	34	37	1.80	96	0.88
	41 U06	36	59	48	43	12	36	43	1.74	93	0.91
Gordon	09 T04	23	50	38	34	9	29	38	1.62	91	0.93
	13 U06	20	47	32	30	5	27	32	1.62	91	0.73
Hooker	11 U06	18	44	30	32	15	15	12	1.95	102	0.87
Howard	27 U03	24	46	36	35	3	32	34	1.99	112	1.01
	45 T04	26	49	39	35	7	32	39	1.89	107	1.01
	46 U06	33	55	44	40	9	36	42	2.01	113	1.22
Spence	09 U06	28	52	38	34	15	23	28	1.81	102	0.74
Wagner	21 U03	22	49	35	33	6	29	31	1.89	102	0.66
	29 T04	24	47	36	33	15	22	26	1.86	101	0.70
	01 U06	34	61	46	41	18	29	35	1.99	108	0.83

(*) N94 = 1994 NCAA Championships; T04 = 2004 U.S. Olympic Trials; U95 = 1995 USATF Ch.; U97 = 1997 USATF Ch.; U98 = 1998 USATF Ch.; U99 = 1999 USATF Ch.; U01 = 2001 USATF Ch.; U02 = 2002 USATF Ch.; U03 = 2003 USATF Ch; U06 = 2006 USATF Ch.

To maximize the vertical range of motion through which force is exerted on the body, it is necessary for the center of mass to be in a low position at the start of the takeoff phase and in a high position at the end of it. The c.m. of most high jumpers is reasonably high by the end of the takeoff phase, but it is difficult to have the c.m. in a low position at the start of the takeoff phase. This is because in that case the body has to be supported by a deeply flexed non-takeoff leg during the next-to-last step of the run-up, and this 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 3 shows the value of h_{TD}, the height of the c.m. at the instant that the takeoff foot is planted on the ground to start the takeoff phase. It is expressed in meters, but also as a percent of the standing height of each athlete. The percent values are more meaningful for the comparison of one athlete with another.

It is possible to achieve an approach run that is fast and low in the last steps, but this requires a considerable amount of effort and training. Appendix 2 describes some exercises that can help high jumpers to lower the c.m. in the last steps of the run-up without losing speed.

Let's say that 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 extension in the final part of the takeoff phase. In other words, the

Table 3

Height of the c.m. at the start of the takeoff phase (h_{TD}, expressed in meters and also as a percent of the standing height of each 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}). Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	h_{TD}		v_{H2}	v_{H1}	v_{HTO}	Δv_H	v_{ZTD}	v_{ZTO}
		(m)	(%)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)
Acuff	15 N94	0.91	48.5	6.1	6.4	3.4	-3.1	-0.7	3.55
	77 U95	0.92	49.0	6.3	6.7	3.6	-3.2	-0.9	3.75
	57 U97	0.92	49.0	6.3	6.3	3.5	-2.8	-0.2	3.80
	45 U98	0.92	49.0	6.4	6.4	3.5	-2.9	-0.5	3.65
	43 U99	0.94	50.0	6.6	6.5	3.7	-2.8	-0.5	3.50
	32 U01	0.94	50.0	6.8	6.5	3.8	-2.7	-0.6	3.35
	19 U02	0.95	50.5	6.7	6.5	3.9	-2.6	-0.6	3.45
	58 U03	0.93	49.5	7.0	6.8	3.9	-2.9	-0.5	3.70
	47 T04	0.93	49.5	7.1	6.8	3.9	-2.9	-0.4	3.60
	41 U06	0.93	49.5	6.9	6.6	3.8	-2.7	-0.6	3.65
Gordon	09 T04	0.86	48.5	6.5	6.2	4.1	-2.1	0.0	3.60
	13 U06	0.85	47.5	6.3	6.1	3.7	-2.4	0.0	3.55
Hooker	11 U06	0.92	48.5	6.3	6.5	3.9	-2.6	-0.3	3.55
Howard	27 U03	0.84	47.5	7.3	7.5	4.6	-3.0	-0.2	3.80
	45 T04	0.83	47.0	7.6	7.4	4.6	-2.8	-0.1	3.85
	46 U06	0.82	46.0	8.0	8.0	4.7	-3.3	-0.3	4.00
Spence	09 U06	0.82	46.5	6.6	6.5	3.5	-3.0	-0.6	3.65
Wagner	21 U03	0.85	46.0	6.5	6.3	3.1	-3.2	-0.4	3.55
	29 T04	0.85	46.0	7.0	6.4	3.7	-2.7	-0.1	3.50
	01 U06	0.87	47.0	6.4	6.3	3.4	-2.9	-0.3	3.40

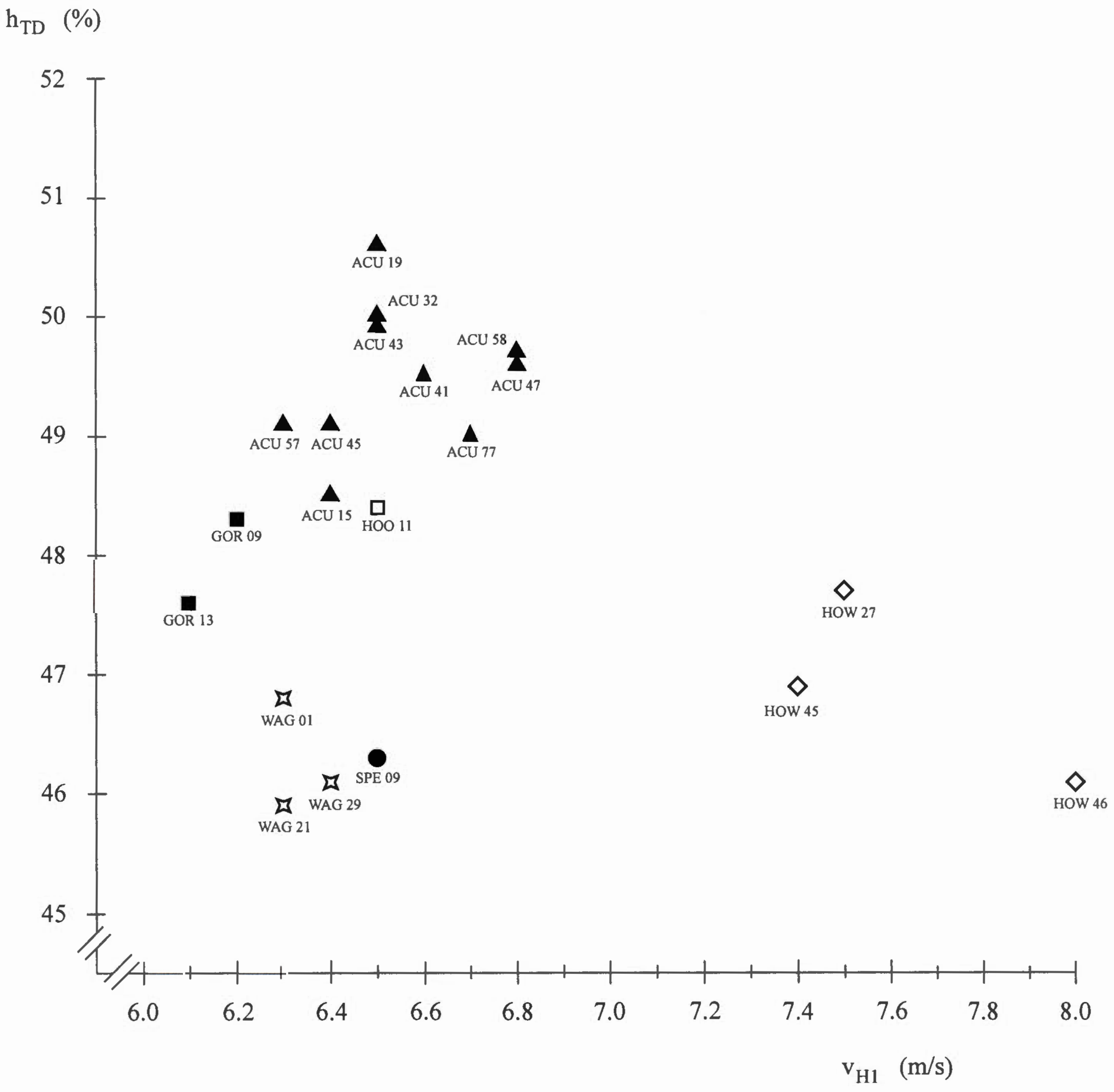
(*) N94 = 1994 NCAA Championships; T04 = 2004 U.S. Olympic Trials; U95 = 1995 USATF Ch.; U97 = 1997 USATF Ch.; U98 = 1998 USATF Ch.; U99 = 1999 USATF Ch.; U01 = 2001 USATF Ch.; U02 = 2002 USATF Ch.; U03 = 2003 USATF Ch; U06 = 2006 USATF Ch.

takeoff leg may buckle (collapse) 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 c.m. height. We will now see how this can be done.

Figure 3 shows a plot of h_{TD} versus v_{H1}. Each point represents one jump by one athlete. (A different symbol has been assigned to each athlete in Figure 3. The same symbol will be used for each athlete in all graphs.) Points in the left part of the graph represent jumps with a slow speed at the end of the run-up; points in the right part of the graph represent jumps with a fast speed at the end of the run-up. Points in the upper part of the graph represent jumps with a high c.m. at the end of the run-up; points in the lower part of the graph represent jumps with a low c.m. at the end of the run-up. This kind of graph permits 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 c.m. at the end of the run-up.

(At this point, it is important to consider the accuracy of these values. All measurements have some degree of error, and depending on what is being measured, the error may be larger or smaller. The errors in the v_{H1} values are small, typically less than 0.1 m/s; the errors in the h_{TD} values can be of greater significance. It is easy for the value of h_{TD} to be half a percent point off for any jump, and occasionally it could be off by as much as one whole percent point. Therefore, if two jumpers had, for instance, h_{TD} values of 46.5% and 49.0%, respectively, we could be pretty sure that the first jumper really was lower than the second one. However, if the two values of h_{TD} were, for instance, 46.5% and 48.0% it would not

Figure 3


h_{TD} (%)
52
51
50
49
48
47
46
45
ACU 19
ACU 32
ACU 43
ACU 58
ACU 47
ACU 41
ACU 57
ACU 45
ACU 77
ACU 15
HOO 11
GOR 09
GOR 13
HOW 27
HOW 45
HOW 46
WAG 01
SPE 09
WAG 29
WAG 21
6.0
6.2
6.4
6.6
6.8
7.0
7.2
7.4
7.6
7.8
8.0
v_{H1} (m/s)

be possible to be completely sure which of the jumpers was lower, because the 46.5% could be really 47.5%, and the 48.0% could be really 47.0%.)

Let's consider what would happen if all the athletes shown in Figure 3 had similar dynamic strength in the takeoff leg. In such 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 center, in the lower left and in the upper right parts of the graph would be somewhere in between with respect to buckling. Therefore, if all the athletes shown in Figure 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 (see Appendix 2), and then experiment with jumps using run-ups that are faster and/or lower than their original ones. The athletes in the center, 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 the jumpers in the lower left part of the graph, and "lower" for the 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 shown in Figure 3 had similar dynamic strength in the takeoff leg. However, this is unlikely. Some high jumpers will be more powerful than others. Since more powerful 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 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 c.m. height will be different for different high jumpers.

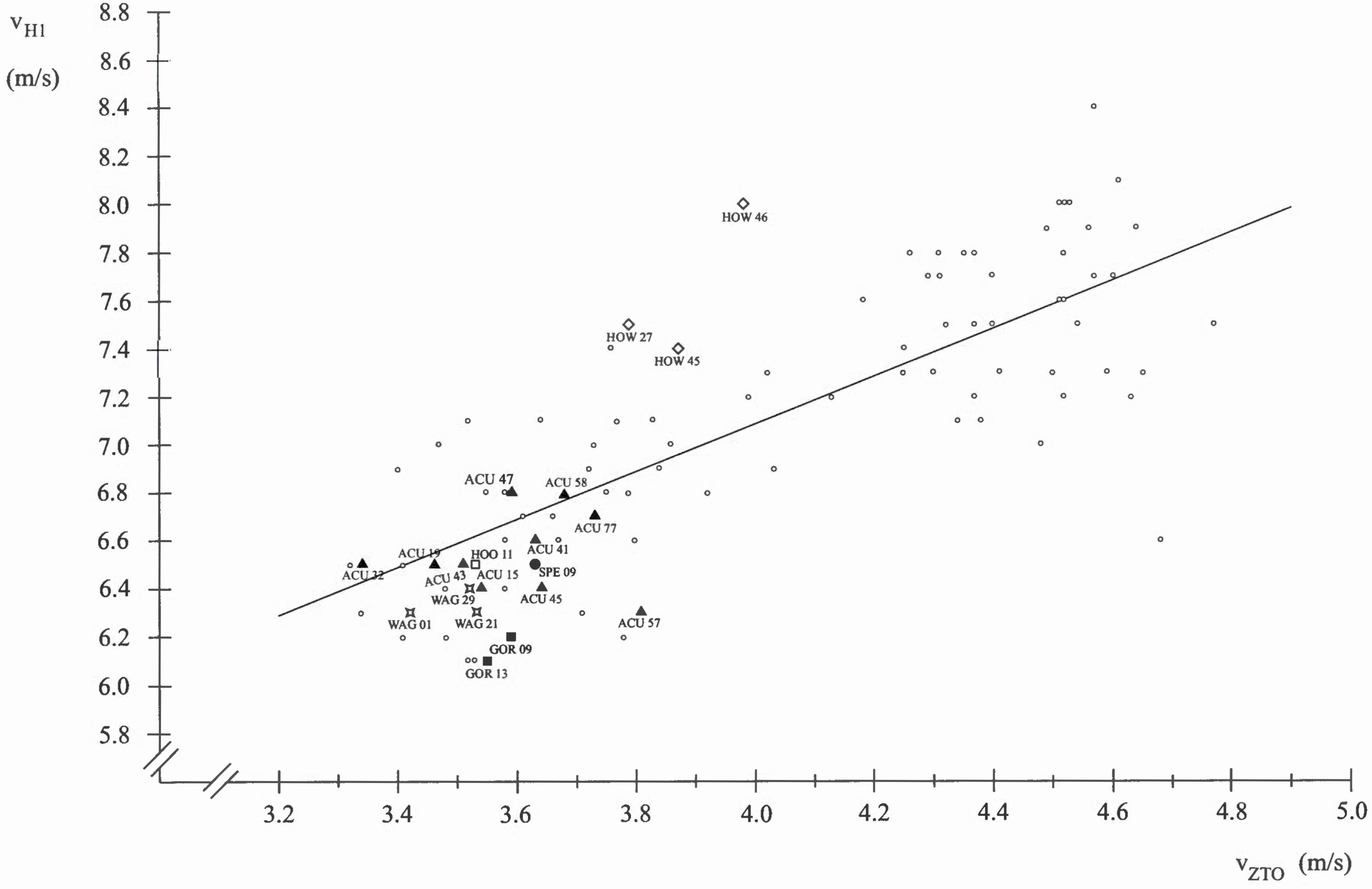
High jumpers with greater dynamic strength in the takeoff leg will be able to handle faster and lower run-ups without buckling during the takeoff phase. However, it is not easy to measure the "dynamic strength" of a high jumper's takeoff leg. The personal record of an athlete in a squat lift or in a 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 in our prediction of 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 sponsored at Indiana University by the United States Olympic Committee and by USA Track & Field (formerly The Athletics Congress) in the period 1982-1987. 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; U.S. Olympic Trials; World Indoor Championships).

Each of the small open circles in Figure 4 represents one jump by one of the athletes in our statistical sample. The other symbols represent the athletes analyzed for the present report. The horizontal axis of the graph shows vertical velocity at takeoff (v_{ZTO}): The most powerful high jumpers are the ones who are 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 final speed of the run-up (v_{HI}). The diagonal "regression" line shows the trend of the statistical data. The graph agrees with our expectations: The more powerful jumpers, those able to get more lift (v_{ZTO}), can also handle faster run-ups (v_{HI}) 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 for a high jumper 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 further jumps. Since buckling will begin to occur at run-up speeds immediately faster than the optimum, this means that few high jumpers should be expected to use regularly 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 sum, 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 indicated by the diagonal regression line, and 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 Figure 5. Each of the small open circles in Figure 5 represents one jump by one of the athletes in our statistical sample. The



v_H1
(m/s)
8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
v_ZTO (m/s)
HOW 46
HOW 27
HOW 45
ACU 47
ACU 58
ACU 77
ACU 19
ACU 32
HOO 11
ACU 41
ACU 43
ACU 15
SPE 09
WAG 29
ACU 45
WAG 01
WAG 21
ACU 57
GOR 09
GOR 13

Figure 4

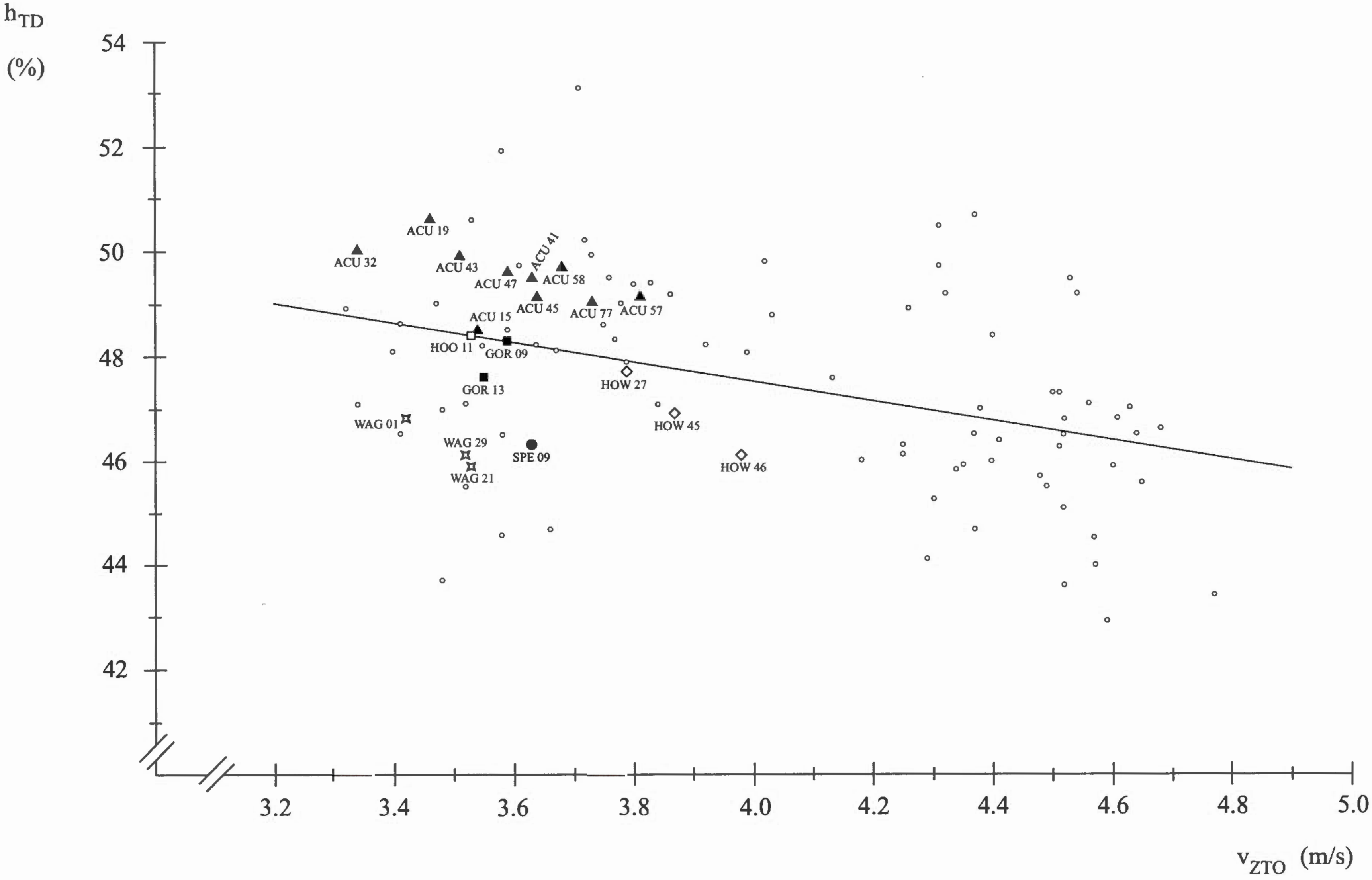

h_TD
(%)
54
52
50
48
46
44
42
ACU 19
ACU 32
ACU 43
ACU 47
ACU 41
ACU 58
ACU 45
ACU 77
ACU 57
ACU 15
HOO 11
GOR 09
GOR 13
HOW 27
HOW 45
HOW 46
WAG 01
WAG 29
WAG 21
SPE 09
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
v_ZTO (m/s)

Figure 5

other symbols represent the athletes analyzed for the present report. The horizontal axis of the graph again shows vertical velocity at takeoff (v_{ZTO}): The most powerful high jumpers are the ones who are 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 c.m. at the start of the takeoff phase (h_{TD}), expressed as a percent of the athlete's standing height. The diagonal regression line shows the trend of the statistical data. Although the data are more "noisy" than in the previous graph (there is a wider "cloud" around the regression line), the graph in Figure 5 also agrees with our general expectations: The more powerful jumpers (larger v_{ZTO} values) are able to be lower at the end of the run-up (smaller h_{TD} values) without buckling. In Figure 5, jumpers on the regression line or above it will have weak techniques, and the optimum will be somewhere below the regression line.

When Figures 4 and 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 pretty much on the regression lines of Figures 4 and 5, or below the regression line in Figure 4 and above the regression line in Figure 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 Figure 4, but markedly below it in Figure 5, the case is different. Since the c.m. 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 that case, it would not be appropriate to advise an increase in run-up speed, even if the athlete's run-up speed was somewhat slow in comparison to what we would expect.

(IMPORTANT CAUTION: The use of a faster and/or lower run-up will put a greater stress on the takeoff leg, and thus it may increase the risk of injury if the leg is not strong enough. Therefore, it is always 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 c.m. 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 (that is, at the start of the takeoff phase) the athlete is moving fast forward, and also slightly downward. In other words, the vertical velocity at the start of the takeoff phase (v_{ZTD}) usually has a small negative value (i.e., downward). 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 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 c.m. 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 c.m. 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, which in turn could lead to a large negative value for v_{ZTD}. Table 2 shows the length of the last step of the run-up (SL_1). This length is expressed in meters, but to facilitate comparisons among athletes it is also expressed as a percent of the standing height of each athlete.

Another factor that has an influence on the vertical velocity at the start of the takeoff phase is the way in which the c.m. 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 c.m. Many athletes lower their c.m. early (two or three steps before the takeoff), and then they move relatively 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 c.m. 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 c.m. in the same way as the first group, but then they raise the c.m. 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, and this is good, but they also waste part of their previous lowering of the c.m.

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. There is a more detailed discussion of these three techniques in Appendix 1.

A graph showing the vertical motion of the c.m. in the final part of the run-up was produced for each athlete, and these graphs are inserted in the report after the individual analysis of each athlete.

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

At the end of the run-up, the high jumper's c.m. is moving at an angle p_1 with respect to the bar (see "Approach angles"). During the takeoff phase, the athlete pushes on the ground vertically downward, and also horizontally. The horizontal force that the foot makes on the ground during the takeoff phase points forward, almost in line with the final direction of the run-up, but usually it is also deviated slightly toward the landing pit (see Figure 6). (The reason for this deviation is explained in Appendix 3.)

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 inward. (See the sequence in Figure 7, obtained from a high-speed videotape taken during the 1988 International Golden High Jump Gala competition in Genk, Belgium –courtesy of Dr. Bart 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 makes the foot be supported less by the outside edge of the foot, and more by the longitudinal (forward-backward) arch of the foot on the medial side. 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; it only means that we can't see it.

In an effort to diagnose the risk of ankle and foot injury for each analyzed high jumper, we measured 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 Figure 6.) The values of these angles are reported in Table 2. For diagnosis of the risk of injury, e_3 is the most important angle. Although the safety limit is not known with certainty at this time, anecdotal evidence suggests that e_3 values smaller than 20° are reasonably safe, that e_3 values between 20° and 25° are somewhat risky, and that e_3 values larger than 25° are dangerous.

Trunk lean

Figure 8 shows BFTD, BFTO, LRTD and LRTO, the backward/forward and left/right angles of lean of the trunk at the start and at the end of the takeoff phase, respectively. The values of these angles are given in Table 4. The trunk normally has a backward lean at the start of the takeoff phase (BFTD). Then it rotates forward, 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 toward the center of the curve at the start of the takeoff phase (LRTD). During the takeoff phase, the trunk rotates toward the right (toward 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 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 has shown that there is 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 c.m.: If two athletes have similar run-up speed, height of the c.m. 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 toward the center 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

Figure 6

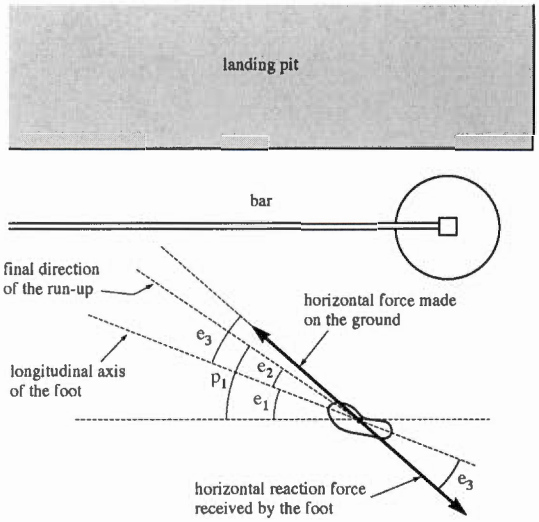
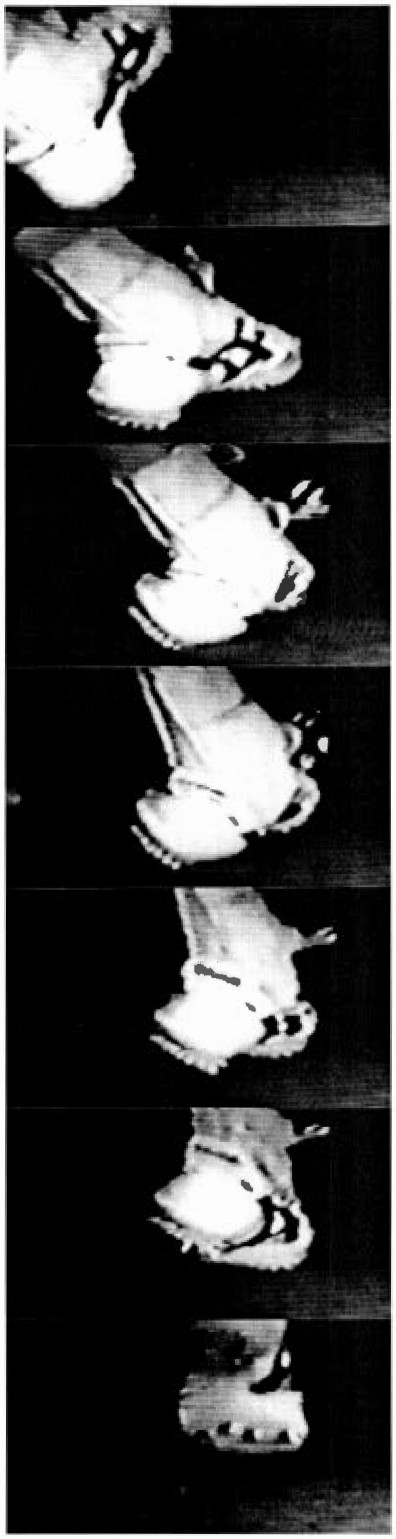


Figure 7



(videotape courtesy of
Bart Van Gheluwe)

Figure 8

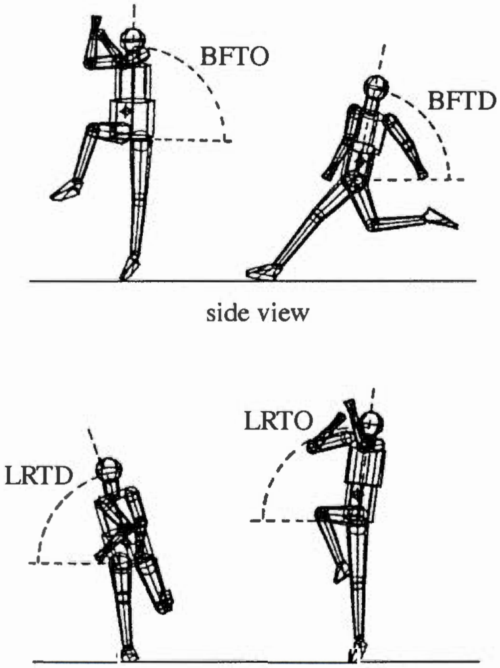


Table 4

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

Athlete	Trial and meet (*)	BFTD (°)	BFTO (°)	ΔBF (°)	LRTD (°)	LRTO (°)	ΔLR (°)	AAN (mm/m)	AAF (mm/m)	AAT (mm/m)	LLA (mm/m)	FLA (mm/m)
Acuff	15 N94	77	89	12	78	89	11	-0.3	6.1	5.8	14.4	20.2
	77 U95	78	88	10	83	94	11	-2.1	8.2	6.2	12.7	18.9
	57 U97	73	87	14	78	92	14	0.5	7.1	7.5	19.1	26.6
	45 U98	75	80	5	81	95	14	0.7	9.1	9.8	21.6	31.4
	43 U99	74	94	20	78	89	11	0.0	8.6	8.6	18.8	27.4
	32 U01	78	98	19	83	95	12	0.8	7.8	8.5	21.7	30.2
	19 U02	79	93	14	79	93	14	0.7	7.0	7.7	18.2	25.9
	58 U03	79	95	17	78	94	16	-1.3	5.3	4.0	14.7	18.7
	47 T04	79	99	19	79	87	7	0.6	4.5	5.0	17.6	22.6
	41 U06	76	91	15	82	88	5	-0.1	4.7	4.6	21.3	25.9
Gordon	09 T04	85	90	5	72	92	20	5.8	8.3	14.1	20.9	35.0
	13 U06	76	72	-4	76	104	28	6.3	9.0	15.3	24.1	39.3
Hooker	11 U06	84	90	6	76	101	25	3.7	9.1	12.8	20.4	33.1
Howard	27 U03	83	95	12	76	93	17	3.1	5.3	8.4	13.0	21.4
	45 T04	83	94	11	74	90	15	2.2	4.9	7.2	10.1	17.3
	46 U06	79	90	11	79	90	11	3.2	3.4	6.6	12.2	18.8
Spence	09 U06	75	82	7	73	95	22	4.6	7.1	11.7	17.1	28.7
Wagner	21 U03	73	79	6	69	103	34	3.9	10.1	14.0	20.4	34.3
	29 T04	76	82	7	79	107	28	5.2	8.9	14.0	15.9	29.9
	01 U06	73	83	10	78	101	23	1.7	6.6	8.3	18.7	27.0

(*) N94 = 1994 NCAA Championships; T04 = 2004 U.S. Olympic Trials; U95 = 1995 USATF Ch.; U97 = 1997 USATF Ch.; U98 = 1998 USATF Ch.; U99 = 1999 USATF Ch.; U01 = 2001 USATF Ch.; U02 = 2002 USATF Ch.; U03 = 2003 USATF Ch; U06 = 2006 USATF Ch.

athletes who 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 backward 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. First of all, 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 can't 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 c.m. We don't understand well the cause-effect mechanisms behind the statistical relationships, and it is possible to offer alternative explanations, such as this one: Weaker athletes are not able to generate much lift, mainly because they are weak. Therefore, they are not able to jump very high. This 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 can't be sure of 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 don't know for sure.

Arm and lead leg actions

The actions of the arms and of the lead leg during the takeoff phase are very important for the outcome of a high jump. When these free limbs are accelerated upward during the takeoff phase, they exert by reaction a compressive force downward on the trunk. This force is transmitted through the takeoff leg to the ground. The increased downward vertical force exerted by the foot 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 c.m. 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 were during the takeoff phase of a high jump. In our reports we have progressively improved our measurement of this important technique factor; the data in the present report were calculated with our latest method which gives more meaningful values than some of the previous ones.

[Note for other researchers (coaches and athletes can skip this paragraph): In this report, arm activeness was expressed as the vertical range of motion of the c.m. 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 was similarly measured as the vertical range of motion of the c.m. 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 was expressed as the number of millimeters contributed by the limb motion to the lifting of the c.m. of the whole body during the takeoff phase, per meter of standing height. Defined in this way, the activeness of each free limb considers 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 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 (AAT), the activeness of the lead leg (LLA) and the combined activeness of all three free limbs (FLA). (As explained in the previous paragraph, coaches and athletes don't need to worry about the fine details of how these values were calculated; they only need to keep in mind that larger numbers indicate greater activeness of the limbs during the takeoff.)

Figure 9 shows a plot of AAF versus AAN for the analyzed trials. The farther to the right that a point is on the plot, the greater the activeness of the arm nearest to the bar; the higher up that a point is on the plot, the greater the activeness of the arm farthest from the bar. 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 forward and up during the takeoff phase. The arms 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 the lower left corner of Figure 9 toward the upper right part of the graph indicates the points for which both arms would have the same 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 forward and upward during the takeoff, and these jumpers usually end up with small 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 forward and up during the takeoff phase. Learning this kind of arm action will take some time and effort, but it should help these athletes to jump higher. If a jumper 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 upward during the takeoff, although usually not quite as hard as with a double-arm action.

Figure 10 shows a plot of LLA versus AAT for the analyzed trials. The farther to the right that a point is on the plot, the greater the combined activeness of the arms; the higher up that a point is on the plot, the greater the activeness of the lead leg. 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

Figure 9

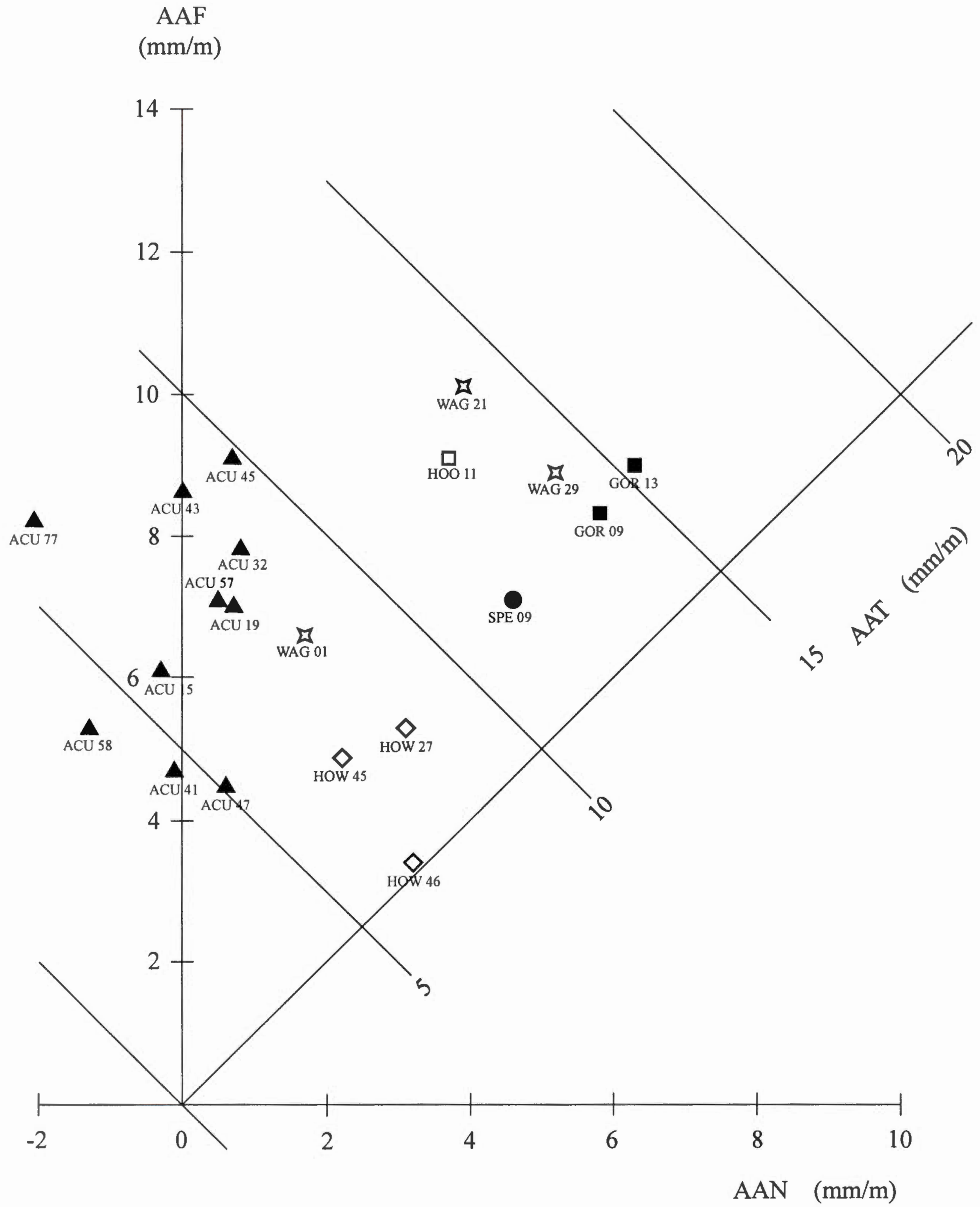
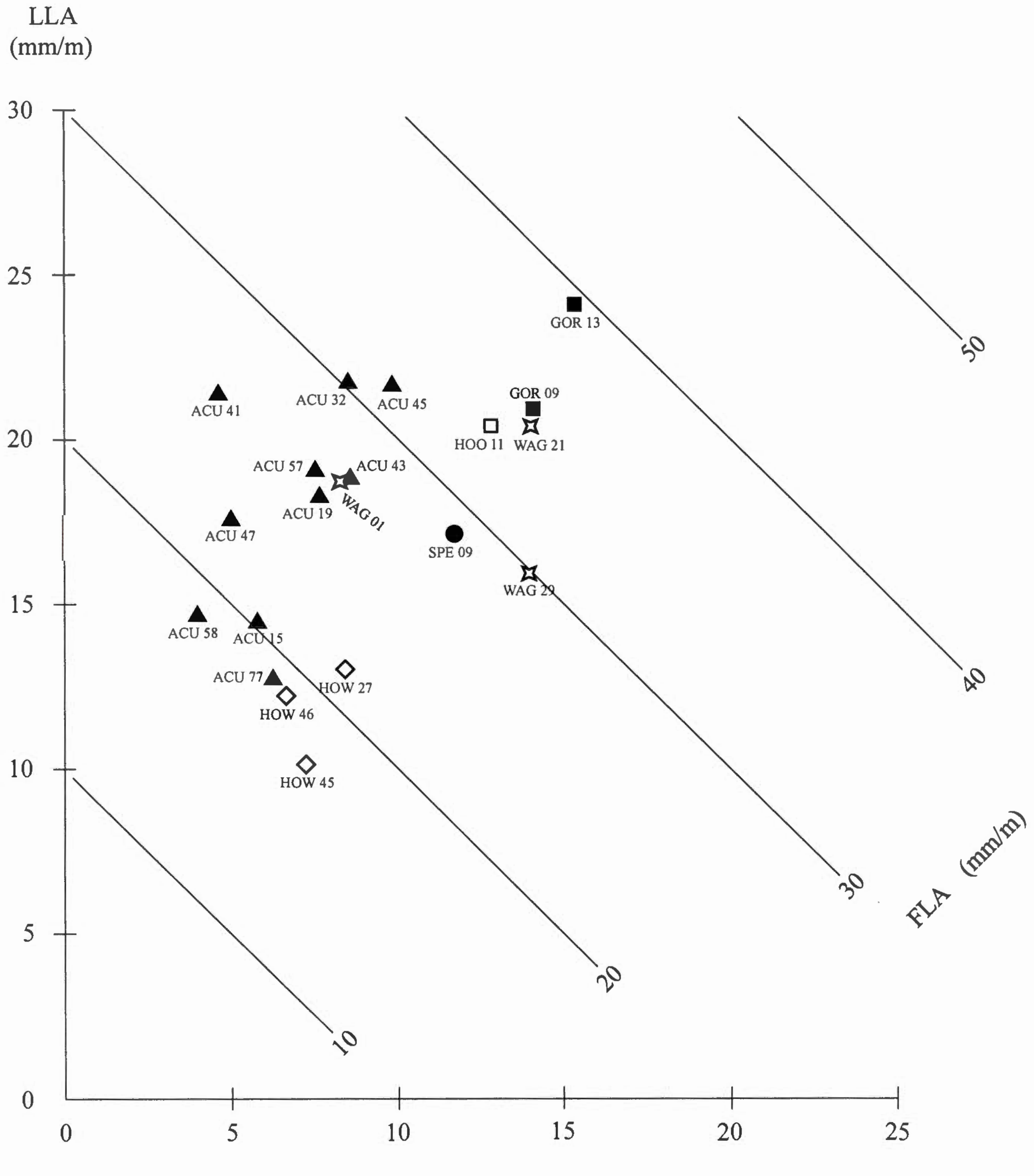

AAF
(mm/m)
14
12
10
8
6
4
2
-2
0
2
4
6
8
10
AAN (mm/m)
AAT (mm/m)
5
10
15
20
WAG 21
HOO 11
WAG 29
GOR 13
GOR 09
SPE 09
WAG 01
ACU 45
ACU 43
ACU 77
ACU 32
ACU 57
ACU 19
ACU 15
ACU 58
ACU 41
ACU 47
HOW 27
HOW 45
HOW 46

Figure 10


LLA
(mm/m)
30
25
20
15
10
5
0
0
5
10
15
20
25
AAT (mm/m)
FLA (mm/m)
10
20
30
40
50
GOR 13
GOR 09
HOO 11
WAG 21
ACU 41
ACU 32
ACU 45
ACU 57
ACU 43
ACU 19
WAG 01
ACU 47
SPE 09
WAG 29
ACU 58
ACU 15
ACU 77
HOW 27
HOW 46
HOW 45

graph.

Takeoff time

The duration of the takeoff phase (T_{TO}) is shown in Table 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 takeoffs go together with a strong action of the takeoff leg (good), but also with weak arm actions and with a high c.m. position at the start of the takeoff phase (bad). In sum, 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 3) are due to the fact that the jumper pushes forward 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 if not enough of it is lost during the takeoff phase, we can say that the run-up is not being used appropriately to help the athlete to jump higher.

Height and vertical velocity of the c.m. at the end of the takeoff phase

The peak height that the c.m. 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 c.m. at the end of the takeoff.

