SCIENTIFIC SERVICES PROJECT

(USA Track & Field)

DISCUS THROW
#1
(Men)

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IMPORTANT INFORMATION FOR COACH AND ATHLETE:

If you or your athlete were one of the discus throwers studied in our project, we hope you will find the information in this report useful for your training.

The mechanics of discus throwing is not well understood yet, and therefore there is plenty of 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. In fact, we are are quite far from having 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 section "General overview of discus throwing technique". If you feel up to it, we strongly advise you to read also the section "Detailed description of discus throwing 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, you should keep in mind that "c.m." stands for "center of mass", a point that represents the average position of all the particles that make up an object or a group of objects called "the system"; the center of mass can also be called 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.

* If you have any questions, please feel free to give us a phone call (1-812-855-8407), to write, or to send electronic mail to us. We will do our best to help you.

If you wish to obtain an extra copy of this report, please write to Mr. Duffy Mahoney, Director of Operations, USA Track & Field, 1 RCA Dome, Suite 140, Indianapolis, IN 46225.

Bloomington, January 2, 1997

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NOTE: *Track & Field News* (June, 2003, p.22) has reported that the UC San Diego landing area was about 1 meter lower than the throwing circle. This probably added about 1.5 m to the length of all throws made in that facility.

INTRODUCTION

This report on men's discus throwing contains a biomechanical analysis of the techniques used by 19 of the throwers in the 1996 UC San Diego Open and 7 of the finalists in the 1994 USATF Championships; two of the athletes were analyzed at both meets.

The project was a combination of research and service, with two separate but related goals. In part, it was a research project in which we tried to gain a better understanding of the basic mechanics of discus throwing technique. But we also made an effort to use that information to evaluate the advantages and disadvantages of the techniques used by the top athletes from the San Diego meet.

The reader needs to keep in mind that current knowledge on the mechanics of discus throwing is limited. The cumulative information obtained through research projects such as this one will gradually permit better evaluations of the techniques of individual throwers, but for now all evaluations need to be considered provisional.

METHODS

Filming and selection of trials

The throws were filmed simultaneously with two motion picture cameras shooting at 50 frames per second. We could not film all the throws in the meets. However, we found for all the athletes presented in this report at least one trial that was representative of the best throws of the athlete during the competition.

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

Film analysis

The locations of 22 landmarks (21 anatomical body landmarks and the discus) were measured ("digitized") in the images obtained by the two cameras. A series of computer programs were then used to calculate the three-dimensional (3D) coordinates of the landmarks from the instant when the discus reached its most backward point in the preliminary swing, to an instant about 6 frames (about 0.12 seconds) after release. Another computer program used these 3D coordinates to calculate mechanical data for each throw.

Motion sequences

Computer graphics were used to produce motion sequences for each throw. They are included in the report immediately after the individual analysis of each athlete.

There are two motion sequences for each trial. The first sequence usually takes four pages; it shows the entire throw, from the instant when the discus reached its most backward point in the preliminary swing to the release. The second sequence takes two pages; it shows the final part of the throw in greater detail. In both sequences, the top row of images shows a view from the right of the circle, the second row from the top shows a view from the back, the third row shows a view from directly overhead, and the bottom row shows an oblique overhead view tilted at a 35° angle with respect to the vertical. (Note: With the data gathering methods that we used, we were able to determine the location of the center of the discus, but not the amount of tilt of the discus nor the direction of its tilt. Since we did not know the true tilt of the discus, the computer that drew the graphics was programmed to assign arbitrarily a more or less neutral tilt to the discus in all images. This means that ***the tilt of the discus in the sequences is not necessarily the true one***. The only other alternative would have been not to draw the discus at all.)

The numbers in the sequences indicate time, in seconds. To facilitate comparisons between throws, the time t = 10.00 seconds was arbitrarily assigned in all trials to the instant in which the athlete planted the left foot on the ground to start the final double-support delivery. (From this point onward, all discussions will refer to right-handed throwers. For left-handed throwers, the words "left" and "right" should be interchanged, as well as the words "clockwise" and "counterclockwise".)

Other graphics

Four additional pages of computer graphics were produced for each throw. (They are described in detail further below.) These graphics were helpful for the technique analysis of each individual thrower.

Subject characteristics and meet results

Table 1 shows general information on the analyzed athletes, and their results in the competitions.

SOME MECHANICAL CONCEPTS AND DEFINITIONS

Some knowledge of biomechanics will help the reader to gain maximum benefit from this report. The concepts explained below should be sufficient. For further information on biomechanics, the reader

Table 1

General information on the analyzed athletes, and distances thrown

Athlete	Trial and meet (*)	Height (m)	Weight (Kg)	Personal best mark (**) (m)	Best throw at meet (m)	Throw analyzed (m)
Andy BLOOM	41 D96	1.85	121	63.48	61.64	59.18
David DUMBLE	23 D96	1.85	113	58.48	58.48	58.48
Kevin FITZPATRICK	40 U94	1.92	118	62.54	59.24	59.24
Kevin FITZPATRICK(***)	*62 D96*	*1.92*	*111*	*62.76*	*58.06*	*~62/63 (circle foul)*
John GODINA	28 U94	1.91	120	62.24	53.26	53.26
Mike GRAVELLE	22 U94	1.96	116	65.24	61.38	61.38
Gregg HART	57 D96	1.93	111	61.92	61.92	61.92
Travis HAYNES	24 D96	1.83	112	55.76	55.76	55.76
Randy HEISLER	36 U94	1.91	113	67.62	60.24	58.60
Erik JOHNSON	10 D96	1.93	112	60.82	60.82	60.82
Gary KIRCHHOFF	34 D96	1.94	118	60.48	58.54	58.54
Scott McPHERRAN	08 D96	1.98	122	57.86	57.86	57.86
Mike MIELKE	22 D96	1.91	116	59.46	59.46	59.46
Steven MUSE	47 D96	1.84	127	61.44	55.96	55.16
Russell NUTI	15 D96	1.93	111	58.72	58.72	58.72
Brent PATERA	01 U94	1.92	109	60.30	54.70	54.70
Jamie PRESSER	09 D96	1.97	116	60.48	60.06	59.04
John SCHULTE	59 D96	1.98	136	58.80	51.30	51.30
Carlos SCOTT	41 U94	1.93	181	63.74	59.32	59.32
Adam SETLIFF(***)	*27 U94*	*1.93*	*122*	*64.08*	*57.44*	*57.44*
Adam SETLIFF	65 D96	1.93	122	65.24	65.24	63.32
Jeremy STAAT	25 D96	1.98	127	55.52	55.52	55.52
Luke SULLIVAN	06 D96	1.85	113	57.78	57.78	57.78
Einar TVEITAA	39 D96	1.86	113	61.12	57.80	57.80
Anthony WASHINGTON	66 D96	1.86	109	67.88	64.18	63.96
John WIRTZ	42 D96	1.89	106	61.64	61.64	61.48
Mean		1.91	119	61.19	58.78	58.44
S.D.		±0.05	±15	±3.18	±3.20	±2.98

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open
(**) by the end of the meet in which the athlete was analyzed
(***) Only one throw per athlete was used for the computation of mean and standard deviation (S.D.) for the group; Fitzpatrick's throw #62 and Setliff's throw #27 (shown in *italics* in all tables) were not used.

may wish to consult one or more of the following publications: Dyson (1970); Ecker (1971, 1976); Hay (1993).

The ***center of mass (c.m.)*** is a point that indicates the average position of the mass of all the particles of material that make up an object or group of objects. The object or group of objects is then called ***"the system"***. In this report, we will be dealing a lot with the c.m. of the combined thrower-plus-discus system. The c.m. is also called the c.g. ("center of gravity").

If a system exerts a force on another system, the second system will exert an equal and opposite force on the first. This is called the principle of ***action and reaction***. It is important to realize that each force is exerted on a different system. The changes that occur in the motion of a system are produced by the forces exerted *on* that system (i.e., on the forces *received* by that system). An example: If the foot of a discus thrower makes on the ground a force that points toward the back of the circle, the ground will exert on the thrower a force that points toward the front of the circle. The thrower's body will then be accelerated toward the front of the circle, because the force that the athlete *receives* points in that direction.

Linear momentum is a mechanical factor that is directly proportional to the speed of translation of the c.m. of a system; it also has the same direction as the speed of translation of the c.m. of the system.

Angular momentum (also called "rotary momentum") is a mechanical factor that is related to how fast a system is rotating (***speed of rotation***), and also to how "spread-out" the system is with respect to the axis of rotation. The faster the system is rotating and the more spread-out the system is with respect to the axis of rotation, the larger the angular momentum of the system.

To change the angular momentum of a system, it is necessary to exert on that system forces that point off-center to its c.m. This is only possible when the system is in direct physical contact with other systems, such as the ground or other objects; when a system is not in contact with other systems, no off-center forces are exerted on it, and therefore its angular momentum remains constant. An example: While a discus thrower's feet are off the ground, such as in the period between the takeoff of the left foot and the landing of the right foot in the middle of the throw, the angular momentum of the thrower-plus-discus system will remain constant.

The generation of angular momentum is facilitated by throwing the free limbs very strongly in the direction of the angular momentum that the athlete wants to obtain. This makes it easier for the thrower's supporting foot (or feet) to exert on the ground the forces that are necessary in order to generate that angular momentum. An example: During the single-support phase on the left leg at the back of the circle, it is helpful for the discus thrower to swing the right leg counterclockwise very fast, very far from the middle of the body, and over the longest possible range of motion. Such a thrust of the swinging right leg helps the athlete to generate (i.e., to obtain) counterclockwise angular momentum about the vertical axis.

It is possible to ***transfer*** angular momentum from one part of a system to another. An example: Shortly before release, a discus thrower can transfer counterclockwise angular momentum from the left arm to other parts of the body (and preferably to the discus). This will be visible as a slowing down of the counterclockwise speed of rotation of the left arm (and/or a shortening of the radius of the left arm with respect to the middle of the body: less "spread-out"), and a speeding up of the rotations of other body parts (or of the discus).

For any given amount of angular momentum that a part of a system has, the closer that this part of the system is kept to an axis of rotation, the faster it will tend to rotate around that axis. An example: If after the left foot takes off from the ground in the middle of the throw, a discus thrower quickly brings both legs near the middle of the body, the legs will tend to rotate faster around the vertical axis. This speeding up of the rotation of the legs will help them to get ahead of the upper body and of the discus (ahead in a *rotational* sense).

GENERAL OVERVIEW OF DISCUS THROWING TECHNIQUE

From the end of the backswing until the instant of release, a discus throw can be broken down into five parts: an initial double-support phase; a single-support phase on the left foot; a non-support phase; a single-support phase on the right foot; and the delivery phase, which occurs mainly in double-support but often ends in single-support or in non-support due to the loss of contact with the ground by one or both feet prior to the release of the discus.

Forces and linear momentum

In the course of a throw, the feet make forces on the ground. By reaction, the ground makes equal and opposite forces on the feet. These reaction forces give linear momentum to the combined thrower-plus-discus system. *Forward* horizontal linear momentum is generated in the early stages of the throw. It makes the system translate horizontally across the throwing circle (Figure 1).

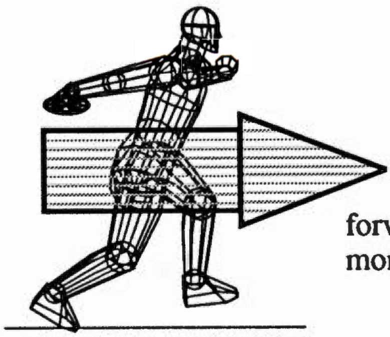

Figure 1

During the delivery phase, the thrower loses part of the forward linear momentum, and obtains *upward* vertical linear momentum (Figure 2). This is done through a process similar to the one used in the high jump takeoff: The forward-moving athlete plants the left foot ahead of the body, and presses forward and downward on the ground. This action helps the athlete to obtain vertical speed at the expense of some loss of horizontal speed. At release, the thrower-plus-discus system will have some leftover forward linear momentum, as well as upward linear momentum.

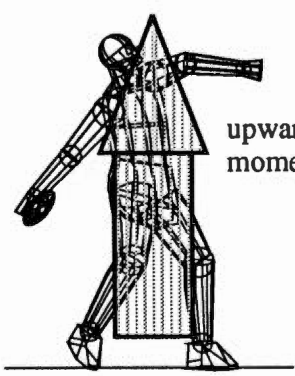

Figure 2

What is the purpose of giving forward and upward linear momentum to the thrower-plus-discus system? We can make an analogy of a discus thrower with a ship firing a cannon. If the shooting platform (the ship) is traveling forward as the cannon is fired, the forward speed of the ship is added to the forward speed of the projectile. The result is a larger total horizontal speed of the projectile than if the ship had been stationary when it fired the cannon. In the vertical direction, the analogy would be a cannon firing vertically from an elevator —an elevator without a ceiling! If the shooting platform (in this case, the elevator) is traveling upward as the gun is fired, the vertical speed of the elevator is added to the vertical speed of the projectile. The result is a larger total vertical speed of the projectile than if the elevator had been stationary. In a similar way, by traveling forward and upward in the final part of the throw, the thrower-plus-discus system (the "throwing platform") contributes to increase the horizontal and vertical speeds of the discus relative to the ground.

The forward and upward motions of the "throwing platform" (the thrower-plus-discus system) contribute to the speed of the discus at release, and this contribution is very welcome. However, it will be shown below that most of the speed of the discus is not due to this, but to the speed of the discus *relative* to the throwing platform, just like the speed of a projectile relative to a ship's cannon makes a much larger contribution to the total speed of the projectile than the forward speed of the ship.

Angular momentum

So we now need to focus on the process that generates the speed of the discus relative to the c.m. of the thrower-plus-discus system. To understand this process, we will need to look at the angular momentum of the thrower, the angular momentum of the discus and the angular momentum of the combined thrower-plus-discus system. (See the definition of angular momentum above, in the section "Some Mechanical Concepts and Definitions".)

The reader may ask why can't we just keep devoting our attention exclusively to speed, since the speed of the discus is ultimately what the thrower is looking for. The reason is that looking only at speeds would make it difficult to understand the mechanical relationships between the speed of the discus, the motions of the thrower, and the forces made by the thrower on the ground. In other words, it would be difficult to understand how the speed of the discus is generated.

By looking at the angular momentum instead, we will be able to understand much better the mechanics of what happens during the throw: The force interaction between the thrower and the ground determines the generation (or the loss) of angular momentum for the thrower-plus-discus system; the force interaction between the thrower and the discus determines the transfer of angular momentum from the thrower to the discus or vice versa. Everything is neatly additive: The angular momentum of the thrower-plus-discus system is equal to the angular momentum of the thrower plus the angular momentum of the discus. This kind of analysis would be impossible if we only looked at speeds.

Fine, but aren't we losing track of what is happening to the speed of the discus, which after all is our ultimate concern? No, because the angular momentum of the discus is pretty much directly proportional to its speed. Therefore, by looking at the angular momentum of the discus we can also tell whether the discus is moving fast or not. In other words, by focusing on angular momentum instead of speed, we gain a mechanical understanding inherent in an analysis of angular momentum, but without losing track of our main objective, which is to understand the process through which the speed of the discus is generated.

The ground reaction forces which produced the *linear* momentum of the thrower-plus-discus system also give *angular* momentum to the thrower-plus-discus system. There is angular momentum in two independent directions: "Z" angular momentum, about the vertical axis, which is visible as a counterclockwise rotation in a view from overhead (Figure 3); and "Y" angular momentum, about a horizontal axis aligned with the midline of the throwing sector, which is visible as a counterclockwise rotation in a view from the back of the circle (Figure 4). A transfer of Z angular momentum from the thrower to the discus imparts *horizontal speed* to the discus (Figure 3); it also tends to slow down the thrower's counterclockwise rotation in the view from overhead. A transfer of Y angular momentum from the thrower to the discus imparts *vertical speed* to the discus (Figure 4); it also tends to slow down any counterclockwise rotation of the thrower in the view from the back of the circle.

Proportions of discus speed generated through linear and angular momentum

On the average, in the throwers of our sample the forward linear momentum of the thrower-plus-discus system contributed 6% of the *horizontal* speed of the discus at release, while the Z angular momentum contributed the remaining 94%; the upward linear momentum contributed 10% of the *vertical* speed of the discus at release, while the Y angular momentum contributed the remaining 90%. In other words, the forward and upward linear momentum of the thrower-plus-discus system made relatively small (although not negligible) contributions to the speed of the discus; the main contributions came from the Z angular momentum and the Y angular momentum.

Previous ideas

It is generally believed that the rotation of the thrower-plus-discus system about a vertical axis can be generated most effectively while both feet are in contact with the ground (Housden, 1959), through a "pull-push" mechanism such as the one shown in Figure 5. There are two such periods in every throw: the first double-support phase at the back of the circle, and the double-support phase during the final delivery.

Until recently, the roles of these two double-support phases have not been clear. Much of the coaching literature has tended to stress the importance of the delivery phase at the expense of the

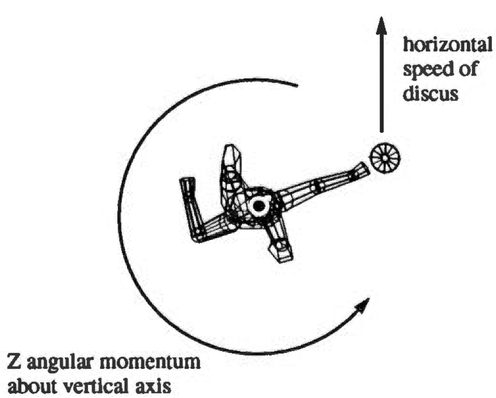

Figure 3

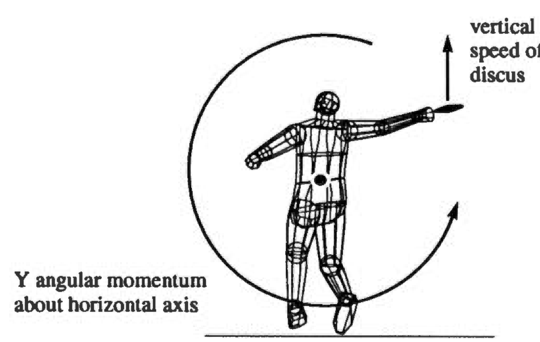

Figure 4

earlier part of the throw, which has often been seen as little more than a mere preparation for the start of the all-important delivery phase (e.g., see Schmolinsky, 1978; Scoles, 1978; Lenz, 1985; Vrabel, 1994). According to most authors, the emphasis should be put mainly on the achievement of a good position of the body at the instant that the left foot is planted, and on the execution of a very dynamic delivery phase; only limited importance is given to the execution of dynamic motions in the part of the throw that precedes the delivery phase. In other words, according to most authors, if a thrower can manage to move at a *slow-to-moderate* pace in the part of the throw prior to the delivery phase, reach the start of the delivery phase in a good position, and then execute a very dynamic delivery, this would constitute a good technique. However, the results of a preliminary investigation at our laboratory (Dapena, 1993a, 1993b, 1994a, 1994b), as well as the results of the present project, indicate that this is not the case: Discus throwers need to be very dynamic in the parts of the throw that precede the delivery phase.

Generation of horizontal speed of the discus through Z angular momentum

Contrary to what the majority of practitioners would expect, most of the angular momentum of the thrower-plus-discus system about the vertical axis (Z angular momentum, or counterclockwise angular momentum in a view from overhead —see Figure 3) was obtained from the ground during the initial double-support phase at the back of the circle and the following single-support phase on the left foot. During the initial double-support phase, the Z angular momentum was probably generated mainly by pull-push forces (Figure 5); during the single-support phase on the left foot, it was generated by an off-center ground reaction force that passed to the right of the c.m. of the thrower-plus-discus system (Figure 6). (Note: The forces shown in the drawings are only approximations; a study using force plates rather than film analysis would be necessary for a more exact measurement of these forces.)

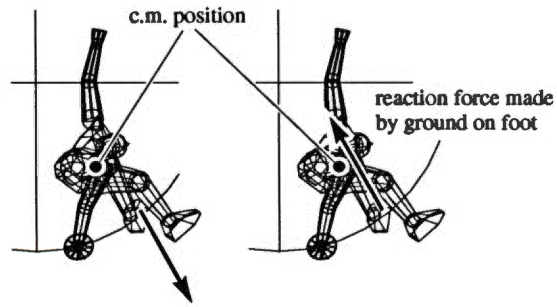

Figure 6

During the single-support over the right foot in the middle of the circle, the right foot generally made on the ground a small horizontal force which pointed forward and somewhat toward the left (Figure 7). The ground reaction force pointed almost directly through the c.m. of the system, and therefore the Z angular momentum of the system remained almost constant during the single-support on the right foot.

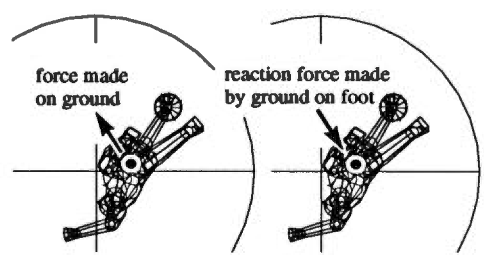

Figure 7

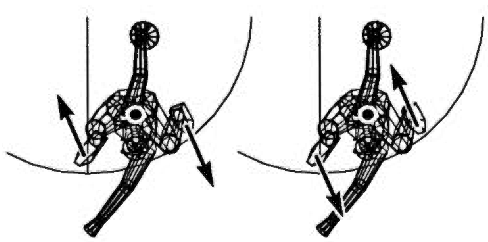

Figure 5

A small (but not negligible) amount of Z angular momentum was added to the system during the final delivery phase. This is a new finding of the present study; in the preliminary study (Dapena, 1993a, 1993b, 1994a, 1994b) this increase in the Z angular momentum of the system during the delivery phase was unclear, due to the small number of subjects analyzed and the variability among subjects. Still, an important point to keep in mind is that the increase in the Z angular momentum of the system during the final delivery was small, only about one tenth of the amount generated previously in the back of the circle.

At this point, we don't know precisely the sizes nor the directions of the forces made by the feet on the ground during the delivery phase. However, we can speculate that the left foot probably pushed on the ground forward and perhaps somewhat toward the right, while the right foot may have exerted on the ground a smaller force which pointed backward and toward the left with respect to the throwing circle (Figure 8). The reactions to these forces produced the observed increase in the counterclockwise Z angular momentum of the system during the delivery.

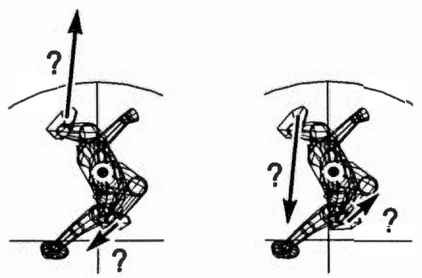

Figure 8

Why wasn't the thrower able to generate a much larger amount of counterclockwise Z angular momentum during the delivery? Presumably, the thrower was already rotating so quickly about the vertical axis by then that the feet found it difficult to make very large horizontal forces on the ground.

We can make an analogy with a child on a scooter as the child tries to pull backward on the ground with one foot to propel the scooter forward (Figure 9). If at first the scooter is not moving, or if it is moving forward at a slow speed, the child will be able to pull backward on the ground with the foot, and this will increase the speed of the scooter. However, if the scooter is already moving forward very fast, the ground will be passing below the child very fast, and it will be impossible to push backward on the ground any more; in this case, the scooter will keep traveling forward at constant speed. (This will be the maximum speed of the scooter.) The conditions in the back of the circle at the start of a discus throw are analogous to those of an initially motionless scooter: From initial stationary conditions, the subject is able to achieve significant increases in speed (in the scooter) or in Z angular momentum (in the early part of a discus throw). The conditions at the start of the double-support delivery phase in the discus throw are analogous to those of a moving scooter: When the subject is already moving very fast, it is difficult or impossible to achieve further increases in speed (in the scooter) or in the Z angular momentum of the whole system (in the double-support delivery phase of a discus throw).

Figure 9

Does the thrower need to make an all-out effort to generate counterclockwise Z angular momentum at the back of the circle? Not necessarily. However, there will be a problem if the thrower is not active enough during that period. Another analogy may help to clarify this point.

Consider a long jumper, four steps prior to the end of the run-up. Let's assume that the athlete is already running at the speed wanted for the end of the run-up. To achieve his/her goal, the athlete will simply have to maintain the current speed. Let's assume a different situation: The long jumper is now running at 98% of the "target" speed wanted for the end of the run-up. The athlete probably will not have much difficulty reaching the target speed in the four remaining steps. Therefore, running at a somewhat sub-maximum speed four steps prior to the end of the run-up is not necessarily a problem for the long jumper. But what would happen if four steps prior to the end of the run-up the athlete were running at 50% of the target speed? In that case, the jumper would not have enough time in the four remaining steps to reach the target speed at the end of the run-up, and the result would be a sub-par jump.

In a similar way, if the Z angular momentum of a discus thrower is somewhat small at the start of the double-support delivery phase, this may not be a problem, because within certain limits the athlete should have the opportunity to increase the Z angular momentum to the "target" value before release. However, if the value of the Z angular momentum is too far below the target value, the thrower will find it impossible to reach the target value before release, and the result will be a sub-par throw. At this time, we do not know how low the Z angular momentum can be at the start of the double-support delivery before it starts to interfere with the final result of the throw. What we do know is that in most of the analyzed throwers the value of the Z angular momentum at the beginning of the double-support delivery was not far below the value that it had at release. This means that although most throwers relied to some extent on an increase in the value of the Z angular momentum of the thrower-plus-discus system during the delivery phase, they relied much more on the angular momentum that they had generated during the first double-support and the early part of the first single-support.

We want to point out that, although the discus thrower needs to generate a large amount of Z angular momentum during the early part of the throw, the motions of the athlete at the back of the circle *should not be rushed.* Instead, during the first double-support and single-support phases the athlete should rotate at a *reasonably fast pace* while keeping the arms and the swinging leg *widely spread.*

Most of the Z angular momentum of the thrower-plus-discus system at the instant of takeoff of the left foot at the back of the circle was "stored" in the thrower; at that point, the discus only had a small share of the total Z angular momentum of the system.

As explained above, in the final part of the throw there was only a small increase in the total Z angular momentum of the system. However, there was a tremendous ***transfer*** of angular momentum *within* the thrower-plus-discus system: a transfer from the thrower to the discus. This transfer of angular momentum actually started during the single-support phase on the right foot, and continued throughout the double-support delivery. The transfer of Z angular momentum from the thrower to the discus is what produced the main increase in the *horizontal speed* of the discus, and it simultaneously produced a marked slowing down of the counterclockwise rotation of the thrower's body.

The interactions of the feet with the ground during the final delivery gave the system an additional amount of counterclockwise Z angular momentum, which was thus made availabe for potential transfer into the discus. However, most of the Z angular momentum available for transfer into the discus during the single-support on the right foot and the double-support delivery was the angular momentum carried by the body of the thrower since the end of the first single-support phase at the back of the circle.

These findings indicate that the thrower made an effort to "unwind" the upper body and right arm relative to the lower body, in part during the single-support phase on the right foot, but mainly during the double-support delivery. This was a very large effort, and it was critical for the result of the throw, because it was needed for the transfer of Z angular momentum from the thrower to the discus, which is how the discus obtained most of its horizontal speed.

Most throwers also succeeded in obtaining for the thrower-plus-discus system a modest additional amount of counterclockwise Z angular momentum from the ground during the double-support delivery phase. This was beneficial for the throw, and certainly very welcome. However, it is important to keep in mind that the most important effort during the double-support delivery was the one previously described, directed to the *transfer* of angular momentum from the thrower to the discus, rather than to the generation of additional angular momentum for the combined thrower-plus-discus system.

Generation of vertical speed of the discus through Y angular momentum

The angular momentum about a horizontal axis aligned with the midline of the throwing sector (Y angular momentum, or counterclockwise angular momentum in a view from the back of the circle —see Figure 4) is important for the generation of the vertical speed of the discus. This angular momentum was generated mainly during the second half of the single-support phase on the right foot and during the first half of the delivery phase.

During the single-support phase, the thrower's right foot exerted on the ground a force that pointed vertically downward, and possibly also somewhat toward the left in the view from the back of the circle (see the top half of Figure 10). The ground reaction to this force passed to the right of the center of mass. Since the reaction force was off-center (in other words, since it did not point directly through the center of mass), it gave the thrower counterclockwise angular momentum in the view from the back of the circle.

We are not so sure of the directions of the forces made by the feet on the ground during the early part of the double-support delivery phase, because this would have required measurements with a force plate. However, our speculation is that the right foot continued to push on the ground downward and perhaps further toward the left than in the single-support (see the bottom half of Figure 10), while the left foot pushed closer to the vertical direction. The reaction force exerted by the ground on the right foot

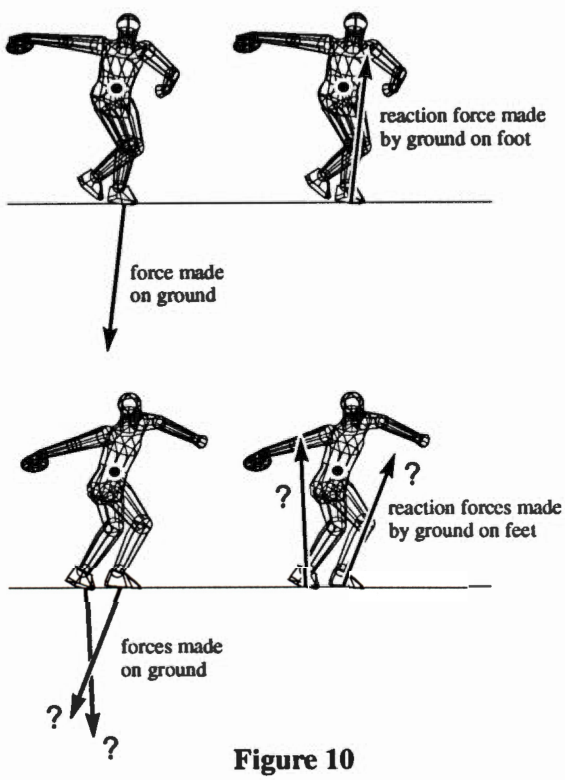

Figure 10

would thus pass to the right of the c.m., and would tend to increase the counterclockwise Y angular momentum of the system, while the reaction force exerted on the left foot would pass to the left of the c.m., and would tend to decrease the angular momentum. Overall, the action of the right leg was dominant, and the result was a net gain of counterclockwise Y angular momentum during the first half of the double-support delivery phase.

In most throwers, during the second half of the delivery phase there was not much further gain of Y angular momentum. However, part of the counterclockwise angular momentum that had been generated during the second half of the single-support phase on the right foot and the first half of the delivery phase was transfered from the thrower to the discus during this period. This transfer of angular momentum during the second half of the delivery phase produced most of the *vertical speed* of the discus.

Aerodynamics

In a hypothetical throw made in a vacuum, the horizontal and vertical speeds of the discus at release (together with some small influence from the precise location of the discus at release) would determine the distance of the throw.

However, in real life the distance of a throw will also be affected by the forces made by the air on the discus during its flight. The effect of these aerodynamic forces will depend primarily on the tilt of the discus at release, and on the direction and speed of the wind. Normally, a tailwind is detrimental for the distance of a throw, while a headwind is beneficial (Frohlich, 1981). The effect of any given wind will generally be different for different throwers: Some throwers are able to obtain a greater advantage from the aerodynamic forces than others. The largest wind-related differences between throwers will tend to occur in the presence of headwinds.

The aerodynamics of discus throwing will be discussed in more detail further below.

Summary

The forward linear momentum of the thrower-plus-discus system contributes to the horizontal speed of the discus, and the upward linear momentum of the system contributes to the vertical speed of the discus. However, most of the speed of the discus is the result of angular momentum. Z angular momentum is an essential factor for the generation of the horizontal speed of the discus, and it is transmitted to the discus during the delivery phase. Y angular momentum is an essential requirement for the generation of the vertical speed of the discus, and it is transmitted to the discus during the second half of the delivery phase. However, very little of either one of them is obtained from the ground during those periods. To an overwhelming extent, both are obtained from the ground in earlier stages of the throw: the Z angular momentum, in the first double-support and single-support phases; the Y angular momentum, in the second half of the single-support phase on the right foot and the first half of the delivery phase. The angular momentum is first stored primarily in the body of the thrower (where it expresses itself as a rotation of the body) before being transmitted to the discus near the end of the throw.

DETAILED DESCRIPTION OF DISCUS THROWING TECHNIQUE, AND GENERAL ANALYSIS OF RESULTS

Horizontal translation of the system c.m. across the circle

The left half of Figure 11 shows an overhead view of the footprints of the athlete, and also the paths of the discus and of the system c.m. in a typical throw. At the back of the circle, the footprints of the

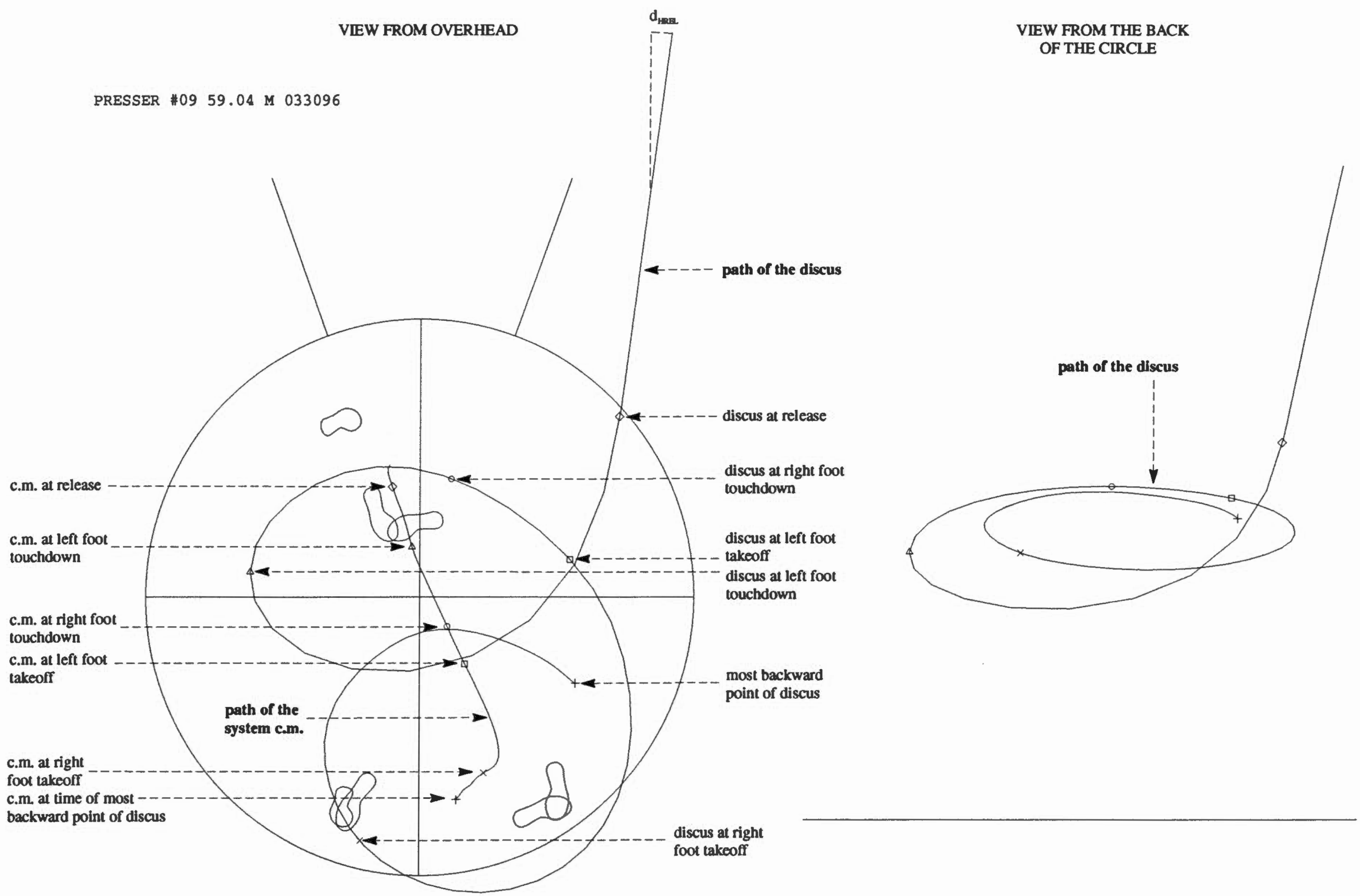
VIEW FROM OVERHEAD
PRESSER #09 59.04 M 033096
path of the discus
discus at release
discus at right foot touchdown
discus at left foot takeoff
discus at left foot touchdown
most backward point of discus
discus at right foot takeoff
c.m. at release
c.m. at left foot touchdown
c.m. at right foot touchdown
c.m. at left foot takeoff
path of the system c.m.
c.m. at right foot takeoff
c.m. at time of most backward point of discus
VIEW FROM THE BACK OF THE CIRCLE
path of the discus

Figure 11

right foot and of the left foot were drawn at the instant when the discus reached its most backward point and at the instant of takeoff of the right foot. In the middle of the circle, the footprint of the right foot was drawn at the instant that it landed and at the instant that the left foot landed. At the front of the circle, the footprint of the left foot was drawn at the instant that it landed. (The footprints appear foreshortened if the heel was higher than the toe, or vice versa.)