At the instant that the takeoff foot loses contact with the ground, the c.m. 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 centers of mass will generally be higher at the instant that they leave the ground.

The vertical velocity of the c.m. at the end of the takeoff phase (v_{ZTO}, shown in Table 3) determines how much higher the c.m. will travel beyond the takeoff height after the athlete leaves the ground.

Height of the bar, peak height of the c.m., and clearance height

The height of the bar (h_{BAR}), the maximum height reached by the c.m. (h_{PK}) and the outcome of the jump are shown in Table 5.

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, even if the jumper had room to spare over it.

Using computer modeling 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 11 shows three images of a high jumper's clearance of a bar set at 2.25 m. Figure 12 shows all the images obtained through film analysis of the bar clearance. In Figure 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 Figure 13 also shows that the maximum height of the "hollow" area left below the body was not perfectly centered 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 digitization of 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 h_{CLS} will be over- or underestimated on the average by between 0.02 m and 0.03 m, but this will be larger or smaller in individual cases. Therefore, the calculated clearance height values should be considered only

Table 5

Takeoff time (T_{TO}), height of the bar (h_{BAR}), outcome of the jump, maximum height of the c.m. (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. Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	T_{TO} (s)	h_{BAR} (m)	Outcome	h_{PK} (m)	h_{CLS} (m)	h_{CLA} (m)	Δh_{CLS} (m)	Δh_{CLA} (m)	H_T (**)	H_F (**)	H_L (**)	H_S (**)
Acuff	15 N94	0.16	1.86	clearance	1.97	1.86	1.90	-0.11	-0.07	45	105	90	140
	77 U95	0.16	1.95	clearance	2.04	1.95	1.96	-0.09	-0.08	45	100	85	135
	57 U97	0.18	1.96	clearance	2.07	1.97	1.97	-0.10	-0.10	30	95	80	125
	45 U98	0.16	1.94	clearance	2.00	1.90	1.93	-0.10	-0.07	35	80	95	125
	43 U99	0.15	1.96	miss	1.95	1.95	1.95	0.00	0.00	35	140	80	165
	32 U01	0.15	1.88	clearance	1.89	1.87	1.87	-0.02	-0.02	40	115	80	140
	19 U02	0.16	1.90	clearance	1.94	1.87	1.88	-0.07	-0.06	35	115	90	145
	58 U03	0.16	1.95	clearance	2.01	1.98	1.98	-0.03	-0.03	30	140	95	170
	47 T04	0.15	1.95	clearance	1.98	1.95	1.95	-0.03	-0.03	30	135	75	155
	41 U06	0.16	1.92	clearance	2.00	1.94	1.94	-0.06	-0.06	35	110	90	140
Gordon	09 T04	0.18	1.84	clearance	1.92	1.83	1.84	-0.09	-0.08	25	65	90	110
	13 U06	0.18	1.83	miss	1.90	1.80	1.86	-0.10	-0.04	40	30	110	115
Hooker	11 U06	0.19	1.83	clearance	1.98	1.90	1.94	-0.08	-0.04	40	75	75	105
Howard	27 U03	0.15	1.89	clearance	1.98	1.90	1.93	-0.08	-0.05	45	100	80	125
	45 T04	0.15	1.95	clearance	2.01	1.96	1.97	-0.05	-0.04	40	100	80	130
	46 U06	0.14	2.01	clearance	2.06	2.02	2.03	-0.04	-0.03	50	95	70	120
Spence	09 U06	0.16	1.83	clearance	1.92	1.81	1.87	-0.11	-0.05	45	60	90	110
Wagner	21 U03	0.22	1.84	clearance	1.94	1.88	1.90	-0.06	-0.04	50	45	110	120
	29 T04	0.21	1.89	miss	1.94	1.83	1.89	-0.11	-0.05	50	40	115	125
	01 U06	0.21	1.83	clearance	1.90	1.81	1.82	-0.09	-0.08	50	50	105	115

(*) N94 = 1994 NCAA Championships; T04 = 2004 U.S. Olympic Trials; U95 = 1995 USATF Ch.; U97 = 1997 USATF Ch.; U98 = 1998 USATF Ch.; U99 = 1999 USATF Ch.; U01 = 2001 USATF Ch.; U02 = 2002 USATF Ch.; U03 = 2003 USATF Ch; U06 = 2006 USATF Ch.

(**) Angular momentum units: $s^{-1} \cdot 10^{-3}$

rough estimates. It is also necessary to keep in mind that high jumpers can generally depress the bar about 0.02 m, sometimes 0.04 m, and occasionally 0.06 m or more without knocking it down.

The differences between the clearance heights and the peak height of the c.m. 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 ($\Delta h_{CLA} = h_{CLA} - h_{PK}$). Larger negative numbers indicate less effective bar clearances.

Table 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}), the absolute maximum height that the athlete would have been able to clear without touching the bar (h_{CLA}), the effectiveness of the bar clearance in the plane of the standards (Δh_{CLS}), and the absolute effectiveness of the bar clearance (Δh_{CLA}) in the analyzed trials.

The most usual 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" (Figure 2). The value of this

Figure 11

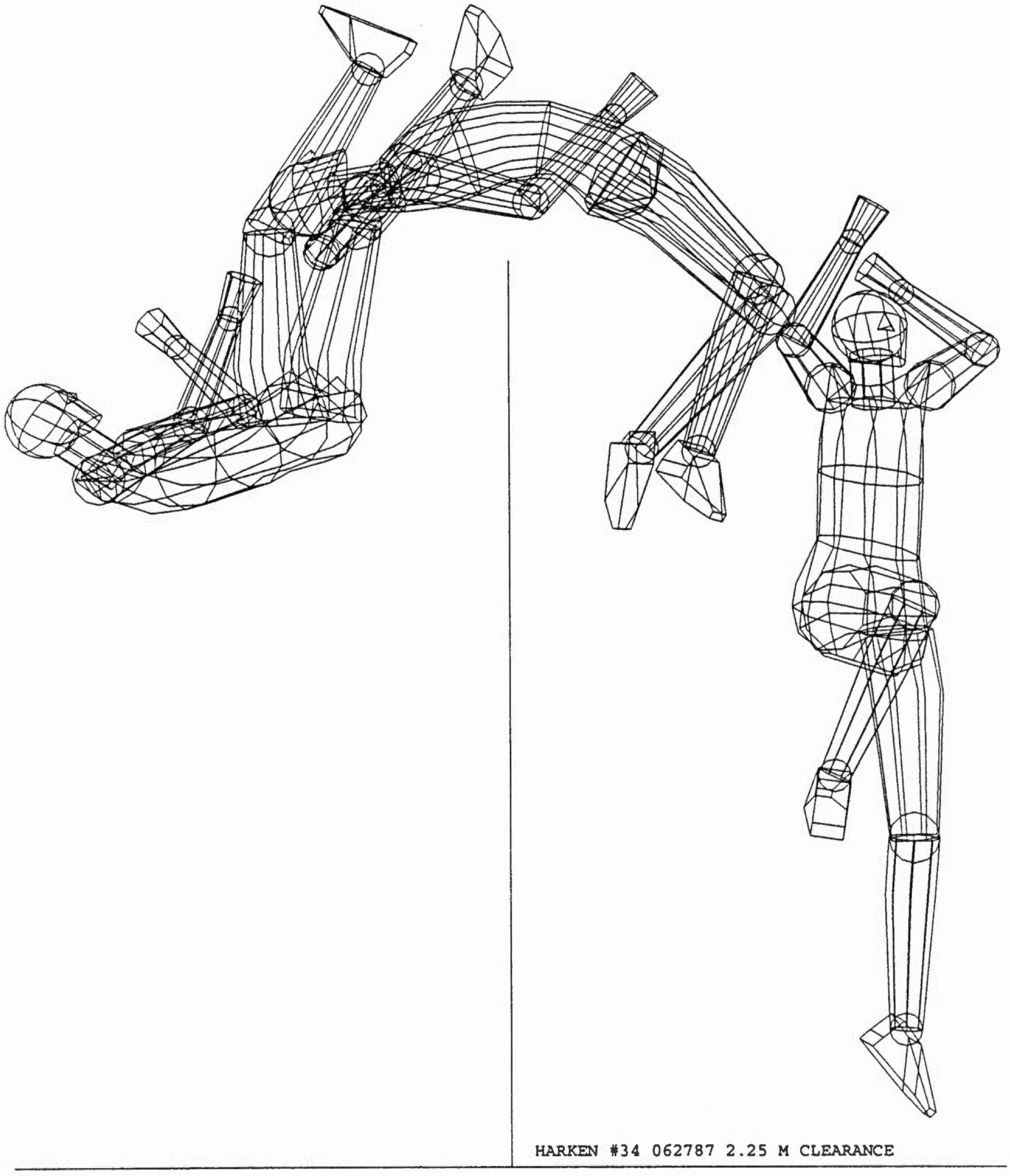


Figure 12

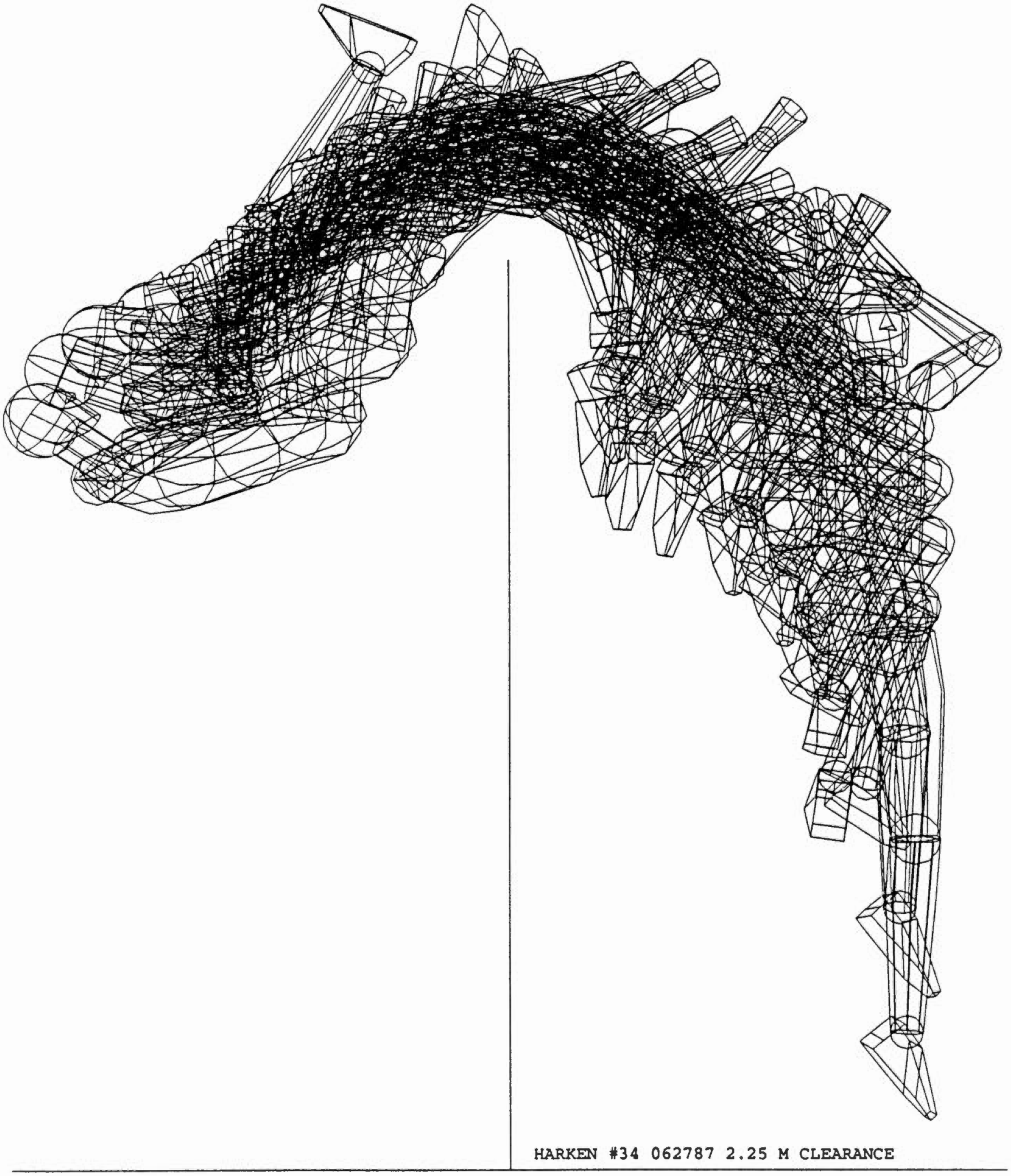
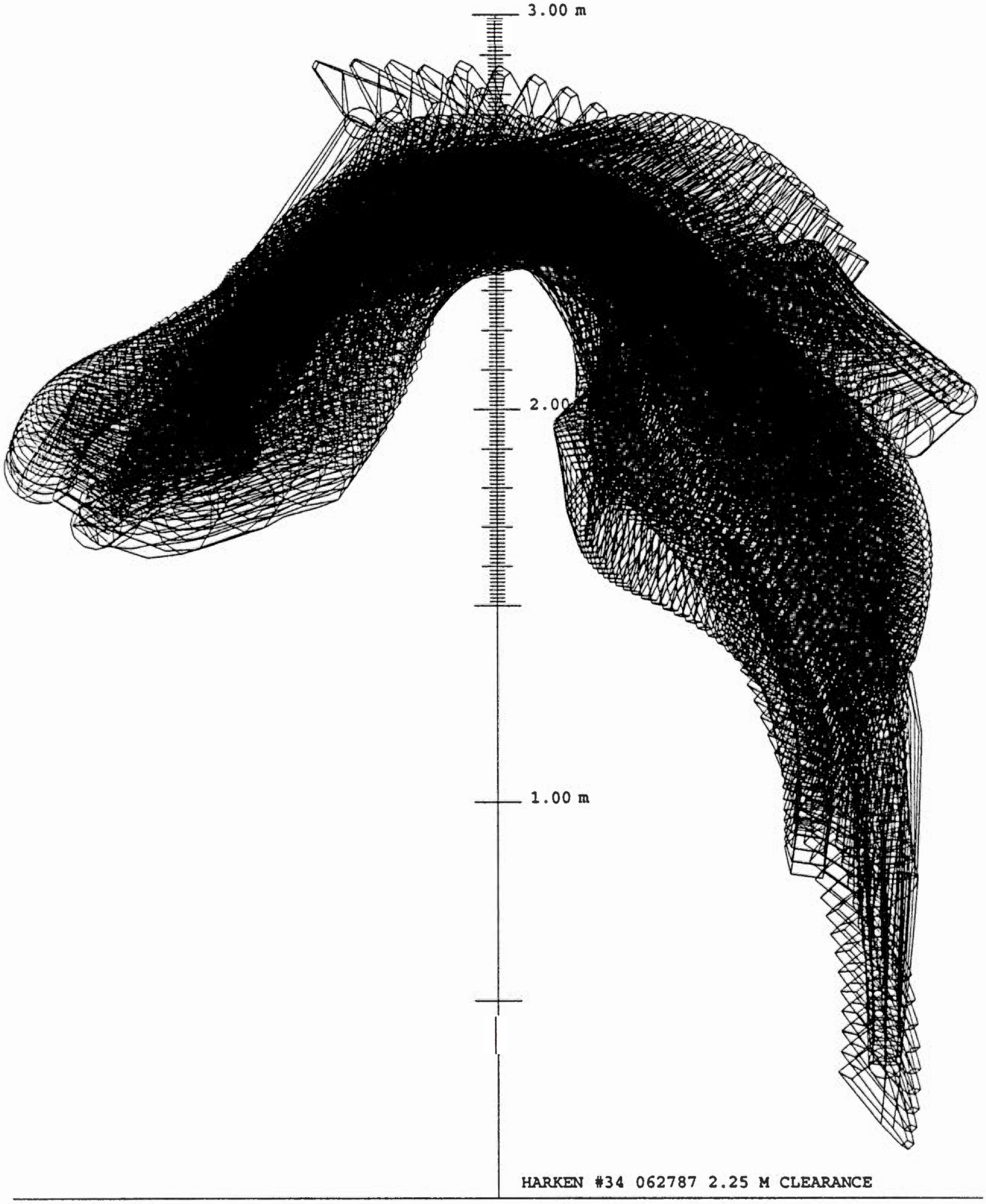


Figure 13



distance is shown in Table 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 c.m. 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 c.m. 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 c.m. 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 2) will also travel more perpendicular to the bar after the completion of the takeoff phase (indicated by large p_0 angles in Table 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 3) will also have more horizontal velocity left after takeoff (indicated by large values of v_{HTO} in Table 3); thus, they will travel through larger horizontal distances after the completion of the takeoff phase than slower jumpers, and they will also need to take off farther from the bar in order for the c.m. 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 toward 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 (also called "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 the 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 sometimes 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 analyzed athletes are shown in Table 5. 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.)

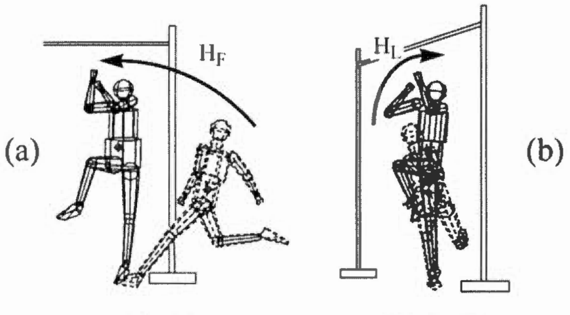
The somersault rotation, which will make the shoulders go down while the knees go up, results from two components: a forward somersaulting component and a lateral somersaulting component.

(a) 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 Figure 14a and the sequence at the top of Figure 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.

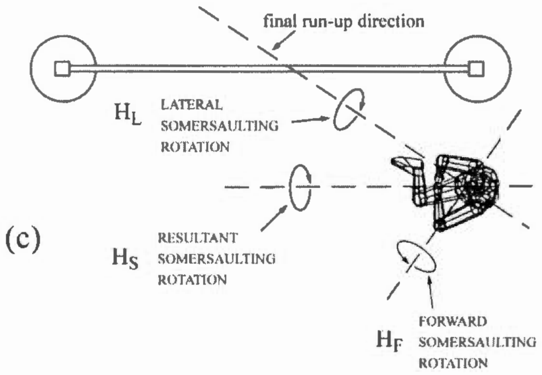
The tilt angles of the trunk at the start and at the end of the takeoff phase (see "Trunk lean") are statistically related to the angular momentum obtained by the athlete. Large changes of the trunk tilt from a backward position toward vertical during the takeoff phase are associated with a larger amount 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 greater 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

Figure 14



side view back view



overhead view

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 Figure 16) they also imply backward (clockwise) rotations of these limbs, which can reduce the total forward somersaulting angular momentum of the body.

To diminish this problem, some high jumpers turn their back toward the bar in the last step of the run-up, and then swing the arms diagonally forward and away from the bar during the takeoff phase (see Figure 17). Since this diagonal arm swing is not a perfect backward rotation, it interferes less with the generation of forward somersaulting angular momentum.

(b) 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 Figure 14b and the bottom sequence in Figure 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 toward the bar at the end of the takeoff. Since a leaning position would result in a lower height of the c.m. 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 c.m. 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 Figure 14b and the bottom sequence in Figure 15). The final upright position contributes to a higher c.m. position at the end of the takeoff phase. Also, the initial lateral tilt contributes to a lower c.m. 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 c.m. 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 toward the center of the curve at the start of the takeoff phase tend to get 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. 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 greater rotation of the trunk during the takeoff phase from its initial lateral direction toward the vertical.

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 c.m. at the peak of the jump. This supports the intuitive feeling of high jumpers that it is necessary to seek a compromise between lift and rotation.

The bottom sequence in Figure 17 shows that in an athlete who takes off from the left leg a diagonal

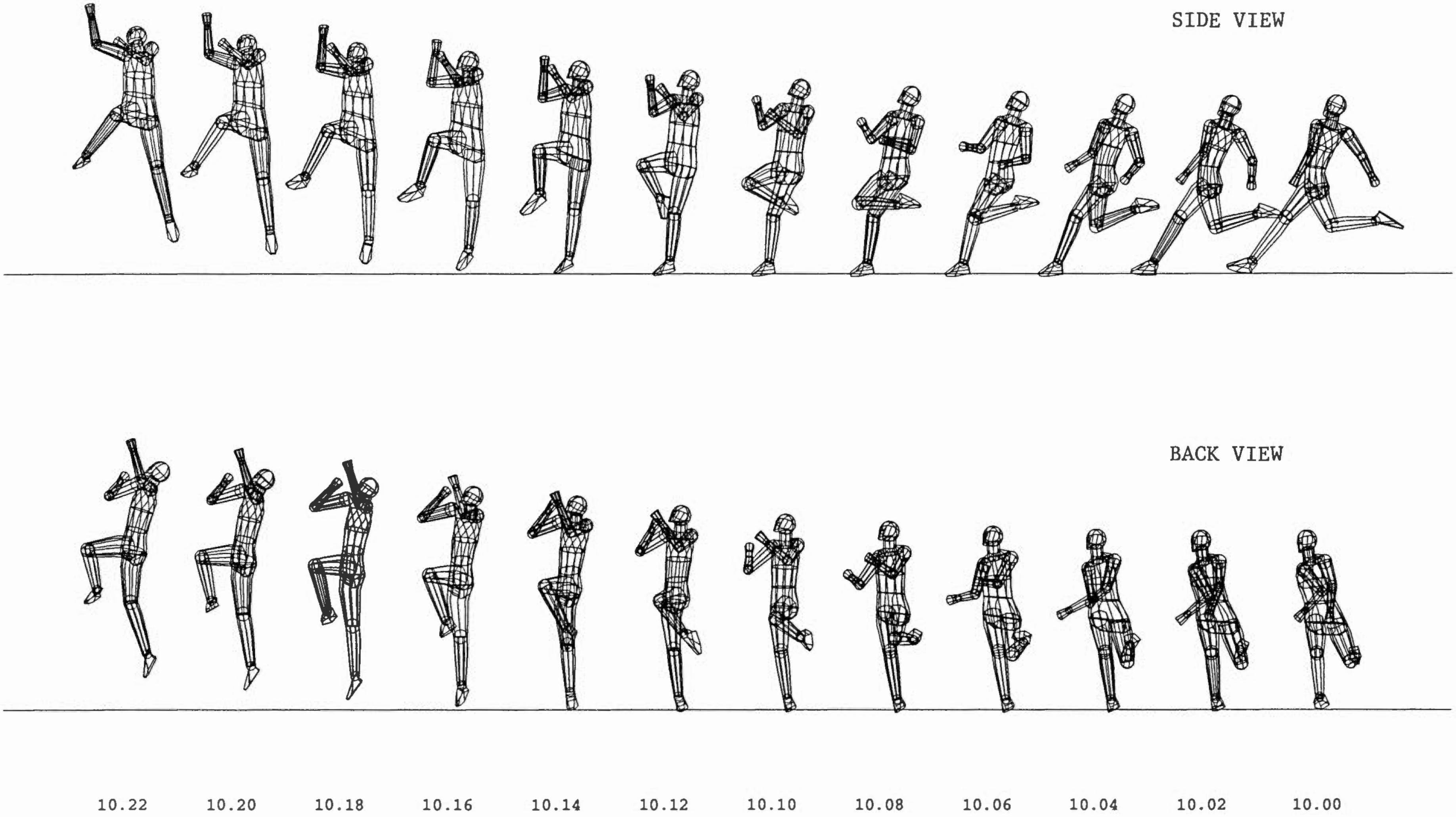

SIDE VIEW
BACK VIEW
10.22
10.20
10.18
10.16
10.14
10.12
10.10
10.08
10.06
10.04
10.02
10.00

Figure 15

DIRECT FORWARD ARM SWING

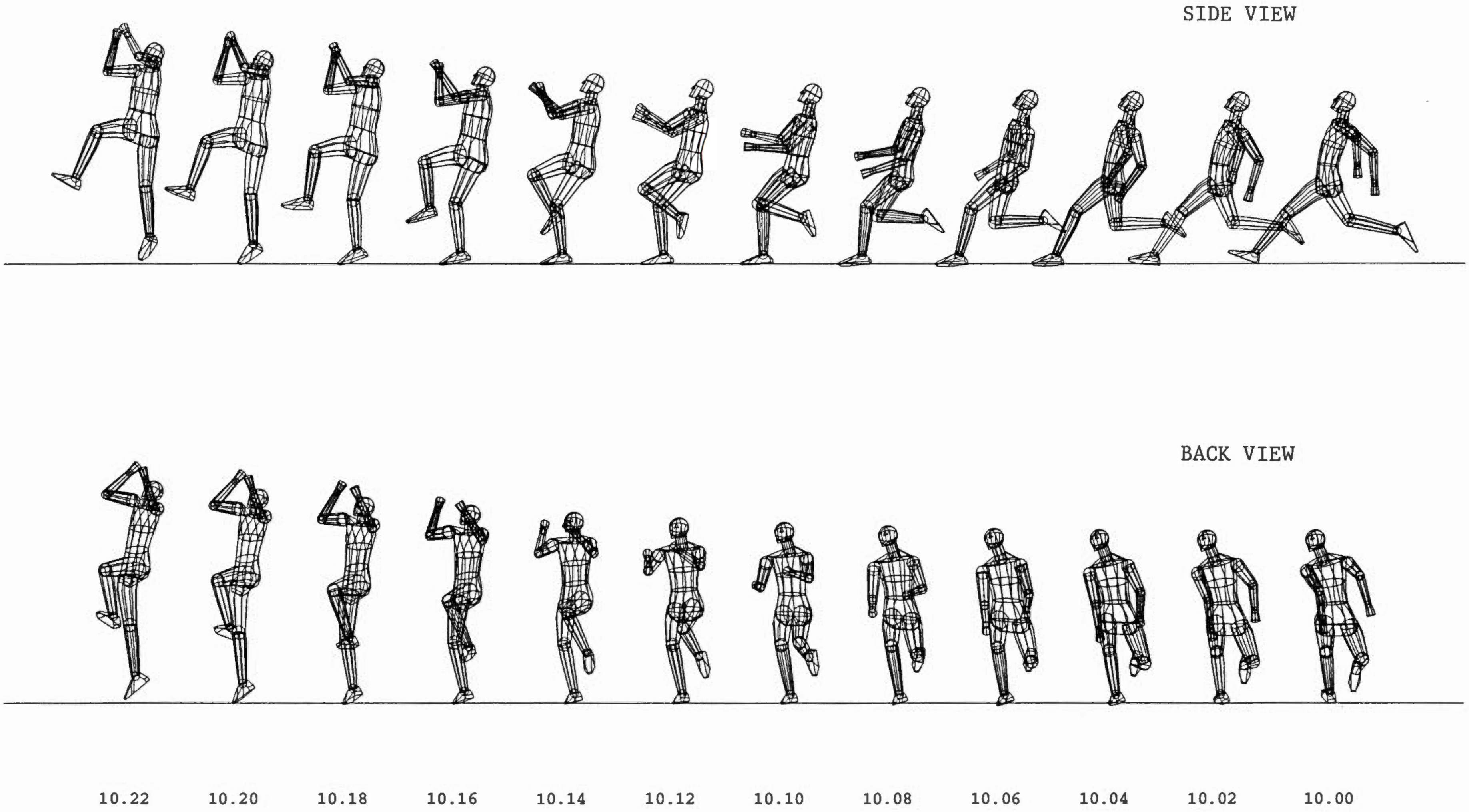


Figure 16

DIAGONAL ARM SWING

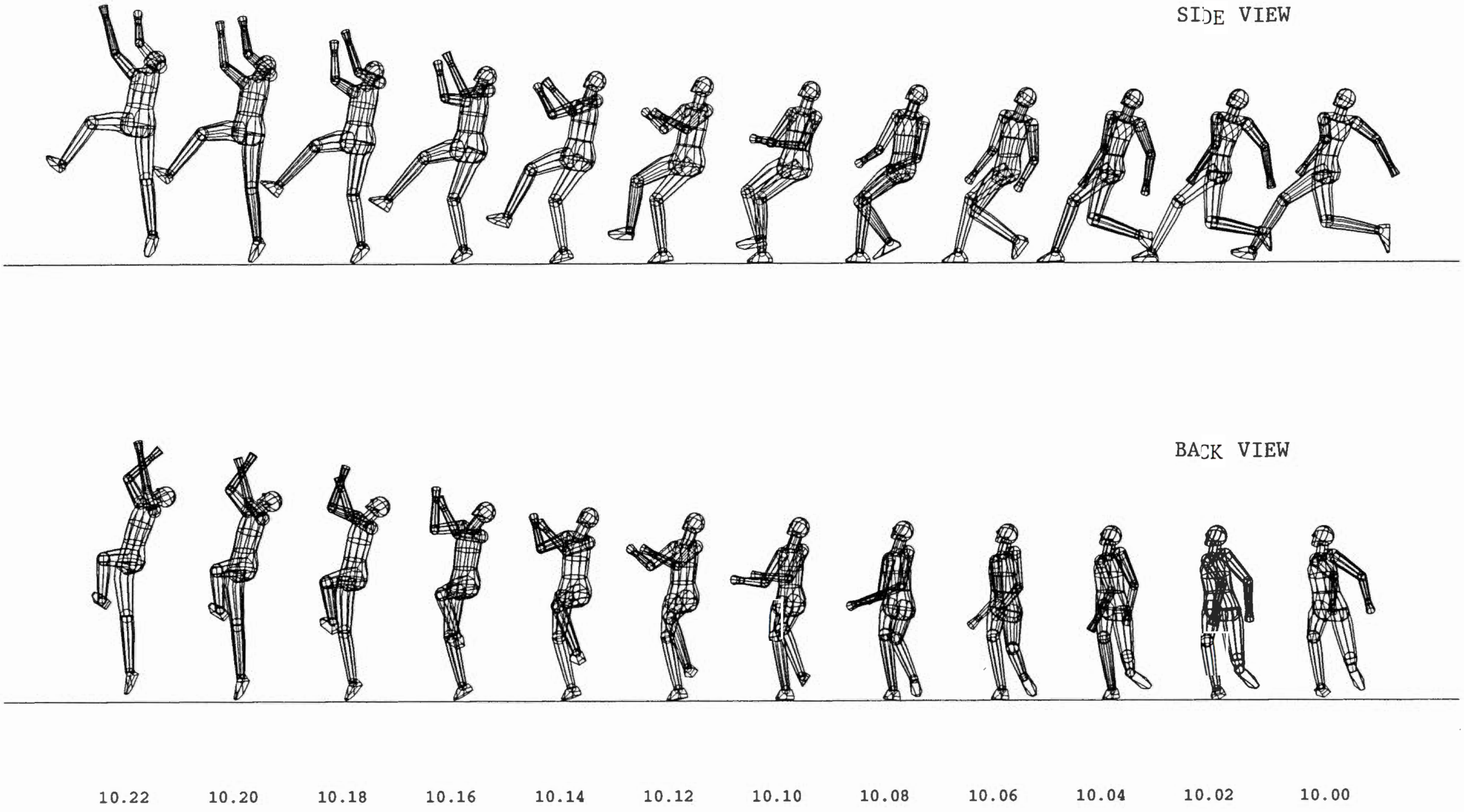


Figure 17

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 (Figure 14c). (This is not a simple addition; the formula is $H_S = \sqrt{H_F^2 + H_L^2}$.)

The forward (H_F), lateral (H_L) and total (H_S) somersaulting angular momentum values of the analyzed athletes are shown in Table 5, and in graphical form in Figure 18. (To facilitate comparisons among athletes, the angular momentum values have been normalized for the weight and standing height of each athlete.) 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 don't jump quite as high, and therefore they need to rotate faster to compensate for the smaller amount of time that they have available between the takeoff and the peak of the jump.

Adjustments in the air

After the takeoff is completed, the path of the c.m. is totally determined, and nothing can be done 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 body parts (the c.m.), 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 c.m., 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.

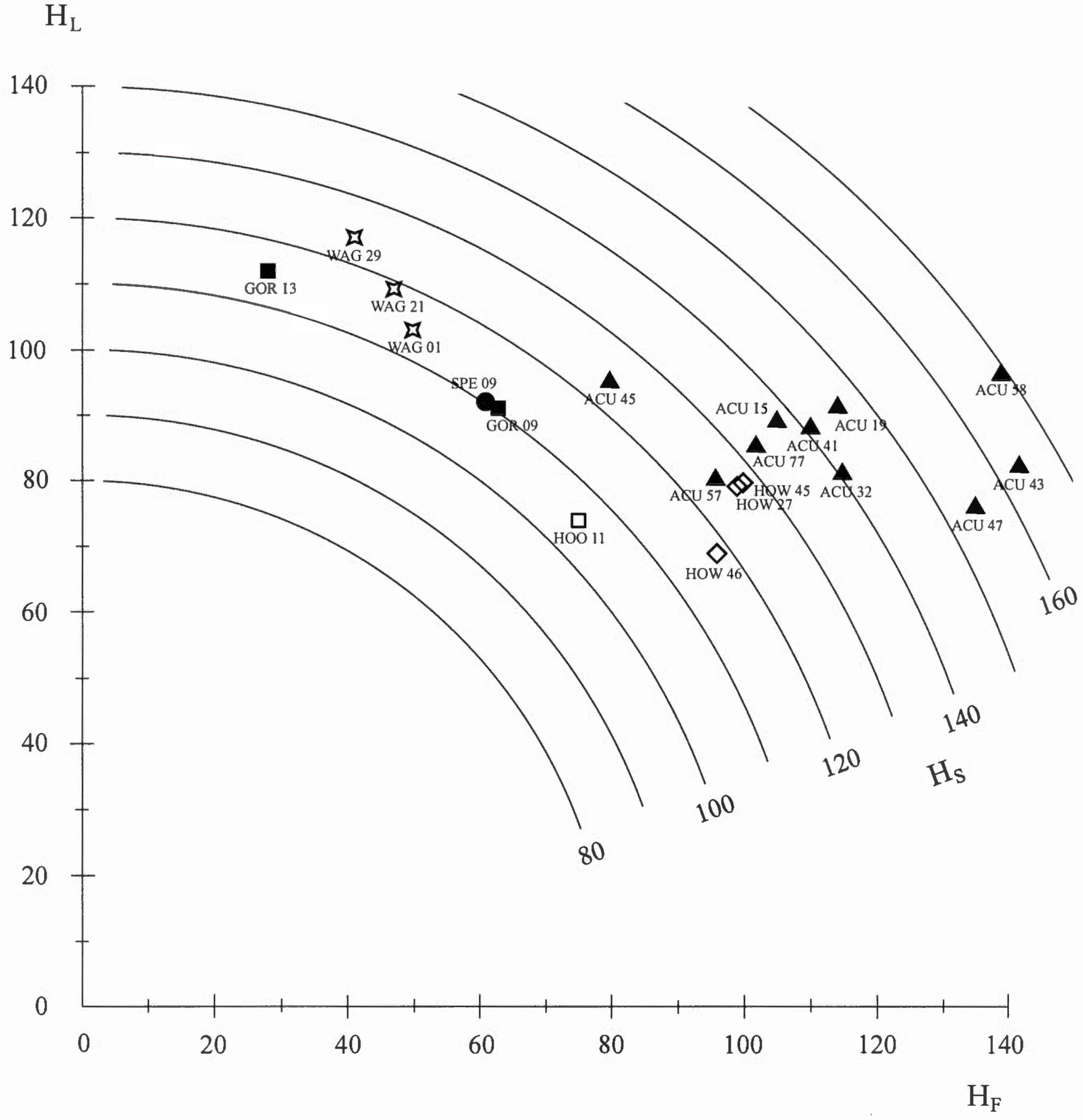
To a great extent, the rotation of the high jumper in the air is also determined once the takeoff phase is completed, because the angular momentum of the athlete cannot be changed during the airborne phase. However, some alterations of the rotation are still possible. By slowing down the rotations of 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 Figure 19a slowed down 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 shown by 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.

There can be several reasons for an athlete's weak arching. The athlete may be unaware that he/she is not arching enough. Or the athlete is not able to coordinate properly the necessary actions of the limbs. Or the athlete is not flexible enough. Or the athlete *is* flexible enough but has weak abdominal muscles and hip flexor muscles (the muscles that pass in front of the hip joint), and therefore is reluctant to arch very much since he/she is aware that the necessary un-arching action that will be required later will be impossible to execute with the necessary forcefulness due to the weakness of the abdominal and hip flexor muscles.

Another way in which rotation can be changed is by altering the "moment of inertia" of the body. 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 Figures 19b and 19c both had the same amount of somersaulting angular momentum. However, the athlete in Figure 19c somersaulted faster: Both jumpers had the same tilt at t = 10.22 s, but at t = 10.94 s the athlete in Figure 19c had a more backward-rotated position than the athlete in Figure 19b. The faster speed of rotation of

Figure 18



H_L
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
H_F
80
100
120
140
160
H_S
GOR 13
WAG 29
WAG 21
WAG 01
SPE 09
GOR 09
ACU 45
HOO 11
ACU 15
ACU 19
ACU 41
ACU 77
ACU 57
HOW 45
HOW 27
ACU 32
HOW 46
ACU 58
ACU 43
ACU 47

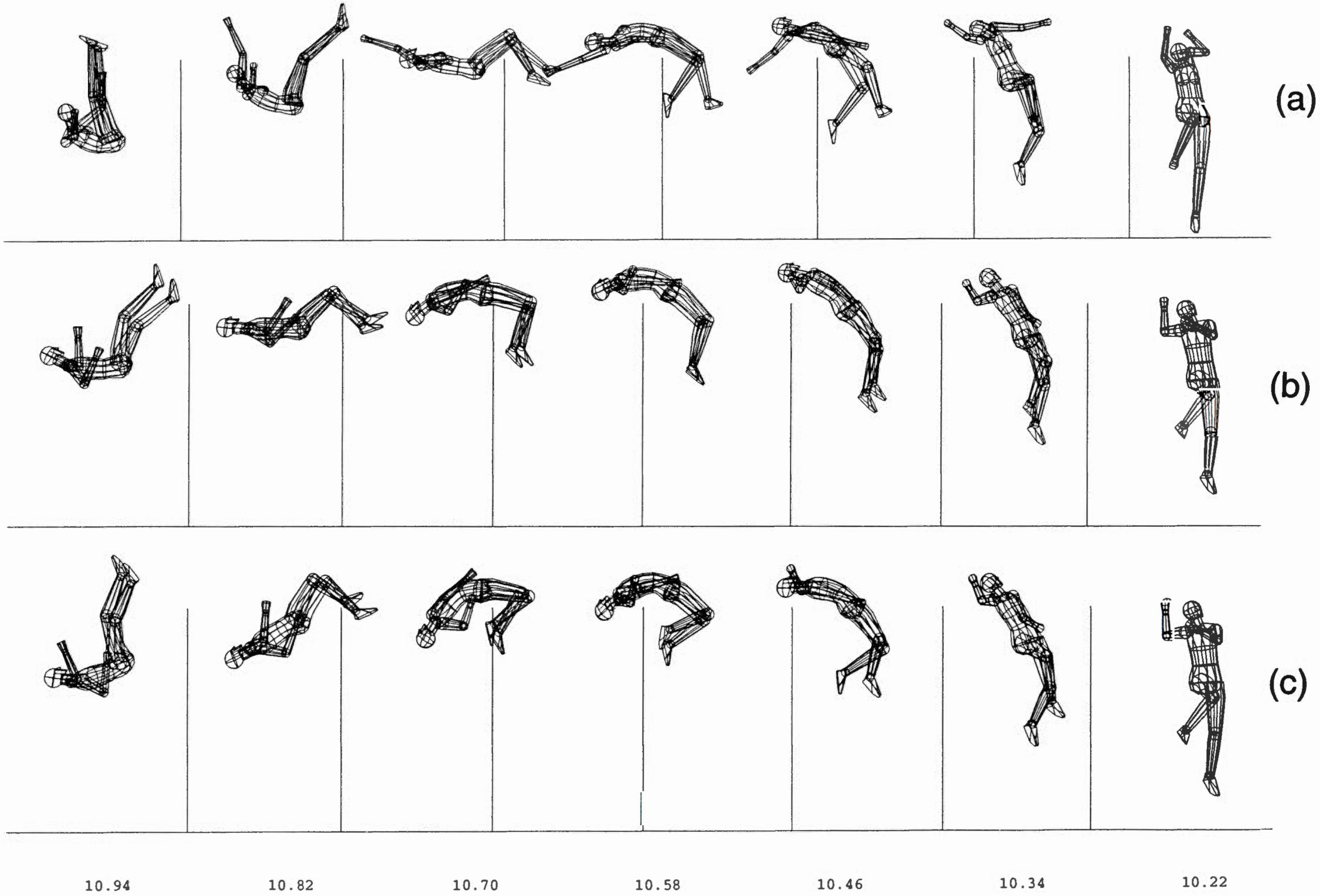


Figure 19

the jumper in Figure 19c was due to his 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 Figures 19b and 19c were artificial jumps produced using computer simulation –see below. 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 Figure 19c can be very helpful for high jumpers with low or moderate amounts of somersaulting angular momentum. Both jumps shown in Figures 19b and 19c had the same amount of angular momentum (H_S = 110), and the center of mass reached a peak height 0.07 m higher than the bar in both jumps. While the athlete in Figure 19b hit the bar with his calves (t = 10.82 s), the faster somersault rotation of the athlete in Figure 19c helped him to pass all parts of the body over the bar with some room to spare.

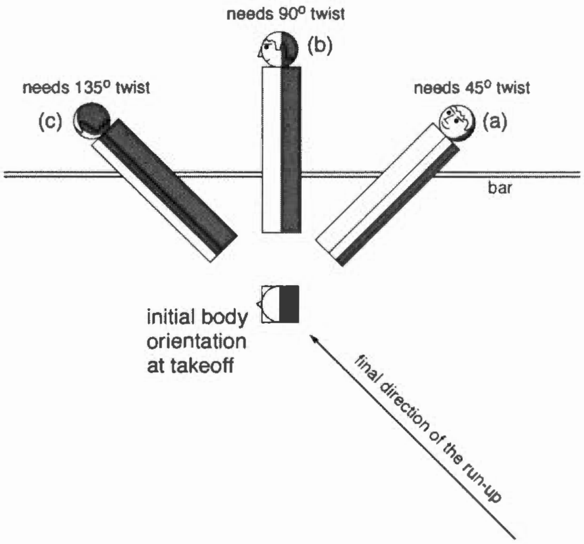
In the rare cases in which a high jumper has a very large amount of angular momentum, the technique shown in Figure 19c could be a liability, because it might accelerate the rotation so much that the shoulders will hit the bar on the way up. For athletes with a large amount of angular momentum, it will be better to keep the legs more extended on the way up to the bar, following the body configuration pattern shown in Figure 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 tilted to one side with one hip lower than the other. One of the most important of these factors is the proportion between the sizes of the forward and lateral components of the somersaulting angular momentum. We will now see how this works.