The small symbols indicate the positions of the discus and of the system c.m. at the instant that the discus reached its most backward point ("+"), at the takeoff of the right foot ("×"), at the takeoff of the left foot (square), at the landing of the right foot (circle), at the landing of the left foot (triangle) and at release (diamond).

During the double-support phase at the back of the circle, the thrower makes horizontal pull-push forces with the feet against the ground (Figure 5), and the ground reactions to these forces generate most of the Z angular momentum that the athlete will need for the throw. But we will examine this in more detail later on; now, we are going to concentrate on the *translation* of the system c.m.

Ideally, it seems that during the double-support phase at the back of the circle the thrower should shift the system c.m. to a position that is almost directly above the left foot, at the same time as the thrower starts to generate the system's Z angular momentum (and consequently its counterclockwise rotation about the vertical axis). Then, after the body has turned around, the athlete should thrust directly backward on the ground with the left foot. The large and slightly off-center ground reaction force would provide a large amount of linear momentum and additional Z angular momentum to the system. The thrower would translate directly forward across the circle. During the double-support delivery phase, the large horizontal linear momentum of the system would help the thrower to obtain upward linear momentum, at the expense of some loss of horizontal linear momentum. The upward linear momentum would help in the generation of the vertical speed of the discus; the leftover horizontal linear momentum would help in the generation of the horizontal speed of the discus.

In actual fact, the throwers generally did not move quite that way. During the double-support phase at the back of the circle, the athletes normally shifted the position of the c.m. of the system in a diagonal direction toward the left foot and toward the front of the circle. (From the point of view of the athlete, this was a shift toward the left and backward.) The mental image of the athlete may be to displace the c.m. to a position that is more or less directly above the left foot before making the main push across the circle, but this did not usually occur, as Hay & Yu (1996a, 1996b) have pointed out. The c.m. got closer to the vertical of the left foot, but did not reach it. Therefore, at the time that the left leg had to start its main horizontal thrust against the ground, the c.m. was ahead and to the left of the position of the left foot (Figure 6). Because of this, the thrust of the foot against the ground was not directly backward, but in an oblique direction backward and toward the right. The reaction force from the ground was forward and toward the left (Figure 6). This made the system c.m. travel in an oblique direction across the throwing circle: forward and toward the left (Figure 11).

What could be the disadvantages of such a technique? We think that the oblique nature of the direction of motion of the system c.m. should not pose a problem for the generation of the *vertical* speed of the discus. As long as the horizontal speed of the system is large, it should help the athlete to obtain vertical linear momentum during the double-support delivery phase, regardless of whether the horizontal translation is directly forward or in an oblique direction.

However, there is a possible problem for the generation of the *horizontal* speed of the discus: The more oblique the direction of motion of the system c.m. with respect to the final horizontal direction of motion of the discus after release, the smaller the contribution of the horizontal speed of the system to the horizontal speed of the discus at release. In the ship analogy, if the ship's cannon does not shoot directly forward but at an angle with respect to the direction of motion of the ship, the two speeds (horizontal speed of the ship, and oblique horizontal speed of the projectile relative to the ship) do not quite add up. In theory, this could be a problem for the discus thrower, and we will evaluate it later on with numerical data.

Instead of using the standard oblique push just described, a thrower could decide to push directly *backward* on the ground, as shown in Figure 12 (and in contrast with what is shown in Figure 6). If the thrower chose to do this when the system c.m. is forward and to the left of the position of the left foot (as it is in most throws), the force that the thrower would be able to exert on the ground would be much smaller than if the push were made in the standard oblique direction shown in Figure 6. This might not pose a problem in regard to the *rotation* of the system: The small ground reaction force shown in

This probably would not be good.

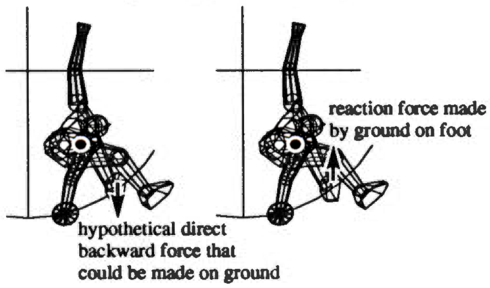

Figure 12

the right half of Figure 12 points more off-center with respect to the c.m. than the oblique ground reaction force shown in Figure 6, and for the generation of Z angular momentum, this would tend to compensate for the smaller size of the force. However, there would be problems in regard to the *translation* of the system. The small size of the horizontal ground reaction force in Figure 12 would reduce the horizontal speed of the system across the circle. This would tend to limit the contribution of the system linear momentum to the horizontal speed of the discus at release. A slower speed of horizontal translation would also make it more difficult for the system to acquire upward linear momentum during the double-support delivery phase. A limited amount of upward linear momentum would result in a limited contribution to the vertical speed of the discus at release. Overall, this approach does not seem advisable.

In summary: Ideally, the thrower should shift the c.m. to a position that is almost directly above the left foot, and then push directly backward on the ground to obtain a good drive directly forward across the throwing circle. However, if the thrower fails to bring the c.m. close enough to the vertical of the left foot (which is usually the case), the thrower should probably make a *strong* horizontal drive across the circle in an *oblique* direction. And this is what most throwers do. In this situation, it probably would not be good to attempt to push directly backward on the ground as shown in Figure 12.

Table 2 shows numerical data on horizontal translation. At the time that the left foot lost contact with the ground at the back of the circle, the system c.m. was traveling with a horizontal speed v_{HLTO} = 2.4 ± 0.2 m/s. The direction of motion was oblique forward and toward the left (a_{LTO} = -23 ± 9°). (The negative sign of the angle indicates that the deviation was toward the left.) The laws of mechanics dictated that this speed and direction of motion remained constant while the athlete was airborne. Some of the horizontal speed was lost during the single-support on the right foot (Δv_{SSR} = -0.4 ± 0.2 m/s). By the time that the left foot landed to start the double-support delivery phase, the system c.m. was traveling with a horizontal speed v_{HLTD} = 2.0 ± 0.2 m/s, and its direction of motion was roughly similar to what it had been when the left foot took off from the ground (a_{LTD} = -17 ± 10°). During the double-support delivery phase there was a greater loss of horizontal speed (Δv_{HDLV} = -0.7 ± 0.3 m/s). By the time of release, the system c.m. was traveling with a horizontal speed v_{HREL} = 1.3 ± 0.3 m/s, and its direction of motion was still similar to what it had been when the left foot took off from the ground (a_{REL} = -22 ± 13°).

The loss of horizontal speed of the system c.m. during the double-support delivery served two purposes: (a) It helped to prevent the thrower from fouling; (b) it was part of the mechanism used to obtain upward linear momentum which was useful for the generation of the vertical speed of the discus.

As previously explained, the horizontal speed of the throwing platform (i.e., of the thrower-plus-discus system) contributes to the horizontal speed of the discus (remember the analogy of the ship firing its cannon forward). But which horizontal speed of the system should we look at? The horizontal speed at the landing of the left foot? At release? We decided to use the average horizontal speed of the system during the last quarter of a turn of the discus (v_{HQ} = 1.3 ± 0.2 m/s). (By coincidence, this had the same mean value as the horizontal speed of the system at release, but the values of these two speeds were usually different within each throw.)

In general, the average horizontal direction of motion of the system c.m. during the last quarter-turn of the discus was still in a diagonal direction forward and toward the left (a_Q = -18 ± 11°). The horizontal direction of motion of the discus after release varied quite a bit from one throw to another, but on the average it pointed forward and slightly toward the right (d_{HREL} = 4 ± 9°). The difference between the two angles (c_Q = -22 ± 16°) indicated the divergence between the horizontal paths of the system and of the discus. The negative sign indicated that during the last quarter-turn of the discus the system c.m. was moving on the average toward the left with respect to the eventual horizontal direction of motion of the discus at release.

The size of the divergence angle c_Q determines how much of the horizontal speed that the system c.m had in the last quarter-turn (v_{HQ}) effectively contributed to the horizontal speed of the discus (v_{HCON}). Table 3 shows that the larger the divergence

Table 2

Horizontal motions of system c.m.

Horizontal speed and direction of motion of the system c.m. at left foot takeoff (v_{HLTO} and a_{LTO}); change in the horizontal speed of the system c.m. during the single support on the right foot (Δv_{SSR}); horizontal speed and direction of motion of the system c.m. at left foot landing (v_{HLTD} and a_{LTD}); change in the horizontal speed of the system c.m. between left foot landing and discus release (Δv_{HDLV}); horizontal speed and direction of motion of the system c.m. at release (v_{HREL} and a_{REL}); average horizontal speed and direction of motion of the system c.m. during the last quarter-turn of the discus (v_{HQ} and a_Q); horizontal direction of motion of the discus at release (d_{HREL}); divergence angle between the horizontal direction of motion of the system c.m. during the last quarter-turn and the horizontal direction of motion of the discus at release (c_Q); effective contribution of v_{HQ} to the horizontal speed of the discus (v_{HCON}). Negative angles are counterclockwise. Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	v_{HLTO} (m/s)	a_{LTO} (°)	Δv_{SSR} (m/s)	v_{HLTD} (m/s)	a_{LTD} (°)	Δv_{HDLV} (m/s)	v_{HREL} (m/s)	a_{REL} (°)	v_{HQ} (m/s)	a_Q (°)	d_{HREL} (°)	c_Q (°)	v_{HCON} (m/s)
Bloom	41 D96	2.6	1	-0.7	1.9	8	-0.7	1.2	-7	1.2	-3	14	-16	1.1
Dumble	23 D96	2.5	-13	-0.3	2.2	-13	-0.8	1.4	-33	1.3	-26	-5	-21	1.2
Fitzpatrick	40 U94	2.8	-22	-0.6	2.3	-18	-1.2	1.1	-15	1.2	-11	-5	-6	1.2
Fitzpatrick	*62 D96*	*2.7*	*-8*	*-0.7*	*2.0*	*-3*	*-0.5*	*1.5*	*-1*	*1.5*	*0*	*11*	*-10*	*1.5*
Godina	28 U94	2.4	-16	-0.6	1.8	-19	-0.9	1.0	-38	1.3	-29	0	-29	1.1
Gravelle	22 U94	2.6	-27	-0.5	2.1	-16	-1.3	0.8	-25	1.4	-14	-6	-8	1.3
Hart	57 D96	2.2	-31	-0.3	1.9	-28	-0.3	1.6	-23	1.5	-22	9	-31	1.3
Haynes	24 D96	2.5	-8	-0.4	2.0	-5	-0.5	1.5	-22	1.6	-13	9	-22	1.5
Heisler	36 U94	2.5	-24	-0.4	2.1	-17	-0.9	1.1	-6	1.3	-8	-4	-5	1.3
Johnson	10 D96	2.4	-34	-0.4	2.0	-19	-0.9	1.1	-39	1.3	-27	4	-32	1.1
Kirchhoff	34 D96	2.4	-25	-0.4	2.0	-18	-0.6	1.4	-27	1.3	-23	25	-48	0.9
McPherran	08 D96	2.2	-19	0.2	2.4	-18	-0.8	1.6	-14	1.4	-16	-2	-14	1.4
Mielke	22 D96	2.2	-31	-0.5	1.7	-27	-0.2	1.5	-23	1.5	-18	-8	-10	1.5
Muse	47 D96	2.2	-26	-0.1	2.1	-15	-0.6	1.5	-27	1.7	-22	14	-36	1.3
Nutl	15 D96	2.4	-36	-0.3	2.1	-27	-0.6	1.6	-45	1.5	-39	6	-45	1.0
Patera	01 U94	2.5	-26	-0.4	2.1	-28	-1.2	0.9	-10	1.2	-13	-6	-6	1.2
Presser	09 D96	2.5	-25	-0.5	2.0	-18	-0.7	1.3	-20	1.2	-21	8	-28	1.1
Schulte	59 D96	2.2	-21	-0.4	1.8	-16	-0.4	1.4	-38	1.4	-28	4	-32	1.2
Scott	41 U94	2.0	-16	-0.6	1.5	-17	-1.0	0.5	12	0.7	15	0	15	0.7
Setliff	*27 U94*	*2.6*	*-17*	*-0.5*	*2.2*	*-8*	*-0.8*	*1.3*	*-21*	*1.6*	*-10*	*-3*	*-8*	*1.6*
Setliff	65 D96	2.5	-17	-0.9	1.6	-6	-0.3	1.3	-35	1.4	-33	13	-46	0.9
Staat	25 D96	2.4	-33	-0.7	1.7	-31	-0.6	1.1	-24	1.1	-15	17	-32	0.9
Sullivan	06 D96	2.5	-14	-0.3	2.2	-12	-0.4	1.8	-8	1.7	-7	-6	-1	1.7
Tveitaa	39 D96	2.3	-27	-0.4	1.9	-7	-0.6	1.3	-21	1.4	-14	20	-35	1.2
Washington	66 D96	2.1	-42	-0.3	1.8	-40	-0.7	1.1	-34	1.2	-30	-2	-28	1.1
Wirtz	42 D96	2.7	-17	-0.4	2.3	-6	-0.9	1.4	-11	1.4	-8	5	-13	1.4
Mean		2.4	-23	-0.4	2.0	-17	-0.7	1.3	-22	1.3	-18	4	-22	1.2
S.D.		±0.2	±9	±0.2	±0.2	±10	±0.3	±0.3	±13	±0.2	±11	±9	±16	±0.2

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

angle c_Q, the greater the loss in the contribution of the horizontal speed of the system to the horizontal speed of the discus (Δv_{HCON}), and therefore the greater the loss in the distance of the throw (ΔD_c). Notice that the losses increase at first very gradually as c_Q changes from 0° to -20°, but much faster after that. Consequently, if the divergence angle is kept within reasonable bounds, the loss of distance is very small. This is what happens in a typical throw. In the analyzed trials, the contribution of the horizontal speed of the system to the horizontal speed of the discus at release was v_{HCON} = 1.2 ± 0.2 m/s, only 0.1 m/s smaller than the value of v_{HQ} (1.3 ± 0.2 m/s). This was because the average divergence angle c_Q was small (-22 ± 16°). Since the average horizontal speed of the discus at release was 19.3 m/s (see below), the 0.1 m/s loss due to the divergence of the system and discus paths was (0.1/19.3=) about one half of 1% of the total horizontal speed. In a hypothetical throw made *in a vacuum*, this would reduce the length of the throw in approximately the same proportion, or about 0.30 meters in a 60-meter throw. In a real-life throw, with the discus subjected to aerodynamic forces, the loss would generally be larger. The exact amount would depend on the wind. Computer simulations made at our lab following Frohlich's (1981) method showed that the effect (with winds anywhere between +10 m/s and -10 m/s) would generally be larger than in a vacuum, but still not much: a total loss of between 0.30 m and 0.50 m (Dapena, unpublished results). In conclusion: As long as a discus thrower drives across the throwing circle at a moderately oblique angle toward the left and does not throw the discus too far toward the right (so that the divergence angle c_Q does not go much beyond -20°), there will not be a significant loss in the distance of the throw. However, if the divergence angle reaches higher values there can be important losses in the distance of the throw.

Table 3

Theoretical effects of the divergence angle (c_Q) on the contribution of the horizontal speed of the system to the horizontal speed of the discus at release (Δv_{HCON}), and on the distance of a 60-meter throw (ΔD_c). Assumptions: horizontal speed of system v_{HQ} = 1.3 m/s; horizontal speed of discus at release v_{HD} = 19.3 m/s. (Note: The *range* reported for the ΔD_c values reflects the approximate variation due to the effects of aerodynamic forces (winds up to ±10 m/s), based on unpublished results obtained at our laboratory with computer simulation of discus flight using the mathematical model proposed by Frohlich, 1981.)

c_Q (°)	Δv_{HCON} (m/s)	ΔD_c (m)
0	0.00	0.0
-10	-0.02	-0.1
-20	-0.08	-0.2/-0.4
-30	-0.17	-0.5/-0.8
-40	-0.30	-0.9/-1.4
-50	-0.46	-1.4/-2.1

Center of mass heights during the delivery phase

At the instant of release, most of the throwers in our sample had both feet off the ground (airborne-release throws), but some of them still had one or both feet in contact with the ground (grounded-release throws). Except where there is a statement to the contrary, all means and standard deviations mentioned in this section and the next one will correspond to the combined sample containing both the airborne-release throws and the grounded-release throws.

Table 4 shows numerical data about the vertical motion of the c.m. of the system during the delivery phase. The right part of the table shows the height of the c.m of the system at the instant that the left foot was planted on the ground to start the delivery phase (h_{LTD}), at the instant that the feet lost contact with the ground —in the airborne-release throws— (h_{TO}), and at release (h_{REL}). These heights were expressed in meters, and also as a percent of each athlete's standing height. The percent values are more useful for comparisons between throwers.

At the instant that the discus was released, the system c.m. was at a height h_{REL} = 56.8 ± 1.9% of standing height in the grounded-release throwers. In the airborne-release throwers, the system c.m. was slightly higher than that at the instant that the feet lost contact with the ground (h_{TO} = 57.9 ± 1.2%), and markedly higher at the instant that the discus was released (h_{REL} = 60.3 ± 1.3%). These numbers seem to make good sense.

Table 4

Vertical motions of system c.m.

Vertical speed of the system c.m. at left foot landing (v_{ZLTD}), at the instant that the thrower lost contact with the ground during the delivery phase (v_{ZTO}), and at release (v_{ZREL}); average vertical speed of the system c.m. during the last quarter-turn of the discus, which is the contribution of the vertical speed of the system to the vertical speed of the discus (v_{ZCON}); height of the system c.m. at left foot landing (h_{LTD}), at the instant that the thrower lost contact with the ground during the delivery phase (h_{TO}), and at release (h_{REL}). The heights of the c.m. are expressed in meters, and also as a percent of the standing height of each subject. Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	v_{ZLTD}	v_{ZTO}	v_{ZREL}	v_{ZCON}	h_{LTD}		h_{TO}		h_{REL}		
		(m/s)	(m/s)	(m/s)	(m/s)	(m)	(%)	(m)	(%)	(m)	(%)	
Bloom	41 D96	-0.4	1.6	1.2	1.6	0.89	48.0	1.08	58.0	1.14	61.5	
Dumble	23 D96	0.1	2.1	1.9	1.8	0.89	48.0	1.09	59.0	1.15	62.0	
Fitzpatrick	40 U94	0.1	1.7	1.3	1.5	0.94	49.0	1.12	58.5	1.19	61.5	
Fitzpatrick	*62 D96*	*-0.1*	*1.3*	*1.0*	*1.3*	*0.95*	*49.5*	*1.11*	*57.5*	*1.15*	*60.0*	
Godina	28 U94	0.3	—	1.4	1.5	0.93	49.0	—	—	1.13	59.5	
Gravelle	22 U94	0.3	—	1.8	1.5	0.93	47.5	—	—	1.12	57.0	
Hart	57 D96	0.0	—	1.1	0.9	0.99	51.5	—	—	1.09	56.5	
Haynes	24 D96	0.4	1.9	1.4	1.6	0.84	46.0	1.03	56.5	1.11	61.0	
Heisler	36 U94	0.0	2.1	1.6	1.7	0.95	50.0	1.12	58.5	1.21	63.0	
Johnson	10 D96	-0.1	2.0	2.0	1.7	0.91	47.5	1.12	58.0	1.13	58.5	
Kirchhoff	34 D96	0.0	1.4	1.0	1.2	1.00	51.5	1.13	58.5	1.19	61.0	
McPherran	08 D96	0.4	1.1	1.0	1.2	0.95	48.0	1.13	57.0	1.14	58.0	
Mielke	22 D96	0.1	—	0.6	0.6	0.95	49.5	—	—	1.02	53.5	
Muse	47 D96	-0.3	1.3	0.9	1.0	0.94	51.0	1.05	57.5	1.10	59.5	
Nutl	15 D96	-0.2	1.9	1.7	1.7	0.95	49.0	1.11	57.5	1.15	59.5	
Patera	01 U94	-0.2	2.0	1.7	1.9	0.90	47.0	1.11	58.0	1.17	60.5	
Presser	09 D96	0.0	1.5	1.3	1.5	0.94	47.5	1.12	57.0	1.15	58.5	
Schulte	59 D96	0.1	1.5	0.8	1.3	0.99	50.0	1.13	57.0	1.21	61.5	
Scott	41 U94	0.0	1.4	1.4	1.5	0.93	48.5	1.19	61.5	1.19	61.5	
Setliff	*27 U94*	*0.0*	—	*1.3*	*1.1*	*0.99*	*51.5*	—	—	*1.12*	*58.0*	
Setliff	65 D96	0.3	—	1.3	1.1	0.97	50.5	—	—	1.11	57.5	
Staat	25 D96	0.0	1.7	1.3	1.6	0.92	46.5	1.12	56.5	1.17	59.5	
Sullivan	06 D96	0.2	1.5	1.1	1.2	0.92	49.5	1.04	56.5	1.09	59.0	
Tveitaa	39 D96	-0.3	1.7	1.5	1.5	0.92	49.5	1.07	57.5	1.11	59.5	
Washington	66 D96	0.0	1.9	1.7	1.7	0.92	49.5	1.10	59.5	1.14	61.0	
Wirtz	42 D96	0.1	1.9	1.6	1.6	0.90	47.5	1.08	57.5	1.14	60.0	
Mean		0.0	—	1.4	1.4	0.93	48.8	—	—	1.14	59.6	(ALL THROWS)
S.D.		±0.2	—	±0.3	±0.3	±0.03	±1.5	—	—	±0.04	±2.1	
Mean		0.0	1.7	1.4	1.5	0.93	48.6	1.10	57.9	1.15	60.3	(AIRBORNE
S.D.		±0.2	±0.3	±0.3	±0.2	±0.04	±1.4	±0.04	±1.2	±0.03	±1.3	RELEASE)
Mean		0.2	—	1.2	1.1	0.95	49.6	—	—	1.09	56.8	(GROUNDED
S.D.		±0.1	—	±0.4	±0.3	±0.02	±1.4	—	—	±0.04	±1.9	RELEASE)

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

A higher position of the system c.m. at the instant of release should also make us expect a higher position of the discus at release. This was confirmed by the data: At the instant of release, the discus was at a height corresponding to 86.0 ± 3.9% of standing height in the grounded-release throwers, and at 90.5 ± 5.9% of standing height in the airborne-release throwers. (These data are not shown in the tables.) Considering the 1.91 m average standing height of the throwers in our sample, 4.5% (i.e., 90.5%-86.0%) of standing height represented a difference of 0.09 m in the height of the discus at release between the two groups of throwers. For a given speed and angle of release of a projectile, a higher position at release will produce a longer distance for the throw, and therefore this was an advantage for the airborne-release throwers. However, a height difference of 0.09 m at release would only produce a trivial difference in the distance of the throw, less than 0.15 m.

Vertical speeds during the delivery phase

The left part of Table 4 shows vertical speeds of the c.m. At the instant that the left foot landed, the c.m. of the system was generally moving in an almost perfectly horizontal direction, with no vertical speed (v_{ZLTD} = 0.0 ± 0.2 m/s). Then the legs (presumably mainly the left leg) pushed forward and downward on the ground during the double-support delivery phase. In reaction, the ground made upward and backward forces on the feet which reduced the horizontal speed of the c.m. and produced a positive (i.e., upward) vertical speed. As a result of this, at the time that the feet lost contact with the ground in the airborne-release throws, the c.m of the system had a vertical speed v_{ZTO} = 1.7 ± 0.3 m/s. When a system is in the air, the c.m. loses vertical speed at a rate of 0.1 m/s with each hundredth of a second that passes by. By the time that the airborne-release throwers released the discus, the vertical speed of the system had slowed down to v_{ZREL} = 1.4 ± 0.3 m/s. On the average, the vertical speed of the system at the instant of release was smaller in the grounded-release throwers (v_{ZREL} = 1.2 ± 0.4 m/s) than in the airborne-release throwers, even though the grounded-release throwers did not experience any loss of vertical speed before release; they simply never reached the vertical speed of the airborne-release throwers. It would appear that the airborne-release technique allows a larger vertical speed of the system at release than the grounded-release technique. However, because of the rather large variability among throwers and the small number of grounded-release throwers in the sample, it would be premature to make any such generalization at this point.

As in the horizontal direction, we assumed that the contribution of the vertical speed of the thrower-plus-discus system to the speed of the discus (v_{ZCON}) was the average vertical speed of the system c.m. during the last quarter of a turn of the discus. In the airborne-release throws, v_{ZCON} was larger than the vertical speed of the system at release (v_{ZCON} = 1.5 ± 0.2 m/s; v_{ZREL} = 1.4 ± 0.3 m/s), while in the grounded-release throws it was smaller than the vertical speed of the system at release (v_{ZCON} = 1.1 ± 0.3 m/s; v_{ZREL} = 1.2 ± 0.4 m/s). This makes sense. In the airborne-release throws, the vertical speed of the system was slowing down prior to release. Therefore, we should expect the average vertical speed within a short period prior to release to be larger than the speed at release. The reverse is true for the grounded-release throws, where the vertical speed of the system was increasing prior to release. The conclusion is that the vertical speed of the system *at release* makes the airborne-release throwers look worse than they should, because that value does not take into account the fact that these throwers were traveling upward faster than that during the last quarter-turn, which is what counts. Vice versa, the vertical speed of the system *at release* makes the grounded-release throwers look better than they should, because that value does not take into account the fact that these throwers were traveling upward more slowly than that during the last quarter-turn, which is what counts.

When we compare in the two groups of throwers the average vertical speed of the system during the last quarter-turn (i.e., the vertical speed that "counts", v_{ZCON}), the airborne-release throwers in the sample had a clear advantage over the grounded-release throwers (v_{ZCON} = 1.5 ± 0.2 m/s for the airborne-release throwers; v_{ZCON} = 1.1 ± 0.3 m/s for the grounded-release throwers). Due to the small number of grounded-release throwers in the sample, a formal test for statistical significance might not be valid. However, we can say that the results *strongly suggest* that the airborne-release technique helps the vertical speed of the system c.m. to make a larger contribution to the vertical speed of the discus than the grounded-release technique. In other words, in the airborne-release technique the throwing platform is traveling upward faster than in the grounded-release technique, and this is an advantage.

How much difference does 0.4 m/s (i.e., 1.5 m/s - 1.1 m/s) make in the distance of a throw? The average vertical speed of the discus at release was 13.6 m/s (see below). That makes the 0.4 m/s difference in the contribution to the vertical speed of the discus in the two techniques (0.4/13.6=) 3% of the total vertical speed. Ignoring momentarily the effects of aerodynamic forces, a 3% loss in the vertical speed of the discus would produce a loss of about 3% in the distance of the throw, or 1.75 meters in a 60-meter throw. But this is what would happen in a hypothetical throw made *in a vacuum*. In a real throw, where aerodynamic forces are present, the effect will generally be smaller. The exact amount would depend on the wind. Our computer simulations showed that the effect (with winds anywhere between +10 m/s and -10 m/s) would generally be smaller than in a vacuum, a total gain of between 1.00 m and 1.75 m (Dapena, unpublished results).

Relationship between the loss of horizontal speed and the gain of vertical speed of the system c.m. during the delivery phase

As previously explained, during the double-support delivery phase the system c.m. experiences a loss of horizontal speed and a gain of vertical speed. These two processes are closely linked. A statistical analysis of the data in Tables 2 and 4 showed that the larger the loss of horizontal speed during the double-support delivery (Δv_{HDLV}), the larger the vertical speed of the system at release (v_{ZREL}). The thrower can choose to make a very "explosive" planting of the left leg on the ground, and thus lose a lot of horizontal speed and also gain a lot of vertical speed, or to plant the left leg more weakly on the ground, and thus lose a smaller amount of horizontal speed and gain a smaller amount of vertical speed. What seems to be very difficult to do is to acquire a large amount of vertical speed with only a small loss of horizontal speed.

If the system has a large amount of horizontal speed at the instant of landing of the left foot, the thrower can (and should!) plant the left leg very explosively on the ground. This will make the system lose a lot of horizontal speed, which will help to prevent fouling but still leave the system with enough forward speed to make a good contribution to the horizontal speed of the discus. It will also make the system gain a large amount of vertical speed, which will make a good contribution to the generation of vertical speed for the discus.

However, if the horizontal speed of the system at the instant of landing of the left foot is small, then the thrower is left with two options, and neither one is good:

In the first option, the thrower will plant the left leg explosively on the ground. This will make the system gain a large amount of vertical speed, which will contribute to the generation of vertical speed for the discus. But it will also make the system lose a large amount of the small horizontal speed that it had initially. This will leave the system with a very small amount of horizontal speed, which will then make only a very limited contribution to the horizontal speed of the discus.

In the second option, the thrower will plant the left leg weakly on the ground. This will allow the system to conserve much of its horizontal speed, which will then make a good contribution to the horizontal speed of the discus. But the system will not gain much vertical speed, and therefore the vertical speed of the system will make only a very limited contribution to the vertical speed of the discus.

This is why the system should have a large horizontal speed at the instant that the left foot is planted on the ground to start the double-support delivery phase.

Relationships between the speed of the system c.m., the speed of the discus relative to the system c.m., and the speed of the discus relative to the ground

While the c.m. of the thrower-plus-discus system translates forward across the throwing circle, the discus rotates counterclockwise around it. The combination of the horizontal translation of the system c.m. with the rotation of the discus produces a fluctuation in the speed of the discus with respect to the ground.

To understand how this happens, we should consider a hypothetical thrower-plus-discus system that is traveling forward across the throwing circle at a constant speed of 2 m/s relative to the ground (Figure 13). Let's assume that the counterclockwise rotation of the discus around the system c.m. gives this discus a constant speed of 8 m/s relative to the

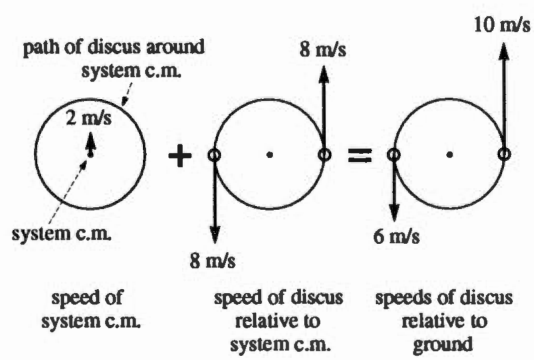

Figure 13

system c.m. When the discus is on the right side of the system c.m., the discus is moving in the same direction as the system c.m. Therefore their speeds add up to produce a discus speed of (8+2=) 10 m/s relative to the ground. However, when the discus is on the left side, the discus and the system c.m. are moving in opposite directions. Therefore, their speeds subtract from each other to produce a discus speed of (8-2=) 6 m/s relative to the ground. Because of this, the combination of the forward motion of the system c.m. with the counterclockwise rotation of the discus around it results in fluctuations in the speed of the discus relative to the ground, with local maximum speed values when the discus is on the right side, and local minimum values when it is on the left side.

At the instant of release, the discus is on the right side, and that is how the forward speed of the system c.m. contributes to increase the speed of the discus relative to the ground. This is something that has already been discussed in previous parts of the report.

But what we are concerned with at this point is the confusion that these fluctuations in the speed of the discus relative to the ground can produce in the interpretation of the mechanics of the throw. The *effort* that the thrower makes to increase the speed of the discus is related to the changes in the speed of the discus *relative to the system c.m.*, and not to the changes that may occur to the speed of the discus relative to the ground. This means that, to produce the hypothetical motion shown in Figure 13, the thrower does not need to make any forces on the discus to speed it up and later to slow it down. The thrower simply needs to "hang on" to the discus to keep it in a circular path around the system c.m., but no effort is required to speed it up nor to slow it down, even though in relation to the ground the discus ***is*** speeding up and later slowing down in alternation. The thrower is doing nothing to speed up nor to slow down the speed of the discus. The alternating speeding up and slowing down occur *"automatically"* because of the fact that the system c.m. is traveling forward and the discus is rotating around it; this requires no effort on the part of the thrower.

The plain curve (without circles) in the graph on the left side of Figure 14 —"discus(abs)"— shows the absolute speed of the discus with respect to the ground in a typical throw. There is a local maximum value roughly at the time that the left foot left the ground (LTO), followed by a "valley" with smaller speed values, before the final very large increase between the instant of landing of the left foot (LTD) and the release of the discus (REL). This pattern has been observed previously by other researchers.

It would be a mistake to assume that the pattern just described means that the thrower made a forward force on the discus to increase its speed prior to the takeoff of the left foot, then a backward force to slow it down, and then waited until the start of the double-support delivery phase (LTD) to make again a forward force on the discus and produce the final speed increase. The speed pattern that we have just been discussing corresponds to the speed of the discus relative to the ground. The peak that occurred in the speed pattern near LTO was due to the fact that the discus was on the right side at that time (see Figure 11, although it corresponds to a different throw), and therefore the speed of the system c.m. contributed to increase the speed of the discus *relative to the ground*; the "valley" that followed (go back again to the left part of Figure 14) was due to the fact that the discus was on the left side at that time, and therefore the speed of the system c.m. contributed to decrease the speed of the discus *relative to the ground*. These increases and decreases in the speed of the discus relative to the ground were thus the result of the forward travel of the system c.m., and not the result of any propulsive nor braking forces exerted by the thrower on the discus.