Figure 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 image b, which would require in addition 90° of twist rotation to generate a face-up orientation. If instead an athlete generated only *lateral* somersaulting angular momentum, the result would be the position shown in image a, 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 image c, 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 of 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.

Figure 20



Another point that we have to take 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. 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 in 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 Figure 21.

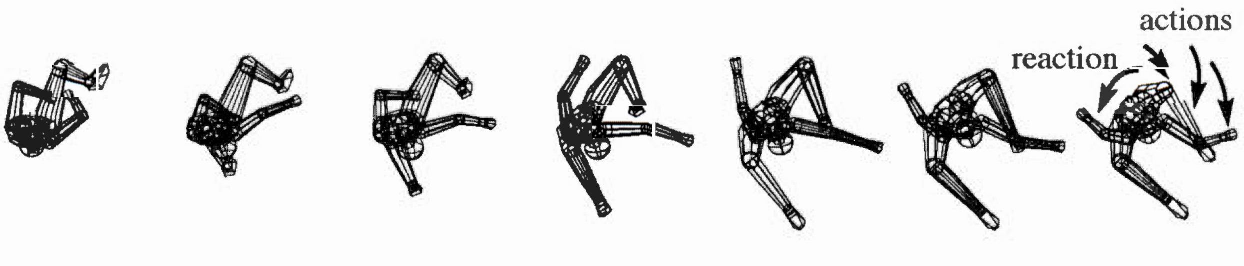
The sequence in Figure 21 covers the period between takeoff and the peak of the jump, and progresses from left to right. All the images are viewed from a direction aligned with the longitudinal axis of the athlete. (The head is the part of the athlete nearest to the "camera".) As the jump progressed, 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 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 toward the right, and then backward. (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 Figure 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 be in 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 backward too far, or is tilting too far toward the right (too far toward 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 that are too complex to explain here.

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

Figure 21



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 backward tilted position of the body at the end of the takeoff phase; a position that is too tilted toward the right at the end of the takeoff phase (toward the left in the case of jumpers taking off from the right foot); premature lowering of the lead leg soon after takeoff.

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

Control of airborne movements; computer simulation

We have seen that the c.m. path and the angular momentum of a high jumper are determined by the time the athlete leaves the ground. We have also seen that in spite of these restrictions on the freedom of the jumper, the athlete still has a certain degree of control over the movements of the body during the airborne phase.

Sometimes it is easy to predict in rough general terms how the actions of certain parts of the body during the airborne phase will affect the motions of the rest of the body, but it is difficult to judge through simple "eyeballing" whether the **amounts** of motion will be sufficient to achieve the desired results. Other times, particularly in complex three-dimensional airborne motions such as those involved in high jumping, it is not even possible to predict the **kinds** of motions that will be produced by actions of other parts of the body, let alone their amounts.

To help solve this problem, a method for the computer simulation of human airborne movements was developed (Dapena, 1981). In this method, we give the computer the path of the c.m. and the angular momentum of the body from an actual jump that was filmed or videotaped. We also give the computer the patterns of motion (angles) of all the body segments relative to the trunk during the entire airborne phase. The computer then calculates how the trunk has to move during the airborne phase to maintain the path of the c.m. and the angular momentum of the whole body the same as in the original jump. If we input to the computer the original patterns of motion of the segments (that is, the patterns of motion that occurred in the original jump), the computer will generate a jump that will be practically identical to the original jump. But if we input to the computer altered patterns of motion of the segments, the computer will generate an altered jump. This is the jump that would have been produced if the high jumper had used the same run-up and takeoff as in the original jump, but then decided to change the motions of the limbs after taking off from the ground. Once the computer has generated the simulated jump, this jump can be shown using graphic representations just like any other jump.

With the simulation method, it is also possible to input to the computer an altered amount of angular momentum. This generates a simulated jump that shows how the athlete would have moved in the air if the run-up and takeoff had been changed to produce a different amount of angular momentum than in the original jump.

The computer simulation method just described can be used to test for viable alternatives in the airborne actions of high jumpers, and also to investigate the effects of different amounts of angular momentum.

SPECIFIC RECOMMENDATIONS FOR INDIVIDUAL ATHLETES

Amy ACUFF

Jump 41 was Acuff's last successful clearance at the 2006 USATF Championships (1.92 m).

Based on Acuff's vertical velocity at takeoff in jump 41 (v_{ZTO} = 3.65 m/s), a technique of average quality would have included a final run-up speed of about 6.7 m/s and a c.m. height at the end of the run-up equal to about 48% of her own standing height. At the end of the run-up, Acuff was slower (v_{H1} = 6.6 m/s) and also higher (h_{TD} = 49.5%) than what would be expected for a technique of average quality. Therefore, the combination of run-up speed and c.m. height that she used in jump 41 was a very weak challenge for the strength of her takeoff leg. She needs to be much faster and/or lower at the end of the run-up. This remains the most important problem in Acuff's technique.

We do not know what was Acuff's speed three steps before takeoff. It seemed quite fast in direct visual observation during the meet, but we do not know for sure because our filming set-up does not allow us to take measurements from that step. We do know that her speed in the next-to-last step of the run-up was 6.9 m/s, not too bad. However, she then lost 0.3 m/s in the support phase over the right foot, and thus ended up at 6.6 m/s at the end of the run-up.

At the end of the run-up, Acuff planted the takeoff foot too parallel to the bar in jump 41. Because of this, the angle between the longitudinal axis of the foot and the horizontal force received by the foot was very large (e_3 = 43°). This was about as large as it has ever been in our analyses of Acuff's jumps. Normally, this would produce a great risk of ankle pronation, and of injury to the ankle and foot. (See the section on "Orientation of the takeoff foot, and potential for ankle and foot injuries" in the main text of the report.) At this point, the danger may be smaller due to the slow final speed of her run-up and to her high body position at the start of the takeoff phase. However, the risk would increase if she follows our advice and adopts a faster and lower run-up. Therefore, the correction of the foot placement should be accomplished before a fast and low run-up is adopted.

As usual, in the last steps of the run-up Acuff did not prepare her arms for a double-arm takeoff. Therefore, the right arm was ahead of her body and in a high position at the start of the takeoff phase. Because of this, the arm actions during the takeoff phase were very weak (AAT = 4.6 mm/m). In contrast, the action of her lead leg was strong (LLA = 21.3 mm/m). The combined actions of Acuff's arms and lead leg were stronger than in 2003 and 2004 (FLA = 25.9 mm/m), but in absolute terms they were still weak.

Acuff's trunk had a good backward lean at the start of the takeoff phase (BFTD = 76°). Then she rotated forward, and by the end of the takeoff her trunk was essentially vertical (BFTO = 91°). This was the best position that she has had at the end of the takeoff, in the view from the side, since 1997. Acuff's good positions at the beginning and at the end of the takeoff allowed her to generate a very large amount of forward somersaulting angular momentum (H_F = 110) without incurring a penalty in lift through excessive lean forward at the end of the takeoff. This was overall the best execution of this aspect of her technique that we have ever measured, even better than in 1994/1997.

Acuff had a moderate lean toward the left at the start of the takeoff phase (LRTD = 82°). She then rotated toward the right, but at the end of the takeoff she still had not quite reached the vertical (LRTO = 88°). In the view from the back, it is normal for high jumpers to go up to 10° past the vertical at the end of the takeoff. This seems to give an optimum compromise between the generation of lift and the generation of enough lateral somersaulting angular momentum to permit a good rotation over the bar. Acuff's rotation toward the right during the takeoff phase was very restricted, and therefore the amount of lateral somersaulting angular momentum that she was able to generate was somewhat small (H_L = 90).

Because of Acuff's very large amount of forward somersaulting angular momentum, and in spite of her somewhat small amount of lateral somersaulting angular momentum, her total amount of somersaulting angular momentum was very large but not huge (H_S = 140). Such an amount of angular momentum can produce extremely effective bar clearances, and yet does not require excessive leans at the end of the takeoff which would produce a loss of lift. So, although it is a smaller amount of angular momentum than what Acuff has been generating in recent years, it is a very good amount of angular momentum for her; she should not generate any more angular momentum than that.

Acuff's c.m. reached a maximum height h_{PK} = 2.00 m in jump 41. The "saturation graph" shows that in this jump she could have cleared cleanly a bar set at about h_{CLS} = 1.94 m. In relation to the peak height of the c.m. (2.00 m), the 1.94 m clean clearance height indicated a bar clearance that was not very effective. The reason was that Acuff used very little arching during the bar clearance. (See the view along the bar at t = 10.46-10.58 s.)

Recommendations

At the end of the run-up of jump 41, Acuff was in a high position, and traveling forward slowly. She needs either a lower position, a larger speed, or a combination of both. This remains the most important problem in Acuff's technique. A combination of v_{HI} = 6.9 m/s and h_{TD} = 47% would probably be good for her.

As explained in previous reports, Acuff needs to increase her speed in the final part of the run-up, but it is particularly important that she also learn to pull backward very actively with her right foot in the very last step of the run-up. Otherwise, any speed increase in the next-to-last step of the run-up will simply get cancelled out by a larger amount of braking as she passes over the right foot. (See Appendix 2 for exercises that will help to facilitate the lowering of the hips in the final part of the run-up without losing running speed.) The faster and lower run-up that we propose would provide a challenge that would be more suited to the strength of Acuff's takeoff leg, and therefore should allow her to generate more lift during the takeoff.

(Standard caution when increasing the run-up speed and/or lowering the c.m. height at the end of the run-up: ***The use of a faster and/or lower run-up will put a greater stress on the takeoff leg, and thus it may increase the risk of injury if the leg is not strong enough. Therefore, it is always 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.***)

The orientation of Acuff's foot during the takeoff phase is another important problem. She should plant the takeoff foot on the ground with the toe pointing more toward the pit, to make the longitudinal axis of the foot be at least 25° more clockwise than in jump 41. Currently, she may be protected to some extent by the fact that she is high and slow at the end of the run-up, which in turn reduces the forces exerted during the takeoff, and consequently the risk of injury –together with the height of the jump. But this is a bad way to provide safety for the ankle and foot. Acuff needs to be faster and/or lower at the end of the run-up, and she also needs to plant her takeoff foot in good alignment with the final direction of the run-up.

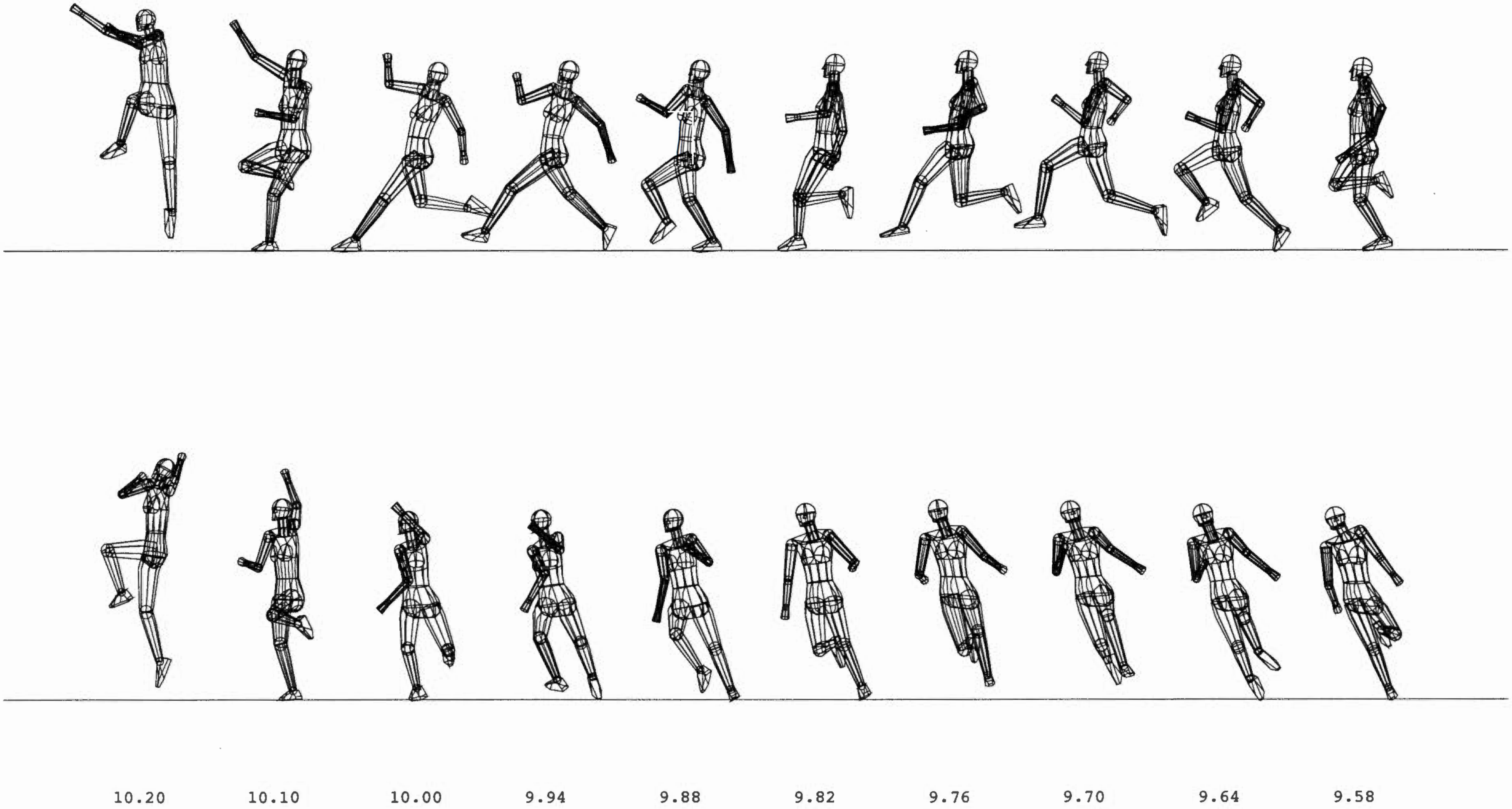
Acuff's body leans at the start and at the end of the takeoff phase, as well as her generation of angular momentum were all very good in jump 41. This was probably the best that she has executed this important aspect of high jumping technique in any of her analyzed jumps. In the future she needs to keep this the way it was in jump 41.

We feel that Acuff should first make the adjustment in the orientation of her takeoff foot. Then, she should concentrate on making the recommended changes in her height and speed at the end of the run-up (faster and/or lower). Those remain the two major problems in her technique, and they should be solved in that order: first the foot placement, and then the changes in speed and height at the end of the run-up.

The remaining technique problems are less important. She should increases her arch at the peak of the jump, and then un-arch with good timing. Also, it would not be a bad idea to strengthen the actions of the arms during the takeoff phase.

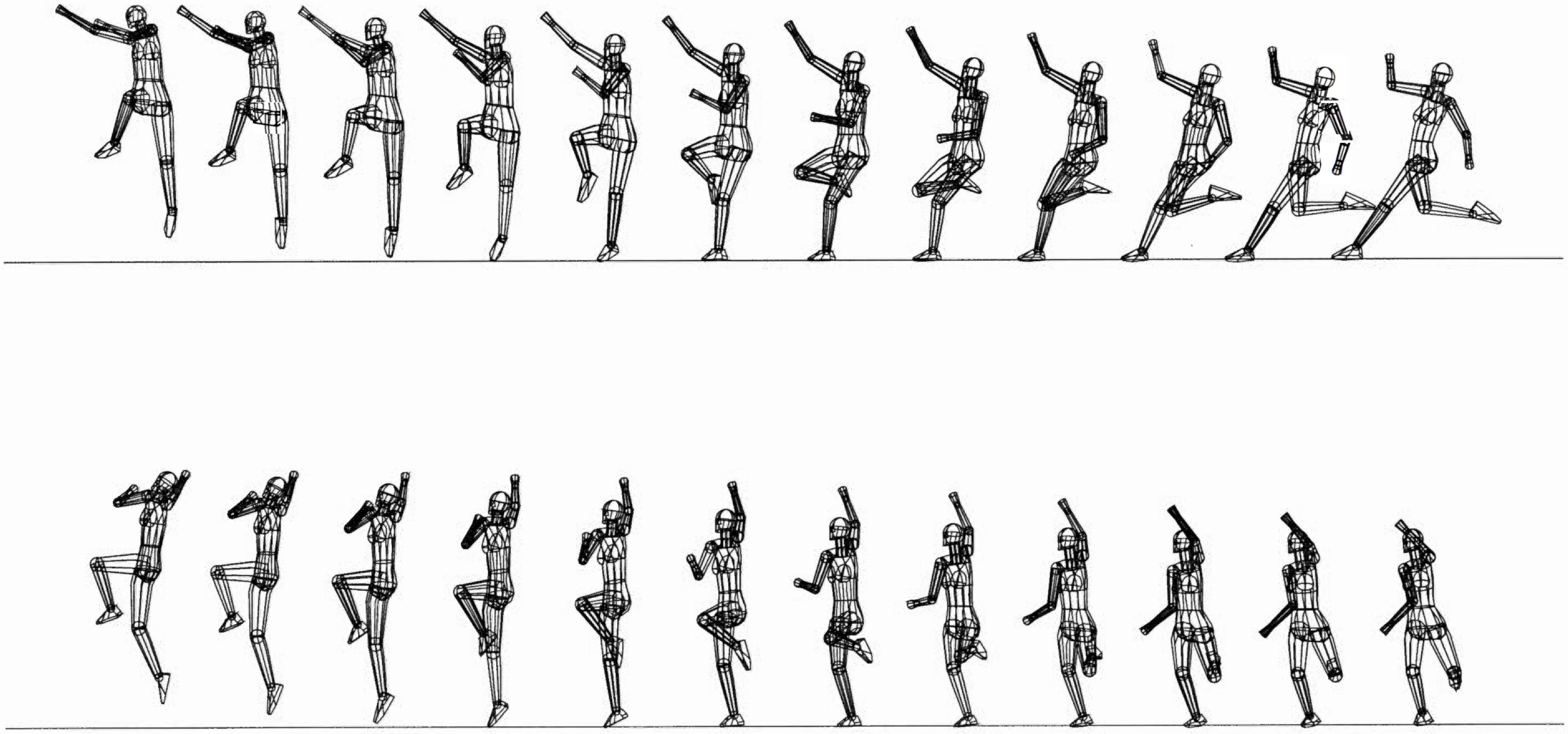
ACUFF #41 062406 1.92 M CLEARANCE

RUN-UP



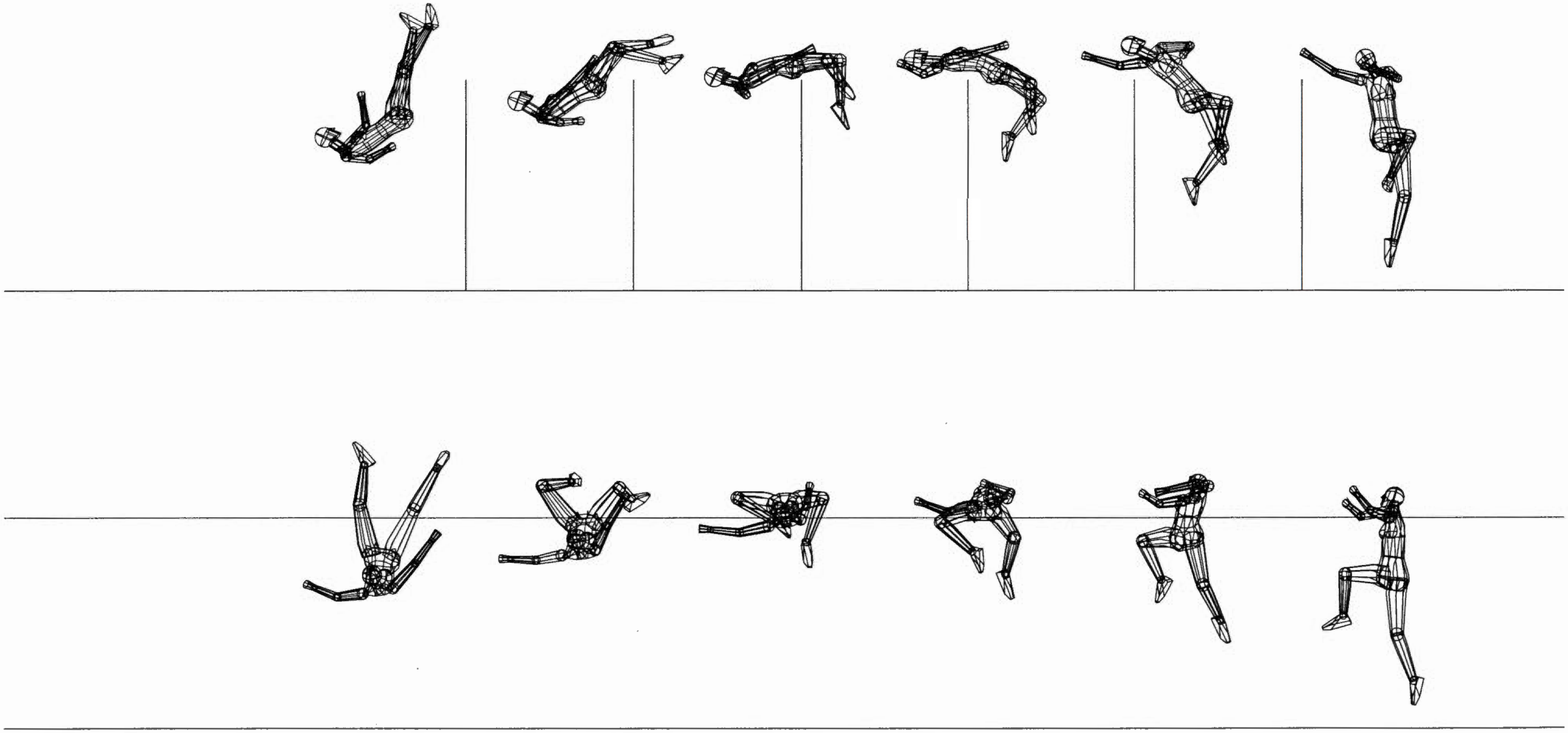
ACUFF #41 062406 1.92 M CLEARANCE

TAKEOFF PHASE

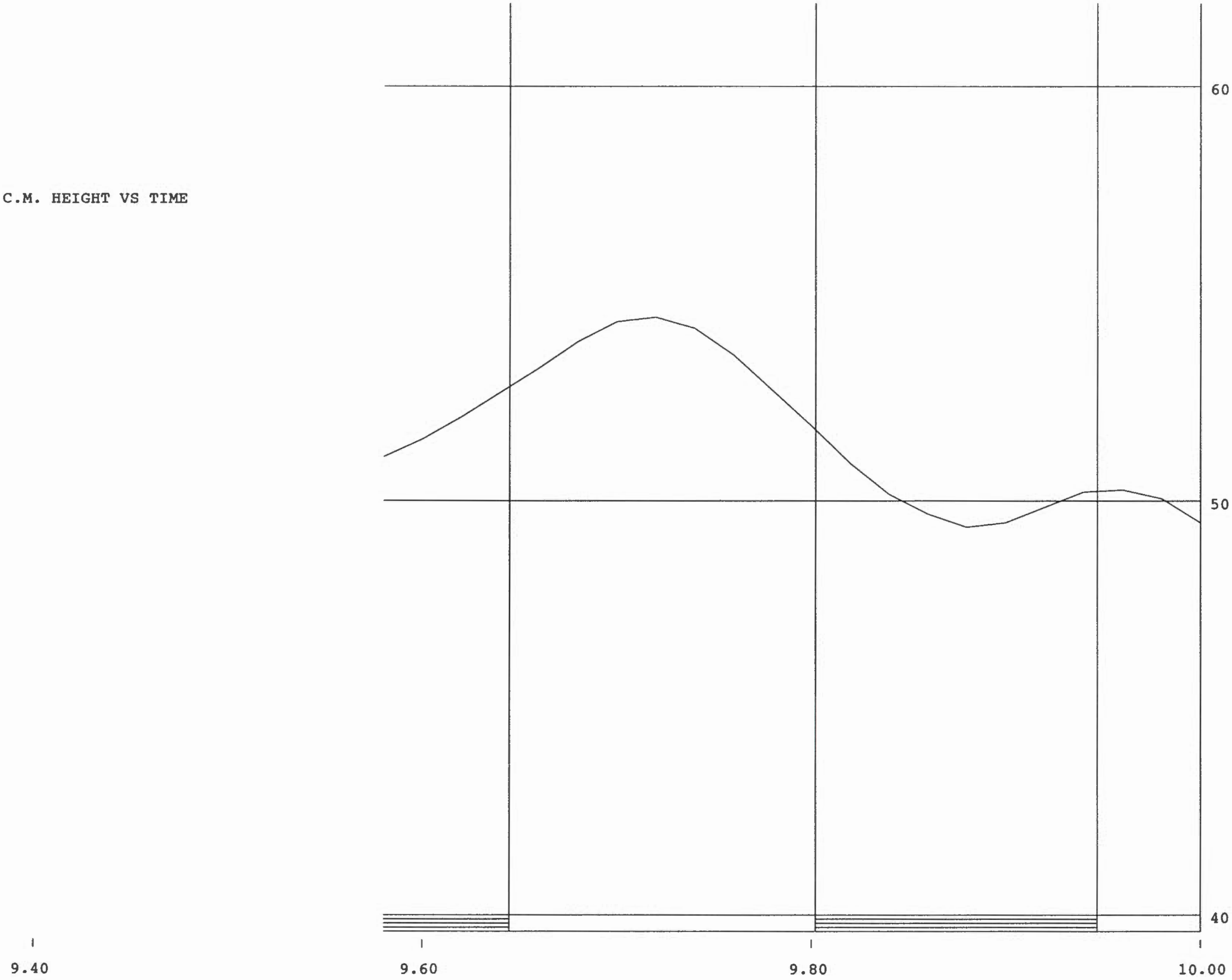


ACUFF #41 062406 1.92 M CLEARANCE

BAR CLEARANCE

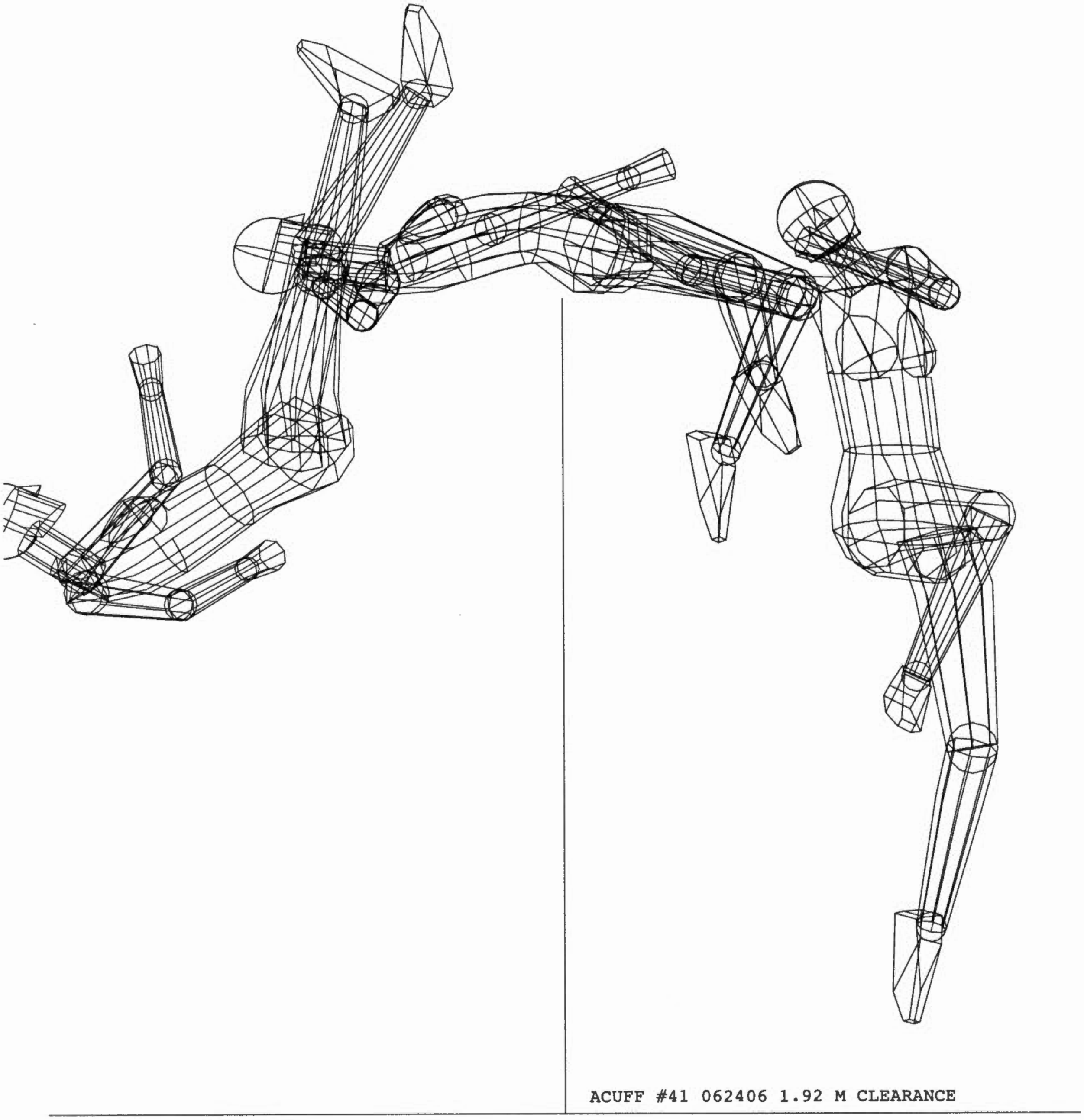


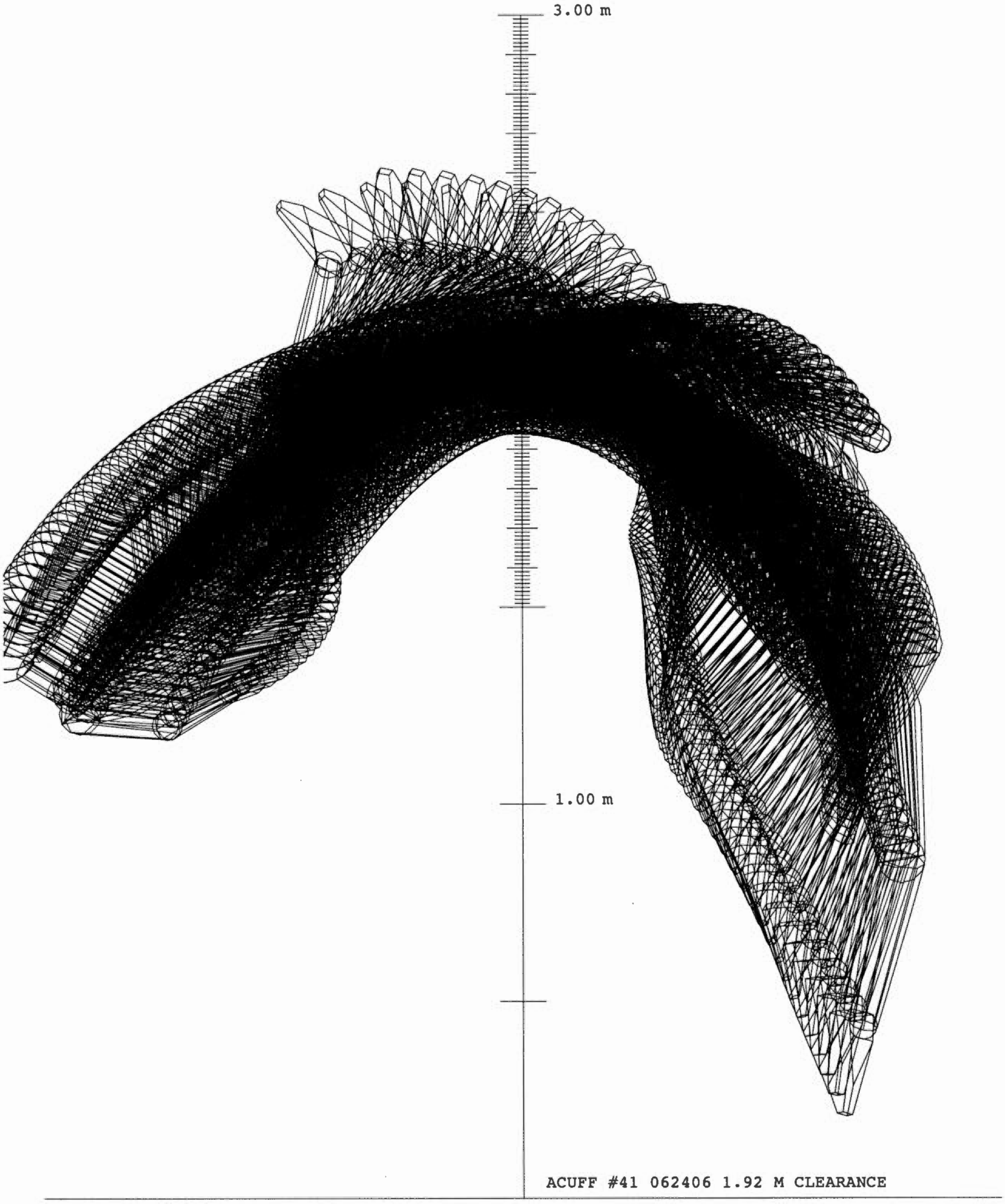
10.82 10.70 10.58 10.46 10.34 10.22



C.M. HEIGHT VS TIME

ACUFF #41 062406 1.92 M CLEARANCE


ACUFF #41 062406 1.92 M CLEARANCE


3.00 m
1.00 m
ACUFF #41 062406 1.92 M CLEARANCE

Sheena GORDON

Jump 13 was Gordon's 2nd attempt at 1.83 m at the 2006 USATF Championships. It was a close miss, and probably her best jump of the day.

Based on Gordon's vertical velocity at takeoff in jump 13 (v_{ZTO} = 3.55 m/s), a technique of average quality would have included a final run-up speed of about 6.6 m/s and a c.m. height at the end of the run-up equal to about 48.5% of her own standing height. In jump 13, Gordon's c.m. was actually slightly lower than the height that would be expected in a technique of average quality (h_{TD} = 47.5%), but she was also extremely slow (v_{H1} = 6.1 m/s), slightly slower even than at the 2004 U.S. Olympic Trials. Overall, the combination of run-up speed and c.m. height that she used in jump 13 was a very weak challenge for the strength of her takeoff leg. She needs to be much faster at the end of the run-up.

Gordon was in a low position in the early part of her support on the right leg, similar to the position that she had in 2004. (See the side view of the run-up sequence at t = 9.88 s and the graphic of "c.m. height vs. time".) Then she raised her hips, and planted the takeoff foot on the ground very soon after the takeoff of the right foot. (See the sequence and the graphic of the c.m. path between t = 9.88 s and t = 10.00 s.) Because of this, Gordon had no downward vertical velocity at all at the start of the takeoff phase (v_{ZTD} = 0.0 m/s). (This technique was similar to the one used by athlete C in Appendix 1.) Gordon executed this action without lifting her hips quite as high as in 2004, and therefore her c.m. was still at a reasonably low height at the start of the takeoff phase. This was all done very well, better than in 2004.

In 2004, Gordon had a very weak body position at the start of the takeoff phase, with an excessive amount of flexion in her takeoff knee and very little backward lean of her trunk. (See the 2004 report.) In jump 13, the backward lean at the start of the takeoff phase was greatly improved (and we will talk more about this later on), but the flexion of the takeoff knee at the start of the takeoff phase was essentially the same as in 2004. (See the side view sequence at t = 10.00 s, and compare it with the one from the 2004 report.) So there was a clear improvement in Gordon's body position at the start of the takeoff phase, but more work is still needed in regard to the angle of the left knee.

At the end of the run-up, Gordon planted the takeoff foot in a better orientation than in 2004, but still too parallel to the bar. Because of this, the angle between the longitudinal axis of the foot and the horizontal force received by the foot was too large (e_3 = 32°). This produced a risk of ankle pronation, and injury to the ankle and foot. (See the section on "Orientation of the takeoff foot, and potential for ankle and foot injuries" in the main text of the report.) Actually, it is possible that, with Gordon's current slow run-up, this may not be much of a problem today. However, it will become a more serious problem if she adopts a faster run-up, as we will advise her to do.

While Gordon's left knee had about the same amount of flexion at the start of the takeoff phase in jump 13 as in 2004, she kept the leg more stiff during the takeoff phase in jump 13, and therefore during the first half of the takeoff phase the knee flexed less than in 2004. (Compare the side view sequences of jump 13 and of jump 09 from the 2004 report at t = 10.08 s.) This was a good improvement, but Gordon still needs to have less flexion of her knee at the start of the takeoff phase. Her large amount of left knee flexion at the start of the takeoff phase made it very difficult for Gordon to push hard against the ground during the takeoff phase, and it would also put the takeoff leg in great risk of collapsing if she tried to have any reasonable amount of speed at the end of her run-up. A much stronger position, with the knee much straighter at the plant, is shown in Figure A2.1 of Appendix 2 and also, for instance, in the sequences of Howard and Acuff in the present report. The fact that Gordon had a very slow horizontal speed at the instant that she planted the takeoff foot on the ground in jump 13 helped to prevent the collapse of the takeoff leg. If Gordon increases her final run-up speed (which we will strongly advise her to do), she will also need to have her left knee more straight at the start of the takeoff phase. It will need to be almost completely straight (although **NOT locked straight**). Otherwise, her left leg probably will not be able to handle the stresses of the takeoff effort, and will collapse.

A high jumper is supposed to have a large horizontal velocity at the end of the run-up, and then lose a fair amount of it during the takeoff phase. The process of losing horizontal velocity during the takeoff phase helps the athlete to generate vertical velocity, and therefore increases the height of the jump. If not enough horizontal velocity is lost during the takeoff phase, this is a sign that the athlete did not use properly the speed of the run-up to generate lift during the takeoff phase. (See the section on "Change in horizontal velocity during the takeoff phase" in the main text of the report.) In jump 09 from 2004, Gordon did not lose enough horizontal velocity during the takeoff phase: $\Delta v_H = -2.1$ m/s, when it should have been about -2.8 m/s. In jump 13, there was a larger loss of horizontal velocity during the takeoff phase, $\Delta v_H = -2.4$ m/s. This was a nice improvement, and it was probably achieved thanks to the greater backward lean of Gordon's trunk at the start of the takeoff phase and to the stiffer use of the left leg during the takeoff phase. The improvement would have been still larger if the left knee had been more straight at the start of the takeoff phase.

Even though Gordon did not prepare her arms for a double-arm action during the takeoff phase, her arm actions during the takeoff phase were reasonably strong (AAT = 15.3 mm/m). This was because she lifted her left elbow and right hand to very high positions by the end of the takeoff. The action of her lead leg was very strong (LLA = 24.1 mm/m), and therefore the overall combination of arm and lead leg actions was very strong (FLA = 39.3 mm/m). This was all very good, even better than in 2004.

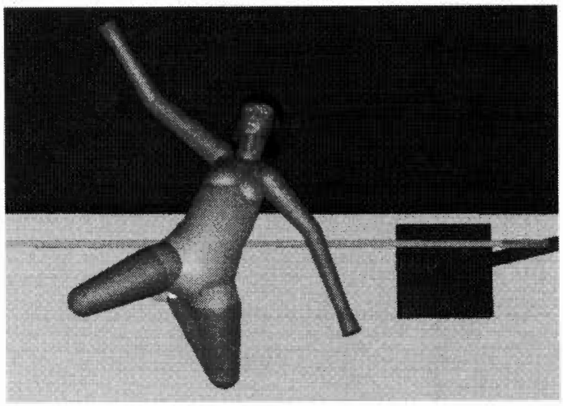
As previously mentioned, in jump 13 Gordon's trunk had a good backward lean at the start of the takeoff phase (BFTD = 76°). This was an excellent improvement in her technique with respect to 2004. However, she then did not rotate forward at all during the takeoff phase. In fact, she rotated slightly *backward*, and thus in the view from the side her trunk was farther from the vertical at the end of the takeoff than at the beginning (BFTO = 72°), when she was supposed to have rotated forward all the way to the vertical (90°). Not surprisingly, this limited the amount of forward somersaulting angular momentum that Gordon was able to generate during the takeoff phase to a very small value ($H_F = 30$).

As in 2004, in jump 13 Gordon's trunk had a very good initial lean toward the left at the start of the takeoff phase (LRTD = 76°). But after that, things were very different from 2004. In 2004, Gordon did not rotate enough toward the right during the takeoff phase, and this limited the amount of lateral somersaulting angular momentum that she was able to generate. Therefore, in our 2004 report we advised Gordon to allow herself to rotate further toward the right by the end of the takeoff. However, she overdid it: In jump 13 she went to the opposite extreme, and rotated excessively toward the right. At the end of the takeoff she was 14° beyond the vertical (LRTO = 104°). In the view from the back, we consider it acceptable (indeed, desirable) to tilt up to 10° past the vertical at the end of the takeoff, because we believe that this may be the best compromise between the generation of lift and the generation of rotation (angular momentum). But 14° beyond the vertical was excessive. By doing this, Gordon was able to generate a large amount of lateral somersaulting angular momentum ($H_L = 110$), but it probably also cost her part of her lift.

Gordon's very small amount of forward somersaulting angular momentum and large amount of lateral somersaulting angular momentum added up to a somewhat small total amount of somersaulting angular momentum ($H_S = 115$), not very different from the total amount that she generated in 2004.

The peak height reached by the c.m. in jump 13 was $h_{PK} = 1.90$ m. The "saturation graph" shows that in this jump Gordon could have cleared cleanly a bar set at about $h_{CLS} = 1.80$ m, and at $h_{CLA} = 1.86$ m if she had taken off about 5 cm closer to the plane of the bar and the standards. In relation to the peak height of the c.m. (1.90 m), the 1.86 m clean clearance height indicated a reasonably effective bar clearance. This was particularly good in view of Gordon's somewhat small total amount of somersaulting angular momentum. One factor that helped her to somersault relatively fast in spite of her somewhat small total amount of somersaulting angular momentum was the marked flexion of her knees during the bar clearance –see the view along the bar between t = 10.34 s and t = 10.58 s. However, in practical terms Gordon's bar clearance is not as effective as these numbers might lead us to believe, as we will see next.