Using the computer, we can subtract the motion of the system c.m. from the motion of the discus, to reveal how the discus was moving relative to the system c.m., and the speed of this relative motion is shown by the curve marked with small circles in the left part of Figure 14 —"discus(rel)". This is the curve that shows the true action of the thrower on the discus. (Note: The small fluctuations —"bumps"— in the curves may not be real; they may be the result of small errors in the data, and the reader should ignore them. The large trends are real, and they are what we should be looking at.) This speed curve marked with the small circles shows an initial increase between the time of the most backward position of the discus (BCK) and an instant roughly around the takeoff of the right foot (RTO), followed by small increases and decreases (which may be real or not!), and a final increase which started (very roughly) around the instant in which the ***right*** foot landed on the ground. This pattern is similar in most of the analyzed throwers, and it indicates that the throwers generally started the final propulsion of the discus *clearly before the landing of the left foot*. The reason why this has remained unnoticed until now is that the discus is on the left side at the instant that the left foot is planted, so the discus and the system c.m. are moving in opposite directions at that time. This reduces the absolute speed of the discus *relative to the ground* at that time, and therefore disguises the

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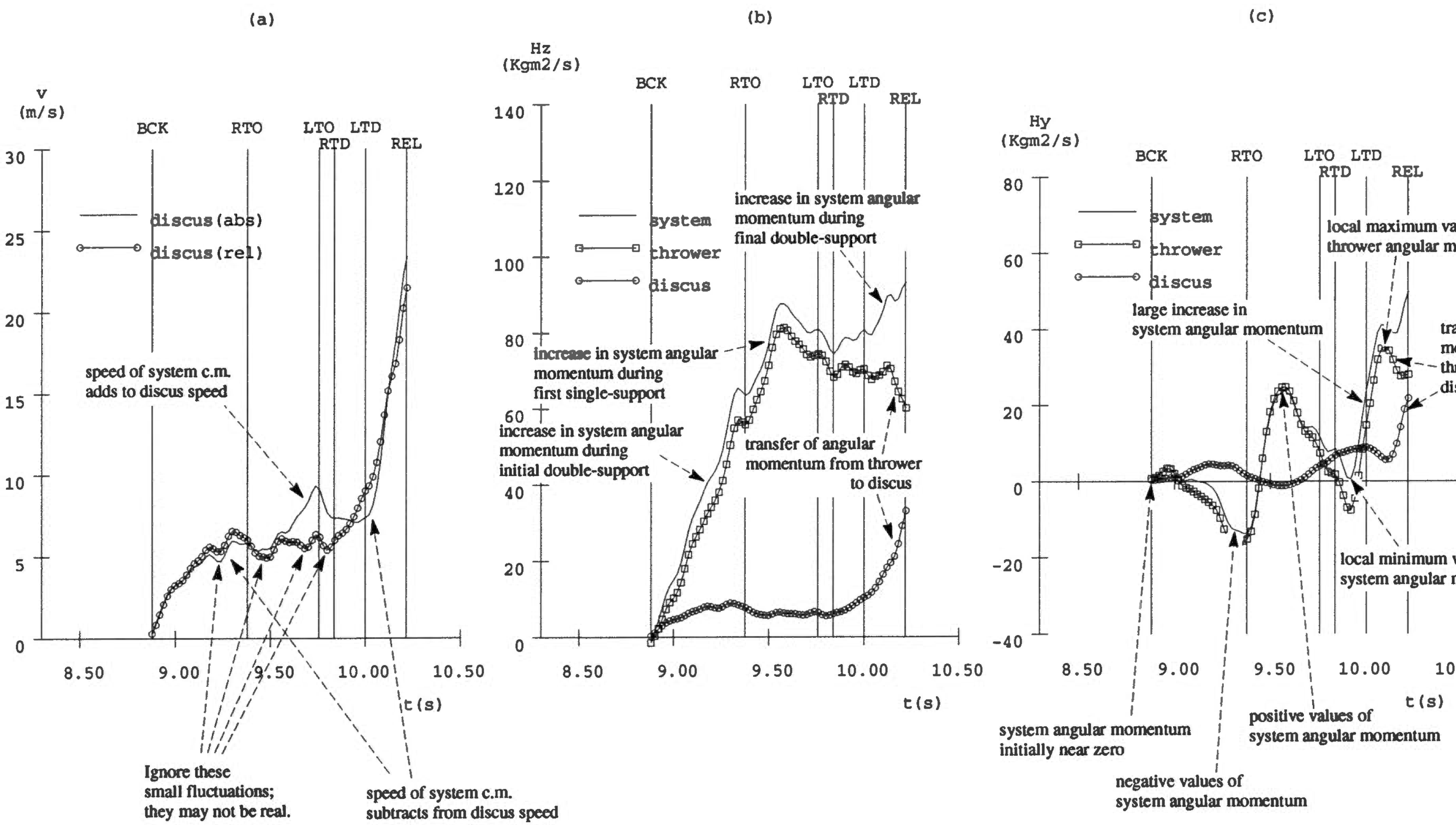

Figure 14

fact that the thrower started the final propulsion of the discus some time before that.

(Note: Due to the nature of this report, there are some oversimplifications in the above discussion which in a formal research paper would require more precise explanations. However, the fact remains that the pattern of the discus speed relative to the system c.m. is a much better indicator of the propulsive or braking forces that the thrower might be making on the discus than the absolute speed of the discus relative to the ground.)

Some practitioners believe that the main propulsion of the discus should not start until the left foot is planted on the ground, when in fact practically all the throwers start the propulsion much earlier than that. If a thrower "follows instructions" literally, and waits until the left foot is planted on the ground before starting the final propulsion of the discus, this could lead to a shortening of the effective final acceleration path of the discus, a reduction in the final speed of the discus at release, and consequently a decrease in the distance of the throw.

Z angular momentum

While 6% of the horizontal speed of the discus at release was due to the forward motion of the c.m. of the thrower-plus-discus system, the remaining 94% was the result of the horizontal motion of the discus *relative* to the system c.m., which in turn was determined by the angular momentum of the discus about the vertical axis. We will now examine how the thrower obtains this angular momentum from the ground, and how it is transmitted to the discus.

In this report, the angular momentum about the vertical axis is called the Z angular momentum, or H_Z. (Note: A capital "H" is normally used to designate angular momentum; it should not be confused with the lower case "h" used to designate heights above the ground.)

Researchers often make an adjustment of angular momentum values which takes into account the height and weight of the individual athlete. The "normalized" angular momentum values that result from the adjustment facilitate comparisons between athletes of different heights and weights. For instance, in the work that we do at our laboratory on high jumping, we don't even look at the raw (non-normalized) angular momentum values; we only deal with the normalized angular momentum.

However, in discus throwing there is a problem when we try to normalize the angular momentum: While different throwers have different heights and weights, the weight of the discus is the same for all. Because of this, *normalized* values are best for making comparisons of the angular momentum of the *body* of the thrower, but *non*-normalized values are best for making comparisons of the angular momentum of the *discus*. It is unfortunate, but we could not come up with a clean solution to this problem. Still, this was only a slight nuisance, and it did not interfere significantly with our capability to interpret the mechanics of the discus throw.

(Note: The standard units of measurement for *non*-normalized angular momentum are $Kg \cdot m^2/s$; for *normalized* angular momentum, they are $s^{-1} \cdot 10^{-3}$. The reader does not need to worry too much about the units; we mention it here because sometimes knowing which units are used for which angular momentum may help the reader to figure out if we are talking at that point about normalized or non-normalized angular momentum.)

The central graph in Figure 14 shows the Z angular momentum values of the combined thrower-plus-discus system (plain curve), of the thrower (curve with small squares) and of the discus (curve with small circles) in the course of a typical throw. (The values shown in this graph are non-normalized.)

Tables 5, 6 and 7 show numerical values for the Z angular momentum of the system, of the thrower and of the discus, respectively, at the time that the discus reached the most backward point in the preliminary swing (BCK), at the takeoff of the right foot (RTO), at the takeoff of the left foot (LTO), at the landing of the right foot (RTD), at the landing of the left foot (LTD), and at release (REL). There are three groups of columns in each table. The left group shows non-normalized angular momentum; the middle group, normalized angular momentum; the right group expresses all values as a percent of the Z angular momentum of the combined thrower-plus-discus system at release.

The central graph in Figure 14 shows typical patterns. The Z angular momentum of the system experienced a very large increase during the initial double-support phase. By the time that the right foot took off from the ground, the Z angular momentum of the system already had 78 ± 10% of the value that it would eventually have at release (see Table 5). It continued to increase during part of the single-support on the left foot. Then, there was usually a decrease before the left foot took off from the ground. Still, in the course of the entire single-support phase on the left foot there was a net increase in the Z angular momentum of the system. At the instant of takeoff of the left foot, its value was 90 ± 10% of what it would be at release. During the non-support phase, the angular momentum of the system remained constant. (This is dictated by the laws of mechanics.

Table 5

Z angular momentum of system

Z angular momentum of the thrower-plus-discus system (H_{zs}) at the time that the discus reached the most backward point in the last preliminary swing (BCK), at the takeoff of the right foot (RTO), at the takeoff of the left foot (LTO), at the landing of the right foot (RTD), at the landing of the left foot (LTD), and at release (REL). It is expressed non-normalized ($Kg \cdot m^2/s$), normalized ($s^{-1} \cdot 10^{-3}$), and as a percent of the Z angular momentum of the system at release (%). Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	H_{zs} (non-normalized) ($Kg \cdot m^2/s$)						H_{zs} (normalized) ($s^{-1} \cdot 10^{-3}$)						H_{zs} (percent of H_{zsREL}) (%)					
		BCK	RTO	LTO	RTD	LTD	REL	BCK	RTO	LTO	RTD	LTD	REL	BCK	RTO	LTO	RTD	LTD	REL
Bloom	41 D96	0.3	55.6	68.3	68.3	73.5	101.0	1	134	165	165	177	244	0	55	68	68	73	100
Dumble	23 D96	-1.4	68.6	82.9	82.9	84.5	90.3	-4	177	214	214	219	234	-2	76	92	92	94	100
Fitzpatrick	40 U94	-6.9	69.5	84.5	84.5	84.6	97.4	-16	160	194	194	194	224	-7	71	87	87	87	100
Fitzpatrick	*62 D96*	*-0.9*	*65.7*	*78.4*	*78.4*	*75.4*	*89.1*	*-2*	*160*	*192*	*192*	*184*	*218*	*-1*	*74*	*88*	*88*	*85*	*100*
Godina	28 U94	-1.9	74.1	94.8	94.8	87.1	85.4	-4	169	217	217	199	195	-2	87	111	111	102	100
Gravelle	22 U94	2.4	78.0	84.6	84.6	80.7	91.2	5	175	190	190	181	205	3	85	93	93	88	100
Hart	57 D96	1.1	71.3	76.9	76.9	80.6	91.0	3	172	186	186	195	220	1	78	85	85	89	100
Haynes	24 D96	-0.9	74.4	89.2	89.2	90.2	89.4	-2	182	218	218	221	219	-1	83	100	100	101	100
Heisler	36 U94	-2.2	73.7	79.4	79.4	83.3	91.3	-5	179	193	193	202	221	-2	81	87	87	91	100
Johnson	10 D96	0.4	64.2	70.0	70.0	74.3	92.2	1	154	168	168	178	221	0	70	76	76	81	100
Kirchhoff	34 D96	-1.6	74.3	79.5	79.5	82.9	95.1	-4	167	179	179	187	214	-2	78	84	84	87	100
McPherran	08 D96	-7.1	56.0	74.6	74.6	76.0	91.3	-15	117	156	156	159	191	-8	61	82	82	83	100
Mielke	22 D96	-1.5	75.4	83.6	83.6	87.2	75.9	-4	178	198	198	206	179	-2	99	110	110	115	100
Muse	47 D96	-0.5	87.4	78.1	78.1	77.6	100.0	-1	203	182	182	180	233	-1	87	78	78	78	100
Nuti	15 D96	-1.7	66.0	70.3	70.3	71.7	81.1	-4	160	170	170	174	196	-2	81	87	87	88	100
Patera	01 U94	2.0	63.2	76.7	76.7	80.6	81.1	5	157	191	191	201	202	2	78	95	95	99	100
Presser	09 D96	1.9	77.6	92.9	92.9	89.5	95.3	4	172	206	206	199	212	2	81	97	97	94	100
Schulte	59 D96	-2.2	87.4	86.9	86.9	86.9	101.4	-4	164	163	163	163	190	-2	86	86	86	86	100
Scott	41 U94	-3.7	104.9	122.9	122.9	114.0	119.4	-6	156	182	182	169	177	-3	88	103	103	95	100
Setliff	*27 U94*	*-4.7*	*76.2*	*83.3*	*83.3*	*79.0*	*94.5*	*-10*	*168*	*183*	*183*	*174*	*208*	*-5*	*81*	*88*	*88*	*84*	*100*
Setliff	65 D96	-2.2	76.0	85.0	85.0	74.3	85.2	-5	167	187	187	164	187	-3	89	100	100	87	100
Staat	25 D96	-0.8	59.1	82.6	82.6	87.2	89.6	-2	119	166	166	175	180	-1	66	92	92	97	100
Sullivan	06 D96	-1.2	68.2	81.2	81.2	79.8	89.7	-3	176	210	210	206	232	-1	76	90	90	89	100
Tveitaa	39 D96	2.2	57.1	70.6	70.6	78.3	84.0	6	146	181	181	200	215	3	68	84	84	93	100
Washington	66 D96	-0.5	70.5	79.3	79.3	85.8	91.0	-1	187	210	210	227	241	-1	77	87	87	94	100
Wirtz	42 D96	-1.1	63.6	78.0	78.0	80.8	93.2	-3	168	206	206	213	246	-1	68	84	84	87	100
Mean		-1.1	71.5	82.2	82.2	83.0	91.8	-2	164	189	189	191	212	-1	78	90	90	91	100
S.D.		±2.4	±10.9	±10.8	±10.8	±8.3	±8.4	±5	±19	±18	±18	±19	±21	±3	±10	±10	±10	±8	±0

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

Table 6

Z angular momentum of thrower

Z angular momentum of the thrower (H_{ZT}) at the time that the discus reached the most backward point in the last preliminary swing (BCK), at the takeoff of the right foot (RTO), at the takeoff of the left foot (LTO), at the landing of the right foot (RTD), at the landing of the left foot (LTD), and at release (REL). It is expressed non-normalized (Kg· m²/s), normalized ($s^{-1}\cdot 10^{-3}$), and as a percent of the Z angular momentum of the system at release (%). Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	H_{ZT} (non-normalized) (Kg· m²/s)						H_{ZT} (normalized) ($s^{-1}\cdot 10^{-3}$)						H_{ZT} (percent of H_{ZSREL}) (%)					
		BCK	RTO	LTO	RTD	LTD	REL	BCK	RTO	LTO	RTD	LTD	REL	BCK	RTO	LTO	RTD	LTD	REL
Bloom	41 D96	0.6	50.6	62.4	62.9	65.3	69.1	2	122	151	152	158	167	1	50	62	62	65	68
Dumble	23 D96	-1.5	60.4	74.3	73.7	72.9	60.5	-4	156	192	190	189	156	-2	67	82	82	81	67
Fitzpatrick	40 U94	-6.3	61.3	77.2	77.1	70.4	65.7	-14	141	177	177	162	151	-6	63	79	79	72	67
Fitzpatrick	*62 D96*	*-0.8*	*56.6*	*70.3*	*69.4*	*62.3*	*59.4*	*-2*	*138*	*172*	*170*	*152*	*145*	*-1*	*64*	*79*	*78*	*70*	*67*
Godina	28 U94	-1.9	66.3	88.8	86.5	73.9	54.4	-4	152	203	198	169	124	-2	78	104	101	87	64
Gravelle	22 U94	2.5	73.8	79.9	79.3	66.6	58.3	6	166	179	178	149	131	3	81	88	87	73	64
Hart	57 D96	0.9	64.4	69.9	70.5	68.3	59.7	2	156	169	170	165	144	1	71	77	77	75	66
Haynes	24 D96	-0.8	67.4	82.9	82.7	79.4	59.2	-2	165	203	202	194	145	-1	75	93	93	89	66
Heisler	36 U94	-1.9	66.9	71.3	70.5	71.5	59.1	-5	162	173	171	173	143	-2	73	78	77	78	65
Johnson	10 D96	0.2	56.8	63.2	61.8	61.4	58.2	1	136	151	148	147	139	0	62	69	67	67	63
Kirchhoff	34 D96	-1.6	64.8	73.3	71.5	73.2	62.4	-4	146	165	161	165	140	-2	68	77	75	77	66
McPherran	08 D96	-6.8	51.2	69.5	68.8	65.9	60.5	-14	107	145	144	138	127	-7	56	76	75	72	66
Mielke	22 D96	-1.6	68.6	77.7	77.2	74.8	44.5	-4	162	184	182	177	105	-2	90	102	102	99	59
Muse	47 D96	-0.8	81.9	71.8	72.5	70.0	66.7	-2	190	167	169	163	155	-1	82	72	72	70	67
Nuti	15 D96	-1.5	59.0	64.1	63.9	62.5	49.7	-4	143	155	154	151	120	-2	73	79	79	77	61
Patera	01 U94	1.9	57.2	71.0	69.9	70.3	50.3	5	142	177	174	175	125	2	70	88	86	87	62
Presser	09 D96	2.0	71.1	84.0	84.2	77.3	59.4	5	158	187	187	172	132	2	75	88	88	81	62
Schulte	59 D96	-2.4	81.0	79.3	79.5	76.9	69.9	-4	152	149	149	144	131	-2	80	78	78	76	69
Scott	41 U94	-3.5	99.3	118.7	117.0	104.4	84.1	-5	147	176	174	155	125	-3	83	99	98	87	70
Setliff	*27 U94*	*-4.1*	*67.2*	*76.1*	*75.9*	*64.8*	*64.5*	*-9*	*148*	*168*	*167*	*143*	*142*	*-4*	*71*	*81*	*80*	*69*	*68*
Setliff	65 D96	-2.1	67.2	78.6	78.9	61.1	55.4	-5	148	173	174	134	122	-2	79	92	93	72	65
Staat	25 D96	-0.8	54.6	76.7	75.9	77.0	60.1	-2	110	154	152	155	121	-1	61	86	85	86	67
Sullivan	06 D96	-1.1	61.1	74.5	74.0	69.0	57.6	-3	158	193	191	178	149	-1	68	83	82	77	64
Tveitaa	39 D96	1.8	52.7	65.8	63.8	67.7	56.6	5	135	168	163	173	145	2	63	78	76	81	67
Washington	66 D96	-0.7	65.1	71.6	71.3	74.7	58.3	-2	173	190	189	198	155	-1	72	79	78	82	64
Wirtz	42 D96	-1.4	55.9	71.8	71.7	70.4	60.1	-4	148	190	189	186	159	-2	60	77	77	76	64
Mean		-1.1	64.9	75.8	75.2	71.9	60.0	-2	149	174	172	165	138	-1	71	83	82	79	65
S.D.		±2.2	±10.8	±11.0	±10.8	±8.4	±7.5	±5	±18	±17	±16	±17	±15	±2	±9	±10	±10	±8	±3

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

Table 7

Z angular momentum of discus

Z angular momentum of the discus (H_{ZD}) at the time that the discus reached the most backward point in the last preliminary swing (BCK), at the takeoff of the right foot (RTO), at the takeoff of the left foot (LTO), at the landing of the right foot (RTD), at the landing of the left foot (LTD), and at release (REL). It is expressed non-normalized (Kg· m²/s), normalized ($s^{1} \cdot 10^{-3}$), and as a percent of the Z angular momentum of the system at release (%). Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	H_{ZD} (non-normalized) (Kg· m²/s)						H_{ZD} (normalized) ($s^{1} \cdot 10^{-3}$)						H_{ZD} (percent of H_{ZSREL}) (%)					
		BCK	RTO	LTO	RTD	LTD	REL	BCK	RTO	LTO	RTD	LTD	REL	BCK	RTO	LTO	RTD	LTD	REL
Bloom	41 D96	-0.4	4.9	5.9	5.4	8.2	31.9	-1	12	14	13	20	77	0	5	6	5	8	32
Dumble	23 D96	0.0	8.2	8.6	9.2	11.6	29.8	0	21	22	24	30	77	0	9	9	10	13	33
Fitzpatrick	40 U94	-0.6	8.1	7.3	7.4	14.2	31.7	-1	19	17	17	33	73	-1	8	7	8	15	33
Fitzpatrick	*62 D96*	*-0.1*	*9.0*	*8.2*	*9.0*	*13.1*	*29.7*	*0*	*22*	*20*	*22*	*32*	*73*	*0*	*10*	*9*	*10*	*15*	*33*
Godina	28 U94	0.0	7.7	6.1	8.3	13.1	31.1	0	18	14	19	30	71	0	9	7	10	15	36
Gravelle	22 U94	-0.2	4.1	4.7	5.3	14.2	32.9	0	9	10	12	32	74	0	5	5	6	16	36
Hart	57 D96	0.2	6.9	7.0	6.5	12.2	31.3	0	17	17	16	30	76	0	8	8	7	13	34
Haynes	24 D96	-0.1	7.0	6.3	6.5	10.8	30.2	0	17	15	16	26	74	0	8	7	7	12	34
Heisler	36 U94	-0.3	6.9	8.0	8.9	11.7	32.2	-1	17	19	22	28	78	0	8	9	10	13	35
Johnson	10 D96	0.1	7.4	6.8	8.3	12.9	34.0	0	18	16	20	31	82	0	8	7	9	14	37
Kirchhoff	34 D96	0.1	9.5	6.2	8.0	9.7	32.7	0	21	14	18	22	74	0	10	7	8	10	34
McPherran	08 D96	-0.3	4.8	5.1	5.8	10.1	30.8	-1	10	11	12	21	64	0	5	6	6	11	34
Mielke	22 D96	0.0	6.8	5.9	6.4	12.3	31.3	0	16	14	15	29	74	0	9	8	8	16	41
Muse	47 D96	0.3	5.5	6.3	5.6	7.6	33.3	1	13	15	13	18	77	0	6	6	6	8	33
Nuti	15 D96	-0.3	7.0	6.2	6.4	9.2	31.4	-1	17	15	16	22	76	0	9	8	8	11	39
Patera	01 U94	0.1	6.0	5.7	6.8	10.4	30.8	0	15	14	17	26	77	0	7	7	8	13	38
Presser	09 D96	-0.1	6.5	8.9	8.7	12.2	35.9	0	15	20	19	27	80	0	7	9	9	13	38
Schulte	59 D96	0.2	6.4	7.7	7.5	10.0	31.5	0	12	14	14	19	59	0	6	8	7	10	31
Scott	41 U94	-0.2	5.6	4.2	5.9	9.5	35.3	0	8	6	9	14	52	0	5	4	5	8	30
Setliff	*27 U94*	*-0.6*	*9.0*	*7.1*	*7.4*	*14.2*	*30.0*	*-1*	*20*	*16*	*16*	*31*	*66*	*-1*	*10*	*8*	*8*	*15*	*32*
Setliff	65 D96	-0.1	8.8	6.4	6.1	13.3	29.8	0	19	14	13	29	65	0	10	8	7	16	35
Staat	25 D96	0.0	4.5	5.9	6.7	10.2	29.5	0	9	12	14	20	59	0	5	7	8	11	33
Sullivan	06 D96	-0.1	7.1	6.7	7.2	10.8	32.2	0	18	17	19	28	83	0	8	7	8	12	36
Tveitaa	39 D96	0.4	4.4	4.8	6.8	10.6	27.5	1	11	12	17	27	70	0	5	6	8	13	33
Washington	66 D96	0.2	5.3	7.6	8.0	11.1	32.7	1	14	20	21	29	87	0	6	8	9	12	36
Wirtz	42 D96	0.3	7.7	6.3	6.4	10.3	33.1	1	20	17	17	27	87	0	8	7	7	11	36
Mean		0.0	6.5	6.4	7.0	11.1	31.8	0	15	15	16	26	74	0	7	7	8	12	35
S.D.		±0.2	±1.4	±1.1	±1.1	±1.7	±1.8	±1	±4	±3	±3	±5	±8	±0	±2	±1	±1	±2	±3

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

Any change visible in the graph of Figure 14 during this phase for the system angular momentum is the result of measurement error. In Table 5, we assigned the *average* value of the system angular momentum during the airborne phase both to the instant of left foot takeoff and to the instant of right foot landing. That was our best estimate of its true value.) During the single-support on the right foot there was, on the average, little change in the Z angular momentum of the system, although this varied quite a bit among different throwers. The average change was 1 ± 5%. At the instant that the left foot landed to start the double-support delivery, the value of the Z angular momentum of the system was 91 ± 8% of the release value. During the double-support delivery there was usually an increase in the Z angular momentum of the system (9 ± 8%) to reach the full value of 100% at release. These results confirmed our previous finding that most of the Z angular momentum of the system (90 ± 10% of the total) is produced during the double-support and single-support phases in the back of the circle. It also showed that a small (but not negligible) fraction of the total Z angular momentum of the system (10 ± 10%) was usually generated in the front of the circle, mostly during the double-support delivery.

The central graph of Figure 14 also shows that during the early and middle parts of the throw most of the Z angular momentum of the system was "stored" in the body of the thrower, and very little in the discus. The data in Tables 5-7 show that at the time that the right foot landed on the ground in the middle of the throwing circle (RTD), only about 10% of the total Z angular momentum that the system had at that time was in the discus; the rest (about 90%) was in the thrower.

Then, during the single-support on the right foot and the double-support delivery, there was a tremendous increase in the Z angular momentum of the discus. (Notice that, as we saw before for the increase in the speed of the discus relative to the system c.m., the increase in the Z angular momentum of the discus began clearly before the start of the double-support delivery phase.) The increase in the Z angular momentum of the discus was accompanied by a decrease in the Z angular momentum of the thrower, indicating a transfer of Z angular momentum from the thrower to the discus. The thrower's loss of angular momentum (from 75.2 Kg·m²/s to 60.0 Kg·m²/s, a difference of 15.2 Kg·m²/s —see Table 6) was smaller than the gain experienced by the discus (from 7.0 Kg·m²/s to 31.8 Kg·m²/s, a difference of 24.8 Kg·m²/s —see Table 7). The reason for this was that the forces received from the ground through the feet during the single-support on the right foot and the double-support delivery helped to reduce the slowing down of the counterclockwise rotation of the thrower. That was good, because the faster the body of the thrower keeps rotating, the easier it is for the thrower to keep accelerating the discus.

The angular momentum that is transmitted to the discus is angular momentum that is syphoned off from the thrower, and this tends to slow down the rotation of the thrower. As the thrower slows down, it becomes more difficult to keep transfering angular momentum to the discus, i.e., to keep accelerating the discus. Therefore, it is advantageous to reduce the thrower's loss of angular momentum. In theory, one way to achieve this would be not to transfer too much angular momentum to the discus. However, that would defeat the whole purpose of the throw! The only other way to reduce the thrower's loss of Z angular momentum is for the thrower to obtain additional counterclockwise angular momentum from the ground, to compensate for part of the angular momentum that the body of the thrower is losing to the discus. This is what the throwers in the sample tended to do. The additional angular momentum gained from the ground is what shows up as an increase in the total angular momentum of the thrower-plus-discus system.

We saw before that the system c.m. had a slightly larger vertical speed during the final part of the delivery in the airborne-release throws than in the grounded-release throws. This gave the airborne-release throws a slight advantage. But now we also need to consider the possibility that the longer time available in ground-support might allow the athletes who use grounded release to obtain an additional amount of counterclockwise Z angular momentum. If they are able to transfer some of this possible additional angular momentum to the discus, it would increase the horizontal speed of the discus, and therefore the distance of the throw. If this potential advantage of the grounded-release throwers really exists, is it large enough to compensate for the known disadvantage in the vertical direction? This is difficult to quantify, and at this point we don't know if the airborne-release technique gives an overall advantage over the grounded-release technique, or vice versa.

We have seen that it is good to increase the Z angular momentum of the system during the double-support delivery, because this makes it easier for the thrower to keep transfering Z angular momentum (and horizontal speed) to the discus. However, if a thrower gains a very large amount of Z angular momentum for the system during the double-support delivery, this could be a sign that not enough was obtained at the back of the circle. As explained previously, if the Z angular momentum of the system is somewhat small at the instant that the left foot is planted on the ground in the front part of the circle, this should not pose a significant problem, because the thrower should be able to increase the angular momentum during the double-support delivery to the maximum of which the thrower is capable. However, if the Z angular momentum of the system is smaller than a certain value at the instant that the left foot lands, the athlete will not be able to compensate for this completely during the double-support delivery: The angular momentum will only reach a sub-maximum value in comparison to what it would have reached if the athlete had been more active in the early part of the throw —remember the long jump analogy. We don't know how small the Z angular momentum of the system has to be before its small size begins to pose a problem, but the athletes who are most likely to be suffering from this problem are those who had the smallest percent amounts of Z angular momentum for the system at the instant that the left foot landed. (See the percent value of H_{ZS} at LTD for each athlete in Table 5.)

To evaluate how well an athlete transfered Z angular momentum from the body to the discus, we should look at the relative amounts of angular momentum that are in the thrower and in the discus at the instant of release. The larger the percent amount that is in the discus (H_{ZD} at release in the right group of columns of Table 7), and the less that is in the thrower (H_{ZT} at release in the right group of columns of Table 6), the better.

As we have seen, practically all throwers started the final acceleration of the discus before the left foot was planted on the ground. We assume that this is probably good. As mentioned previously, an excessive delay in the start of this final acceleration could lead to a shortening of the effective final acceleration path of the discus, a reduction in the final speed of the discus at release, and consequently a decrease in the distance of the throw. To check if a thrower might have started the acceleration of the discus too late, we can look at the percent value of the angular momentum of the discus at the time that the left foot was planted on the ground to start the double-support delivery (H_{ZD} at LTD in the right group of columns of Table 7). For a good technique, this number should not be too low.

Y angular momentum

While 10% of the vertical speed of the discus at release was due to the upward motion of the c.m. of the thrower-plus-discus system, the remaining 90% was the result of the vertical motion of the discus *relative* to the system c.m. In turn, the latter was determined primarily by the angular momentum of the discus about a horizontal axis pointing from the back of the circle toward the front of the circle (Figure 4). This is called the Y angular momentum, or H_Y. The thrower needs to obtain Y angular momentum from the ground, and then pass a good amount of it to the discus. We will now examine how the thrower obtains this angular momentum from the ground, and how it is transmitted to the discus.

The graph on the right side of Figure 14 shows the Y angular momentum values of the combined thrower-plus-discus system (plain curve), of the thrower (curve with small squares) and of the discus (curve with small circles) in the course of a typical throw. The values shown in this graph are non-normalized. Positive values imply counterclockwise rotation in the view from the back of the circle.

In all throwers, the Y angular momentum of the system (the plain curve in the graph on the right side of Figure 14) started near zero at the instant that the discus was at its most backward position. Then it generally followed a wavy pattern in which it acquired negative values and subsequently positive values before returning to a local minimum value near zero at an instant within the single-support phase on the right foot (i.e., between RTD and LTD). In this report, we will not be very concerned with what happened to the Y angular momentum during the early part of the throw; we will concentrate our analysis on the changes that occurred in the Y angular momentum after the instant when the system angular momentum reached its local minimum value during the single-support on the right foot.

In all throws, the Y angular momentum of the system increased quite a bit after the local minimum. (See the graph on the right side of Figure 14.) During the early double-support, most of the Y angular momentum of the system was stored in the body of the thrower; the discus only had a small fraction of it. The Y angular momentum in the body of the thrower reached a local maximum value roughly about half-way into the double-support delivery, and then decreased. This decrease in the Y angular momentum of the thrower was accompanied by an increase in the Y angular momentum of the discus. This implies that there was a transfer of Y angular momentum from the thrower to the discus during the second half of the delivery phase.

Tables 8, 9 and 10 show numerical values for the Y angular momentum of the system, of the thrower and of the discus, respectively, at the time that the Y

Table 8

Y angular momentum of system

Y angular momentum of the thrower-plus-discus system (H_{YS}) at the instant that the Y angular momentum of the system reached its local minimum value during the single-support on the right foot (RS), at the landing of the left foot (LTD), at the time that the Y angular momentum of the thrower reached its local maximum value during the double-support (DS), and at release (REL). It is expressed non-normalized (Kg· m²/s), normalized ($s^{-1}\cdot10^{-3}$), and as a percent of the Y angular momentum of the system at release (%). Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	H_{YS} (non-normalized) (Kg· m²/s)				H_{YS} (normalized) ($s^{-1}\cdot10^{-3}$)				H_{YS} (percent of H_{YSREL}) (%)			
		RS	LTD	DS	REL	RS	LTD	DS	REL	RS	LTD	DS	REL
Bloom	41 D96	-0.2	3.8	45.2	51.4	-1	9	109	124	0	7	88	100
Dumble	23 D96	4.6	15.5	46.4	50.1	12	40	120	130	9	31	93	100
Fitzpatrick	40 U94	5.4	29.4	49.5	51.1	12	68	114	117	11	58	97	100
Fitzpatrick	*62 D96*	*3.9*	*28.0*	*33.4*	*39.9*	*10*	*68*	*82*	*98*	*10*	*70*	*84*	*100*
Godina	28 U94	18.1	47.7	54.6	58.3	41	109	125	133	31	82	94	100
Gravelle	22 U94	11.0	37.8	40.6	61.2	25	85	91	137	18	62	66	100
Hart	57 D96	-0.1	34.6	41.5	51.5	0	84	100	124	0	67	81	100
Haynes	24 D96	9.2	20.6	39.3	40.4	23	50	96	99	23	51	97	100
Heisler	36 U94	-1.6	20.5	46.7	50.6	-4	50	113	123	-3	40	92	100
Johnson	10 D96	1.2	31.4	46.1	60.0	3	75	110	144	2	52	77	100
Kirchhoff	34 D96	-0.7	19.8	43.3	44.3	-2	45	97	100	-2	45	98	100
McPherran	08 D96	14.5	39.5	51.7	58.4	30	83	108	122	25	68	88	100
Mielke	22 D96	6.8	43.7	50.2	63.1	16	103	119	149	11	69	80	100
Muse	47 D96	-13.0	1.6	32.9	24.6	-30	4	77	57	-53	6	134	100
Nuti	15 D96	-5.8	14.8	33.8	49.7	-14	36	82	120	-12	30	68	100
Patera	01 U94	1.4	14.2	41.3	42.5	3	35	103	106	3	33	97	100
Presser	09 D96	-4.5	-0.2	38.7	38.4	-10	0	86	85	-12	-1	101	100
Schulte	59 D96	-2.1	17.9	35.1	28.0	-4	33	66	53	-7	64	125	100
Scott	41 U94	-8.4	14.8	59.5	59.5	-13	22	88	88	-14	25	100	100
Setliff	*27 U94*	*8.7*	*43.6*	*46.8*	*35.0*	*19*	*96*	*103*	*77*	*25*	*125*	*134*	*100*
Setliff	65 D96	2.0	30.8	41.1	36.1	4	68	91	79	6	85	114	100
Staat	25 D96	-6.1	12.6	40.5	53.8	-12	25	81	108	-11	23	75	100
Sullivan	06 D96	1.9	23.6	41.9	43.7	5	61	108	113	4	54	96	100
Tveitaa	39 D96	-4.3	12.1	38.2	32.9	-11	31	98	84	-13	37	116	100
Washington	66 D96	-2.2	11.0	38.4	45.5	-6	29	102	121	-5	24	84	100
Wirtz	42 D96	0.6	23.6	40.9	49.2	2	62	108	130	1	48	83	100
Mean		1.2	21.7	43.2	47.7	3	50	100	110	1	44	94	100
S.D.		±7.0	±12.7	±6.3	±10.2	±16	±29	±14	±25	±16	±23	±16	±0