Normally, we would say that Gordon is able to clear a bar 4 cm lower than the peak height of her c.m., and that all she needs to do to ensure that her bar clearance is this effective is to take off at the appropriate distance from the bar. The problem is that, in Gordon's case, this would be very difficult to do; she would need to be extremely precise in the placement of her takeoff foot to be able to clear a bar set only 4 cm below the peak height of her c.m. path. This is because the hollow area below her body path is very narrow, and thus small errors in the position of her takeoff point would result in great losses in the bar height that she would be able to clear. (See Gordon's saturation graph, the last page of Gordon's graphics that follow these comments. Notice how narrow the hollow area below her body is, from left to right; compare it with the much wider –and therefore more forgiving– hollow areas below the bodies of most of the other jumpers in this report.) Because of this, Gordon will usually need her c.m. to reach a peak height that is much higher than 4 cm above the bar in order to clear it, and that is not good. There seem to be two main reasons for this problem:



(1) One reason is the disproportion between the sizes of Gordon's forward and lateral somersaulting angular momentum components ($H_F = 30$; $H_L = 110$). This disproportion puts her body in a slanted position on top of the bar, with her head closer to the right standard and her legs closer to the left standard. (See the 3D computer graphic above.) Thus, her upper body was nearer to the vertical plane of the bar than it had to be as it traveled downward after clearing the bar, while her legs were also nearer to the vertical plane of the bar than they had to be as they traveled up toward the bar. This tended to "strangle" the hollow area below her body. (2) The other problem is that Gordon spread her knees far apart on the way up to the bar. (See the graphic above.) This allowed her to somersault a little bit faster because it made her body a little bit more compact in the view along the bar, but it also brought the right knee even closer to the bar, thus narrowing still further the hollow area below the body.

Recommendations

Gordon's arm and lead leg actions were good, as were her leans backward and toward the left at the start of the takeoff phase, but there were important problems in many other aspects of her jumping. The correction of these problems should produce substantial improvements in her performance.

Gordon needs to plant the takeoff foot on the ground with the longitudinal axis of the foot more in line with the final direction of the run-up: The foot needs to be planted with the toe pointing at least 15° more toward the landing pit than in jump 13. This technique change will help to prevent ankle pronation, and injury to the ankle and foot.

Gordon needs to be much faster at the end of the run-up than she was in jump 13. We would suggest a final speed $v_{H1} = 7.0$ m/s, while keeping her c.m. at the same height as in jump 13. (See Appendix 2 for exercises that will help to facilitate this technique change.) This faster run-up will allow Gordon to make a larger vertical impulse on the ground during the takeoff phase, and thus will allow her to reach a larger height at the peak of the jump.

(Standard caution when increasing the run-up speed and/or lowering the c.m. height at the end of the run-up: ***The use of a faster and/or lower run-up will put a greater stress on the takeoff leg, and thus it may increase the risk of injury if the leg is not strong enough. Therefore, it is always 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.***)

Gordon needs to plant her takeoff leg with the knee straighter than in jump 13. In fact, it should be almost completely straight. As in jump 13, the leg should be planted very firmly on the ground (that is, it should be very stiff, although **NOT locked completely straight**). If she plants her takeoff leg with the knee more straight than in jump 13, she will be able to use a faster run-up speed without creating an unreasonable risk of collapse of the takeoff leg during the takeoff phase. It will also facilitate the use of the horizontal speed of the run-up to generate more vertical velocity, and will thus contribute to increase the height of the jump.

Gordon's arm and lead leg actions were very strong. Therefore, no changes should be made in them.

Gordon's leans backward and toward the left at the start of the takeoff phase were quite good. What was not good was how she rotated during the takeoff phase. In the view from the side she rotated backward instead of forward, and in the view from the back she rotated excessively toward the right. As a result, she ended up with an excessive lean toward the right, and without getting in exchange the partial benefit of a greatly increased angular momentum. Also, the disproportion between her forward and lateral components of somersaulting angular momentum led to a slanted position at the peak of the jump, with the head closer to the right standard and the feet closer to the left standard., which in turn created problems for her bar clearance. Our advice is to adopt permanently the good leans backward and toward the left that she had at the start of the takeoff phase in jump 13. But then she needs to allow the trunk to rotate forward during the takeoff phase, all the way to the vertical at the end of the takeoff, in the view from the side. She also needs to allow the trunk to rotate toward the right during the takeoff phase, but not so far as in jump 13. In a view from the back, it should only reach a tilt between 5° and 10° beyond the vertical at the end of the takeoff. By making these changes, Gordon should be able to generate a larger amount of forward somersaulting angular momentum than in jump 13. Yes, she would also probably generate a smaller amount of lateral somersaulting angular momentum, but the total amount of somersaulting angular momentum should end up being roughly about the same as in jump 13. There would be two advantages to this: (1) there would not be an excessive lean toward the right at the end of the takeoff, which should allow a greater generation of lift; and (2) there would be less disproportion between the sizes of the forward and lateral components of somersaulting angular momentum, which in turn would make the body be in a less slanted position at the peak of the jump, and therefore would widen the hollow gap below the body, thus creating better consistency in the effectiveness of the bar clearance.

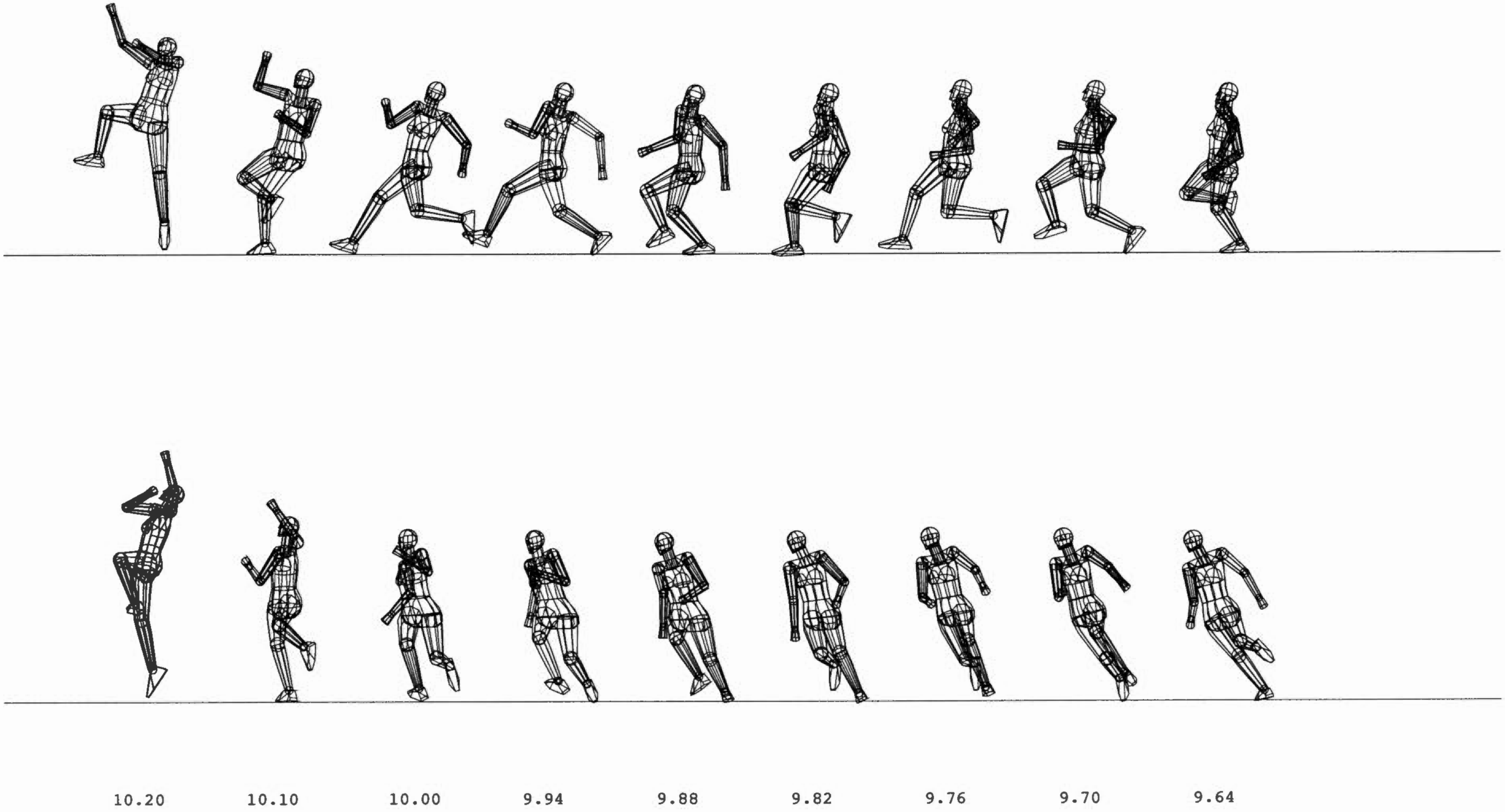
Gordon should also keep her knees closer together at the peak of the jump.

We recommend that the changes be made in the following order: (1) First, Gordon should change the orientation of her takeoff foot. This is necessary for the protection of the ankle and knee against the increased risk of injury that will be produced by the larger stresses to which the left leg will be subjected during the takeoff phase when a faster run-up is used. (2) Once the takeoff foot is getting planted consistently in a good orientation, Gordon should progressively straighten more her left knee before planting the takeoff foot on the ground. (3) The third step should be to increase the final speed of her run-up. (4) The last step would be to allow herself to rotate further forward (in the view from the side) and less toward the right (in the view from the back) by the end of the takeoff.

Note: If Gordon succeeds in increasing the final speed of her run-up, it is very likely that she will also have a larger amount of leftover horizontal speed after the completion of the takeoff phase. In turn, this will require her to take off farther from the bar than in jump 13 in order to reach the peak of the jump directly over the bar, and not beyond the plane of the bar and the standards.

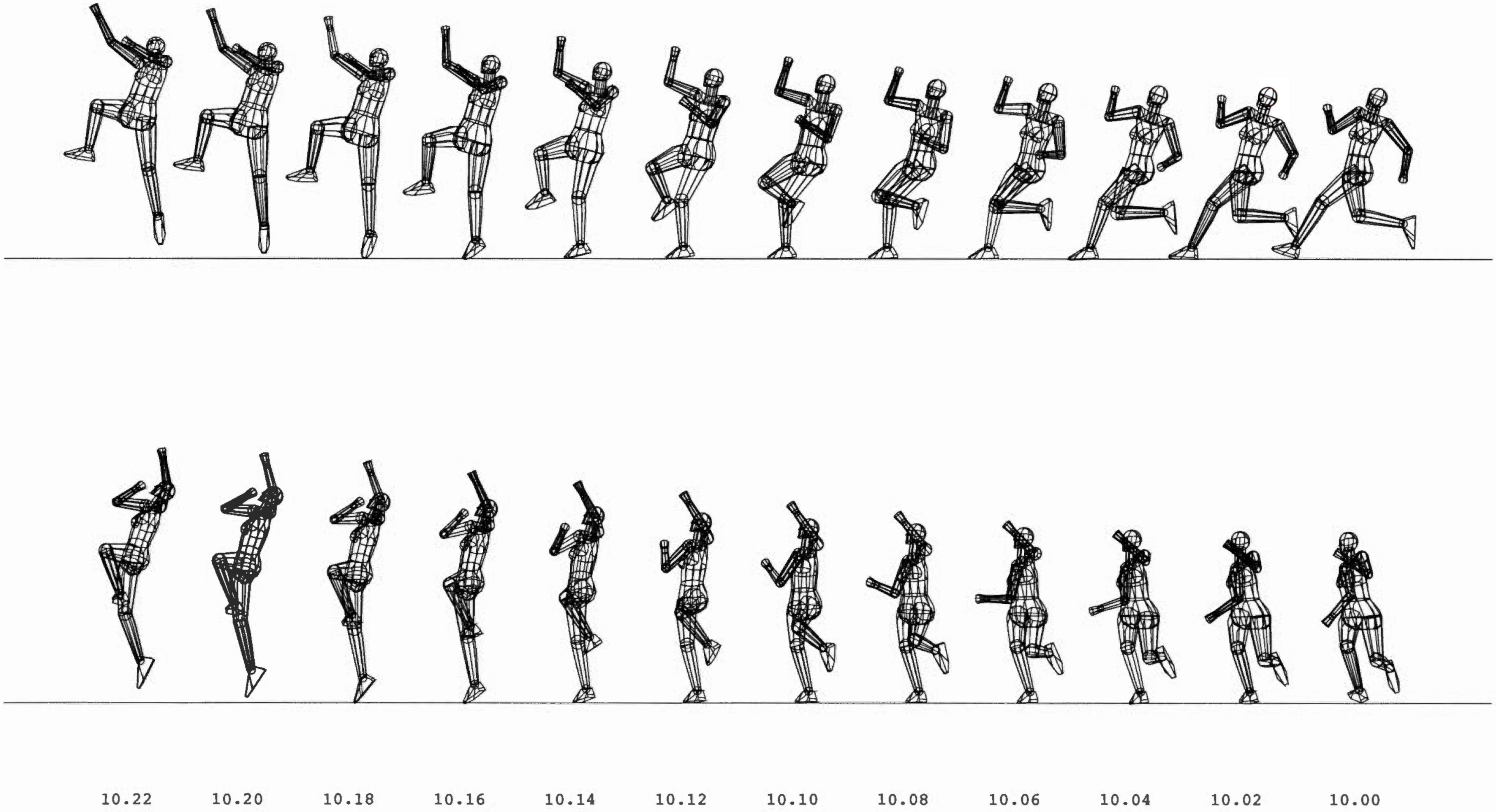
GORDON #13 062406 1.83 M MISS

RUN-UP



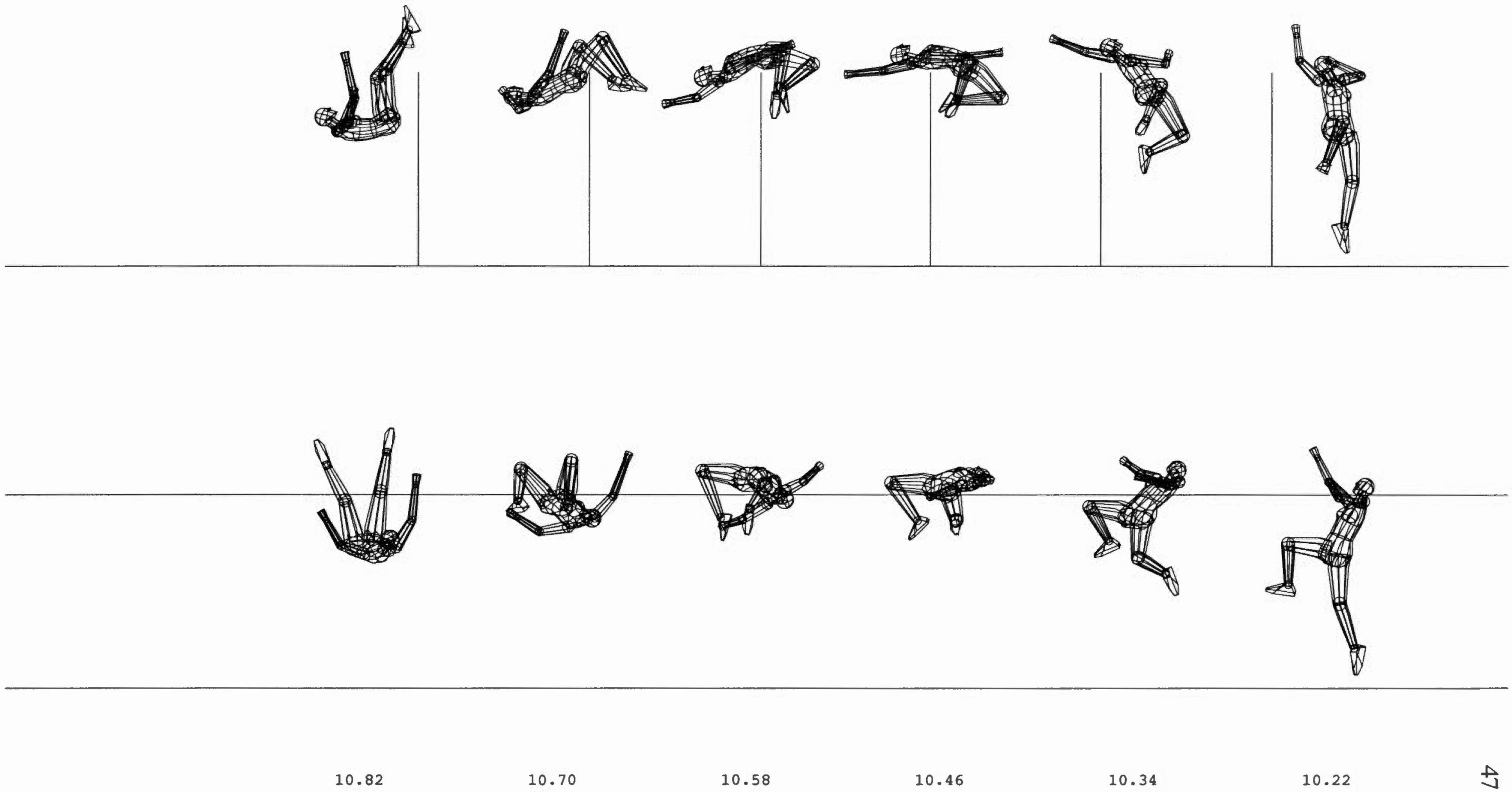
GORDON #13 062406 1.83 M MISS

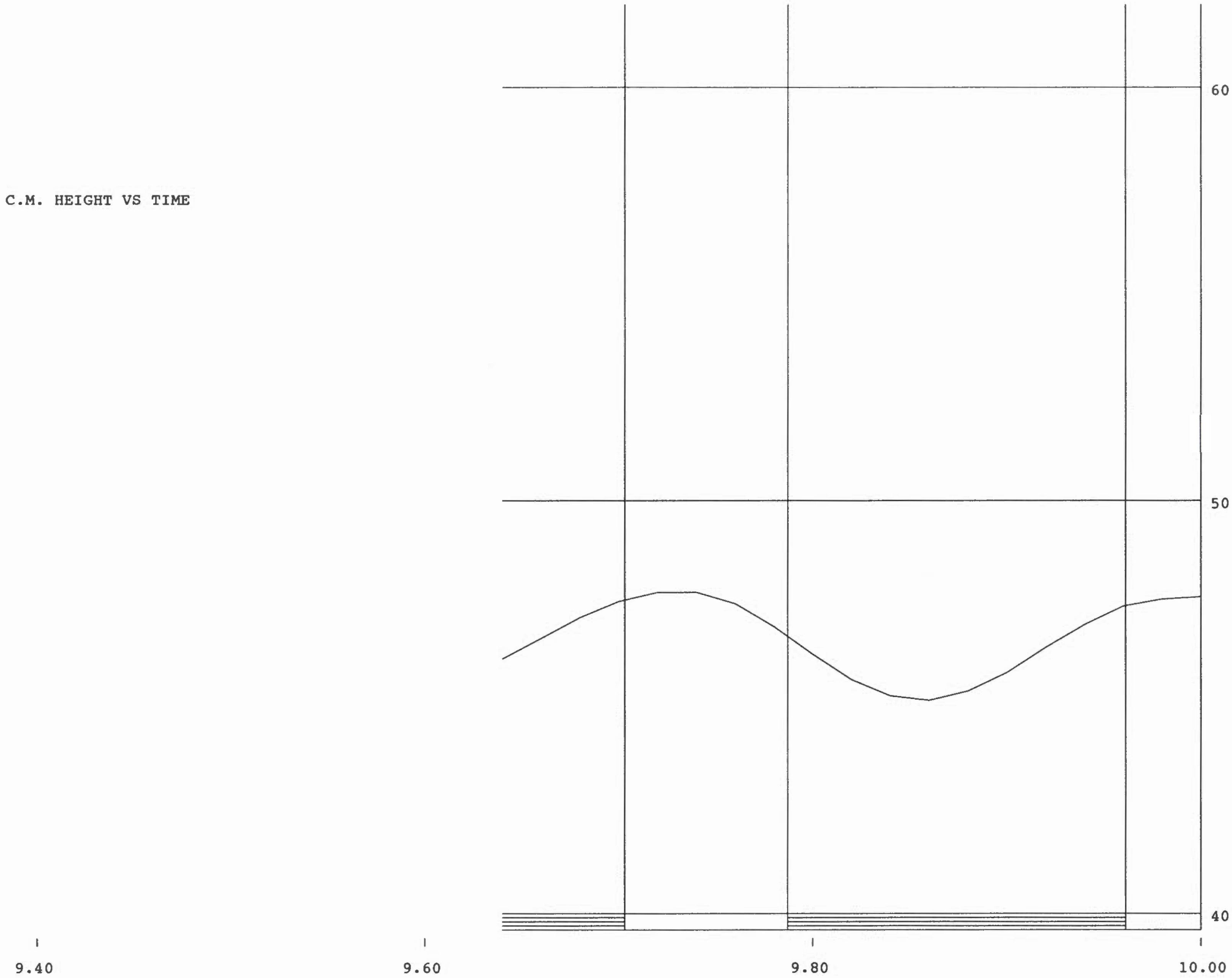
TAKEOFF PHASE



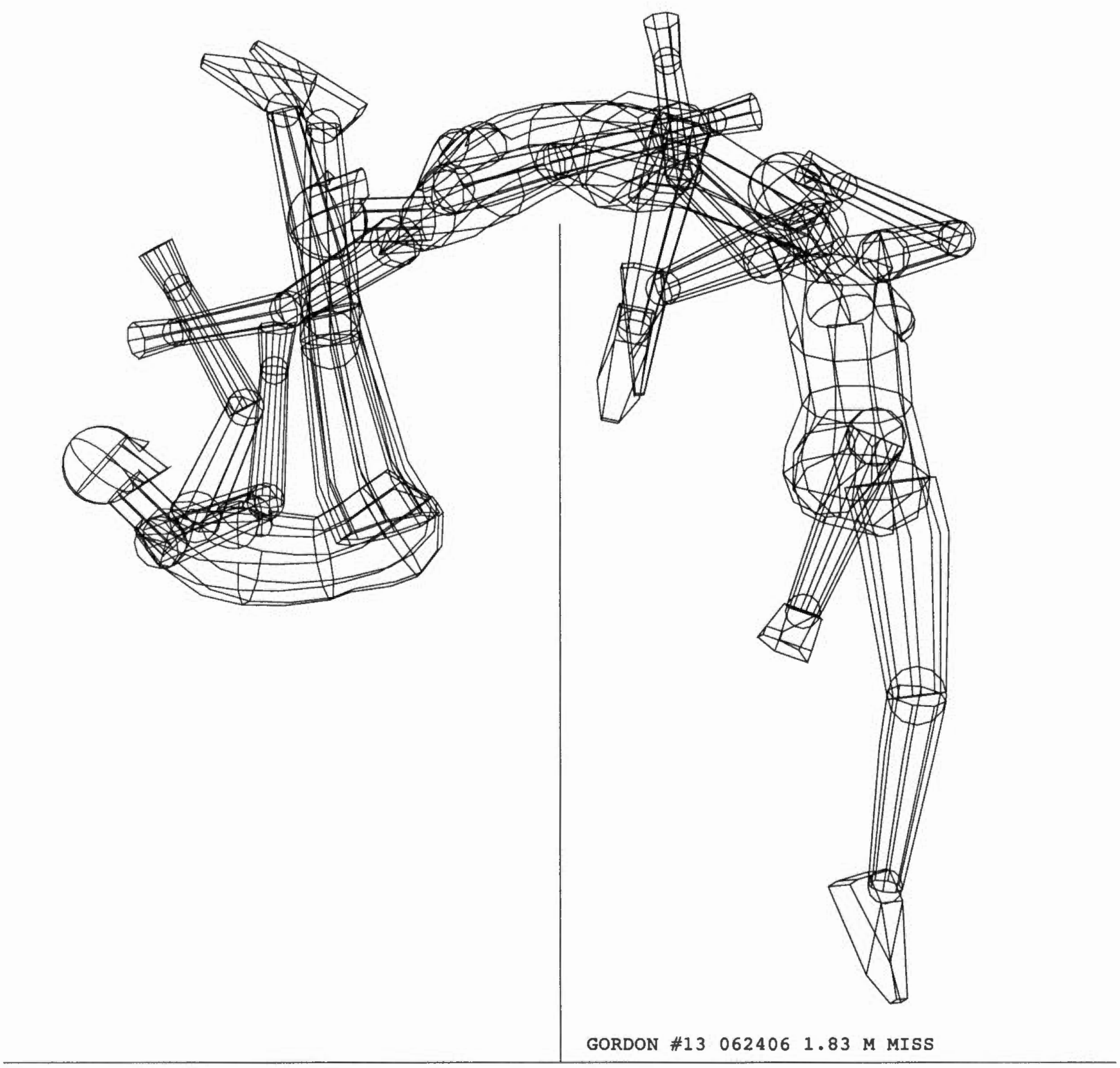
GORDON #13 062406 1.83 M MISS

BAR CLEARANCE

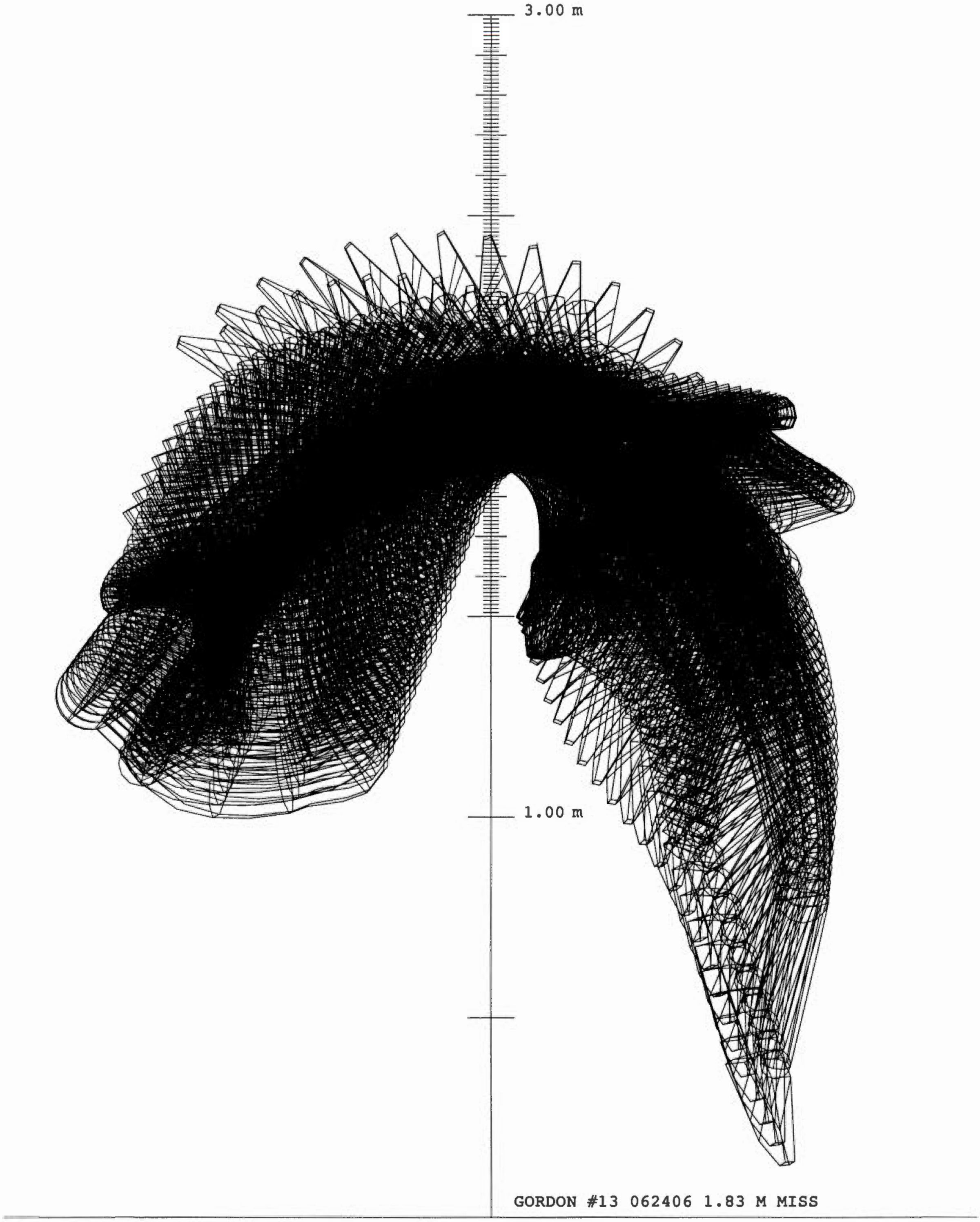




GORDON #13 062406 1.83 M MISS



GORDON #13 062406 1.83 M MISS


3.00 m
1.00 m
GORDON #13 062406 1.83 M MISS

Destinee HOOKER

Jump 11 was Hooker's 1.83 m clearance at the 2006 USATF Championships. Although Hooker also cleared 1.86 m later in the meet, and then made three attempts at 1.89 m, jump 11 seemed to be clearly her highest jump of the day, and therefore we selected it for our analysis.

Based on Hooker's vertical velocity at takeoff in jump 11 (v_{ZTO} = 3.55 m/s), a technique of average quality would have included a final run-up speed of about 6.6 m/s and a c.m. height at the end of the run-up equal to about 48.5% of her own standing height. In jump 11, Hooker's c.m. was actually at the height that would be expected in a technique of average quality (h_{TD} = 48.5%), and slightly slower (v_{HI} = 6.5 m/s). Overall, the combination of run-up speed and c.m. height that she used in jump 11 was a weak challenge for the strength of her takeoff leg. (Keep in mind that a technique of *average* quality is not the technique of *optimum* quality, which is what we want.) Hooker needs to be faster and/or lower at the end of the run-up.

At the end of the run-up, Hooker planted the takeoff foot at a very safe angle (e_3 = 12°). This was very good.

Hooker's arm actions during the takeoff phase were reasonably strong (AAT = 12.8 mm/m), and the action of her lead leg was strong (LLA = 20.4 mm/m). Therefore, the overall combination of arm and lead leg actions was strong (FLA = 33.1 mm/m). This was also good.

Hooker's trunk had a very small amount of backward lean at the start of the takeoff phase (BFTD = 84° in the view from the side). This was not good. Then she rotated forward, and she was vertical at the end of the takeoff (BFTO = 90°). This was a good final position, but due to her insufficient amount of backward lean at the start of the takeoff phase, the amount of forward somersaulting angular momentum that she was able to generate during the takeoff phase was somewhat small (H_F = 75).

Hooker's trunk had a very good initial lean toward the left at the start of the takeoff phase (LRTD = 76° in the view from the back). Then she rotated toward the right, and at the end of the takeoff she has 11° beyond the vertical (LRTO = 101°). In the view from the back, it is normal for high jumpers to go up to 10° past the vertical at the end of the takeoff. This seems to give an optimum compromise between the generation of lift and the generation of enough lateral somersaulting angular momentum to permit a good rotation over the bar. Since Hooker was 11° past the vertical, she was essentially at the acceptable limit, and we consider her to be OK in this regard. So both her lean toward the left at the start of the takeoff phase and her small-enough lean toward the right at the end of the takeoff phase were close to perfect. Normally, this should have led to the generation of a good amount of lateral somersaulting angular momentum, a value of about 95 or 100. However, this was not the case. Hooker was only able to generate a small amount of lateral somersaulting angular momentum (H_L = 75). We don't understand why this happened, particularly since during the takeoff phase Hooker used a very marked diagonal arm swing, which tends to favor the generation of lateral somersaulting angular momentum.

Whatever the reason for the small amount of lateral somersaulting angular momentum, Hooker's somewhat small amount of forward somersaulting angular momentum and small amount of lateral somersaulting angular momentum added up (not surprisingly) to a small total amount of somersaulting angular momentum (H_S = 105). A small total amount of somersaulting angular momentum tends to make it difficult to rotate properly over the bar, so it is a disadvantage.

The peak height reached by the c.m. in jump 11 was h_{PK} = 1.98 m. The "saturation graph" shows that in this jump Hooker could have cleared cleanly a bar set at about h_{CLS} = 1.90 m, and at h_{CLA} = 1.94 m if she had taken off about 10 cm closer to the plane of the bar and the standards. In relation to the peak height of the c.m. (1.98 m), the 1.94 m clean clearance height indicated a reasonably effective bar clearance. This was a particularly good achievement in view of Hooker's small total amount of somersaulting angular momentum.

Recommendations

Hooker needs to be faster and/or lower at the end of the run-up than she was in jump 11. A combination of v_{HI} = 6.9 m/s and h_{TD} = 47.5% would probably be good for her. (For comparison purposes, this proposed height is similar to what was used by Gordon and by Wagner at the end of their respective run-ups in the 2006 USATF Championships.) See Appendix 2 for exercises that will help to facilitate these technique changes. This faster and lower run-up should allow Hooker to make a larger vertical impulse on the ground during the takeoff phase, and thus would allow her to reach a larger height at the peak of the jump.

(Standard caution when increasing the run-up speed and/or lowering the c.m. height at the end of the run-up: ***The use of a faster and/or lower run-up will put a greater stress on the takeoff leg, and thus it may increase the risk of injury if the leg is not strong enough. Therefore, it is always 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.*****)**

Hooker planted her takeoff foot in a very good, safe orientation. Therefore, no changes are needed in the foot's orientation.

Hooker's arm and lead leg actions were good, so we also do not recommend any changes in them.

In the last step of the run-up, Hooker needs to thrust her hips further forward. This will allow her trunk to acquire the necessary amount of backward lean at the start of the takeoff phase. Wagner and Acuff do this very well. Look closely at their side-view sequences between t = 9.82 s and t = 10.00 s. From this marked backward-leaning position at the start of the takeoff phase, Hooker should then rotate forward up to the vertical by the end of the takeoff phase. She already rotated forward all the way up to the vertical in jump 11, but in that jump she started from an initial position with only 6° of backward lean (BFTD = 84°), and then rotated through an angle of just 6° to the vertical (BFTO = 90°). With an increased amount of initial backward lean at the start of the takeoff phase, we are proposing that she rotate from an initial position with maybe about 15-17° of backward lean (BFTD = 73-75°) all the way to the vertical. By doing this, she should be able to generate a larger amount of forward somersaulting angular momentum. In turn, this would contribute to increase her total amount of somersaulting angular momentum, which in turn should help her to rotate better over the bar, and ultimately to produce a more effective bar clearance.

The forward position of the hips at the start of the takeoff phase will offer an additional advantage: It will allow Hooker to withstand better the impact of her takeoff foot against the ground when she adopts a faster and lower run-up.

In regard to Hooker's leans toward the left at the start of the takeoff phase and toward the right at the end of the takeoff phase, our advice is to keep these angles they way they were in jump 11.

Hooker's actions over the bar were actually quite good: She was able to produce a reasonably effective bar clearance in spite of her small total amount of somersaulting angular momentum. If she manages to increase her total amount of somersaulting angular momentum (for instance, by adopting a greater backward lean at the start of the takeoff phase, as previously explained), the effectiveness of her bar clearance will improve easily.

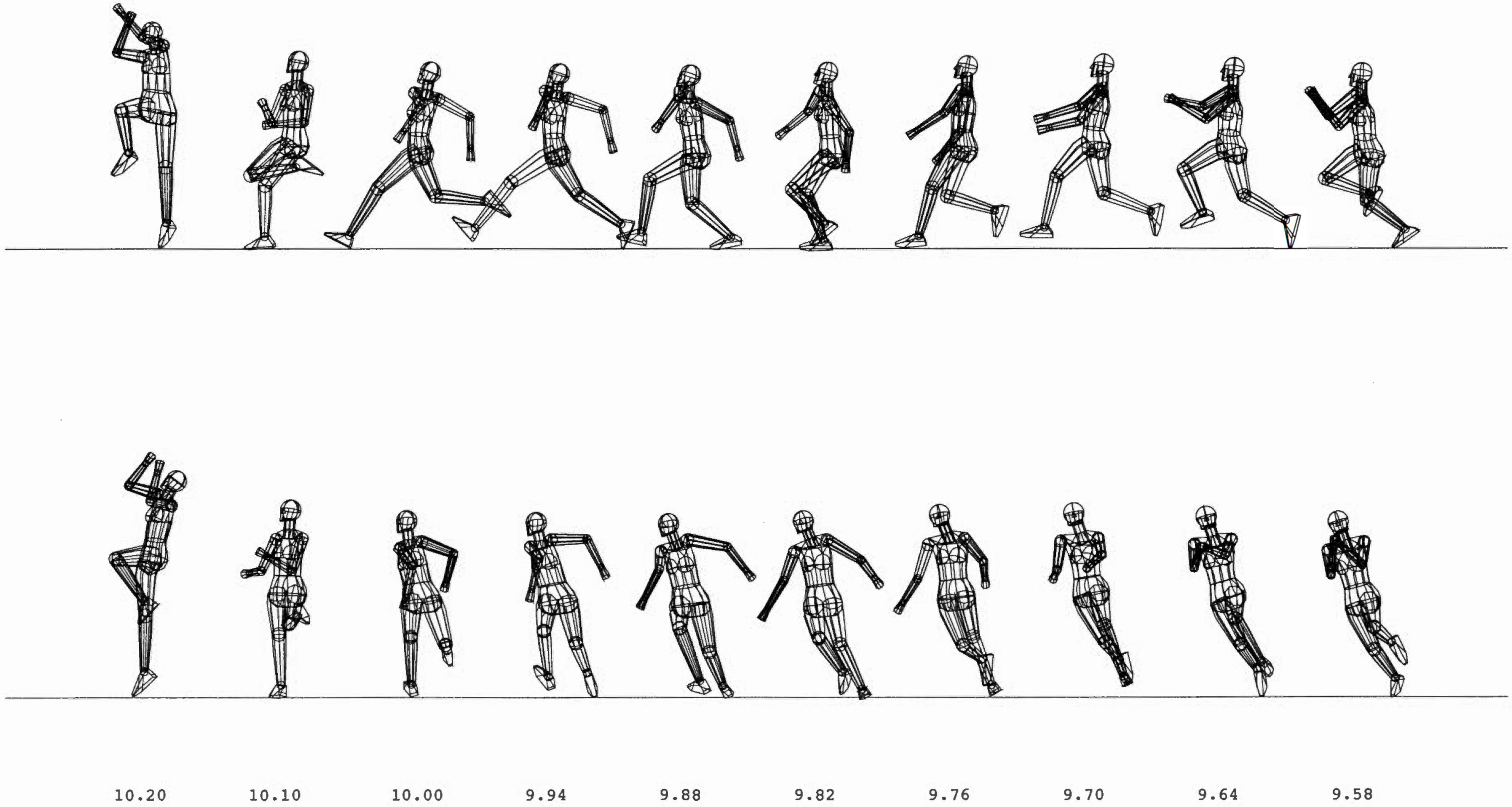
Hooker needs to take off closer to the bar than she did in jump 11. In our lab, we judge the effectiveness of an athlete's bar clearance by the value called Δh_{CLA} in Table 5. It is the vertical distance between the peak height reached by the center of mass of the athlete and the highest point of the hollow gap below the path followed by the body. For instance, look at Hooker's "saturation graph", the last page of Hooker's graphics that follow these comments. The effectiveness of the bar clearance is defined by the distance between the peak height of the c.m. (which was 1.98 m in this jump) and the highest point of the white "wedge" below the blackened path covered by the body (1.94 m). However, it is obvious that a bar set at 1.94 m would have been knocked down by Hooker in this jump, because the hollow gap below the body was not well centered over the bar. We are counting on the athlete to find the right place to take off from, so that the peak of the hollow gap below the body path is almost perfectly centered over the bar. As shown by the saturation graph, this was not the case in Hooker's jump 11: She took off too far from the bar, so she could only have cleared cleanly a bar set at about 1.90 m in this jump. At the 2006 USATF Championships, Hooker seemed to be taking off too far from the bar in many of her jumps: She was taking off, reaching the peak of the jump in front of the bar, and then falling on the bar. In jump 11, Hooker planted her takeoff foot with the toe at a distance of 0.87 m from the plane of the bar and the standards. Instead, the foot should have been planted at a distance of about 0.77 m from the plane of the bar and the standards.

Of course, if Hooker adopts a faster run-up, as we advise her to do, it is likely that she will have a larger amount of leftover horizontal velocity at the end of the takeoff, and then she should take off *farther* from the plane of the bar, or else the peak of her jump will be beyond the plane of the bar, over the pit, which would not be good either. A good rule of thumb to figure out if an athlete is taking off too close to the bar or too far from the bar is to pay attention to *when* the bar gets hit. If the bar gets hit very late, this suggests that the athlete took off too far from the bar, reached the peak, and then fell on the bar. If the bar gets hit very early, this suggests that the athlete took off too close to the bar, and hit it on the way up toward the peak.

The analysis presented here is based on Hooker's best jump at the meet. But she had an additional problem that does not show up in the analysis of her best jump: inconsistency. Direct visual observation during the meet suggested that Hooker had a lot of variability from one jump to the next: No two jumps were alike. She needs to improve the technique of her best jump, but she also needs to acquire better consistency, to make all jumps as similar as possible to her best jump.

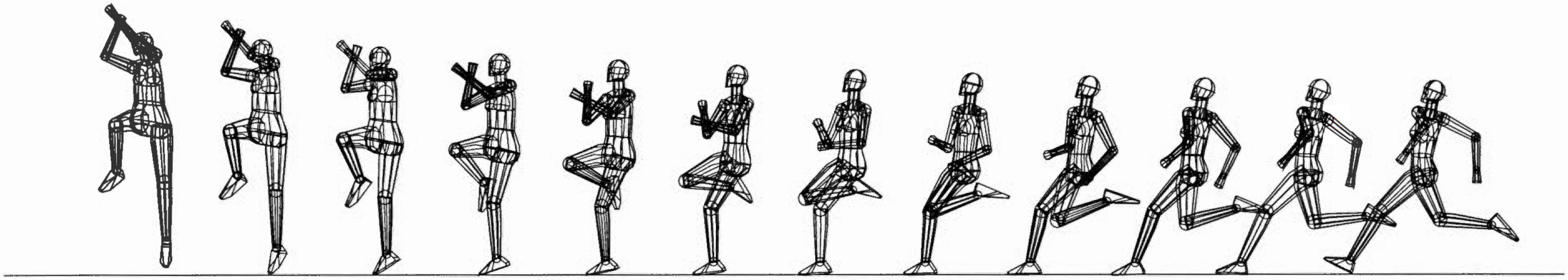
HOOKER #11 062406 1.83 M CLEARANCE

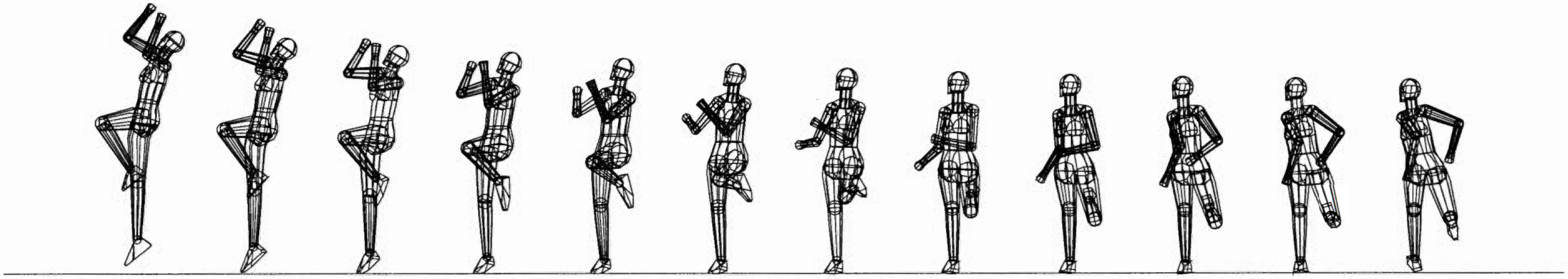
RUN-UP



HOOKER #11 062406 1.83 M CLEARANCE

TAKEOFF PHASE

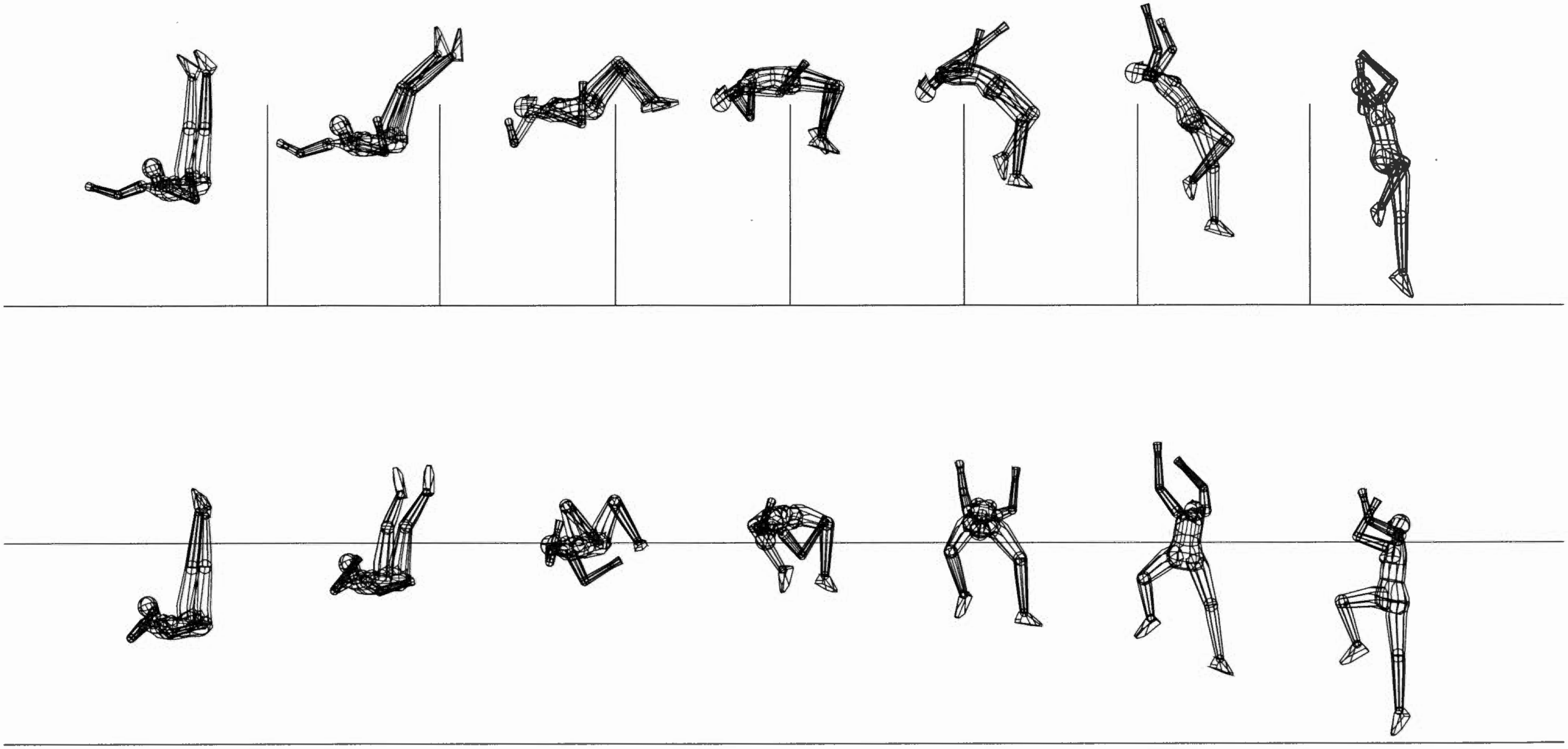


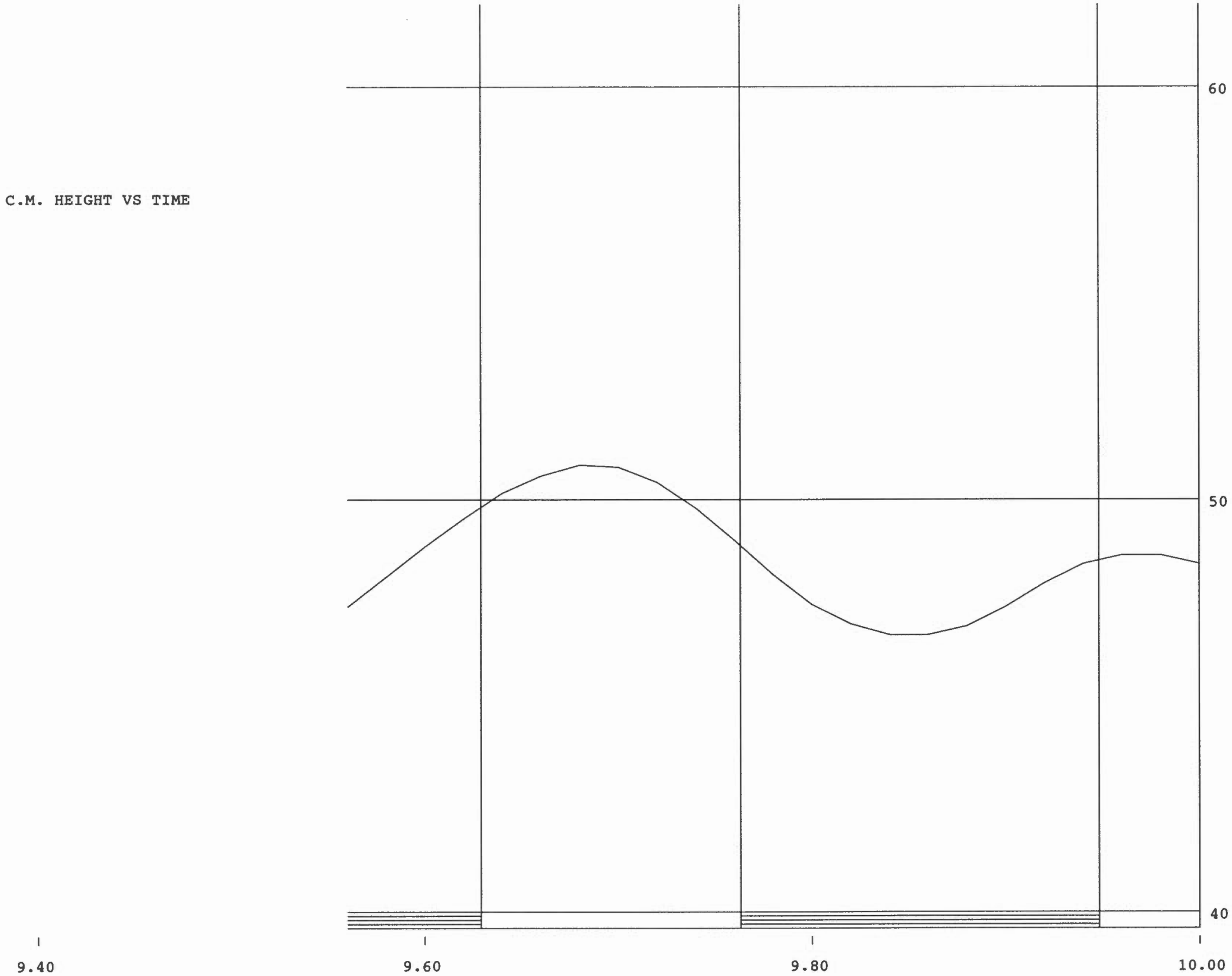


10.22 10.20 10.18 10.16 10.14 10.12 10.10 10.08 10.06 10.04 10.02 10.00

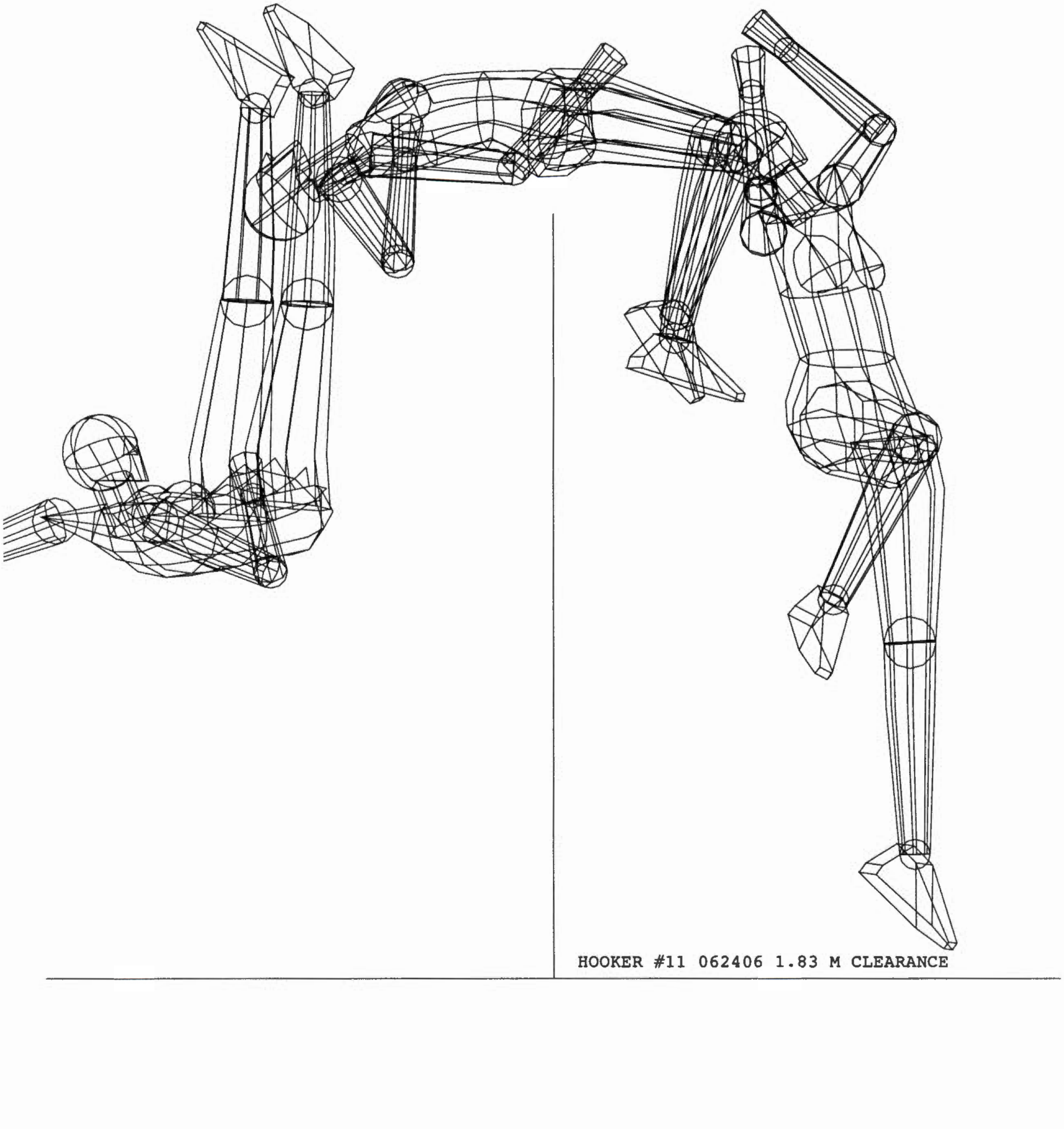
HOOKER #11 062406 1.83 M CLEARANCE

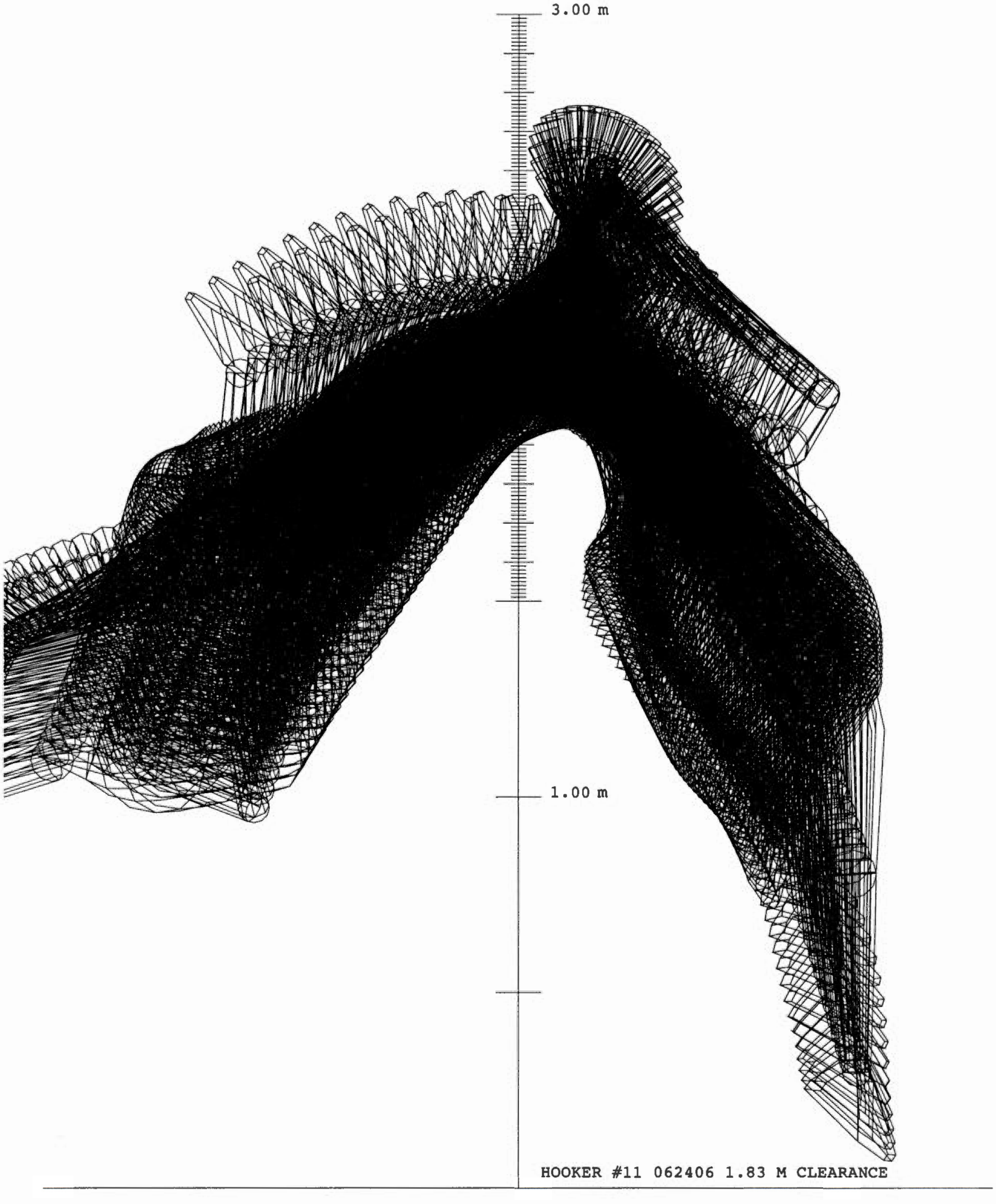
BAR CLEARANCE





HOOKER #11 062406 1.83 M CLEARANCE


HOOKER #11 062406 1.83 M CLEARANCE


3.00 m
1.00 m
HOOKER #11 062406 1.83 M CLEARANCE

Chaunte HOWARD

Jump 46 was Howard's last successful clearance at the 2006 USATF Championships (2.01 m).

Based on Howard's vertical velocity at takeoff in jump 46 (v_{ZTO} = 4.00 m/s), a technique of average quality would have included a final run-up speed of about 7.1 m/s and a c.m. height at the start of the takeoff phase equal to about 47.5% of her own standing height. In jump 46, Howard's c.m. was in a lower position at the end of the run-up (46%) than what would be expected for a technique of average quality, and her speed (v_{H1} = 8.0 m/s) was much, much faster. This final run-up speed was 0.5 m/s faster than what we have ever measured in any other female high jumper. The combination of run-up speed and c.m. height that Howard used in jump 46 was extremely demanding. To put in perspective just how demanding it was, it is the combination that we would consider optimum if Howard had a takeoff leg strong enough to produce a successful bar clearance at 2.27 m. While Howard's takeoff leg is obviously very strong, it is not *that* strong. This raises the possibility that she might actually be too fast at the end of the run-up. We will see below that Howard's use of very weak arm and lead leg actions partly compensates for this, but we still have some concern that she might be going too fast at the end of the run-up.

At the end of the run-up, Howard planted the takeoff foot too parallel to the bar. Because of this, the angle between the longitudinal axis of the takeoff foot and the horizontal force received by the foot was extremely large (e_3 = 42°), and created a very large risk of ankle pronation, and injury to the ankle and foot. (See the section on "Orientation of the takeoff foot, and potential for ankle and foot injuries" in the main text of the report.) This problem has become progressively worse every year. The risk of injury is aggravated by Howard's use of an extremely fast run-up, and also by the fact that she is planting her left leg on the ground very stiffly, without allowing it to flex much at the knee during the takeoff phase. While the use of a fast run-up and of a rather stiff takeoff leg are generally good for the generation of lift, they also increase the stress placed on the ankle joint of the takeoff leg. In our opinion, the misalignment of Howard's takeoff foot is, by far, the most important problem in her current technique

Howard's arm actions during the takeoff phase were weak (AAT = 6.6 mm/m), and the action of her lead leg was very weak (LLA = 12.2 mm/m). In consequence, the overall combination of arm and lead leg actions was very weak (FLA = 18.8 mm/m). Normally, we would say that this is a technique deficiency. However, in Howard's case it is probably beneficial. The use of strong arm and lead leg actions during the takeoff phase helps to generate lift, but it also increases the stress placed on the takeoff leg. Given Howard's astounding run-up speed, even a moderate amount of arm and lead leg action might have been enough to produce the collapse of the takeoff leg. Therefore, the use of weak arm and lead leg actions during the takeoff phase is almost certainly beneficial for Howard.

In jump 46, Howard's trunk had less forward lean than in 2004 as she passed over the right foot (see the side view sequence at t = 9.88 s). Then she thrust her hips forward reasonably well in the last step of the run-up. (See the side view sequence from t = 9.88 s to t = 10.00 s.) This allowed her trunk to acquire a moderate amount of backward lean by the time that Howard planted the left foot on the ground to start the takeoff phase (BFTD = 79°). This was a better backward lean than in 2004. Then she rotated forward during the takeoff phase, and at the end of the takeoff (at t = 10.14 s) her trunk was perfectly vertical in a view from the side (BFTO = 90°). This was a nice improvement in comparison to the excessive forward lean that she had at the end of the takeoff in 2004. Through these actions, Howard was able to generate a very large amount of forward somersaulting angular momentum (H_F = 95) without losing any lift. This was good, and it fit exactly with the recommendations that we made to her in the 2004 report. However, a word of caution is necessary here: Howard jumped in the way described above when the bar went up to 2.01 m, but when the bar was lower during the early part of the meet she did not acquire as much backward lean at the start of the takeoff phase, and thus ended up with an excessive forward lean at the end of the takeoff (and consequently with a loss of lift). She did not correct the problem until the bar was raised to 2.01 m.

Howard's trunk had a good lean toward the left at the start of the takeoff phase (LRTD = 79°). But then, as in 2004, she was rather conservative in the rotation of her trunk toward the right during the takeoff, and was vertical in the view from the back at the end of the takeoff (LRTO = 90°), while we believe that it is beneficial to allow the trunk to go up to 10° beyond the vertical at the end of the takeoff in this view. By doing this, Howard ended up with only a small amount of lateral somersaulting angular momentum (H_L = 70). However, due to her very large amount of forward somersaulting angular momentum, she still ended up with a good total amount of somersaulting angular momentum (H_S = 120).

Howard's c.m. reached a maximum height h_{PK} = 2.06 m in jump 46. The "saturation graph" shows that in this jump she could have cleared cleanly a bar set at about h_{CLS} = 2.02 m, and at h_{CLA} = 2.03 m if she had taken off about 10 cm farther from the plane of the bar and the standards. In relation to the peak height of the c.m. (2.06 m), the 2.03 m clean clearance height indicated a very effective bar clearance. The view along the bar in the bar clearance sequence showed that Howard timed the start of her un-arching better than in 2003 and 2004. This was probably what improved the effectiveness of her bar clearance

Recommendations

Howard's current technique is very impressive. There were improvements in most aspects of her technique from 2004 to 2006. The only major problem that has not been solved yet is the orientation of her takeoff foot.

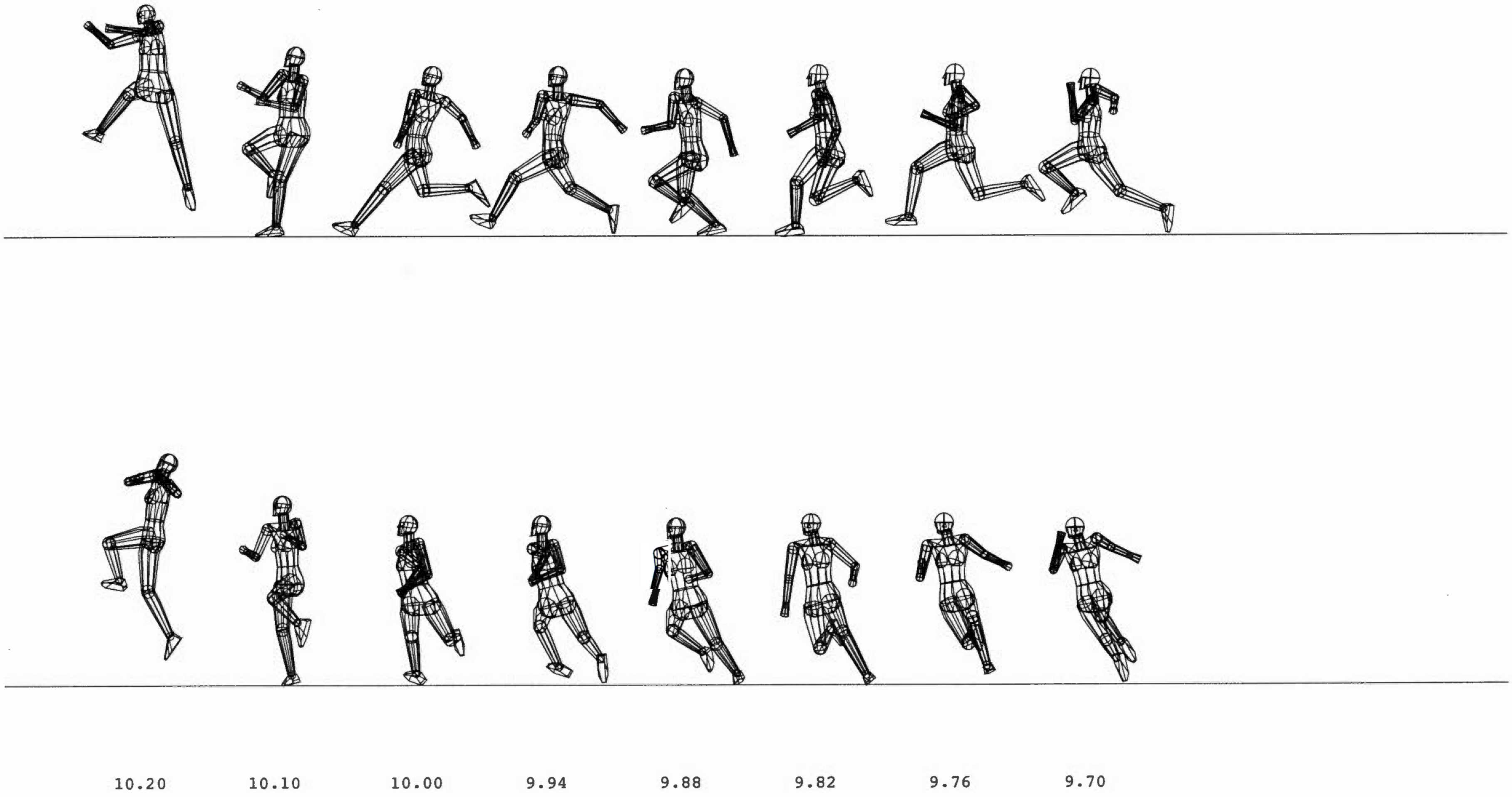
We marvel at the tremendous amount of speed that Howard used in jump 46 (and seemingly during the entire meet), but at the same time we have some concerns about it. Such an amount of speed (8.0 m/s) is unheard of in women's high jumping, and in fact it is faster than the run-up speed used by most elite male high jumpers. It is the run-up speed that we would expect in a jumper with a personal record between 2.25 m and 2.30 m. It is possible that this extremely fast run-up speed works just fine for Howard, particularly given the fact that she is also using very weak arm and lead leg actions. But it is also possible that this huge speed might be "too much of a good thing". We are not going to advise Howard outright to slow down her run-up, but she and her coach need to keep an eye out for any possible problems.

Howard has improved her backward lean at the start of the takeoff phase, and because of that, also her position at the end of the takeoff phase in the view from the side. Her lean toward the left at the start of the takeoff phase remains good. The only thing that could be improved in regard to her leans is her lean toward the right at the end of the takeoff. If, instead of rotating toward the right only up to the vertical at the end of the takeoff phase, she rotated beyond that to a position 5-10° beyond the vertical, she would probably be able to generate a little bit more lateral somersaulting angular momentum with hardly any loss of lift. In turn, the increase in the angular momentum would help her to rotate still a little bit better over the bar, and therefore possibly to improve the effectiveness of her bar clearance a little bit more. This is a small change in technique which should be expected to produce also a small improvement in performance. Therefore, it may not be worthwhile to put a lot of time and effort into the implementation of this change.

Howard planted her takeoff foot too parallel to the bar. As in our 2004 report, we feel that this by far the most important problem in her technique, because it poses a high risk of injury, and it has been getting worse every year. The takeoff foot should be planted on the ground with the longitudinal axis of the foot more in line with the final direction of the run-up: It should be planted on the ground with the toe pointing at least 25° more toward the landing pit than in jump 46. This technique change will help to prevent ankle pronation, and injury to the ankle and foot. It may be difficult to implement this change during the execution of full-effort jumps at high heights. It may be best to work on the correction of the foot orientation in jumps at lower heights in which slower run-up speeds can be utilized, and then hope that the improved foot position will stay with her for the full-effort jumps.

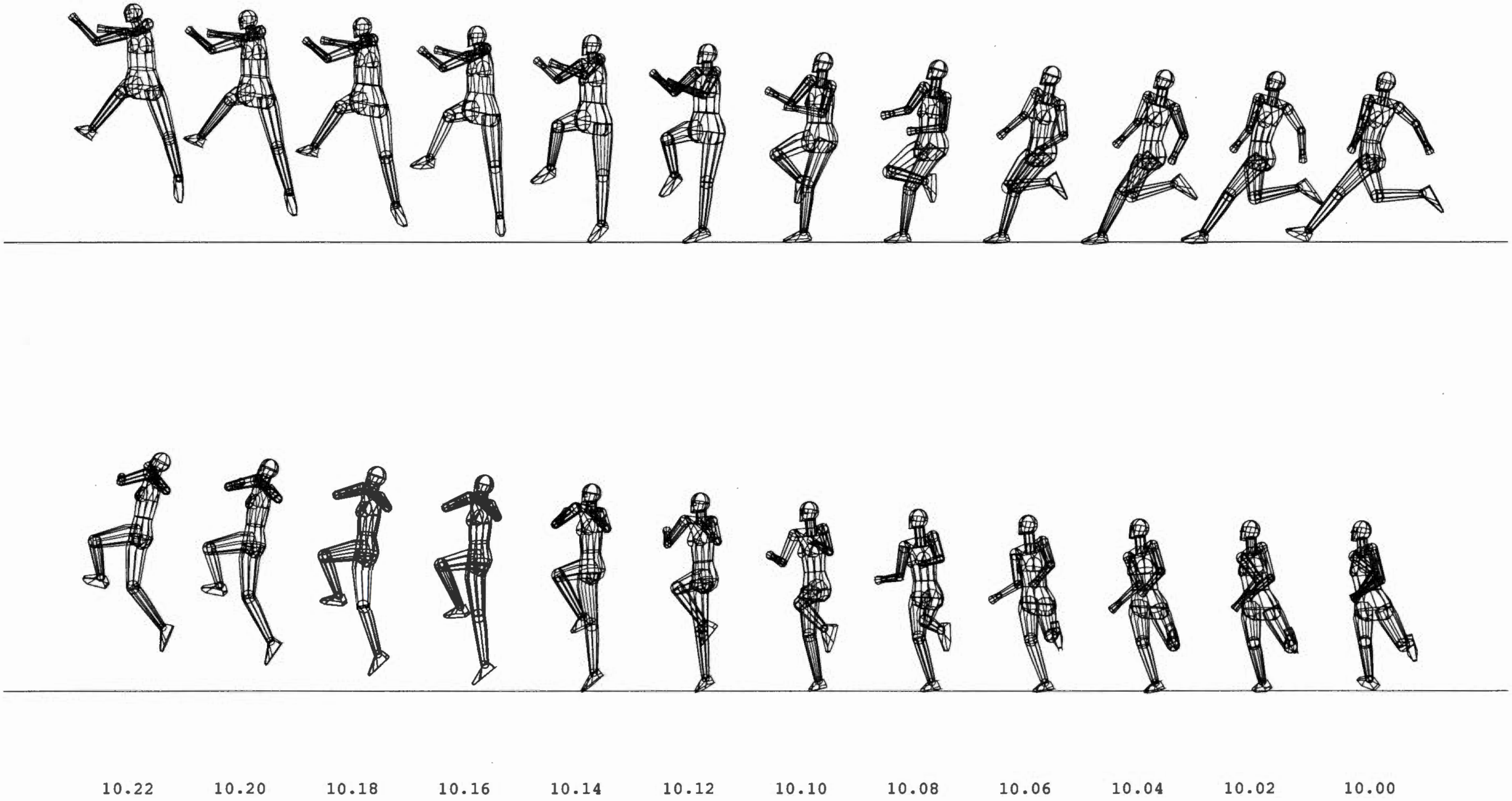
HOWARD #46 062406 2.01 M CLEARANCE

RUN-UP



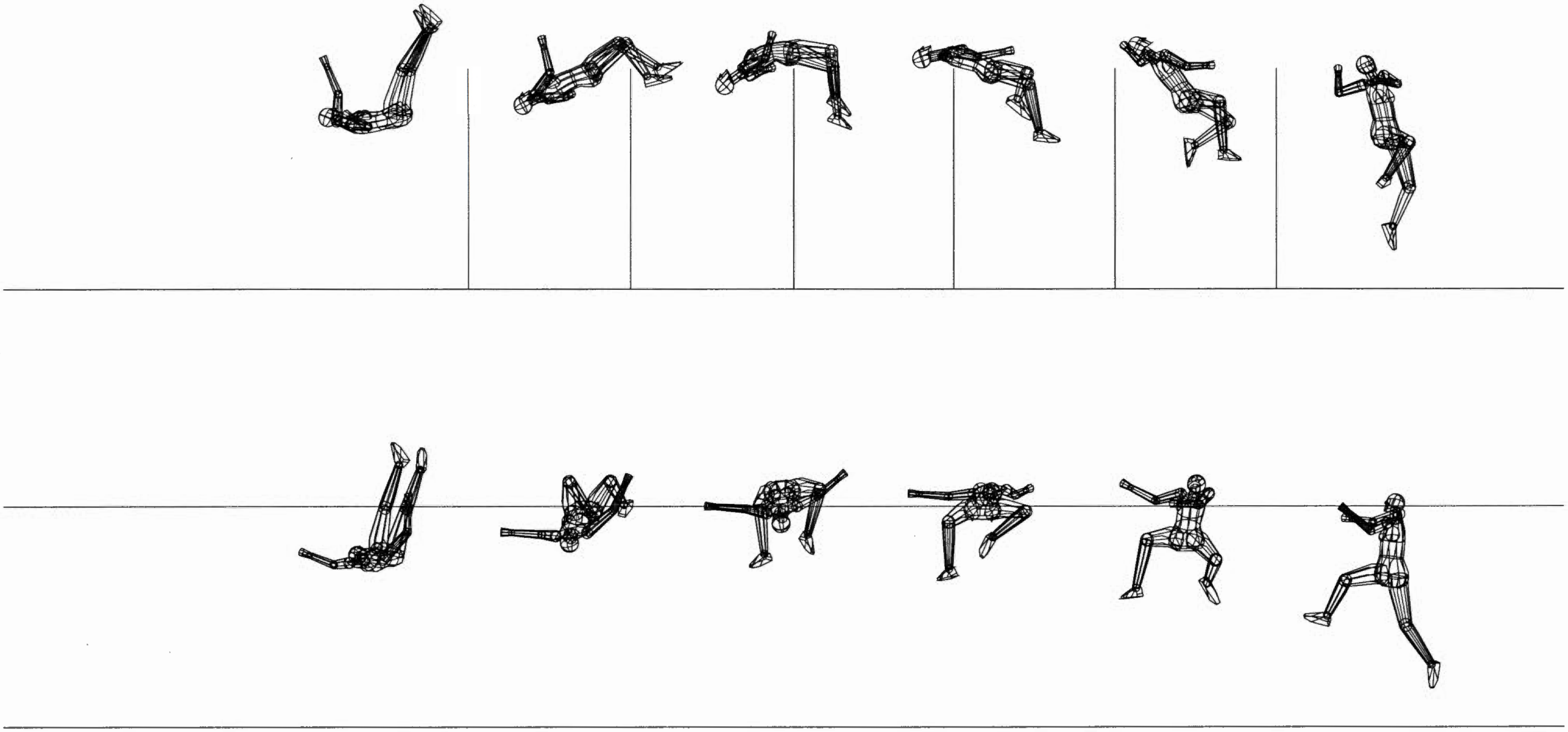
HOWARD #46 062406 2.01 M CLEARANCE

TAKEOFF PHASE

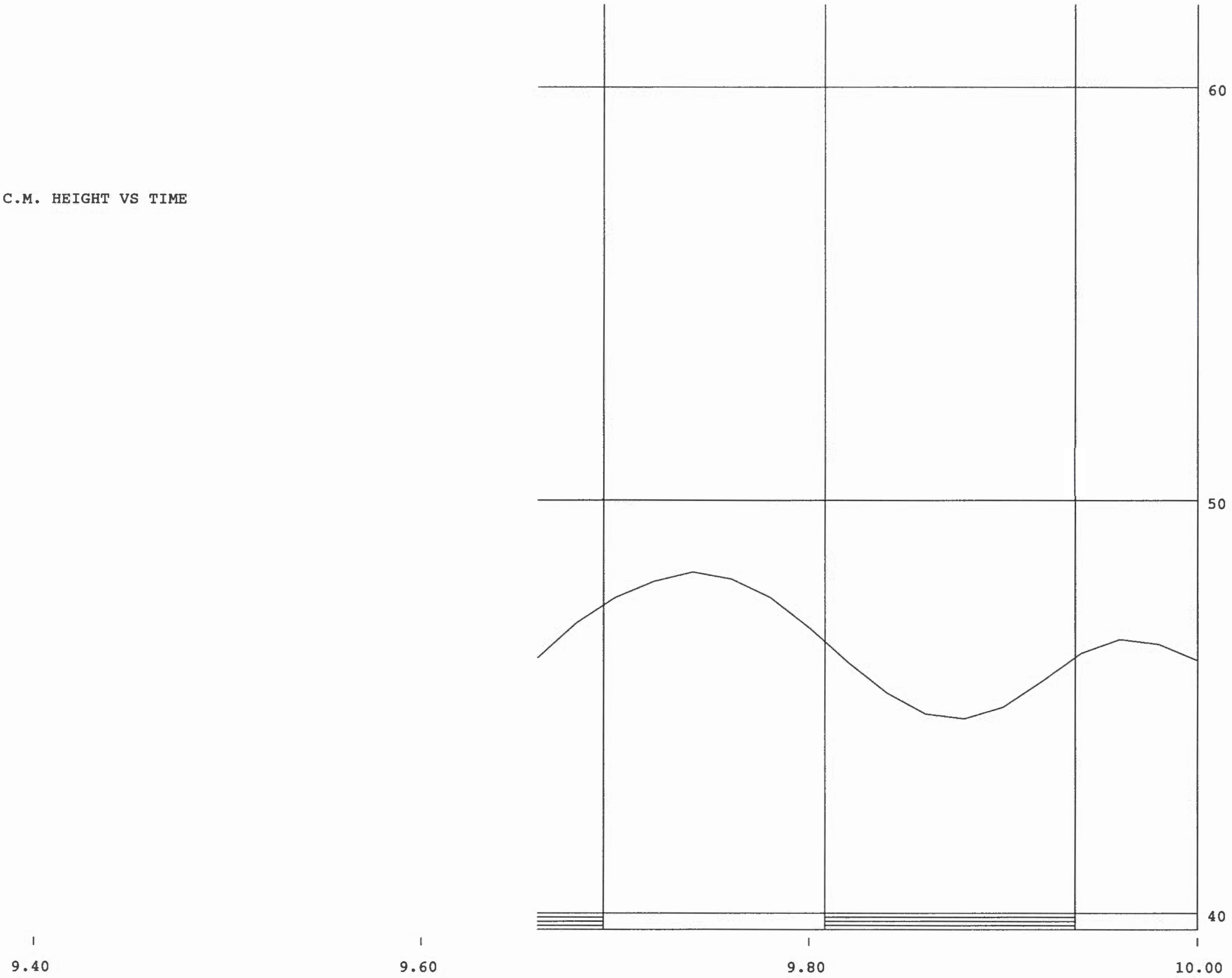


HOWARD #46 062406 2.01 M CLEARANCE

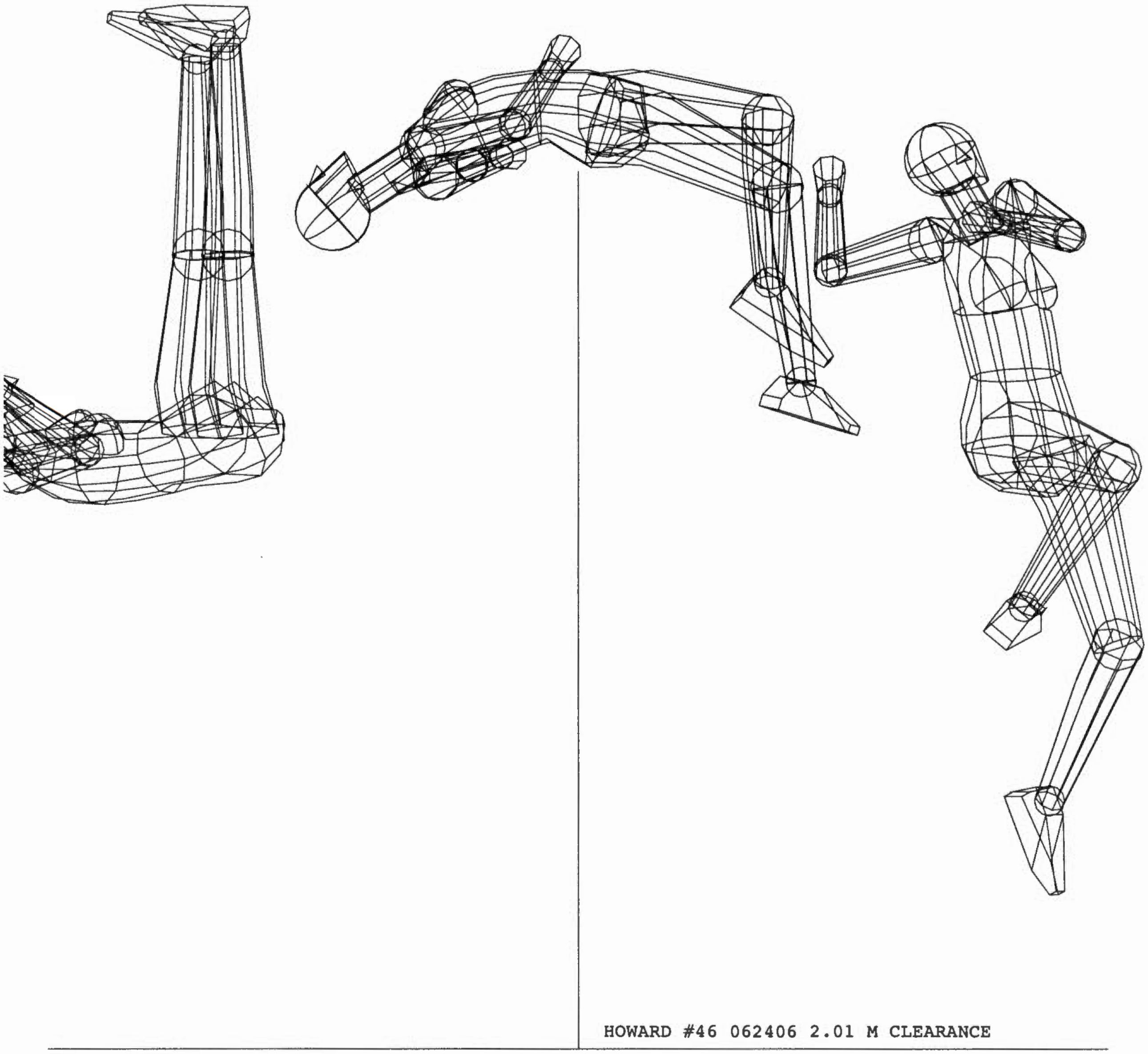
BAR CLEARANCE

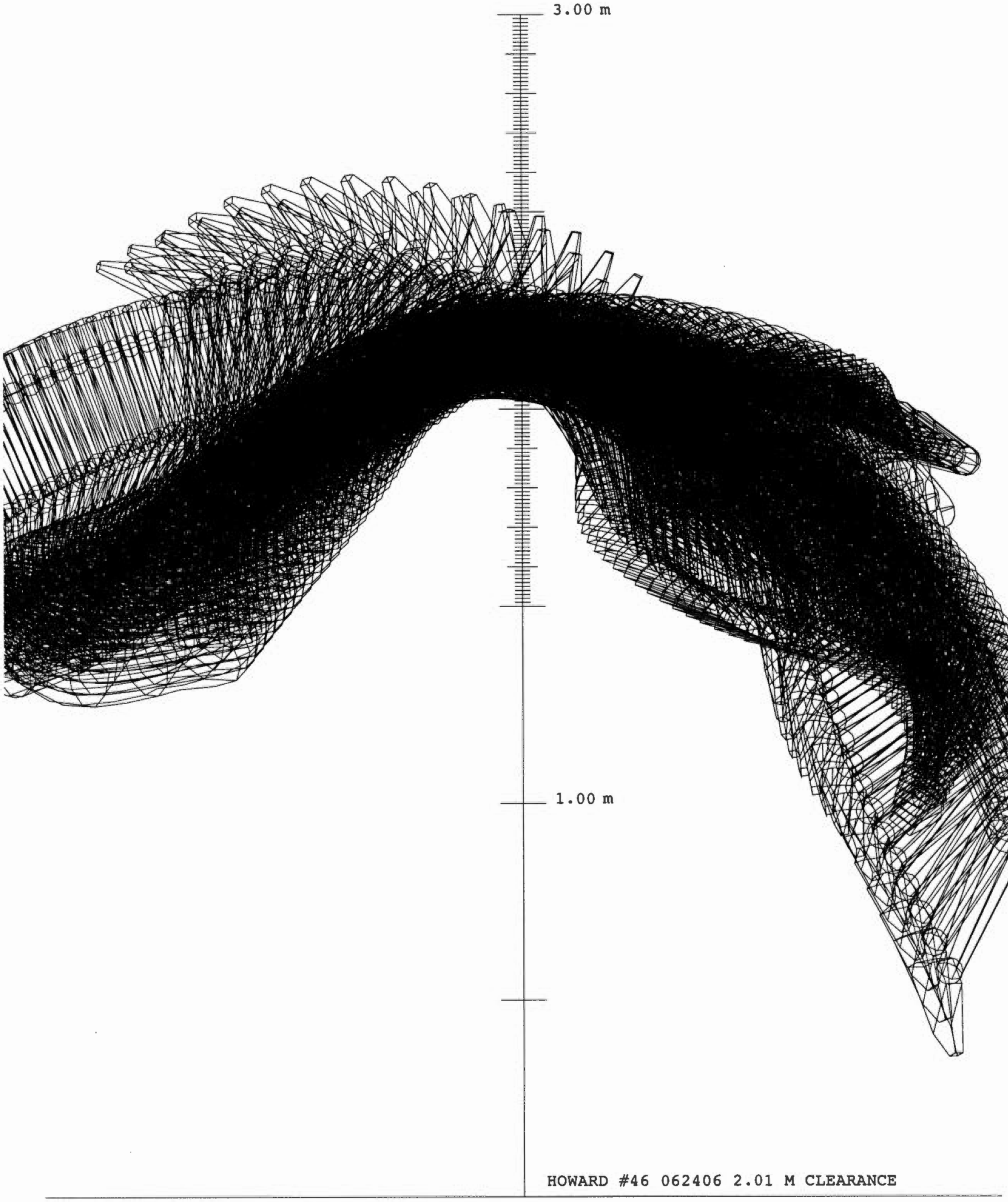


C.M. HEIGHT VS TIME



HOWARD #46 062406 2.01 M CLEARANCE


HOWARD #46 062406 2.01 M CLEARANCE



HOWARD #46 062406 2.01 M CLEARANCE

Christine SPENCE

Jump 09 was Spence's last successful clearance at the 2006 USATF Championships (1.83 m).