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

Table 9

Y angular momentum of thrower

Y angular momentum of the thrower (H_{YT}) at the instant that the Y angular momentum of the system reached its local minimum value during the single-support on the right foot (RS), at the landing of the left foot (LTD), at the time that the Y angular momentum of the thrower reached its local maximum value during the double-support (DS), and at release (REL). It is expressed non-normalized (Kg·m²/s), normalized ($s^{-1}\cdot10^{-3}$), and as a percent of the Y angular momentum of the system at release (%). Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	H_{YT} (non-normalized) (Kg·m²/s)				H_{YT} (normalized) ($s^{1}\cdot10^{-3}$)				H_{YT} (percent of H_{YSREL}) (%)			
		RS	LTD	DS	REL	RS	LTD	DS	REL	RS	LTD	DS	REL
Bloom	41 D96	-5.2	-1.8	42.4	37.6	-13	-4	102	91	-10	-3	83	73
Dumble	23 D96	-4.8	9.1	42.1	30.0	-12	23	109	78	-10	18	84	60
Fitzpatrick	40 U94	-1.3	21.6	44.4	27.8	-3	50	102	64	-3	42	87	54
Fitzpatrick	*62 D96*	*-3.5*	*17.5*	*27.4*	*18.1*	*-8*	*43*	*67*	*44*	*-9*	*44*	*69*	*45*
Godina	28 U94	8.8	38.7	47.2	33.3	20	88	108	76	15	66	81	57
Gravelle	22 U94	3.8	31.8	35.8	38.1	9	71	80	85	6	52	59	62
Hart	57 D96	-6.6	29.6	38.2	34.3	-16	71	92	83	-13	57	74	67
Haynes	24 D96	0.7	13.6	35.5	24.0	2	33	87	59	2	34	88	59
Heisler	36 U94	-9.3	13.7	44.8	30.5	-23	33	109	74	-18	27	89	60
Johnson	10 D96	-5.2	23.5	40.5	39.8	-12	56	97	95	-9	39	68	66
Kirchhoff	34 D96	-6.1	13.0	37.5	28.8	-14	29	84	65	-14	29	85	65
McPherran	08 D96	3.6	29.7	48.5	37.7	8	62	101	79	6	51	83	64
Mielke	22 D96	2.2	37.6	44.6	40.0	5	89	106	95	3	60	71	63
Muse	47 D96	-14.2	-0.3	32.5	11.5	-33	-1	75	27	-57	-1	132	47
Nuti	15 D96	-9.7	7.7	29.0	31.2	-23	19	70	76	-20	16	58	63
Patera	01 U94	-8.0	5.4	37.3	20.7	-20	13	93	51	-19	13	88	49
Presser	09 D96	-10.1	-5.4	33.1	19.2	-23	-12	74	43	-26	-14	86	50
Schulte	59 D96	-7.3	11.4	30.2	9.8	-14	21	57	18	-26	41	108	35
Scott	41 U94	-12.4	10.8	55.3	36.1	-18	16	82	54	-21	18	93	61
Setliff	*27 U94*	*3.1*	*38.5*	*43.0*	*16.6*	*7*	*85*	*95*	*36*	*9*	*110*	*123*	*47*
Setliff	65 D96	-2.4	25.0	36.9	19.5	-5	55	81	43	-7	69	102	54
Staat	25 D96	-11.4	6.0	34.4	31.8	-23	12	69	64	-21	11	64	59
Sullivan	06 D96	-7.2	15.2	37.6	20.2	-19	39	97	52	-16	35	86	46
Tveitaa	39 D96	-8.6	6.1	32.2	14.2	-22	16	82	36	-26	19	98	43
Washington	66 D96	-5.2	6.7	33.0	23.5	-14	18	87	62	-11	15	72	52
Wirtz	42 D96	-7.6	14.7	35.3	28.0	-20	39	93	74	-15	30	72	57
Mean		-5.1	15.1	38.7	27.8	-12	35	89	64	-13	30	84	57
S.D.		±5.5	±11.9	±6.3	±8.7	±12	±27	±14	±20	±14	±22	±16	±9

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

Table 10

Y angular momentum of discus

Y angular momentum of the discus (H_{YD}) at the instant that the Y angular momentum of the system reached its local minimum value during the single-support on the right foot (RS), at the landing of the left foot (LTD), at the time that the Y angular momentum of the thrower reached its local maximum value during the double-support (DS), and at release (REL). It is expressed non-normalized (Kg· m²/s), normalized ($s^{-1} \cdot 10^{-3}$), and as a percent of the Y angular momentum of the system at release (%). Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	H_{YD} (non-normalized) (Kg· m²/s)				H_{YD} (normalized) ($s^{-1} \cdot 10^{-3}$)				H_{YD} (percent of H_{YSREL}) (%)			
		RS	LTD	DS	REL	RS	LTD	DS	REL	RS	LTD	DS	REL
Bloom	41 D96	5.0	5.6	2.8	13.7	12	14	7	33	10	11	5	27
Dumble	23 D96	9.4	6.4	4.3	20.1	24	17	11	52	19	13	9	40
Fitzpatrick	40 U94	6.7	7.8	5.1	23.3	15	18	12	54	13	15	10	46
Fitzpatrick	*62 D96*	*7.4*	*10.5*	*5.9*	*21.9*	*18*	*26*	*15*	*53*	*18*	*26*	*15*	*55*
Godina	28 U94	9.4	9.0	7.4	25.0	21	21	17	57	16	16	13	43
Gravelle	22 U94	7.2	6.1	4.8	23.1	16	14	11	52	12	10	8	38
Hart	57 D96	6.5	5.0	3.4	17.2	16	12	8	42	13	10	7	33
Haynes	24 D96	8.5	7.0	3.8	16.4	21	17	9	40	21	17	9	41
Heisler	36 U94	7.7	6.8	1.9	20.1	19	16	5	49	15	13	4	40
Johnson	10 D96	6.4	7.9	5.6	20.2	15	19	13	48	11	13	9	34
Kirchhoff	34 D96	5.4	6.8	5.8	15.6	12	15	13	35	12	15	13	35
McPherran	08 D96	10.9	9.8	3.2	20.8	23	20	7	43	19	17	5	36
Mielke	22 D96	4.6	6.1	5.6	23.1	11	14	13	54	7	10	9	37
Muse	47 D96	1.2	1.9	0.5	13.1	3	4	1	31	5	8	2	53
Nuti	15 D96	3.9	7.0	4.8	18.4	10	17	12	45	8	14	10	37
Patera	01 U94	9.3	8.8	4.0	21.8	23	22	10	54	22	21	10	51
Presser	09 D96	5.6	5.2	5.5	19.2	12	12	12	43	15	14	14	50
Schulte	59 D96	5.2	6.5	4.9	18.2	10	12	9	34	19	23	17	65
Scott	41 U94	4.0	4.0	4.2	23.3	6	6	6	35	7	7	7	39
Setliff	*27 U94*	*5.6*	*5.1*	*3.8*	*18.4*	*12*	*11*	*8*	*41*	*16*	*15*	*11*	*53*
Setliff	65 D96	4.4	5.9	4.3	16.5	10	13	9	36	12	16	12	46
Staat	25 D96	5.3	6.6	6.1	21.9	11	13	12	44	10	12	11	41
Sullivan	06 D96	9.1	8.4	4.3	23.5	23	22	11	61	21	19	10	54
Tveitaa	39 D96	4.3	6.0	6.1	18.8	11	15	16	48	13	18	18	57
Washington	66 D96	3.0	4.3	5.4	21.9	8	11	14	58	7	9	12	48
Wirtz	42 D96	8.2	8.9	5.6	21.2	22	24	15	56	17	18	11	43
Mean		6.3	6.6	4.6	19.9	15	15	11	46	14	14	10	43
S.D.		±2.3	±1.8	±1.5	±3.1	±6	±5	±4	±9	±5	±4	±4	±9

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

angular momentum of the system reached its local minimum value during the single-support on the right foot (RS), at the landing of the left foot (LTD), at the time that the Y angular momentum of the thrower reached its local maximum value during the double-support (DS), and at release (REL). As in Tables 5, 6 and 7, there are three groups of columns in each table. The left group shows non-normalized angular momentum; the middle group, normalized angular momentum; the right group expresses all values as a percent of the Y angular momentum of the combined thrower-plus-discus system at release.

The ideal is to obtain from the ground the largest possible amount of Y angular momentum during the single-support on the right foot and the double-support delivery, and then pass as much as possible of it from the thrower to the discus during the second half of the double-support phase. This is what produces most of the vertical speed of the discus at release.

Propulsive swinging drives of the right leg and of the left arm in the back of the circle

After the right foot takes off from the ground in the back of the circle, the right leg should make a wide counterclockwise rotation around the body (view from overhead), and then it should be thrust very strongly toward the front of the circle. This action of the right leg facilitates the generation of Z angular momentum, because it helps the left foot to exert on the ground the forces that are necessary for generating that angular momentum.

The right leg should be thrust in a controlled way, but very fast, far from the middle of the body, and over the longest possible range of motion. The single mechanical factor that best measures this combination of features may be the "integral of the angular momentum of the right leg", which we will simply call the "right leg action", or RLA. The value of RLA is normalized for height and weight, and therefore can be compared directly across subjects.

[Note for other researchers (coaches and athletes can skip this paragraph): RLA is the time-integral of the angular momentum of the right leg about the vertical axis passing through the system c.m. between the takeoff of the right foot and the takeoff of the left foot, normalized for the subject's height and weight.]

The value of the right leg action (RLA) for each throw is shown in Table 11. The larger its value, the better. If the value of RLA was small in a particular athlete, it is advisable to find out what made it be small: Either the average angular momentum of the right leg was small, or the duration of the swing of the right leg was too short. To help us to distinguish between the two, Table 11 also shows the average normalized angular momentum of the right leg about the vertical axis passing through the system c.m. ($H_{RL\text{-}LSS}$), and the duration of the single-support on the left foot (t_{LSS}). The product of these two factors is equal to the value of RLA. By comparing their values in an individual subject with the mean of their values in all subjects, it is possible to see which of the two factors was mainly responsible for a small value of their product (RLA).

If the conclusion is that the *angular momentum* of the leg was small, this could be due in turn either to a slow speed of rotation of the leg or to a short distance between the c.m. of the leg and the c.m. of the system. Table 11 shows the average distance between the c.m. of the right leg and the vertical axis passing through the system c.m. (right leg radius during the single-support on the left foot, or $r_{RL\text{-}LSS}$). This value is expressed in meters, and also as a percent of the athlete's standing height; the latter is the value that should be used for comparisons between subjects. If the normalized angular momentum of the right leg is small in a particular athlete, we need to compare the right leg radius of the athlete with the mean value of the right leg radius in all the athletes in our sample (remember, we should compare *percent* values, not values expressed in meters). If the right leg radius of the athlete is much smaller than the mean, this would indicate that a short radius was the reason for the low angular momentum. Otherwise, the reason would be a slow speed of rotation of the leg.

The graph in the upper left part of Figure 15 shows the rotation of the c.m. of the right leg about a vertical axis passing through the c.m. of the thrower-plus-discus system between the takeoff of the right foot and the takeoff of the left foot in a typical throw. The graph shows successive positions of the c.m. of the right leg at 0.02-second intervals. The combined area of all the triangles (i.e., the area swept by the c.m. of the right leg about the c.m. of the system between the takeoff of the right foot and the takeoff of the left foot) is roughly proportional to the value of RLA. This kind of graphical information may help us to visualize better the nature of the problem if an athlete's RLA value is small.

(Note: The graphs in Figure 15 can be used to compare the areas swept by each leg in different periods of the throw, as well as in different throws. They can also be used to compare the areas swept by the left arm in different periods of the throw, as well as in different throws. However, for reasons which are too complex to explain in this report, the areas

Table 11

Propulsive swinging actions of the right leg and left arm in the back of the circle

Right leg action (RLA), average normalized angular momentum of the right leg about the vertical axis passing through the system c.m. ($H_{RL\text{-}LSS}$), time (t_{LSS}) and average right leg radius ($r_{RL\text{-}LSS}$) between the takeoff of the right foot and the takeoff of the left foot; left arm action (LAA), average normalized angular momentum of the left arm about the vertical axis passing through the system c.m. ($H_{LA\text{-}DSLSS}$), time (t_{DSLSS}), and average left arm radius ($r_{LA\text{-}DSLSS}$) between the instant when the discus reached its most backward point and the takeoff of the left foot; combined right leg and left arm action (RLLAA). The radii are expressed in meters, and also as a percent of standing height. Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	Right leg					Left arm					Both
		RLA ($Kg{\cdot}m^2{\cdot}10^{-3}$/ $Kg{\cdot}m^2$)	$H_{RL\text{-}LSS}$ ($s^{-1}{\cdot}10^{-3}$)	t_{LSS} (s)	$r_{RL\text{-}LSS}$ (m)	(%)	LAA ($Kg{\cdot}m^2{\cdot}10^{-3}$/ $Kg{\cdot}m^2$)	$H_{LA\text{-}DSLSS}$ ($s^{-1}{\cdot}10^{-3}$)	t_{DSLSS} (s)	$r_{LA\text{-}DSLSS}$ (m)	(%)	RLLAA ($Kg{\cdot}m^2{\cdot}10^{-3}$/ $Kg{\cdot}m^2$)
Bloom	41 D96	22.3	54	0.41	0.279	15.1	26.8	29	0.93	0.531	28.7	49.1
Dumble	23 D96	24.0	71	0.34	0.271	14.7	34.3	43	0.81	0.530	28.6	58.3
Fitzpatrick	40 U94	23.2	60	0.39	0.256	13.3	37.4	39	0.96	0.524	27.3	60.6
Fitzpatrick	*62 D96*	*24.3*	*65*	*0.37*	*0.270*	*14.0*	*33.2*	*36*	*0.92*	*0.535*	*27.9*	*57.5*
Godina	28 U94	21.1	59	0.36	0.259	13.6	32.3	36	0.89	0.556	29.1	53.4
Gravelle	22 U94	34.0	73	0.46	0.322	16.4	45.5	37	1.22	0.622	31.7	79.5
Hart	57 D96	23.5	65	0.36	0.267	13.8	36.2	38	0.96	0.607	31.4	59.7
Haynes	24 D96	24.5	75	0.33	0.274	15.0	36.0	38	0.95	0.556	30.4	60.5
Heisler	36 U94	15.7	49	0.32	0.215	11.2	35.0	38	0.93	0.560	29.3	50.7
Johnson	10 D96	23.0	59	0.39	0.274	14.2	36.7	34	1.09	0.567	29.4	59.7
Kirchhoff	34 D96	22.1	57	0.39	0.238	12.3	33.6	39	0.86	0.591	30.5	55.7
McPherran	08 D96	21.4	51	0.42	0.258	13.0	27.0	25	1.08	0.554	28.0	48.4
Mielke	22 D96	26.4	68	0.39	0.270	14.2	34.4	39	0.89	0.583	30.5	60.8
Muse	47 D96	24.3	72	0.34	0.264	14.3	33.4	41	0.83	0.562	30.5	57.7
Nuti	15 D96	21.5	59	0.36	0.258	13.4	26.9	30	0.90	0.559	29.0	48.4
Patera	01 U94	28.5	72	0.40	0.269	14.0	29.9	29	1.04	0.504	26.2	58.4
Presser	09 D96	27.4	75	0.36	0.297	15.1	29.7	32	0.92	0.578	29.4	57.1
Schulte	59 D96	27.9	58	0.48	0.268	13.6	35.7	33	1.08	0.599	30.3	63.6
Scott	41 U94	28.1	67	0.42	0.278	14.4	35.1	33	1.05	0.631	32.7	63.1
Setliff	*27 U94*	*29.8*	*65*	*0.46*	*0.272*	*14.1*	*38.8*	*37*	*1.05*	*0.626*	*32.5*	*68.6*
Setliff	65 D96	31.8	66	0.48	0.285	14.8	37.0	34	1.09	0.596	30.9	68.8
Staat	25 D96	23.3	57	0.41	0.262	13.2	36.1	29	1.26	0.608	30.7	59.4
Sullivan	06 D96	29.0	82	0.35	0.291	15.7	31.0	36	0.85	0.484	26.2	60.0
Tveitaa	39 D96	24.9	65	0.38	0.260	14.0	32.9	30	1.09	0.552	29.7	57.8
Washington	66 D96	20.9	66	0.32	0.265	14.3	35.0	44	0.79	0.598	32.1	56.0
Wirtz	42 D96	28.3	75	0.38	0.307	16.3	33.3	38	0.88	0.556	29.4	61.6
Mean		24.9	65	0.38	0.270	14.2	33.8	35	0.97	0.567	29.7	58.7
S.D.		±3.9	±8	±0.04	±0.021	±1.2	±4.0	±5	±0.12	±0.036	±1.6	±6.5