Based on Spence's vertical velocity at takeoff in jump 09 (v_{ZTO} = 3.65 m/s), a technique of average quality would have included a final run-up speed of about 6.7 m/s and a c.m. height at the end of the run-up equal to about 48% of her own standing height. Spence's c.m. was actually in a lower position than what would be expected with a technique of average quality (h_{TD} = 46.5%), but her final run-up speed (v_{HI} = 6.5 m/s) was also slower. Overall, the combination of run-up speed and c.m. height that Spence used in jump 09 was not bad, but also not particularly good.

At the end of the run-up, Spence planted the takeoff foot too parallel to the bar. Because of this, the angle between the longitudinal axis of the foot and the horizontal force received by the foot was too large (e_3 = 28°). This produced a risk of ankle pronation, and injury to the ankle and foot. (See the section on "Orientation of the takeoff foot, and potential for ankle and foot injuries" in the main text of the report.)

Spence's arm actions during the takeoff phase were somewhat weak (AAT = 11.7 mm/m), and the action of her lead leg was also weak (LLA = 17.1 mm/m). Therefore, the overall combination of arm and lead leg actions was somewhat weak (FLA = 28.7 mm/m).

Spence's trunk had a very good backward lean at the start of the takeoff phase (BFTD = 75°). Then she rotated forward, but not enough, and at the end of the takeoff she was still far from the vertical (BFTO = 82°). Because of this, she was only able to generate a small amount of forward somersaulting angular momentum (H_F = 60).

Spence's trunk also had a very good lean toward the left at the start of the takeoff phase (LRTD = 73°). Then she rotated toward the right, and at the end of the takeoff she was 5° past the vertical (LRTO = 95°). In the view from the back, it is normal for high jumpers to go up to 10° past the vertical at the end of the takeoff. This seems to give an optimum compromise between the generation of lift and the generation of enough lateral somersaulting angular momentum to permit a good rotation over the bar. Therefore, Spence's position at the end of the takeoff was very good. With those angles, we would have expected Spence to generate a good amount of lateral somersaulting angular momentum, but the amount of lateral somersaulting angular momentum that she ended up with was somewhat small (H_L = 90). We are not sure of the reason for this.

Spence's small forward and somewhat small lateral components of somersaulting angular momentum added up to a small total amount of somersaulting angular momentum (H_S = 110).

The peak height reached by the c.m. in jump 09 was h_{PK} = 1.92 m. The "saturation graph" shows that in this jump Spence could have cleared cleanly a bar set at about h_{CLS} = 1.81 m, and at h_{CLA} = 1.87 m if she had taken off about 10 cm closer to the bar. In relation to the peak height of the c.m. (1.92 m), the 1.87 m clean clearance height indicated a reasonably effective bar clearance. This was a particularly good achievement in view of Spence's small total amount of somersaulting angular momentum.

After takeoff, Spence acquired a compact position in the view along the bar, with both knees very flexed. (See view along the bar at t = 10.34 s.) This helped her to somersault faster, which was good in view of the limited amount of angular momentum that she had available. Then, she arched her trunk, and extended her legs downward (t = 10.34 - 10.46 s). Her pronounced lowering of the legs helped to lift the rest of the body, including the pelvis. However, the marked extension of the legs also made Spence's body less compact (more elongated) in the view along the bar, and therefore slowed down the speed of her backward somersault rotation. Given the small amount of somersaulting angular momentum available to Spence, we wondered if this action was a good choice, and whether Spence might have been able to improve her bar clearance with an alternative set of actions over the bar.

To answer this question, we made tests using computer simulation of the bar clearance. We made two computer simulations. In the first one of these computer-generated jumps ("simulation #1") we kept the position of the body at takeoff, the angular momentum, the path of the c.m. and the motions of the body segments relative to each other after takeoff the same as in the original jump 09. Graphic sequences of this simulation (view from overhead; view perpendicular to the plane of the bar and the standards; view in line with the bar) are shown in one of the graphics pages that follow these comments. The result was a simulated jump very similar to the original jump. This is a standard practice in computer simulation, to check that the simulation program is functioning properly. The graphic sequences of this unaltered simulated jump are shown here to provide a basis for comparison with simulation #2.

In simulation #2 we kept the position at takeoff, the angular momentum and the path of the c.m. the same as in the original jump. However, after takeoff we made Spence increase the flexion of her knees between t = 10.34 and t = 10.58 s as if she wanted to kick the bar from below with her heels. Then, we had her un-arch with good timing. We also made some minor changes in the position of the left arm, to keep it farther away from the bar. (See the graphics sequence of simulation #2.) Theoretically, we should expect the technique used in simulation #2 to lower the hips a little, because the legs don't reach downward as they did in the original jump. But we would also expect it to increase the speed of rotation of the somersault. This might outweigh the disadvantage of having the hips in a slightly lower position. Let's now examine what the simulation told us. Look at the sequence of simulation #2, and compare it with simulation #1 –the original jump. The sequence of simulation #2 (view along the bar) shows an increase in the amount of somersault rotation in comparison with simulation #1. For instance, compare the orientation of the trunk and the orientations of the legs at t = 10.70 s in both simulations (view along the bar). The "saturation graph" of simulation #2 (the last two pages of Spence's graphics after this text) showed that, with this technique, Spence would have been able to clear cleanly a bar set at a height of 1.89 m, if she had also taken off about 7 cm closer to the bar than in the original jump. A height of 1.89 m is 0.02 m higher than the 1.87 m height (h_{CLA}) of the original jump, and only 0.03 m lower than the peak height reached by the c.m. (1.92 m). This would qualify as a very effective bar clearance. So, while Spence's original bar clearance technique was not bad, it could be improved a little bit further by using the airborne actions performed in simulation #2.

Recommendations

The most important problem in Spence's technique is her slow speed at the end of the run-up. We would advise her to keep the c.m. at the end of the run-up at the same height as in jump 09 (h_{TD} = 46.5%), but to increase the final speed of the run-up from her current 6.5 m/s to 6.8 m/s. (See Appendix 2 for exercises that will help to facilitate this.)

(Standard caution when increasing the run-up speed and/or lowering the c.m. height at the end of the run-up: ***The use of a faster and/or lower run-up will put a greater stress on the takeoff leg, and thus it may increase the risk of injury if the leg is not strong enough. Therefore, it is always 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.*****)**

Spence needs to plant the takeoff foot on the ground with the longitudinal axis of the foot more in line with the final direction of the run-up: The foot needs to be planted with the toe pointing at least 10° more toward the landing pit than in jump 09. This technique change will help to prevent ankle pronation, and injury to the ankle and foot.

Spence's arm and lead leg actions could be improved a bit by lifting the elbows and the right knee higher at the end of the takeoff. This is not a major problem, but it may be worthwhile to correct.

Spence's leans backward and toward the left at the start of the takeoff phase in jump 09 were very good. Her rotation toward the right during the takeoff phase was also very good. What she needs to do now is to allow herself to rotate forward further, all the way to the vertical (in the view from the side). This will allow her to generate a larger amount of forward somersaulting angular momentum, which in turn will contribute to a larger total amount of somersaulting angular momentum, a better rotation over the bar, and ultimately a more effective bar clearance.

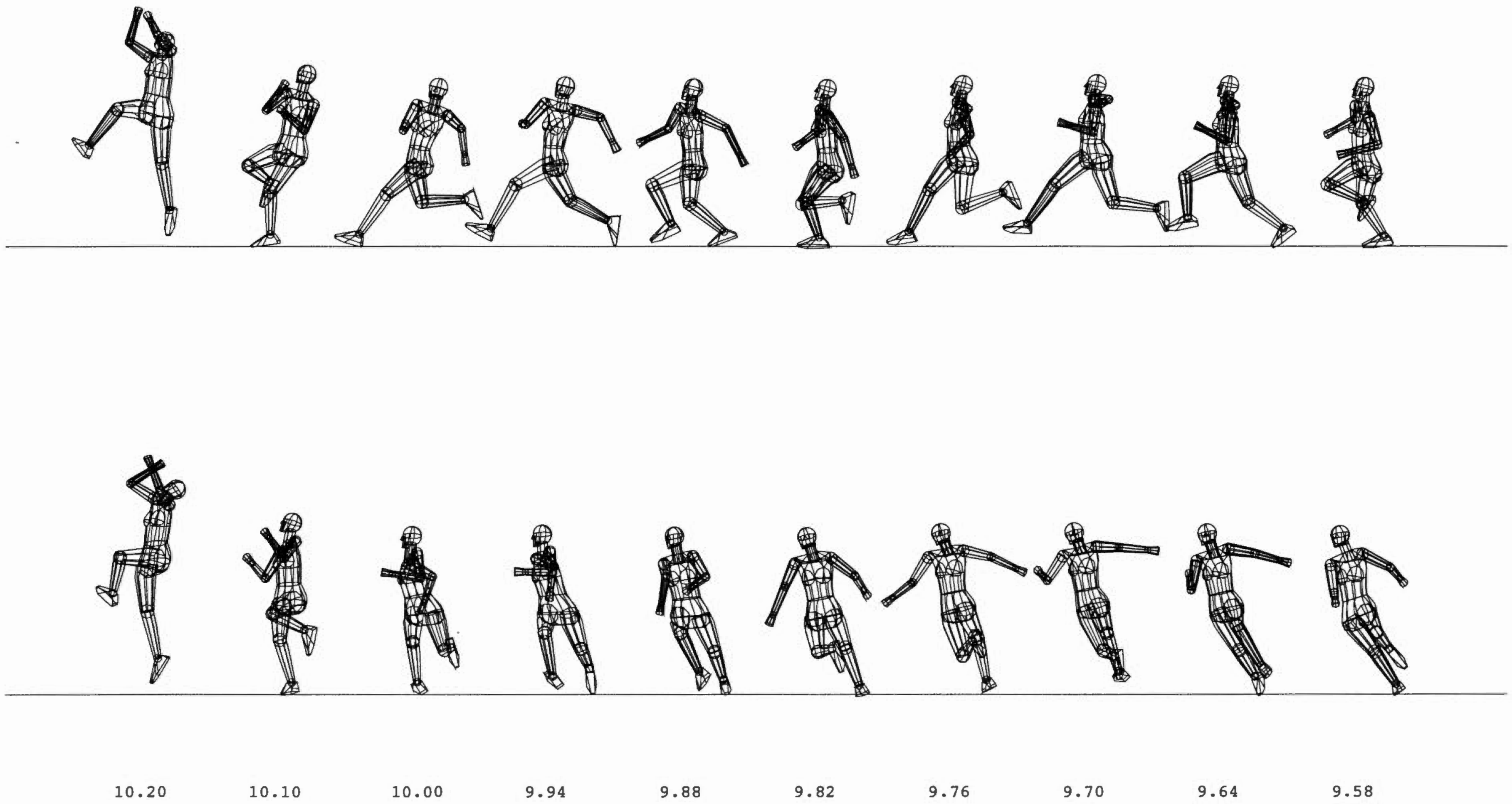
Spence's actions over the bar in jump 09 were good, with a compact body configuration on the way up to the bar, and a good arch at the peak of the jump. Our computer simulations indicated that she would be able to improve the effectiveness of her bar clearance a little bit further (a couple of centimeters) if, shortly before reaching the bar, she flexed her knees as if to kick the bar from below with her heels, and then un-arched with good timing.

Of course, it is also very important for Spence to take off from an appropriate location, so that the highest point of the jump is directly above the bar. At the 2006 USATF Championships, this was a major problem for Spence. In jump 09 she took off about 10 cm too far from the bar, and this cost her about 6 cm in the height that she was able to clear (the difference between h_{CLS} = 1.81 m and h_{CLA} = 1.87 m).

So, if Spence makes a jump with the same run-up and takeoff as in jump 09, she should take off about 10 cm closer to the plane of the bar than she did in jump 09. However, we also need to take into account what will happen if she increases her final run-up speed, as we advise. If she adopts a faster run-up, it is likely that she will have a larger amount of leftover horizontal velocity at the end of the takeoff, and then she should take off *farther* from the plane of the bar, or else the peak of the jump will be beyond the plane of the bar, over the pit, which would not be good either. A good rule of thumb to figure out if an athlete is taking off too close to the bar or too far from the bar is to pay attention to *when* the bar gets hit. If the bar gets hit very late, this suggests that the athlete took off too far from the bar, reached the peak, and then fell on the bar. If the bar gets hit very early, this suggests that the athlete took off too close to the bar, and hit it on the way up toward the peak.

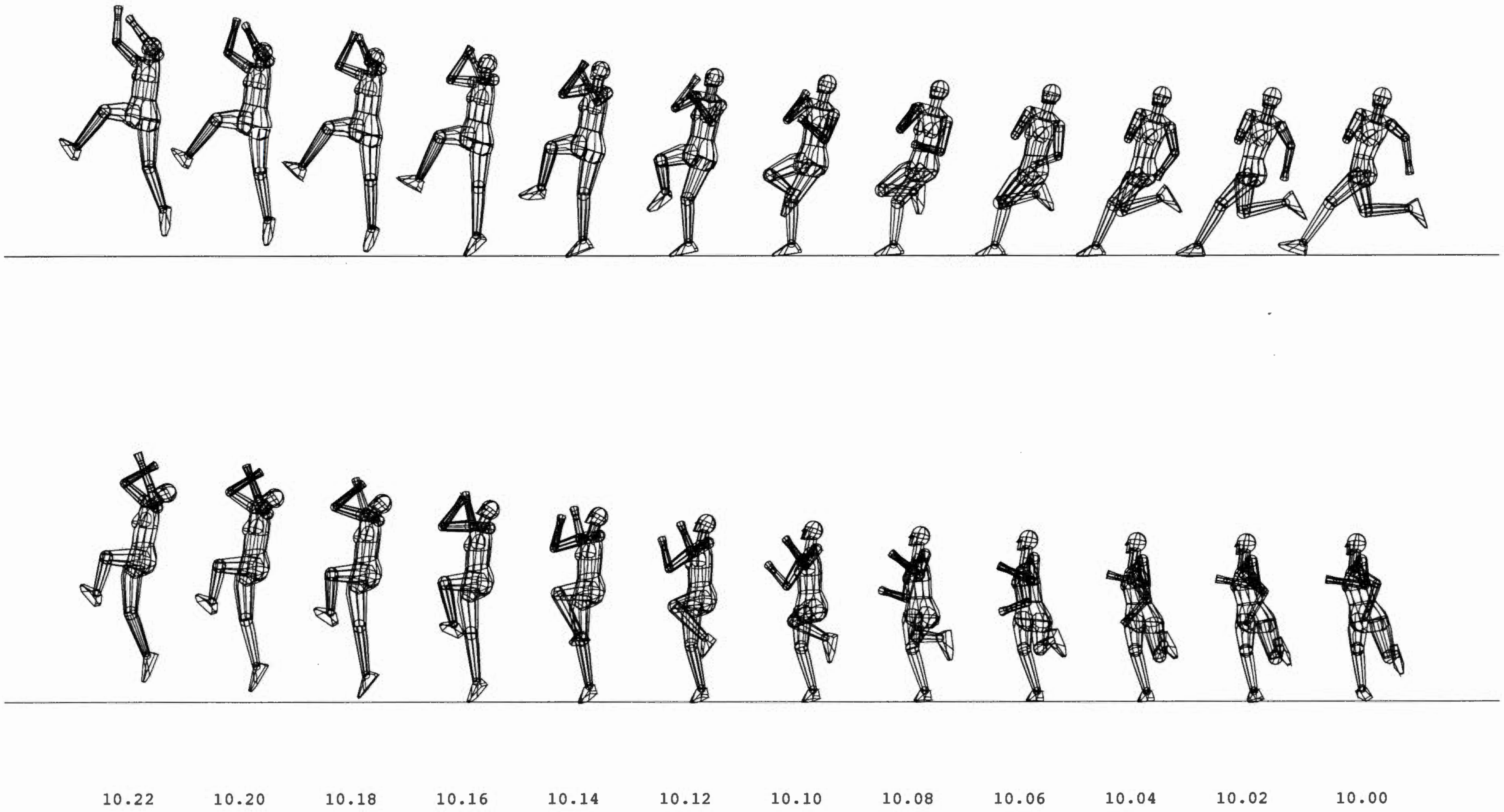
SPENCE #09 062406 1.83 M CLEARANCE

RUN-UP



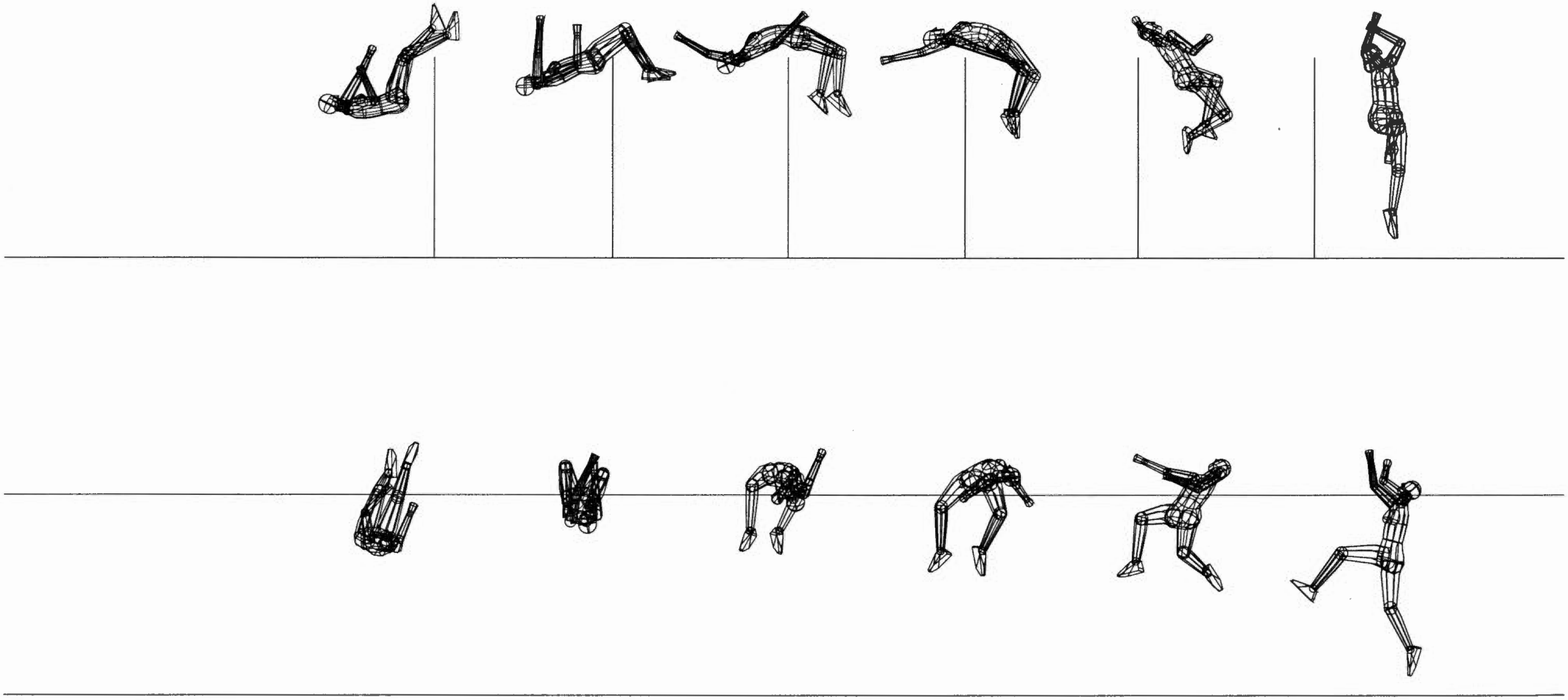
SPENCE #09 062406 1.83 M CLEARANCE

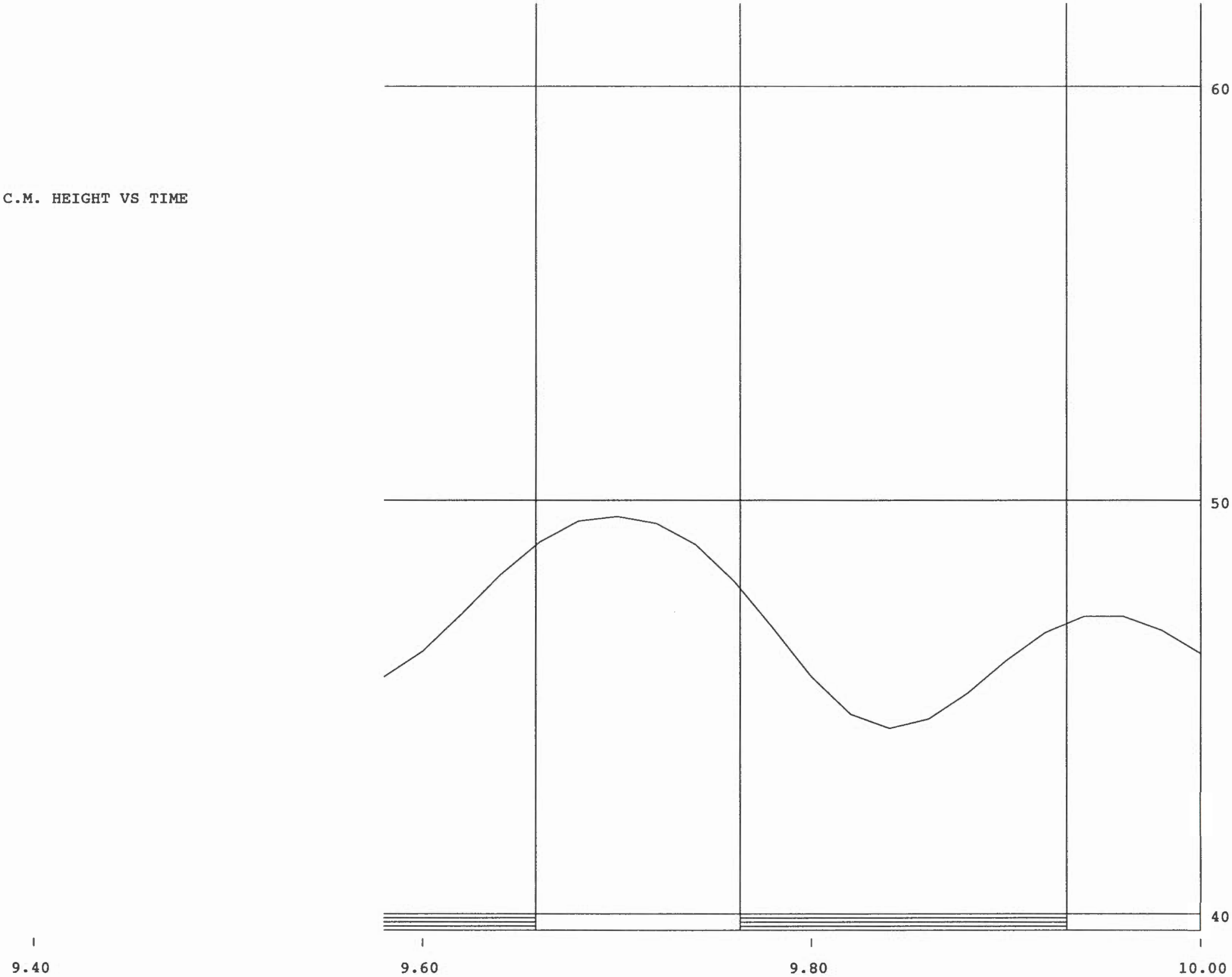
TAKEOFF PHASE



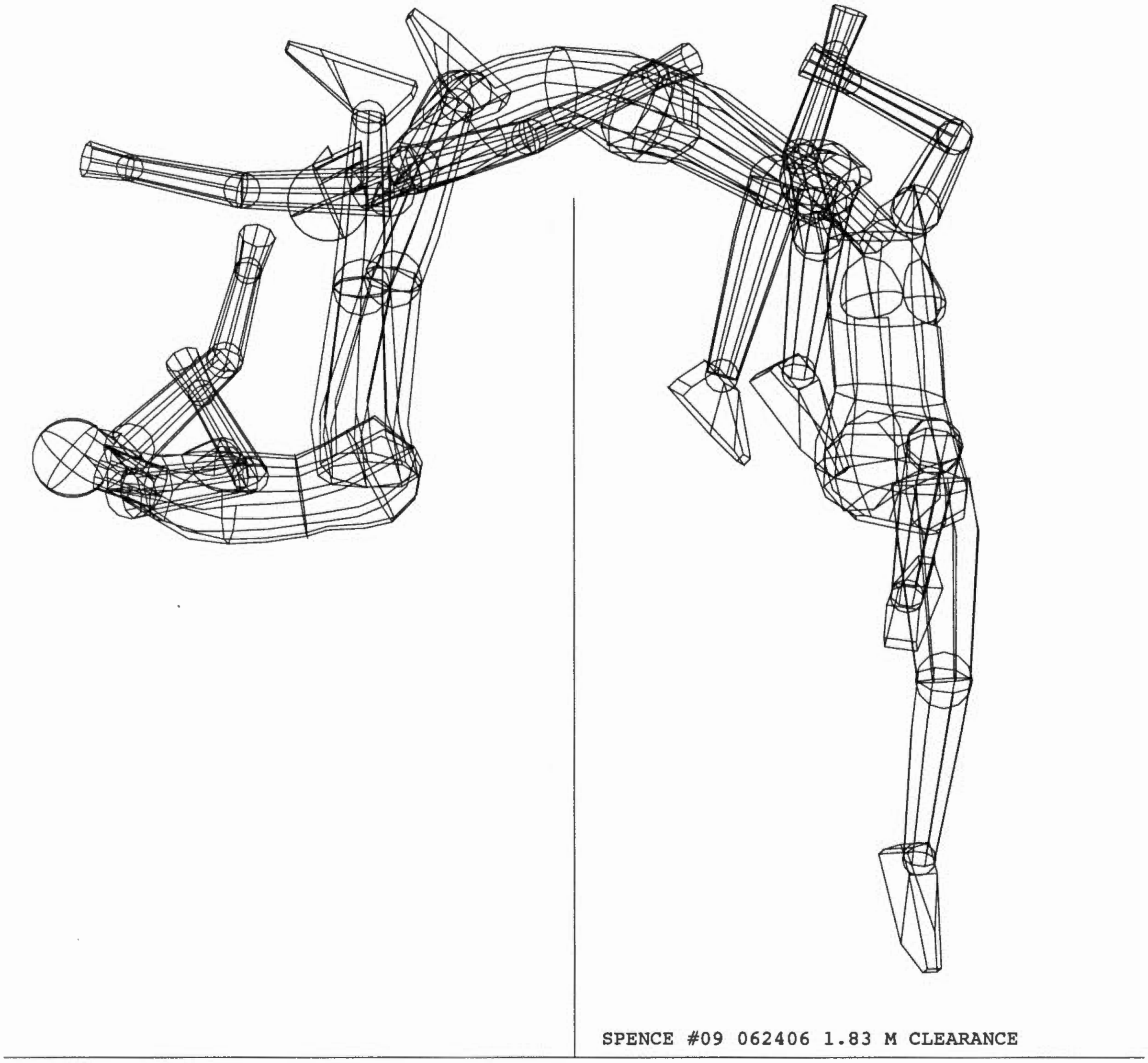
SPENCE #09 062406 1.83 M CLEARANCE

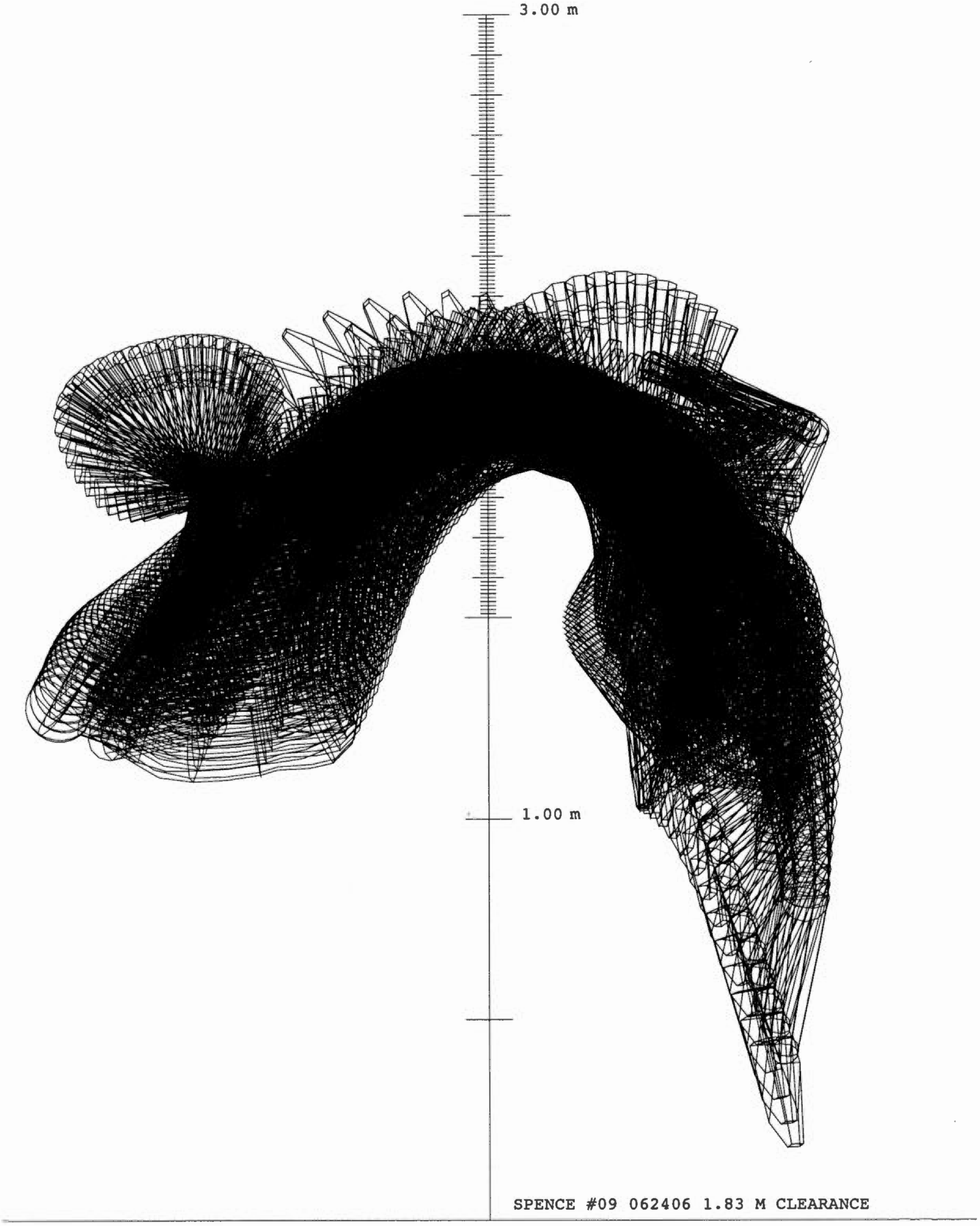
BAR CLEARANCE





SPENCE #09 062406 1.83 M CLEARANCE


SPENCE #09 062406 1.83 M CLEARANCE

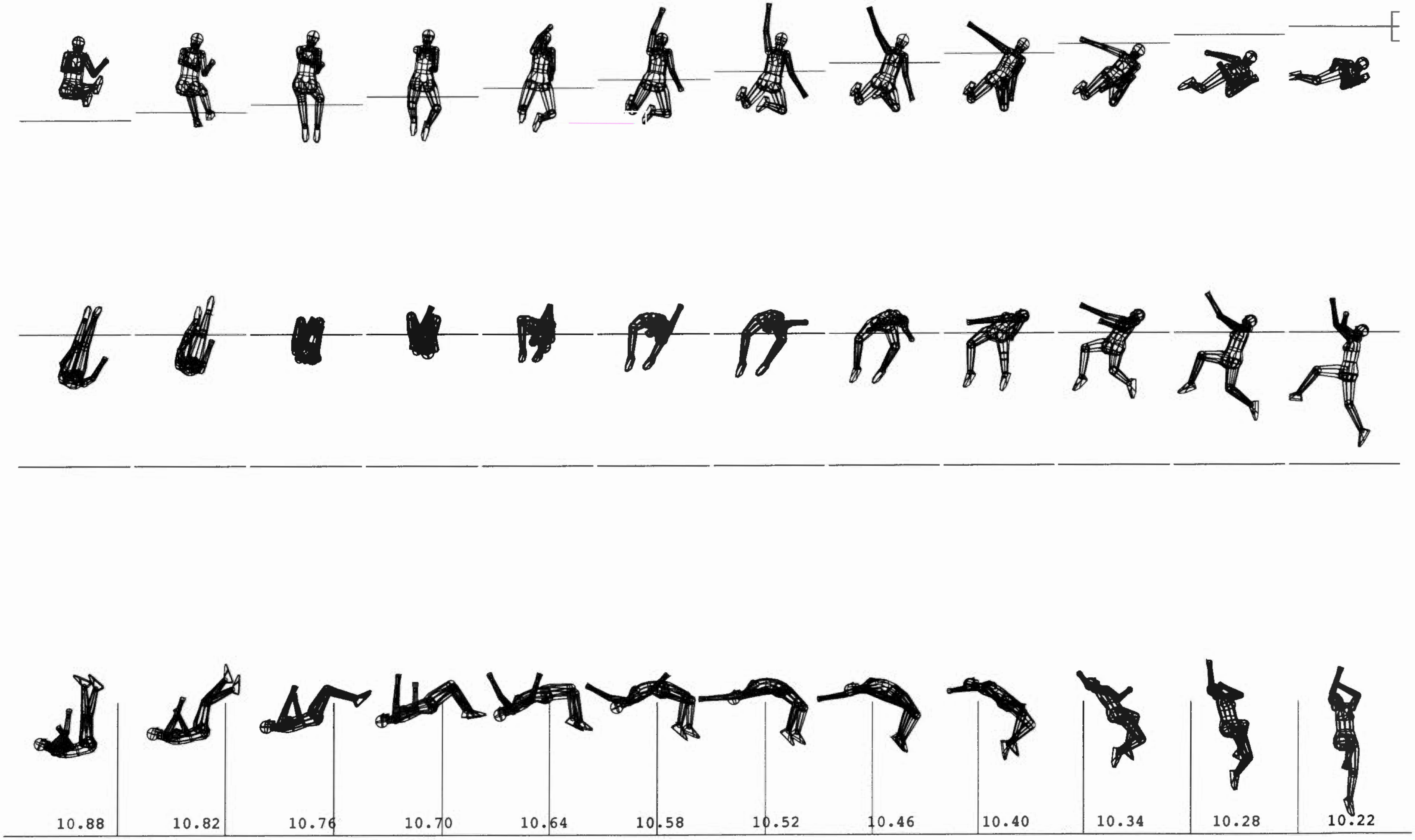


SPENCE #09 062406 1.83 M CLEARANCE

SPENCE #09 062406 1.83 M CLEARANCE

COMPUTER-SIMULATED JUMP

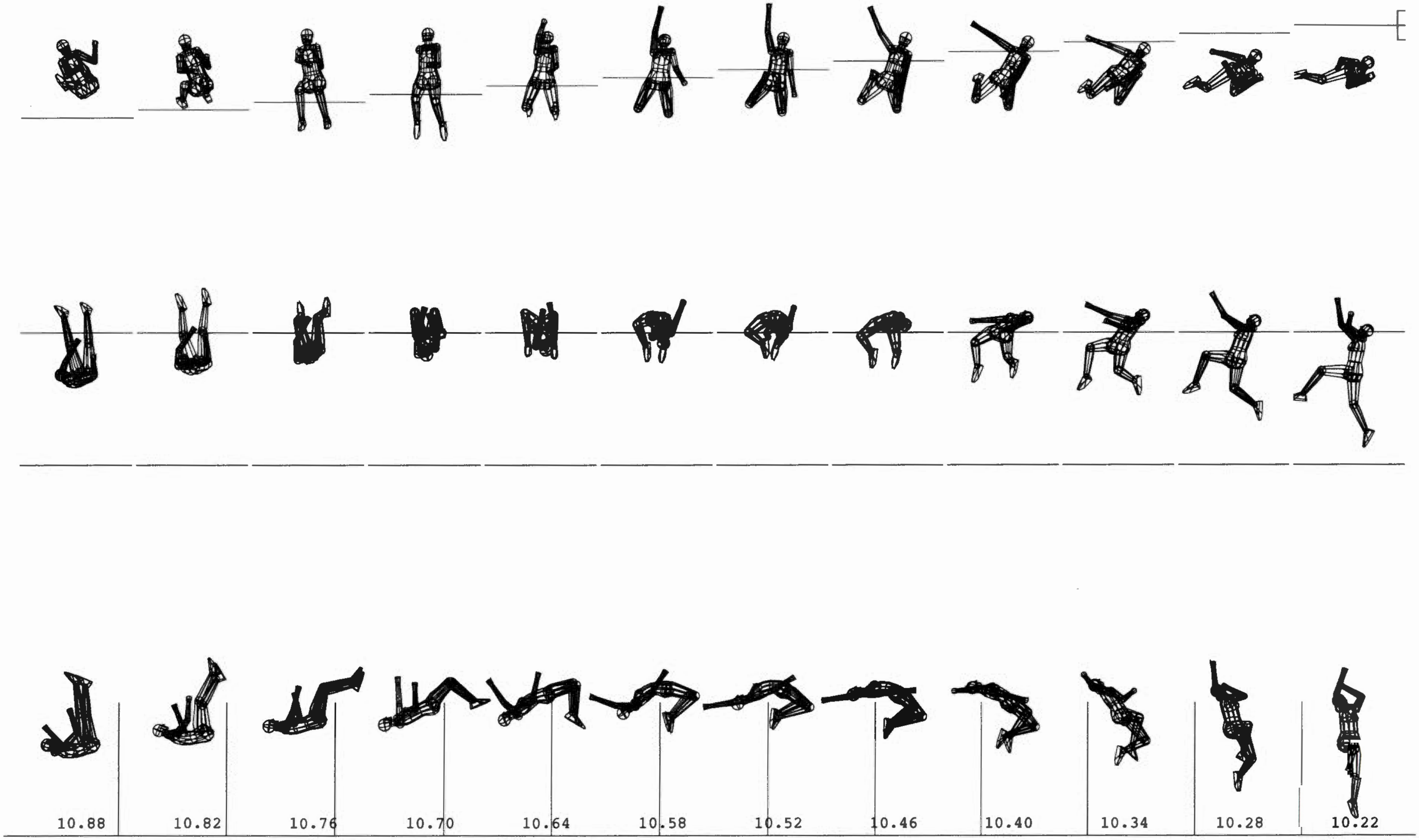
SIMULATION #1



SPENCE #09 062406 1.83 M CLEARANCE

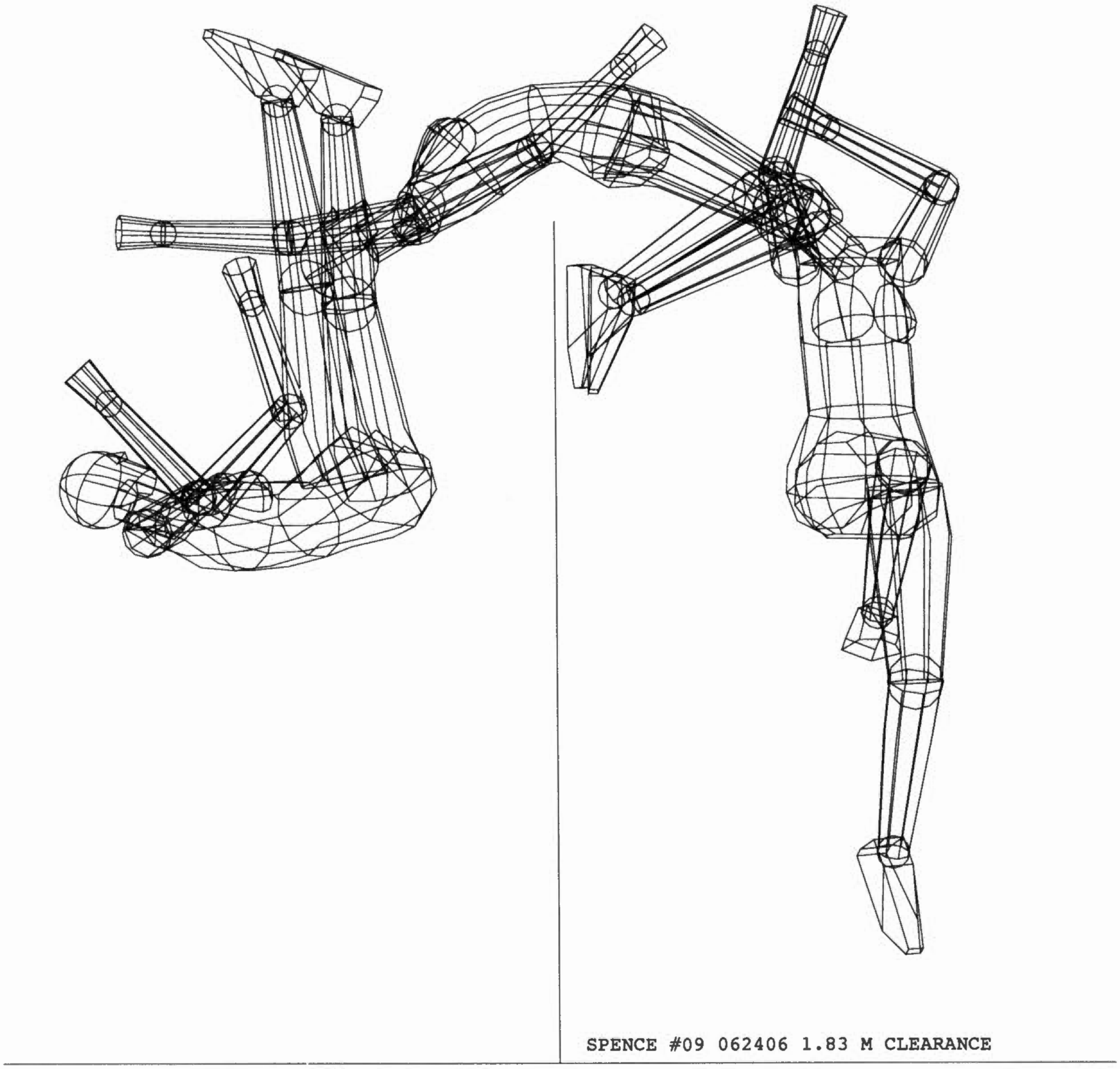
COMPUTER-SIMULATED JUMP

SIMULATION #2



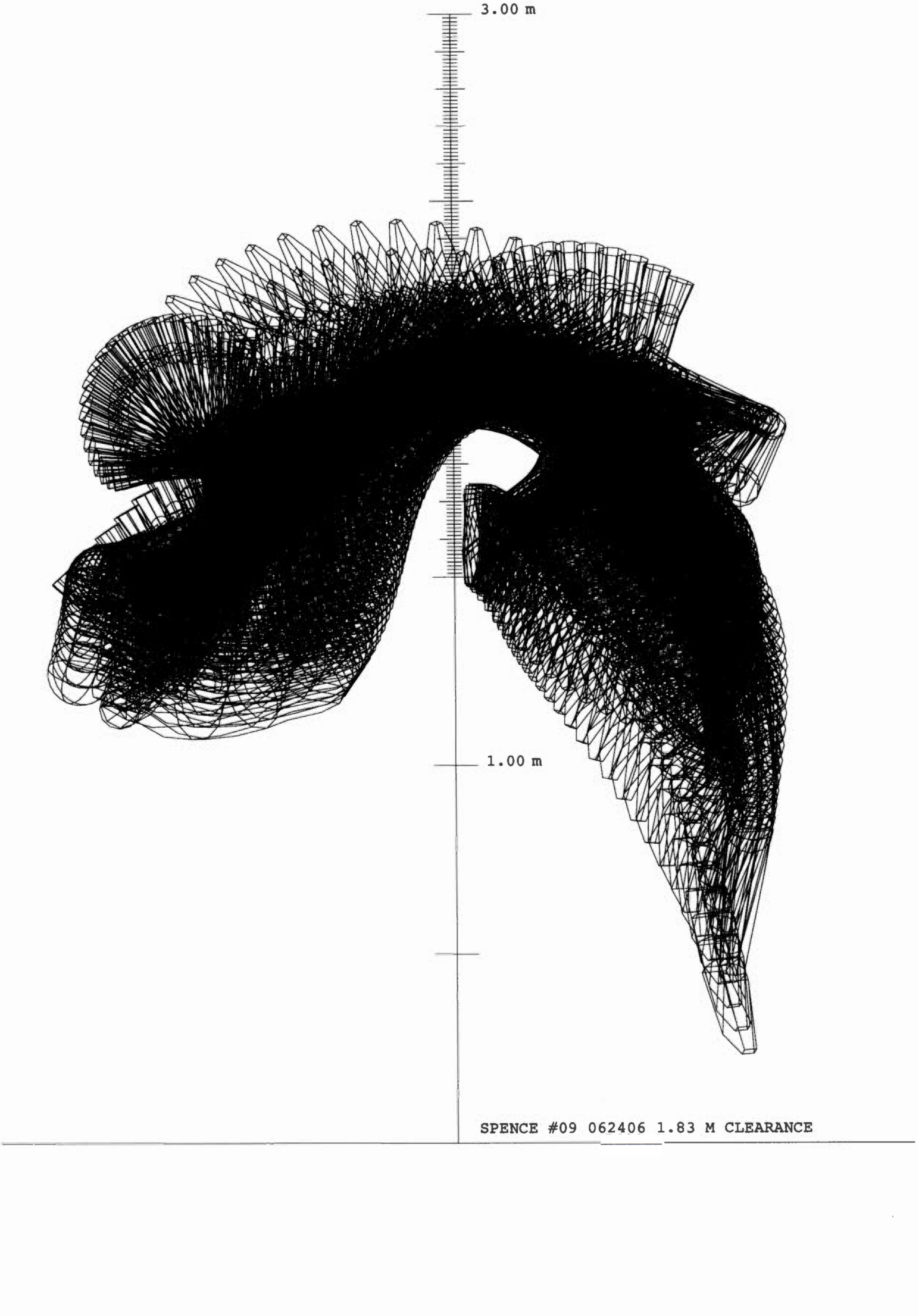
COMPUTER-SIMULATED JUMP

SIMULATION #2



COMPUTER-SIMULATED JUMP

SIMULATION #2



Kaylene WAGNER

Jump 01 was Wagner's last successful clearance at the 2006 USATF Championships (1.83 m).

Based on Wagner's vertical velocity at takeoff in jump 01 (v_{ZTO} = 3.40 m/s), a technique of average quality would have included a final run-up speed of about 6.5 m/s and a c.m. height at the end of the run-up equal to about 48.5% of her own standing height. Wagner's c.m. was actually lower (h_{TD} = 47%), but her final run-up speed (v_{H1} = 6.3 m/s) was also slower than what would be expected with a technique of average quality. Thus, the overall combination of run-up speed and c.m. height that Wagner used in jump 01 was not bad, but also not particularly good. It was not very different from the combinations that she used in 2003 and 2004. Wagner's jumps give the impression that her motions in the final two or three steps of the run-up are not fully automated, that she is hesitant of what to do, and thus probably travels more slowly than what her legs are capable of achieving. This is just a subjective impression based on direct ("live") observation of her jumps. This problem may be linked to the difficulty that she has in the preparation of her arms for the takeoff. (See below.)

At the end of the run-up, Wagner planted the takeoff foot too parallel to the bar. Because of this, the angle between the longitudinal axis of the takeoff foot and the horizontal force received by the foot was too large (e_3 = 35°), and created a very large risk of ankle pronation, and injury to the ankle and foot. (See the section on "Orientation of the takeoff foot, and potential for ankle and foot injuries" in the main text of the report.) This is a larger problem than in either of her two previous analyzed jumps.

In the last steps of the run-up, Wagner's arm preparations remained very similar to those of her previous two analyzed jumps: Both arms were back one step before the start of the takeoff (see the side-view sequence of the run-up at t = 9.76 s), and then the right arm moved forward in the last step of the run-up (t = 9.76-10.00 s). Therefore, at the start of the takeoff phase (t = 10.00 s) the right arm was ahead of the body.

Wagner's arms have not been in very good positions at the start of the takeoff phase for the execution of strong arm actions in any of her three analyzed jumps. However, in her jumps from 2003/2004 Wagner lifted her right arm a fair amount during the takeoff phase, and the swing of her left arm was also good. Therefore, her arm actions were judged to be reasonably strong. But in jump 01 she did not lift her elbows high enough by the end of the takeoff phase. (See the positions of the arms at t = 10.20/10.22 s for jump 01 in the sequence of the takeoff in this report, and compare them with those in the reports from 2003/2004.) Because of this, Wagner's arm actions were weak in jump 01 (AAT = 8.3 mm/m). In contrast, the action of her lead leg was reasonably strong (LLA = 18.7 mm/m). Still, the overall combination of Wagner's arm and lead leg actions was weak (FLA = 27.0 mm/m).

Wagner's trunk had a very good backward lean at the start of the takeoff phase in jump 01 (BFTD = 73°). Then she limited very much the amount of forward rotation that her trunk went through during the takeoff phase, and at the end of the takeoff she was still far short of the vertical (BFTO = 83°). Although this was slightly further forward than in either one of her two previous analyzed jumps, it still was not nearly enough, and it limited to a small value (H_F = 50) the amount of forward somersaulting angular momentum that she was able to generate during the takeoff phase.

Wagner's trunk had a good lean toward the left at the start of the takeoff phase (LRTD = 78°). Then she rotated toward the right, and at the end of the takeoff she has 11° beyond the vertical (LRTO = 101°). In the view from the back, it is normal for high jumpers to go up to 10° past the vertical at the end of the takeoff. This seems to give an optimum compromise between the generation of lift and the generation of enough lateral somersaulting angular momentum to permit a good rotation over the bar. Since Wagner was 11° past the vertical, she was essentially at the acceptable limit, and we consider her to be OK in this regard. This was a clear improvement in comparison to her jumps from 2003/2004, in which her lean toward the right at the end of the takeoff was clearly beyond the acceptable limit, which surely made Wagner lose part of her lift. However, there was some price to be paid for Wagner's reduced final lean in jump 01: She was not able to generate quite as much lateral somersaulting angular momentum as in 2003/2004. Still, she was able to generate a large amount of it (H_L = 105).

Wagner's forward and lateral components of somersaulting angular momentum added up to a somewhat small total amount of somersaulting angular momentum (H_S = 115). This value was slightly smaller than in 2003/2004, but it is necessary to keep in mind that it was linked to a reduction in her lean toward the right at the end of the takeoff, which must have helped her to improve her lift.

Overall, we consider Wagner's leans at the beginning and at the end of the takeoff phase, and the process of generation of angular momentum, to be improved in jump 01 with respect to her jumps from 2003/2004.

Wagner's c.m. reached a maximum height h_{PK} = 1.90 m in jump 01. The "saturation graph" shows that in this jump she could have cleared cleanly a bar set at about h_{CLS} = 1.81 m, and at h_{CLA} = 1.82 m if she had taken off slightly farther from the plane of the bar and the standards. In relation to the peak height of the c.m. (1.90 m), the 1.82 m clean clearance height indicated a bar clearance that was not very effective. This was probably due to Wagner's insufficient arch at the peak of the jump. (See the view along the bar at t = 10.58 s in jump 01, and compare it with the same view in the jumps from 2003/2004.)

Recommendations

Wagner's technique problems are similar to the ones she had in 2003/2004. The most important problem is her slow speed at the end of the run-up. We would advise her to keep the c.m. at the end of the run-up at the same height as in jump 01 (h_{TD} = 47%), but to increase the final speed of the run-up from 6.3 m/s to about 6.7 m/s. (See Appendix 2 for exercises that will help to facilitate this.)

(Standard caution when increasing the run-up speed and/or lowering the c.m. height at the end of the run-up: ***The use of a faster and/or lower run-up will put a greater stress on the takeoff leg, and thus it may increase the risk of injury if the leg is not strong enough. Therefore, it is always 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.***)

In regard to the preparation of the arms in the final part of the run-up, the two best options for Wagner are probably the following: Either (a) prepare for a double-arm takeoff, or (b) just keep alternating the motions of the arms with the motions of the legs all the way to the end of the run-up. The former would provide (when mastered) stronger contributions by the arms to the height of the jump, while the latter would facilitate a faster final run-up speed, which in turn would also contribute to increase the height of the jump. But a third option (c) can't be ignored. This would be to *commit* to her present type of preparation. This is a preparation that starts one step too early, and thus makes the arms be in the backward position (i.e., ready to start the takeoff actions) one whole step before takeoff, and then the right arm drifts forward in the last step, so that the preparation does not achieve anything beyond what would be achieved using the much simpler preparation method "b". Preparation method "c" makes no sense, even though it has been used by other high jumpers in the past, notably Ulrike Meyfarth when she won the gold medal at the 1972 Olympic Games. However, even though arm preparation "c" serves no purpose, it is possible that Wagner may have it so ingrained in her mental program that changing it into either one of the two other patterns (a or b) may slow down all of her motions while she tries (unsuccessfully so far) to execute those other preparation patterns, even though pattern "b" is clearly simpler than pattern "c". So it is possible that, given Wagner's previous learning experience, the best way for her to reach the fastest possible speed at the end of the run-up might be through the use of preparation pattern "c". It is possible that if Wagner simply goes for pattern "c" (with no thought whatsoever of trying to execute patterns "a" or "b"), she might be able to improve her final speed to a higher value than if she tries to use either one of those two other patterns. We are not saying that pattern "c" is necessarily the best choice for Wagner, only that it is a third possible choice that should be considered.

In 2003, Wagner had a second important problem: the placement of her takeoff foot. The problem decreased in 2004, but in jump 01 it has become much worse than in 2003. The takeoff foot needs to be planted with the toe pointing more toward the landing pit than in jump 01: The heel-to-toe line should be oriented about 15° more clockwise than in jump 01. This technique change will help to prevent ankle pronation, and injury to the ankle and foot.

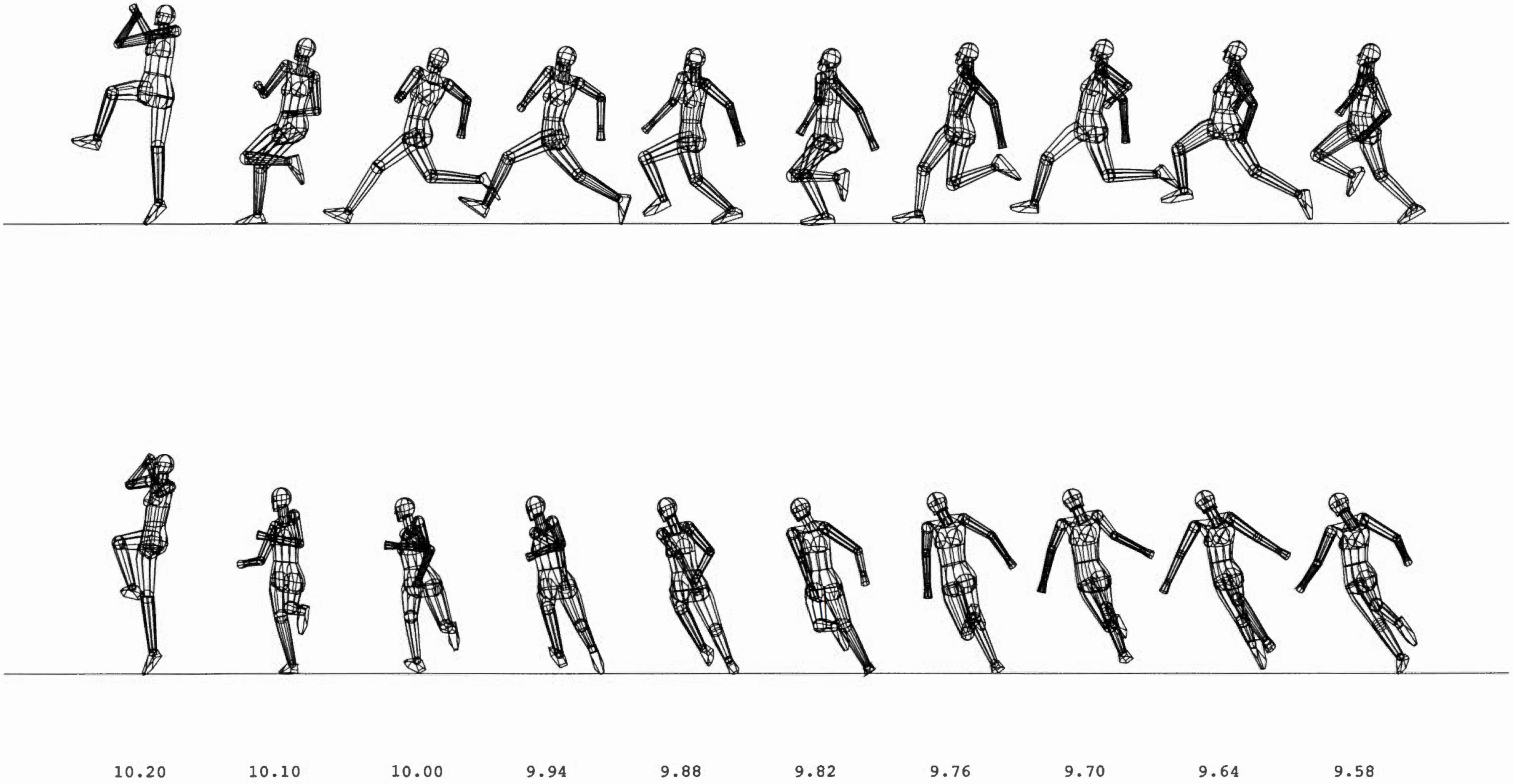
Wagner needs to thrust her elbows to a higher position by the end of the takeoff, as she did in 2003/2004. This will help her to generate more lift.

Wagner's leans backward and toward the left at the start of the takeoff phase were good in jump 01. Her rotation toward the right during the takeoff phase was also good. What she needs to do now is to allow herself to rotate forward further, all the way to the vertical (in the view from the side). This will allow her to generate a larger amount of forward somersaulting angular momentum, which in turn will contribute to a larger total amount of somersaulting angular momentum, a better rotation over the bar, and ultimately a more effective bar clearance.

Wagner also needs to arch more markedly at the peak of the jump, and then to un-arch with good timing.

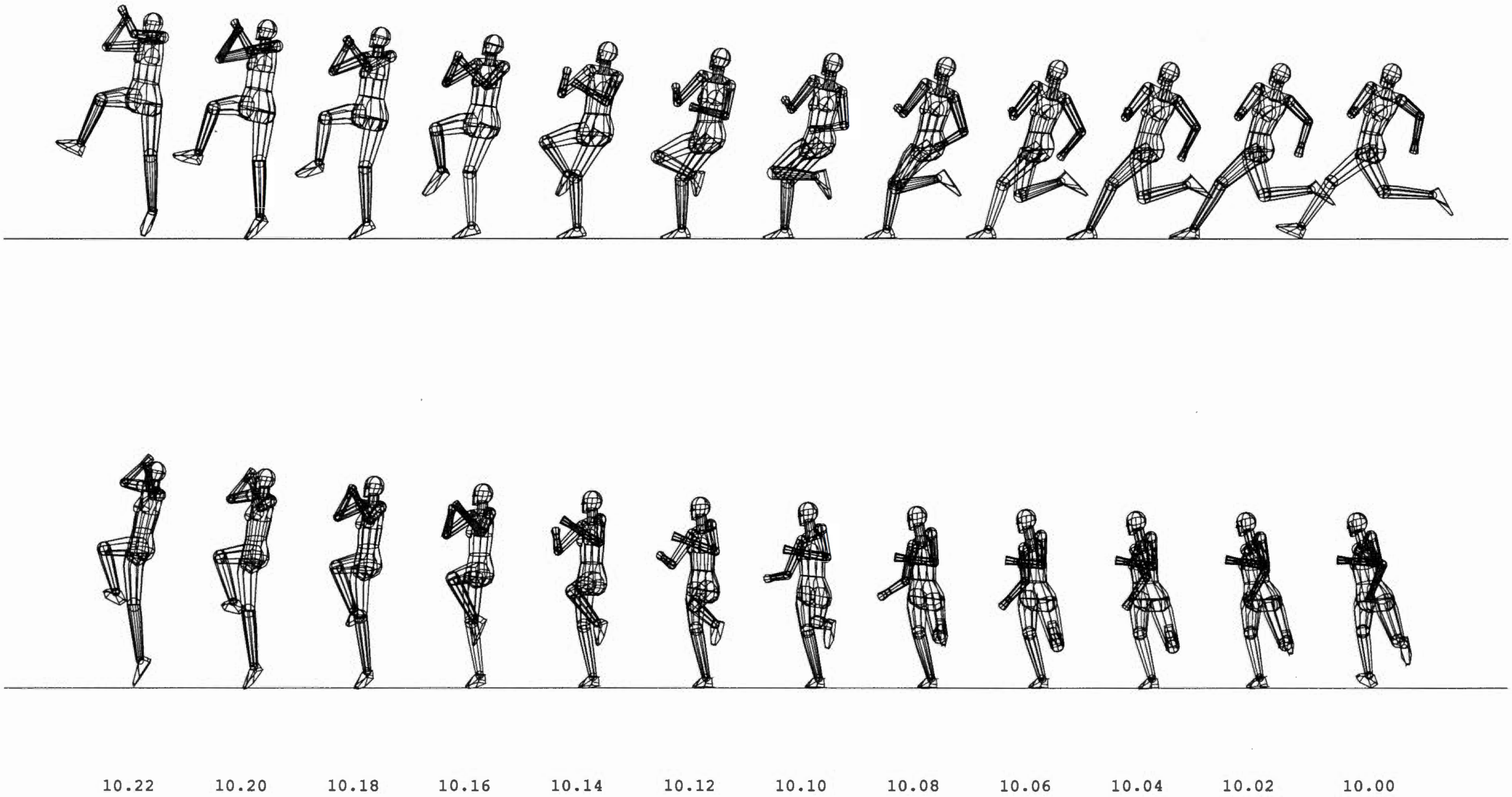
WAGNER #01 062406 1.83 M CLEARANCE

RUN-UP



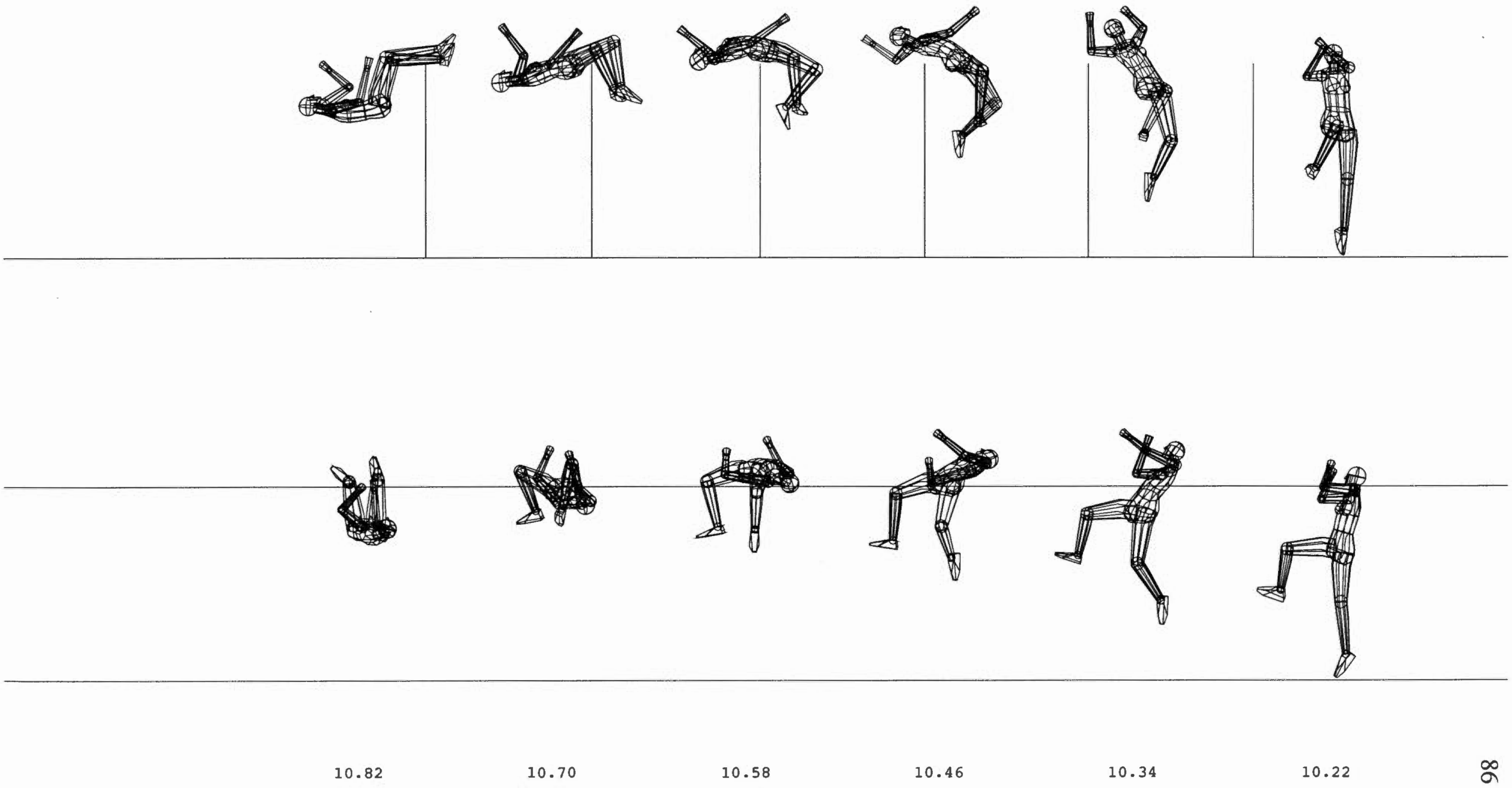
WAGNER #01 062406 1.83 M CLEARANCE

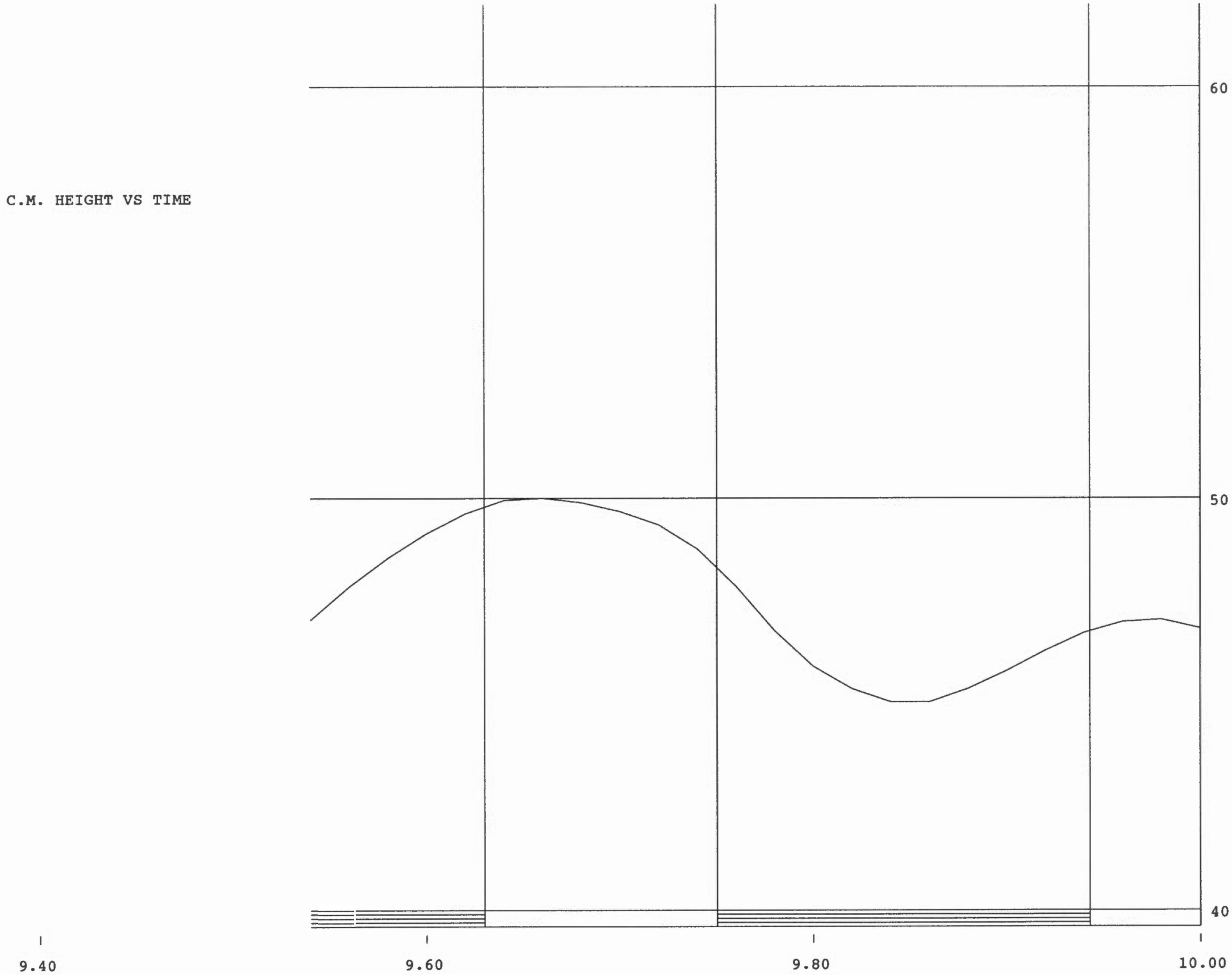
TAKEOFF PHASE



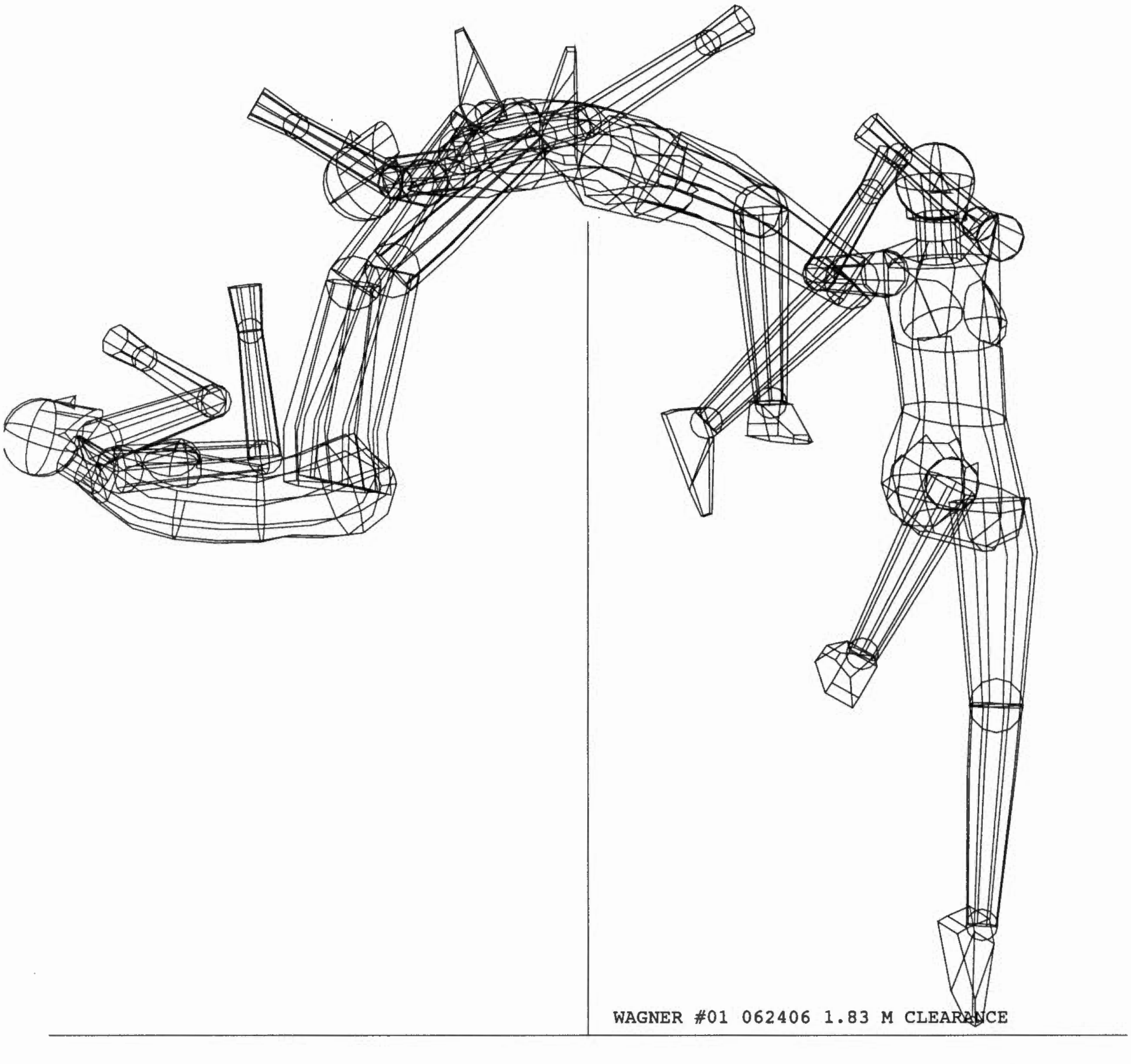
WAGNER #01 062406 1.83 M CLEARANCE

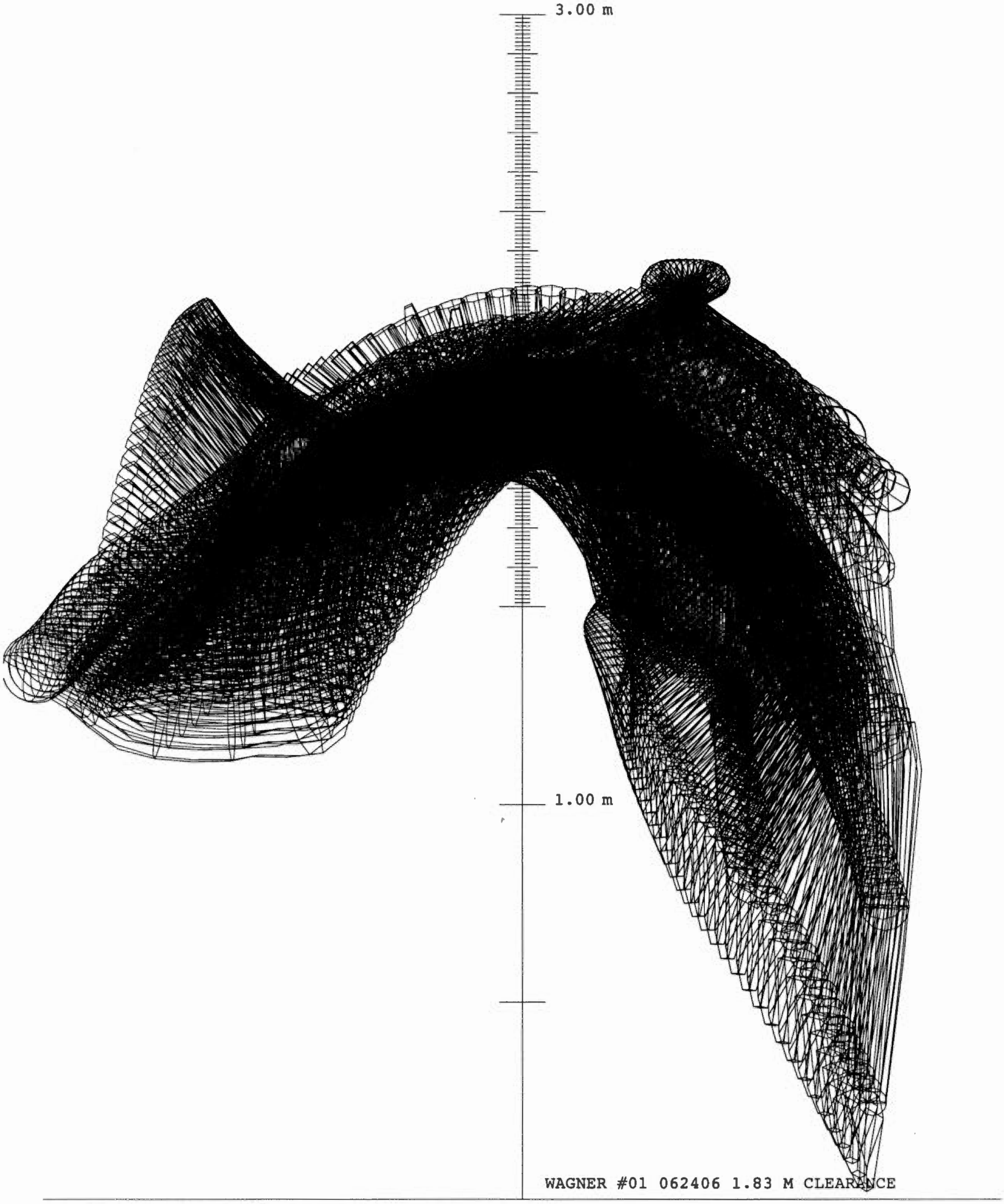
BAR CLEARANCE




C.M. HEIGHT VS TIME

WAGNER #01 062406 1.83 M CLEARANCE


WAGNER #01 062406 1.83 M CLEARANCE


3.00 m
1.00 m
WAGNER #01 062406 1.83 M CLEARANCE

REFERENCES

1. Dapena, J. Mechanics of translation in the Fosbury-flop. *Med. Sci. Sports Exerc.* 12:37-44, 1980a.
2. Dapena, J. Mechanics of rotation in the Fosbury-flop. *Med. Sci. Sports Exerc.* 12:45-53, 1980b.
3. Dapena, J. Simulation of modified human airborne movements. *J. Biomech.* 14:81-89, 1981.
4. Dapena, J. Basic and applied research in the biomechanics of high jumping. *Current Research in Sports Biomechanics*, Eds. B. Van Gheluwe and J. Atha. Karger, Basel, 19-33, 1987a.
5. Dapena, J. Biomechanical analysis of high jump, #7 (Men). *Report for Scientific Services Project (USOC/TAC).* U.S. Olympic Training Center, Colorado Springs, 215 pp, 1987b.
6. Dapena, J. Biomechanical analysis of high jump, #8 (Women). *Report for Scientific Services Project (USOC/TAC).* U.S. Olympic Training Center, Colorado Springs, 221 pp, 1987c.
7. Dapena, J. How to design the shape of a high jump run-up. *Track Coach* 131:4179-4181, 1995a.
8. Dapena, J. The rotation over the bar in the Fosbury-flop high jump. *Track Coach* 132:4201-4210, 1995b.
9. Dapena, J., M. Ae and A. Iiboshi. A closer look at the shape of the high jump run-up. *Track Coach* 138:4406-4411, 1997a.
10. Dapena, J., W.J. Anderst and M.K. LeBlanc. High jump, #14 (Men). *Report for Scientific Services Project (USATF).* USA Track & Field, Indianapolis, 113 pp, 1995b.
11. Dapena, J., R.M. Angulo-Kinzler, J.M. Caubet, C. Turró, X. Balius, S.B. Kinzler, J. Escoda and J.A. Prat. Track and field: high jump (Women). *Report for 1992 Summer Olympic Games Biomechanics Projects (IOC: Medical Commission / Biomechanics Subcommission).* International Olympic Committee, Lausanne, Switzerland, 261 pp, 1993a.
12. Dapena, J., R.M. Angulo-Kinzler, C. Turrì, J.M. Caubet, X. Balius, S.B. Kinzler, J. Escoda and J.A. Prat. Track and field: high jump (Men). *Report for 1992 Summer Olympic Games Biomechanics Projects (IOC: Medical Commission / Biomechanics Subcommission).* International Olympic Committee, Lausanne, Switzerland, 212 pp, 1993b.
13. Dapena, J. and R. Bahamonde. Biomechanical analysis of high jump, #9 (Men). *Report for Scientific Services Project (USOC/TAC).* The Athletics Congress, Indianapolis, 190 pp, 1991.
14. Dapena, J., R. Bahamonde, M. Feltner, I. Oren and O. Nicklass. Biomechanical analysis of high jump, #3 (Men). *Report for Elite Athlete Project (USOC/TAC).* U.S. Olympic Training Center, Colorado Springs, 86 pp, 1983b.
15. Dapena, J. and C.S. Chung. Vertical and radial motions of the body during the take-off phase of high jumping. *Med. Sci. Sports Exerc.* 20:290-302, 1988.
16. Dapena, J. and M. Feltner. Biomechanical analysis of high jump, #6 (High School Males). *Report for Scientific Services Project (USOC/TAC).* U.S. Olympic Training Center, Colorado Springs, 128 pp, 1986c.
17. Dapena, J., M. Feltner and R. Bahamonde. Biomechanical analysis of high jump, #5 (Men). *Report for Scientific Services Project (USOC/TAC).* U.S. Olympic Training Center, Colorado Springs, 200 pp, 1986b.
18. Dapena, J., M. Feltner, R. Bahamonde and C.S. Chung. Biomechanical analysis of high jump, #4 (Women). *Report for Scientific Services Project (USOC/TAC).* U.S. Olympic Training Center, Colorado Springs, 273 pp, 1986a.
19. Dapena, J., M. Feltner, R. Bahamonde, O. Nicklass and I. Oren. Biomechanical analysis of high jump, #2 (Women). *Report for Elite Athlete Project (USOC/TAC).* U.S. Olympic Training Center, Colorado Springs, 119 pp, 1983a.
20. Dapena, J. and B.J. Gordon. High jump, #17 (Women). *Report for Scientific Services Project (USATF).* USA Track & Field, Indianapolis, 139 pp, 1998a.
21. Dapena, J. and B.J. Gordon. High jump, #19 (Women). *Report for Scientific Services Project (USATF).* USA Track & Field, Indianapolis, 115 pp, 1999.
22. Dapena, J. and B.J. Gordon. High jump, #27 (Women). *Report for Scientific Services Project (USATF).* USA Track & Field, Indianapolis, 112 pp, 2004a.
23. Dapena, J., B.J. Gordon, L. Hoffman and M.K. LeBlanc. High jump, #15 (Women). *Report for Scientific Services Project (USATF).* USA Track & Field, Indianapolis, 94 pp, 1997b.
24. Dapena, J., B.J. Gordon and B.W. Meyer. High jump, #25 (Women). *Report for Scientific Services Project (USATF).* USA Track & Field, Indianapolis, 117 pp, 2003a.
25. Dapena, J., B.J. Gordon and A.P. Willmott. High jump, #21 (Women). *Report for Scientific Services Project (USATF).* USA Track & Field, Indianapolis, 99 pp, 2001a.
26. Dapena, J., B.J. Gordon and A.P. Willmott. High jump, #24 (Women). *Report for Scientific Services Project (USATF).* USA Track & Field, Indianapolis, 91 pp, 2002b.
27. Dapena, J., E. Harman, P. Stewart, G. Lunt and R. Hintermeister. Biomechanical analysis of high jump, #1 (Men and Women). *Report for Elite Athlete Project (USOC/TAC).* U.S. Olympic Training Center, Colorado Springs, 152 pp, 1982.
28. Dapena, J., L. Hoffman, B.J. Gordon and M.K. LeBlanc. High jump, #16 (Men). *Report for Scientific Services Project (USATF).* USA Track & Field, Indianapolis, 112 pp, 1997c.
29. Dapena, J. and M.K. LeBlanc. High jump, #13 (Women). *Report for Scientific Services Project (USATF).* USA Track & Field, Indianapolis, 157 pp, 1995a.
30. Dapena, J., M.K. LeBlanc, R. E. Vaughn, G. Lewis Johnston and W.J. Anderst. High jump, #11 (Men). *Report for Scientific Services Project (USATF/USOC).* USA Track & Field, Indianapolis, 178 pp, 1994a.
31. Dapena, J., M.K. LeBlanc, R.E. Vaughn, G. Lewis Johnston and W.J. Anderst. High jump, #12

(Women). *Report for Scientific Services Project (USATF/USOC)*. USA Track & Field, Indianapolis, 125 pp, 1994b.

32. Dapena, J., C. McDonald and J. Cappaert. A regression analysis of high jumping technique. *Int. J. Sport Biomech.* 6:246-261, 1990.
33. Dapena, J., R. E. Vaughn and G. Lewis Johnston. High jump, #10 (Men). *Report for Scientific Services Project (USATF)*. USA Track & Field, Indianapolis, 165 pp, 1993c.
34. Dapena, J. and A.P. Willmott. High jump, #22 (Men). *Report for Scientific Services Project (USATF)*. USA Track & Field, Indianapolis, 128 pp, 2001b.
35. Dapena, J. and A.P. Willmott. High jump, #23 (Men). *Report for Scientific Services Project (USATF)*. USA Track & Field, Indianapolis, 85 pp, 2002a.
36. Dapena, J., A.P. Willmott and B.J. Gordon. High jump, #18 (Men). *Report for Scientific Services Project (USATF)*. USA Track & Field, Indianapolis, 98 pp, 1998b.
37. Dapena, J., A.P. Willmott and B.J. Gordon. High jump, #20 (Men). *Report for Scientific Services Project (USATF)*. USA Track & Field, Indianapolis, 97 pp, 1999b.
38. Dapena, J., A.P. Willmott and B.J. Gordon. High jump, #28 (Men). *Report for Scientific Services Project (USATF)*. USA Track & Field, Indianapolis, 105 pp, 2004b.
39. Dapena, J., A.P. Willmott and B.W. Meyer. High jump, #26 (Men). *Report for Scientific Services Project (USATF)*. USA Track & Field, Indianapolis, 117 pp, 2003b.
40. Dyatchkov, V.M. The high jump. *Track Technique* 34:1059-1074, 1968.
41. Krahl, H. and K.P. Knebel. Foot stress during the flop takeoff. *Track Technique* 75:2384-2386, 1979.
42. Ozolin, N. The high jump takeoff mechanism. *Track Technique* 52:1668-1671, 1973.

ACKNOWLEDGEMENTS

This research project was funded by a grant from USA Track & Field.

APPENDIX 1

TECHNIQUES FOR LOWERING THE CENTER OF MASS IN THE LAST STEPS OF THE RUN-UP

The first steps of a high jump run-up are normal running steps. The c.m. is lowered only near the end, and this is achieved mainly through the combination of a lateral lean toward the center of the curve and the flexion of the knee of the supporting leg (see Figure A2.1 in Appendix 2). At the instant that the takeoff foot is planted on the ground to begin the takeoff phase, the c.m. should be comparatively low, and it should have a large horizontal velocity.

At the instant that the foot lands on the ground in a normal running step, the c.m. of the athlete has a large horizontal velocity and also some downward vertical velocity. But in the last step of a high jump run-up it is important that the downward vertical velocity be minimized, in order not to waste effort braking this downward motion during the takeoff phase. Consequently, the run-up of a high jumper should ideally lead to the following conditions at the start of the takeoff phase: large horizontal velocity, reasonably low c.m., and minimal downward vertical velocity.

Figures A1.1, A1.2 and A1.3 show examples of three techniques used by high jumpers to lower the c.m. In these three figures, the horizontals of the graphs show time (the shaded bars at the bottom indicate ground support phases; the clear bars indicate nonsupport phases, in which both feet are off the ground; t = 10.00 s was arbitrarily assigned to the start of the takeoff phase). The verticals of the graphs show the height of the center of mass over the ground, expressed as a percent of the standing height of the athlete.

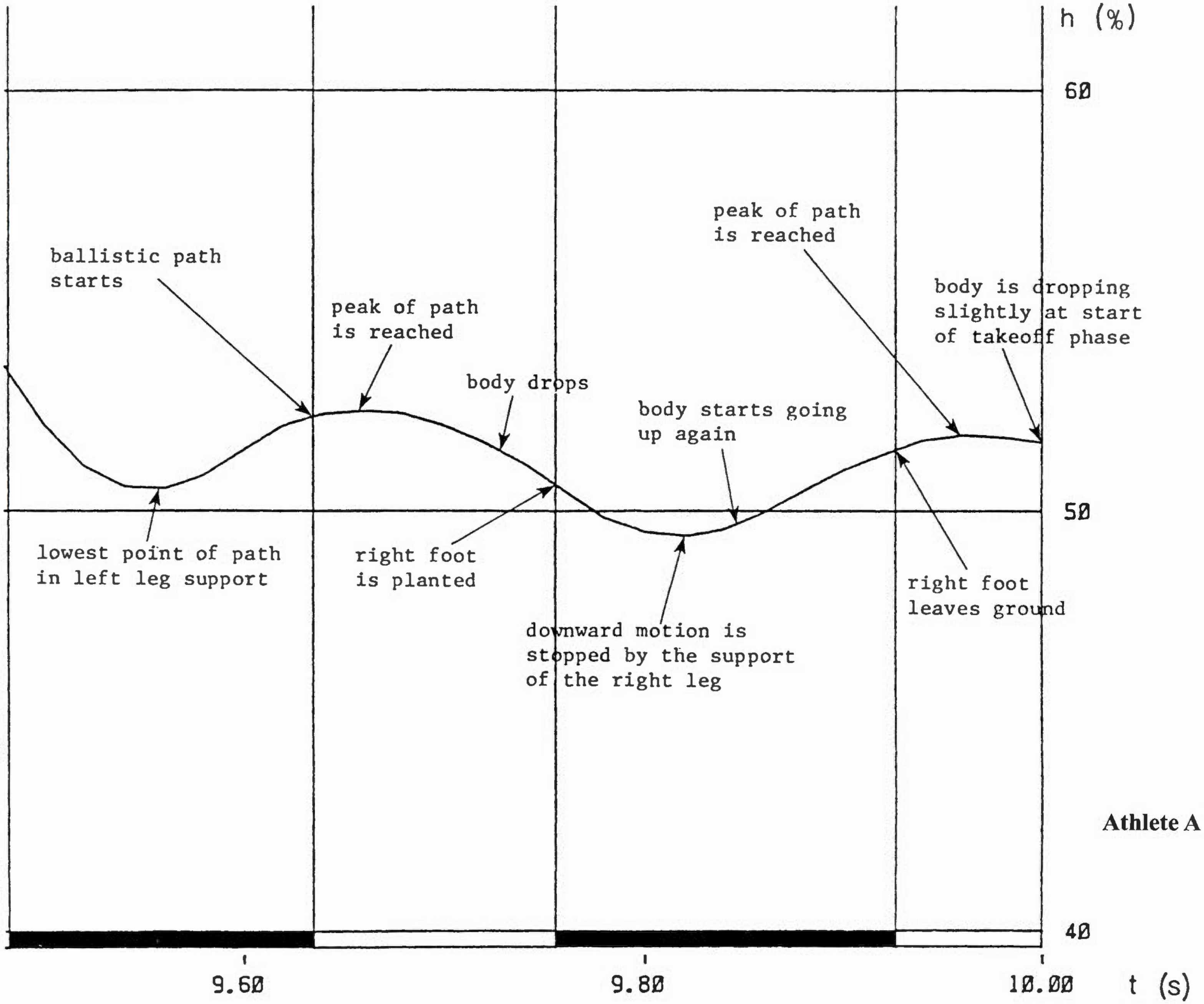
The graphs correspond to three female high jumpers with similar personal best marks. To facilitate the explanation of these techniques, we will assume that all three athletes took off from the left foot. The c.m. of athlete A, shown in Figure A1.1, was gradually lowered in the late part of the run-up. At about t = 9.48 s (two steps before the takeoff phase started), the c.m. was already rather low. Then, as the athlete pushed with the left leg into the next-to-last step, the c.m. went up to start a short projectile path in the air (t = 9.63 s). The c.m. reached the peak of the path at t = 9.66 s, and then started dropping again. By the time that the right foot was planted, at t = 9.75 s, the c.m. was dropping at about -0.9 m/s. Then the support of the right leg reversed the vertical motion of the c.m., first stopping the downward motion at t = 9.82 s (at a height somewhat lower than in the previous support phase), and then pushing the c.m. up again, so that by the time that the right foot lost contact with the ground at t = 9.93 s the c.m. was moving upward at 0.4 m/s. Then, during the last nonsupport phase (t = 9.93 - 10.00 s), the c.m. made another short projectile path, in which it reached a maximum height and then started dropping again. The c.m. drops with more and more speed with every hundredth of a second that passes by before the takeoff leg is planted. That is why it is recommended that high jumpers plant their takeoff leg very soon, so that they will not be dropping with too much speed at the start of the takeoff phase. The c.m. of this athlete was dropping at -0.3 m/s at the start of the takeoff phase (v_{ZTD} = -0.3 m/s).

So in the technique shown by athlete A, the c.m. is already low two steps before the start of the takeoff phase, and it may be lowered still a little bit more in the last step. When the takeoff foot finally makes contact with the ground to start the takeoff phase, the c.m. is more or less low but not dropping very fast (if there is not a long delay in the planting of the takeoff foot; if there were a long delay, the speed of dropping could be large).

Figure A1.2 shows athlete B, with a very different technique. The c.m. was very high two steps before the takeoff phase (after the athlete pushed off into the next-to-last step, the c.m. reached a height of about 59% of the standing height of the athlete). Running with such a high c.m. is much more comfortable than running like athlete A, but it is not possible to start a normal takeoff phase unless the c.m. is lower than that. Therefore, athlete B, consciously or subconsciously, realized that the c.m. had to be lowered. For this, the athlete simply did not stop the drop completely during the period of support over the right foot (t = 9.84 - 9.95 s). When the right foot left the ground at t = 9.95 s, the athlete was much lower than in the previous step, but the c.m. was not going up at this time: It was still dropping. The speed of dropping became still larger in the following nonsupport phase. Even though the athlete planted the takeoff foot very soon, by then the c.m. was dropping at a very large speed (-0.7 m/s), and this is not good for the takeoff phase of the jump.

The advantage of the technique used by jumper B is that it made it very easy for the athlete to maintain (and even increase) a fast run-up speed in the last steps. Athlete A was not able to maintain speed quite as well, because it is difficult to run fast over a deeply flexed support leg. The disadvantage of the technique of athlete B was that the c.m. was dropping with a large speed at the start of the takeoff phase, while the c.m. of athlete A was moving more flat.

The ideal would be to lower the hips early, as



ballistic path starts

peak of path is reached

body drops

right foot is planted

lowest point of path in left leg support

body starts going up again

downward motion is stopped by the support of the right leg

peak of path is reached

body is dropping slightly at start of takeoff phase

right foot leaves ground

Athlete A

Figure A1-1

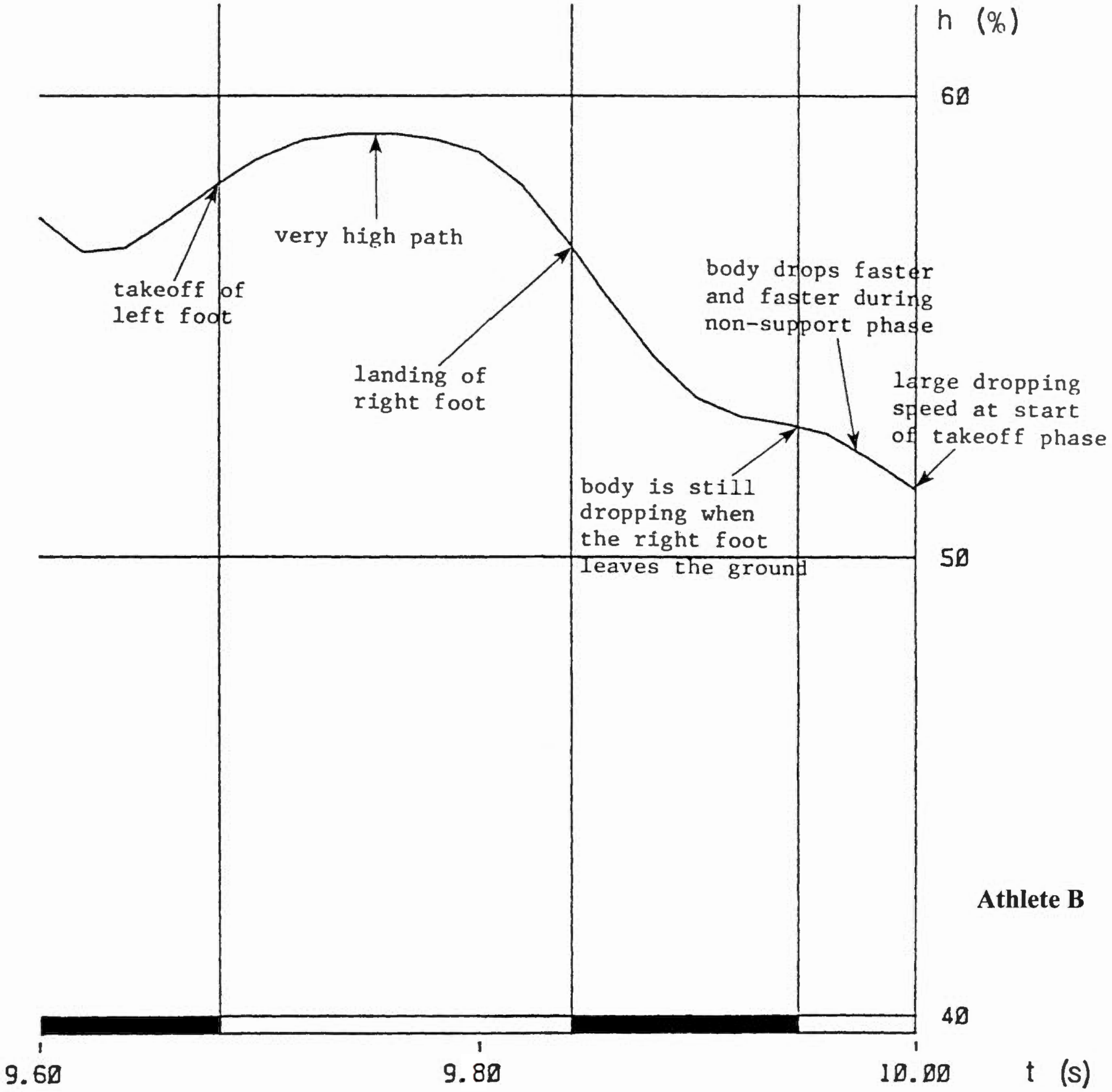

h (%)
60
50
40
t (s)
9.60
9.80
10.00
very high path
takeoff of left foot
landing of right foot
body drops faster and faster during non-support phase
large dropping speed at start of takeoff phase
body is still dropping when the right foot leaves the ground
Athlete B

Figure A1-2

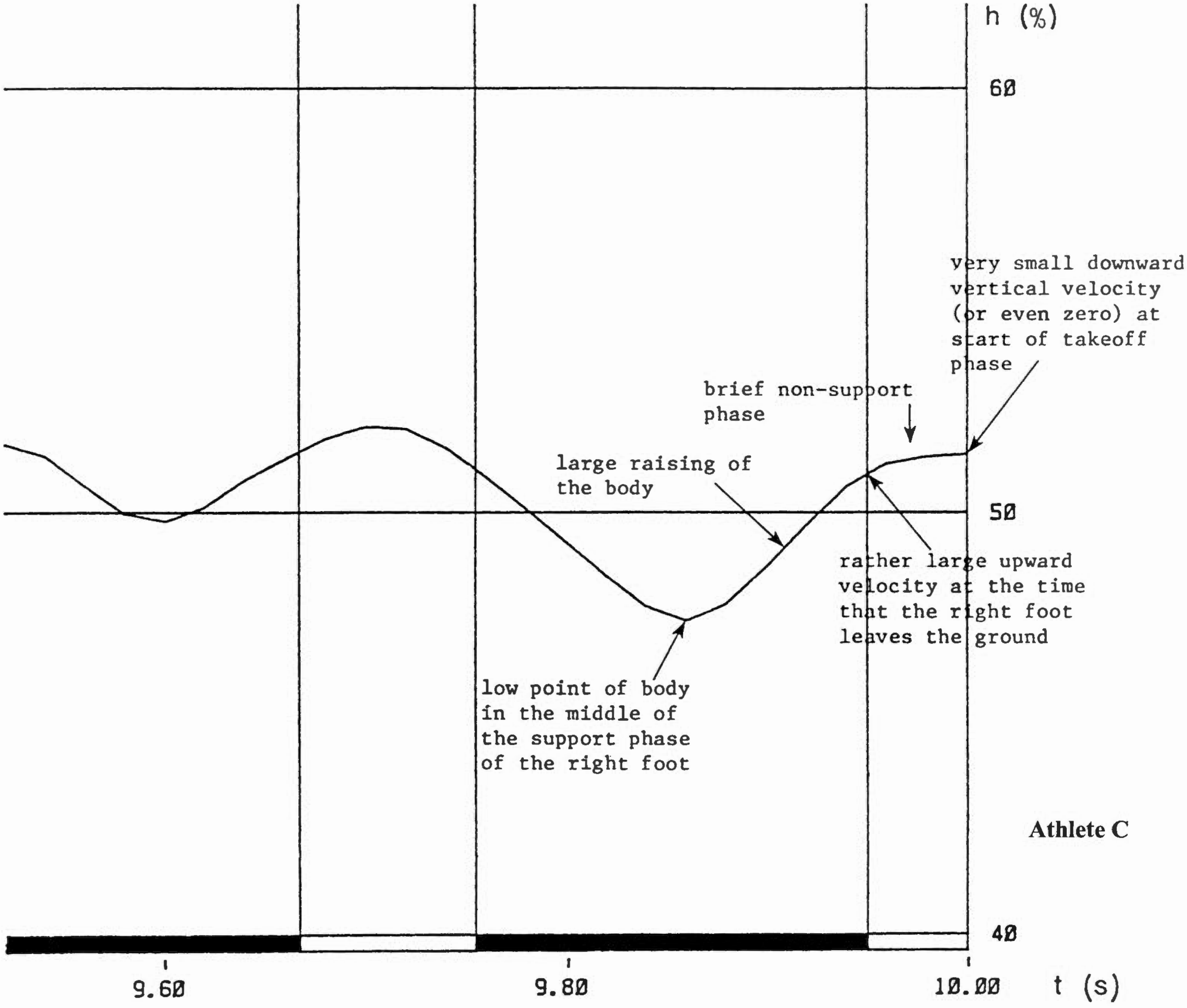

h (%)
60
50
40
t (s)
9.60
9.80
10.00
very small downward vertical velocity (or even zero) at start of takeoff phase
brief non-support phase
large raising of the body
rather large upward velocity at the time that the right foot leaves the ground
low point of body in the middle of the support phase of the right foot
Athlete C

Figure A1-3

athlete A did, but avoiding any loss of horizontal speed. For this, athlete A would need special drills and exercises (see Appendix 2); athlete B would need to start lowering the c.m. earlier, two or three steps before takeoff, and this athlete would also need to do the drills and exercises; otherwise, she would brake the horizontal speed of the run-up when she lowered the hips.

Figure A1.3 shows an interesting technique by a third athlete (athlete C). In the middle of the last support phase of the approach run (t = 9.85 s), the c.m. of athlete C was lower than those of athletes A and B, but in the second half of this support phase the athlete lifted the c.m. considerably, and by the end of it (t = 9.95 s) the c.m. had a rather large upward vertical velocity (0.5 m/s). The airborne phase that followed was very brief. By the beginning of the takeoff phase (t=10.00 s), the c.m. was at about the same height as those of the other two jumpers, but it was not dropping at all: The vertical velocity of athlete C at the start of the takeoff phase was 0.0 m/s.

At this point, it is not possible to decide whether athlete C would have been better off maintaining a lower path of the c.m. in the last step, at the expense of a moderate negative vertical velocity at the start of the takeoff phase (like athlete A), or with the present technique, in which she sacrificed part of the previous lowering of the c.m. in order to avoid having any negative vertical velocity at the start of the takeoff phase.

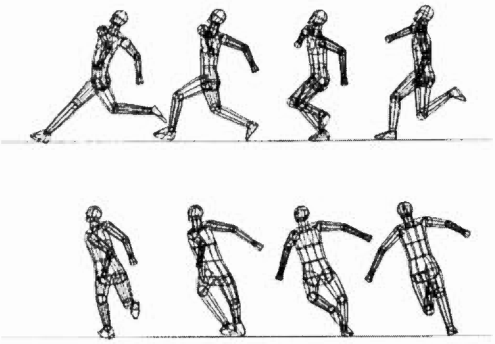
In sum, based on the information presently available, the techniques used by athletes A and C to lower the c.m. appear to be equally good, but the technique used by athlete B seems to be worse, because it leads to a very large downward velocity at the start of the takeoff phase.

APPENDIX 2

EXERCISES TO HELP THE LOWERING OF THE CENTER OF MASS IN THE LAST STEPS OF THE RUN-UP

Many high jumpers have difficulties in the last steps of the approach run: They are unable to run fast while keeping their hips low. This is a typical problem in high jumping technique. It takes some effort to correct this problem, but the improvements that the correction produces are definitely worth the effort.

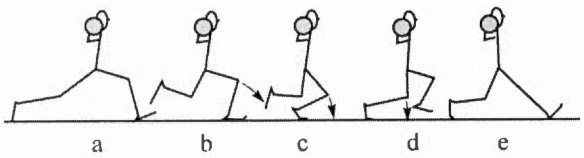
Figure A2.1



The greatest difficulty is to be able to pass over the deeply-flexed non-takeoff leg in the next-to-last step, and have the non-takeoff leg support the whole body with no sign of collapse or of braking. This is demonstrated very well by the athlete in Figure A2.1.

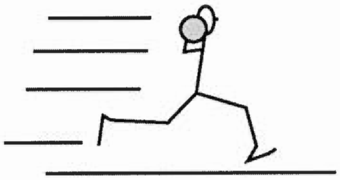
Figure A2.2 shows an exercise with weights that can help the high jumper to acquire the necessary support strength in the non-takeoff leg. (This exercise was devised by Arturo Oliver.) The start of the exercise is in a static position (a). Then, the athlete pushes off gently with the back leg (the takeoff leg), to place the weight of the body over the non-takeoff leg. The body then slowly passes over the non-takeoff leg (positions b-d), and finally, at the last instant, the takeoff leg is placed ahead on the ground, to stop the forward motion. After stopping momentarily in position e, the takeoff leg makes a slight push forward on the ground, and by reaction the athlete goes backward again to position a. The exercise is repeated over and over until the non-takeoff leg gets tired.

Figure A2.2



Important points to consider: The whole motion should be very slow. The knee of the non-takeoff leg should be kept very flexed at about 90° throughout the whole exercise. From positions a to d the athlete should feel as if he/she were going to kneel with the non-takeoff leg, with the hip well forward. The most difficult point of the exercise is at position d. Between positions d and e, the non-takeoff leg should not be extended significantly. The idea is to thrust the hips forward (**but without extending the knee of the non-takeoff leg**) at the last instant, just before losing balance forward. Immediately afterward, the foot of the takeoff leg is planted ahead of the body to stop the forward motion (position e). It would possibly be desirable, from the point of view of motor learning, to have the trunk acquire between positions d and e some backward lean, similar to the one that occurs in actual jumping (see Figure A2.1). However, this is difficult to do with the weights, and it is not crucial for the exercise. The exercise should first be done with only a 10 Kg bar without weights. Then, when the athlete has learned the exercise, very light weights can be added. As the athlete gets stronger, the weights should gradually be increased.

Figure A2.3



A second exercise is shown in Figure A2.3. It was also devised by Arturo Oliver, and it consists of 30 to 50-meter runs at about 50% of maximum speed, with the hips held low (as low as in the last steps of a high jump approach run), and carrying a 20-25 Kg barbell on the shoulders (IMPORTANT: Wrap a towel around the bar). The main idea is to force the athlete to run with low, flat, non-bouncy steps; if the athlete makes bouncy steps, the barbell will bounce on the shoulders, the athlete will notice it, and make adjustments in the running to prevent the excessive bouncing. **Make sure that no one is in your way when you do this exercise!**

When the athlete is able to do these exercises fairly well (say, after one month of practice), it will be time to start introducing the new motions into actual jumping. It may be good to start with low-intensity "pop-ups" using a short run-up (four or six steps) at a slow speed. The emphasis should be on lowering the hips in the last two or three steps without losing any speed. Then, the length and speed of the run-up for these pop-ups should be increased gradually, and after a few days (or weeks --it depends on how quickly the athlete assimilates the new movements), the athlete will be practicing with a full high jump run-up and a bar. When jumping using the full speed of a normal high jump, it will be more difficult to avoid braking while the athlete passes over the deeply-flexed non-takeoff leg in the last support of the run-up. **To avoid braking, the athlete will have to concentrate intensely on trying to pull backward with the non-takeoff foot when it lands on the ground.**

APPENDIX 3

PRODUCTION OF LATERAL SOMERSAULTING ANGULAR MOMENTUM

The main text of this report explains that high jumpers need a combination of forward somersaulting angular momentum (H_F) and lateral somersaulting angular momentum (H_L) to be able to achieve a normal rotation over the bar (see "Angular momentum"). In this section of the report we will deal in greater depth with H_L and how it is produced.

The three images in the upper left part of Figure A3.1 show a back view sequence of the takeoff phase of a high jumper and the force that the athlete makes on the ground during the takeoff phase (actually, this force will change from one part of the takeoff phase to another, but for simplicity the average force has been drawn here in all three images). The three images in the upper right part of Figure A3.1 show the same sequence, but the force shown here is the equal and opposite force that the ground makes on the athlete in reaction to the force that the athlete makes on the ground.

The athlete shown in the six images in the top row of Figure A3.1 had a standard technique: At the start of the takeoff phase, the athlete was leaning toward the center of the curve (in this case, to the left). The takeoff foot was planted pretty much directly ahead of the c.m., and therefore in this back view the foot appears almost directly underneath the c.m. (the small circle inside the body). During the takeoff phase, the athlete exerted a force on the ground, and by reaction the ground exerted a force on the athlete. The force exerted by the ground on the athlete made the athlete start rotating clockwise in this back view. By the end of the takeoff phase, the athlete was rotating clockwise, and the body had reached a pretty much vertical position.

A key element for the production of the clockwise rotation of the athlete is the force exerted by the ground on the athlete. This force must pass clearly to the left of the c.m. If the force passes too close to the c.m., there will be very little rotation, and if it passes directly through the c.m. there will be no rotation at all. So the force must be pointing up and slightly to the left, and this is what the three images in the upper right part of Figure A3.1 show. To obtain these forces, the athlete must push on the ground down and slightly to the right, as the three images in the upper left part of Figure A3.1 show. Most athletes are not aware that during the takeoff phase they push with their takeoff foot slightly away from the center of the curve, but they do.

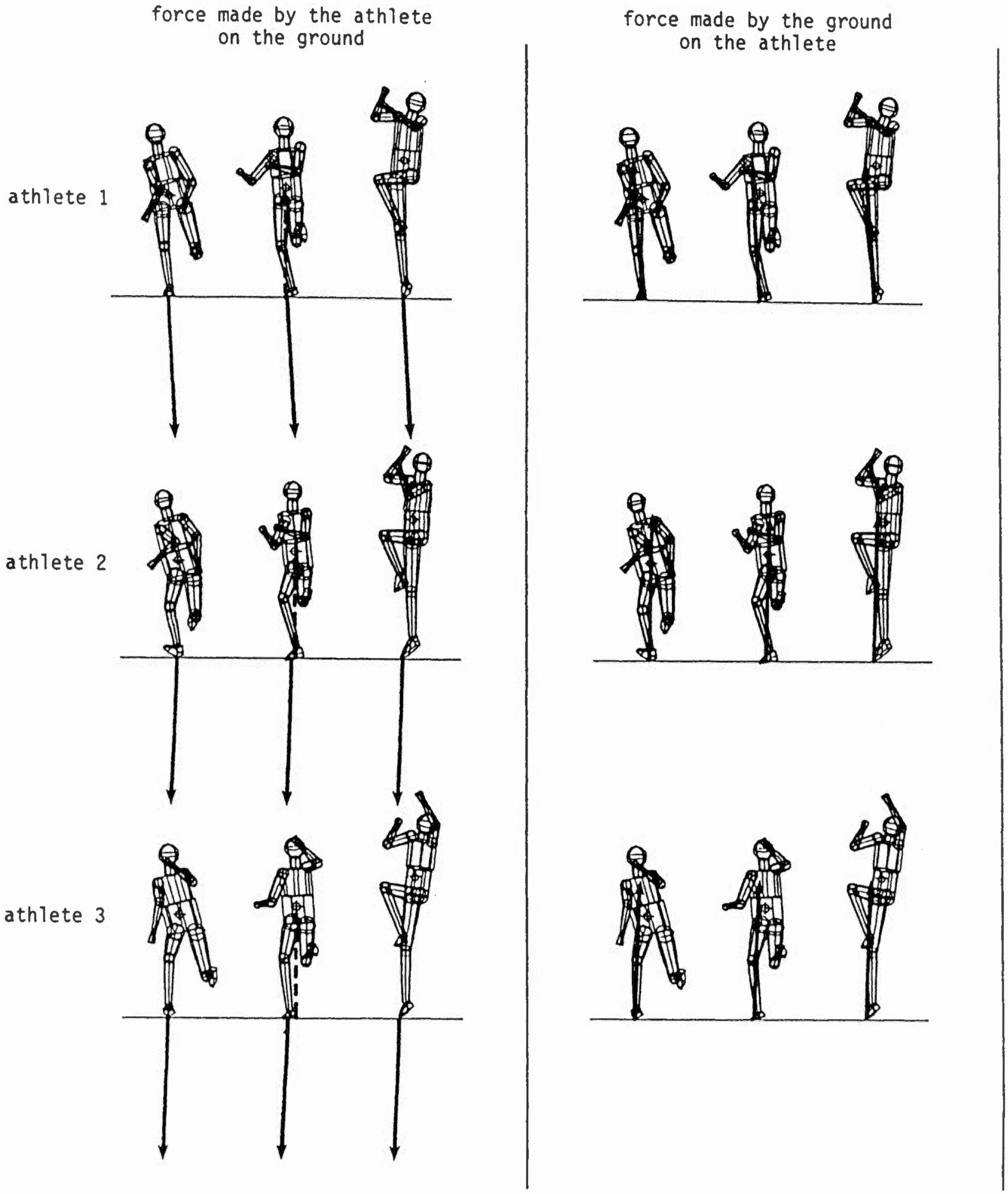
As the force exerted by the ground on the athlete usually points upward and to the left in this view from the back, it causes the path of the c.m. of the athlete to deviate a little bit to the left during the takeoff phase, making angle p_0 be generally somewhat smaller than angle p_1 (see Figure 2 and Table 2 in the main text of the report). This is interesting for us, because it implies that by comparing the sizes of these two angles we can check whether an athlete pushed away from the center of the curve during the takeoff phase or not.

The technique described above is used by most athletes. However, some jumpers push directly down, or even toward the center of the curve, during the takeoff phase (in these jumpers, angle p_0 is equal to p_1 or larger than p_1, respectively). This leads to problems. If the athlete placed the takeoff foot directly ahead of the c.m., the athlete would not get any lateral somersaulting rotation the result could even be a counterclockwise lateral somersaulting rotation. Therefore, some of these athletes place the takeoff foot ahead of the c.m. but slightly to the left (see athlete 2, in the middle row of Figure A3.1). This allows these athletes to obtain some lateral somersaulting angular momentum, but not much, because during the takeoff phase the force exerted by the ground on the athlete passes only slightly to the left of the c.m.

Other athletes that push toward the center of the curve during the takeoff phase want more angular momentum than that, and therefore they place the takeoff foot on the ground ahead of the c.m. and very markedly to the left (see athlete 3, in the bottom row of Figure A3.1). In these athletes the force exerted by the ground on the athlete passes clearly to the left of the c.m., and therefore they get a good amount of lateral somersaulting angular momentum. However, they pay a price for this: Because the foot is placed so far to the left, the c.m. is always to the right of the foot in a view from the back, and therefore the body has a marked lean toward the right by the end of the takeoff phase.

Most high jumpers push away from the center of the curve during the takeoff phase without needing to think about it. Therefore, it generally is not necessary to tell athletes that they have to do this. However, a jumper with the problems demonstrated by athletes 2 and 3 of Figure A3.1 will need to be told to push with the takeoff leg away from the center of the curve, and the coach should make up drills to help to teach the athlete how to do this if the problem occurs.

Figure A3-1


force made by the athlete
on the ground
force made by the ground
on the athlete
athlete 1
athlete 2
athlete 3

APPENDIX 4

DRAWING THE PATH OF A HIGH JUMP RUN-UP

The curved run-up used in the Fosbury-flop style of high jumping makes the athlete lean toward the center of the curve. This helps the jumper to lower the c.m. in the last steps of the run-up. It also allows the athlete to rotate during the takeoff phase from an initial position in which the body is tilted toward the center of the curve to a final position in which the body is essentially vertical; therefore, it allows the athlete to generate rotation (lateral somersaulting angular momentum) without having to lean excessively toward the bar at the end of the takeoff.

A curved run-up has clear benefits over a straight one, and therefore all high jumpers should use a curved run-up. However, a curved run-up is also more complex. Therefore, it is more difficult to learn, and requires more attention from the athlete and the coach.

The curved run-up can also be a source of inconsistency: There are many different possible paths that the jumper can follow between the start of the run-up and the takeoff point. If the athlete does not always follow the same path, the distance between the takeoff point and the bar will vary from one jump to another. This inconsistency will make it difficult for the athlete to reach the peak of the jump directly over the bar.

To make it easier for a high jumper to follow a given run-up path consistently, it can be useful to mark the desired path on the ground for practice sessions (Dapena, 1995a; Dapena *et al.*, 1997a). But before drawing the run-up path, it will first be necessary to choose values for the two main factors that determine the path: (a) the final direction of the run-up and (b) the radius of curvature.

Deciding the final direction of the run-up path (angle p_1)

The final direction of the run-up can be defined as the angle between the bar and the direction of motion of the c.m. in the last airborne phase of the run-up immediately before the takeoff foot is planted on the ground. This angle is called p_1 in this report, and its values are given in Table 2. (The angle of the final run-up direction should not be confused with the angle between the bar and the line joining the last two footprints. This latter angle is called t_1, and it is generally 10-15 degrees smaller than the angle of the final run-up direction, p_1.) Jumpers analyzed in this report should use the value of p_1 given in Table 2 (or in some cases a different value proposed for the athlete in the Specific Recommendations section). Jumpers not included in this report should first assume that their ideal p_1 angle is 40°. Then, if the run-up curve drawn based on that angle does not feel comfortable, they should experiment with other p_1 values until they find an angle that feels good. For most athletes the optimum value of p_1 will be somewhere between 35° and 45°.

Deciding the radius of curvature of the run-up path (distance r)

The run-up curve needs to have an optimum radius of curvature. If the radius is too small, the curve will be too tight, and the athlete will have difficulty running; if the radius is too large, the curve will be too straight, and the athlete will not lean enough toward the center of the curve. The optimum radius will depend on the speed of the jumper: The faster the run-up, the longer the radius should be. We can make a rough estimate of the optimum value of the radius of curvature for an individual high jumper using the equation $r = v^2 / 6.8$ (men) or $r = v^2 / 4.8$ (women), where r is the approximate value of the radius of curvature (in meters), and v is the final speed of the run-up (in meters/second). Jumpers who know their final run-up speed (such as the jumpers analyzed in this report) can make a rough initial estimate for their optimum radius of curvature by substituting into the appropriate equation their own v_{H1} value from Table 3 (or a different value of v_{H1} proposed for that athlete in the Specific Recommendations section). For jumpers not analyzed in this report, it is more difficult to select a good initial estimate for the radius of curvature, but the following rough guidelines can be followed for olympic-level high jumpers: 6.5-11 m for men; 7.5-13 m for women. In all cases (even for the jumpers analyzed in this report), the *optimum* value of the radius of curvature for each individual athlete will ultimately have to be found through fine-tuning, using trial and error.

Actual drawing of the run-up

Materials needed: a measuring tape (at least 15 meters long), a piece of chalk, and white adhesive tape.

Tell the athlete to make a few jumps at a challenging height, using his/her present run-up. Using adhesive tape, make a cross on the ground to mark the position of the takeoff point (point A in Figure A4.1).

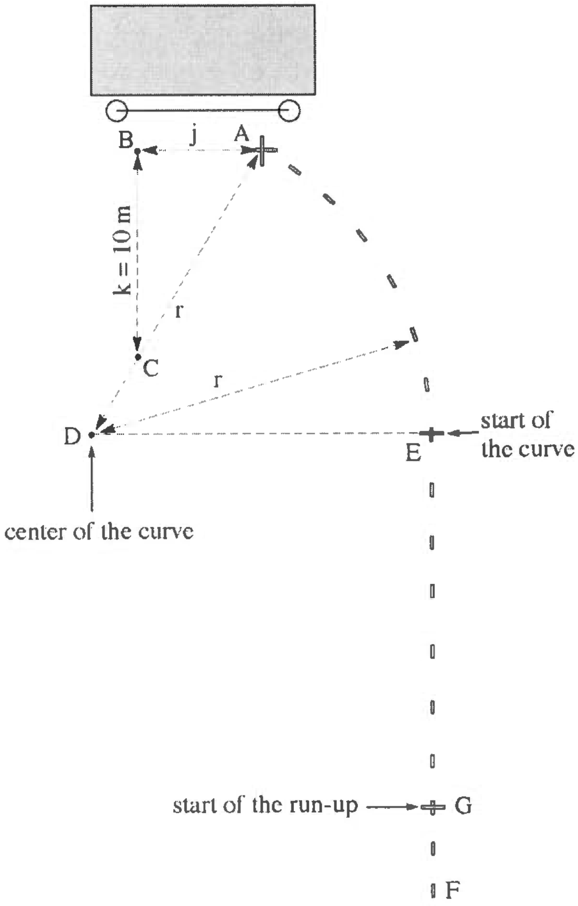
Put one end of the measuring tape at point A, and measure a distance j parallel to the bar. The value of j depends on the final direction desired for the run-up (p_1):

p_1	j
25°	1.75 m
30°	2.70 m
35°	3.65 m
40°	4.65 m
45°	5.75 m
50°	7.00 m

(General guidelines for the optimum value of p_1 were given previously in this Appendix. If you want to try a p_1 angle intermediate between the ones given in this table, you should use a value of j intermediate between the ones given in the table.)

Mark the new point (B) with chalk. Put one end of the tape at point B, and measure a distance k = 10 meters in the direction perpendicular to the bar. Mark the new point (C) with chalk. The line joining point A and point C indicates the direction of the center of the curve relative to the takeoff point.

Figure A4.1



To find the center of the curve (point D), put one end of the tape at point A, and make the tape pass over point C. The center of the curve will be aligned with points A and C, and it will be at a distance r from point A. (General guidelines for the optimum value of r were given previously in this Appendix.) Mark point D with chalk.

With center in point D and radius r, draw an arc from point A to point E. (Point E has to be at the same distance from the plane of the bar and the standards as point D.) The arc from A to E is the run-up curve. Mark it with strips of adhesive tape. Put a transverse piece of tape at point E to mark the start of the curve.

Starting at point E, draw a straight line perpendicular to the bar (E-F), and mark it with strips of adhesive tape. Set the bar at a challenging height, and have the jumper take a few jumps. By trial and error, find the optimum position for the start of the run-up (point G), and mark it with a transverse piece of adhesive tape.

The run-up is now ready. The set-up just described can be left in place for training, and it will contribute to drill into the athlete the pattern that the run-up should follow.

Things to remember:

- Point E indicates the place where the curve should start, but the athlete does not necessarily have to step on this point.
- Some jumpers may find it difficult to follow exactly the path marked by the adhesive tape in the transition from the straight to the curved part of the run-up. This should not be a problem: It is acceptable to deviate somewhat from the path marked by the adhesive tape in the area around point E, as long as the athlete deviates consistently in the same way in every jump.
- It is important to follow the tape very precisely in the middle and final parts of the curve.

The set-up described above can be left in place for training. However, one or two marks will have to suffice for competitions. Distances a, b, c and d should be measured in the training set-up (see Figure A4.2). In the competition, distance a will be used to reconstruct the position of point H. Distances b and c will then be used to reconstruct the triangle formed by the standard and points G and H. This will allow the athlete to locate the start of the run-up (point G). Distance d can be used to find the position of point E if the rules of the competition allow for a mark to be placed at that point.

Figure A4.2