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

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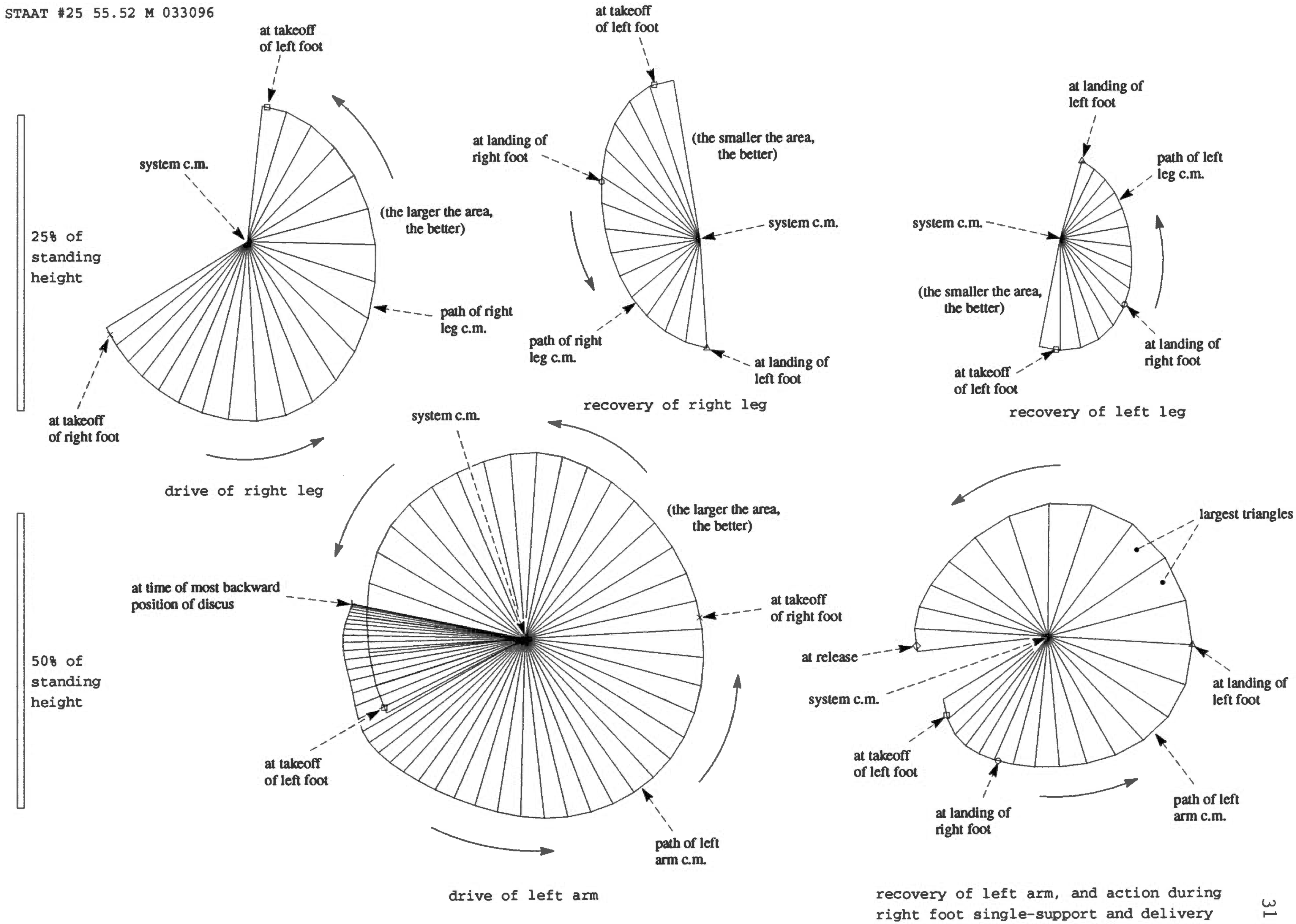

Figure 15

swept by the legs should not be compared with the areas swept by the left arm.)

The function of the left arm in the back of the circle is similar to the function of the right leg. From the instant at which the discus reaches its most backward position until the takeoff of the left foot, the left arm should make a wide counterclockwise rotation around the body (view from overhead). This facilitates the generation of Z angular momentum, following the same mechanism as the action of the right leg.

The left arm should be thrust in a controlled way, but at a high speed, far from the middle of the body, and over the longest possible range of motion. The single mechanical factor that best measures this combination of features may be the "integral of the angular momentum of the left arm", which we will simply call the "left arm action", or LAA. The value of LAA is normalized for height and weight, and therefore can be compared directly across subjects.

[Note for other researchers (coaches and athletes can skip this paragraph): LAA is the time-integral of the angular momentum of the left arm about the vertical axis passing through the system c.m. between the instant when the discus reaches its most backward position and the takeoff of the left foot, normalized for the subject's height and weight.]

The value of the left arm action (LAA) for each throw is shown in Table 11. The larger its value, the better. On the average, the action of the left arm in the back of the circle contributed about a third more than the action of the right leg to the rotation of the system (LAA = 33.8 ± 4.0 · 10^{-3} Kg·m²/Kg·m² for the left arm; RLA = 24.9 ± 3.9 · 10^{-3} Kg·m²/Kg·m² for the right leg).

Table 11 also shows the average normalized angular momentum of the left arm about the vertical axis passing through the system c.m. ($H_{LA-DSLSS}$), and the combined duration of the double-support and the single-support on the left foot (t_{DSLSS}), which was the period during which the arm made its counterclockwise thrust. The product of these two factors is equal to the value of LAA. The average angular momentum of the left arm was only about half as large as that of the right leg ($H_{LA-DSLSS}$ = 35 ± 5 · 10^{-3} s^{-1} for the left arm; H_{RL-LSS} = 65 ± 8 · 10^{-3} s^{-1} for the right leg), but the swing of the left arm lasted two and a half times longer than the swing of the right leg (t_{DSLSS} = 0.97 ± 0.12 s for the left arm; t_{LSS} = 0.38 ± 0.04 s for the right leg). So the longer duration of its swing is what allowed the left arm to make a larger contribution to the rotation of the system than the right leg in the average subject.

If the LAA value of a particular athlete was small, it is advisable to find out what made it be small: Either the angular momentum of the arm was small, or the combined duration of the double-support and single-support on the left foot at the back of the circle was too short. To distinguish between the two possibilities, we need to compare the values of these two factors ($H_{LA-DSLSS}$ and t_{DSLSS}) in the particular athlete with their average value in all the subjects of the sample. That way, we will see which of the two factors was mainly responsible for a small value of their product (LLA).

If the conclusion is that the *angular momentum* of the left arm was small, this could be due in turn either to a slow speed of rotation of the arm or to a short distance between the c.m. of the arm and the c.m. of the system. Table 11 shows the average distance between the c.m. of the left arm and the vertical axis passing through the system c.m. (left arm radius during double-support at the back of the circle and single-support on the left foot, or $r_{LA-DSLSS}$). This value is expressed in meters, and also as a percent of the athlete's standing height; the latter is the value that should be used for comparisons between subjects. If the normalized angular momentum of the left arm is small in a particular athlete, we need to compare the left arm radius of the athlete with the mean value of the left arm radius in all the athletes in our sample (remember, we should again compare *percent* values, not values expressed in meters). If the left arm radius of the athlete is much smaller than the mean, this will indicate that a short radius was the reason for the low angular momentum. Otherwise, the reason would be a slow speed of rotation of the arm.

The graph in the lower left part of Figure 15 shows the rotation of the c.m. of the left arm about a vertical axis passing through the c.m. of the thrower-plus-discus system between the instant when the discus reached its most backward position and the takeoff of the left foot in a typical throw. The graph shows successive positions of the c.m. of the left arm at 0.02-second intervals. The combined area of all the triangles (i.e., the area swept by the c.m. of the left arm about the c.m. of the system during the double-support at the back of the circle and the single-support on the left foot) is roughly proportional to the value of LAA. This graphical information may help us to visualize better the nature of the problem if an athlete's LAA value is small.

Table 11 also shows the combined action of the right leg and of the left arm (RLLAA). The larger its value, the better.

Recoveries of the right and left legs

When the athlete is off the ground, no more angular momentum can be generated. Because of this, after the takeoff of the left foot in the middle of the throw there are changes in the roles of the right leg and left arm, and also of the left leg. We will deal first with the legs, and later on we will discuss the actions of the left arm.

After the left foot loses contact with the ground in the middle of the throw, the legs are no longer useful for the generation of angular momentum. Instead, their new function is to increase their own speeds of rotation relative to the upper body. This will permit an earlier planting of the left foot, and it will also help the athlete to acquire a wound-up body configuration in which the lower body is rotated markedly ahead of the upper body and the discus. As explained previously in the section "Some mechanical concepts and definitions", one way to achieve a faster rotation of the legs is to bring them closer to the axis of rotation.

(From this point of the throw onward, the radius of motion of each limb will be judged by the distance from the limb c.m. to a line called the "principal longitudinal axis" of the system —"longitudinal axis" for short— instead of the vertical axis as we did previously. The longitudinal axis of the system has a precise mathematical definition (Hinrichs, 1978). However, all the reader needs to know for the purposes of this report is that the longitudinal axis passes through the system c.m., and points from the lower part of the system to the upper part of the system. If the system tilts, the longitudinal axis tilts with it.)

The graphs in the upper central and upper right parts of Figure 15 show the "recovery" paths of the c.m. of the right leg and of the left leg, respectively, during the non-support phase and the single-support on the right foot, for a typical throw. These are views from a direction aligned with the longitudinal axis of the system; the longitudinal axis passes through the system c.m., and points directly at the reader. During the period shown in the graphs, the athlete needs to make the distance between the c.m. of each leg and the longitudinal axis of the system be as small as possible. Table 12 shows the average value of each of these distances ($r_{RL\text{-}NSRSS}$ and $r_{LL\text{-}NSRSS}$ for the right leg and the left leg, respectively) as well as the mean value for the two legs ($r_{LAVG\text{-}NSRSS}$) during the non-support in the middle of the throw and the single-support on the right foot. The radii are expressed in meters, but also as a percent of standing height. For comparisons between throwers, it is best to look at the percent values rather than at the values expressed in meters. During this period, the lower the radius values of the legs, the better.

Recovery of the left arm

After the left foot takes off from the ground in the back of the circle, the left arm also becomes unable to contribute to the generation of any additional angular momentum for the system, because the feet are not in contact with the ground. So the role of the left arm changes during this non-support phase: The left arm should slow down its counterclockwise rotation and/or decrease its radius of motion. By doing this, the arm will be using a smaller amount of the total angular momentum of the system. This will make angular momentum available to other parts of the system. In other words, the left arm will be transfering part of its own angular momentum to the rest of the system. Through the use of the appropriate mid-trunk musculature, the thrower can then decide to channel the transfered angular momentum into the legs, where it is needed most.

A slowing down of the counterclockwise rotation of the left arm during the non-support phase produces two advantages. We have just seen that, in cooperation with the mid-trunk musculature, the slowing down of the rotation of the left arm can contribute to speed up the rotations of the legs, and can thus help to produce an earlier planting of the left foot. However, there is a second advantage: A slowing down of the left arm will make this arm fall behind in its rotation with respect to the rest of the system, which in turn will make it possible for the arm to make a second counterclockwise swinging thrust after ground support is reestablished. By making this thrust, the left arm will help to generate more angular momentum for the system during the single-support on the right foot and the double-support delivery; we will examine that process in more detail below.

The graph in the lower right corner of Figure 15 shows the path of the c.m. of the left arm from the instant of takeoff of the left foot at the back of the circle to the instant of release of the discus in a typical thrower. At this point, we will focus our attention only on the brief period between the takeoff of the left foot and the landing of the right foot. The individual triangles during this period were rather narrow, indicating that the arm was moving slowly, which is what the thrower needs.

Table 12 shows the average angular momentum of the left arm relative to the longitudinal axis of the system during the non-support phase ($H_{LA\text{-}NS} = 35 \pm 9\ s^{-1} \cdot 10^{-3}$). For an individual thrower, the lower this value, the better.

Table 12

Recoveries of the legs and of the left arm

Average right leg radius ($r_{RL-NSRSS}$), average left leg radius ($r_{LL-NSRSS}$) and the mean of these two values ($r_{LAVG-NSRSS}$) between the takeoff of the left foot and the landing of the left foot; average normalized angular momentum of the left arm (H_{LA-NS}), and average left arm radius ($r_{LA-DSLSS}$) between the takeoff of the left foot and the landing of the right foot. All values are relative to the longitudinal axis of the system; radii are expressed in meters, and also as a percent of standing height. Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	Right leg		Left leg		Both legs (mean)		Left arm		
		$r_{RL-NSRSS}$		$r_{LL-NSRSS}$		$r_{LAVG-NSRSS}$		H_{LA-NS}	r_{LA-NS}	
		(m)	(%)	(m)	(%)	(m)	(%)	($s^{-1}\cdot10^{-3}$)	(m)	(%)
Bloom	41 D96	0.193	10.5	0.173	9.3	0.183	9.9	21	0.472	25.5
Dumble	23 D96	0.190	10.3	0.148	8.0	0.169	9.1	35	0.503	27.2
Fitzpatrick	40 U94	0.185	9.6	0.148	7.7	0.166	8.7	35	0.445	23.2
Fitzpatrick	*62 D96*	*0.188*	*9.8*	*0.158*	*8.2*	*0.173*	*9.0*	*37*	*0.447*	*23.3*
Godina	28 U94	0.200	10.5	0.167	8.7	0.184	9.6	33	0.455	23.8
Gravelle	22 U94	0.228	11.6	0.174	8.9	0.201	10.2	48	0.545	27.8
Hart	57 D96	0.223	11.6	0.195	10.1	0.209	10.8	52	0.577	29.9
Haynes	24 D96	0.208	11.4	0.148	8.1	0.178	9.7	48	0.496	27.1
Heisler	36 U94	0.178	9.3	0.140	7.3	0.159	8.3	41	0.412	21.6
Johnson	10 D96	0.188	9.8	0.153	7.9	0.171	8.8	27	0.451	23.4
Kirchhoff	34 D96	0.191	9.9	0.165	8.5	0.178	9.2	49	0.477	24.6
McPherran	08 D96	0.187	9.4	0.169	8.6	0.178	9.0	16	0.406	20.5
Mielke	22 D96	0.213	11.2	0.164	8.6	0.189	9.9	44	0.500	26.2
Muse	47 D96	0.224	12.2	0.167	9.1	0.196	10.6	27	0.408	22.2
Nuti	15 D96	0.216	11.2	0.208	10.8	0.212	11.0	34	0.412	21.3
Patera	01 U94	0.205	10.7	0.168	8.7	0.187	9.7	18	0.393	20.5
Presser	09 D96	0.199	10.1	0.171	8.7	0.185	9.4	35	0.493	25.0
Schulte	59 D96	0.203	10.2	0.170	8.6	0.186	9.4	31	0.534	27.0
Scott	41 U94	0.204	10.5	0.177	9.2	0.190	9.9	30	0.448	23.2
Setliff	*27 U94*	*0.193*	*10.0*	*0.162*	*8.4*	*0.177*	*9.2*	*45*	*0.553*	*28.6*
Setliff	65 D96	0.197	10.2	0.155	8.0	0.176	9.1	43	0.497	25.7
Staat	25 D96	0.189	9.6	0.144	7.3	0.166	8.4	32	0.453	22.9
Sullivan	06 D96	0.199	10.8	0.160	8.7	0.180	9.7	33	0.449	24.2
Tveitaa	39 D96	0.196	10.5	0.155	8.3	0.176	9.4	41	0.471	25.3
Washington	66 D96	0.183	9.8	0.162	8.7	0.172	9.3	39	0.479	25.8
Wirtz	42 D96	0.210	11.1	0.169	9.0	0.190	10.0	37	0.452	23.9
Mean		0.200	10.5	0.165	8.6	0.183	9.5	35	0.468	24.5
S.D.		±0.013	±0.8	±0.015	±0.8	±0.013	±0.7	±9	±0.045	±2.3

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

If the value of H_{LA-NS} is large in an individual thrower (i.e., clearly larger than the average), this could be due to one of two reasons: Maybe the arm was rotating too fast, or maybe the radius of the arm was kept too long. To help us to distinguish between these two possibilities, Table 12 also shows the average radius of the left arm during the non-support phase (r_{LA-NS}). Its value is given in meters, and also as a percent of standing height; as usual, the percent values are the ones that should be used for making comparisons between throwers. If the angular momentum of an athlete's left arm was larger than average, but the radius was small or near average, this would indicate that the reason for the problem was an insufficient slowing down of the arm during the non-support phase; otherwise, the reason would be an excessively long radius of the left arm during that period.

At this point, it is not completely clear what would be preferable during the non-support phase, a slowing down of the arm or a shortening of the arm radius, but we think that slowing down the arm during this period may give an advantage over a shortening of the radius. Either method would contribute equally well to the counterclockwise acceleration of the legs. But slowing down the arm would, in addition, help to provide a long range of motion for the arm in the subsequent single-support and double-support, while a mere shortening of the radius would allow the left arm to keep traveling counterclockwise quite fast during the non-support, which would leave a smaller range of motion available for the arm during the subsequent single-support and double-support.

Second propulsive drive of the left arm

After the right foot lands in the middle of the circle, the athlete swings the left arm very strongly counterclockwise. This is clearly visible in the graph shown in the lower right part of Figure 15. The successive positions of the arm c.m. relative to the system c.m. are joined by the bases of the triangles (outward sides). After the landing of the right foot, the bases of the triangles grew progressively longer, which indicates that the c.m. of the left arm gained a considerable amount of speed. The increasing *areas* of the triangles indicate that the angular momentum of the left arm also became progressively larger. This action of the left arm facilitates the generation of angular momentum for the thrower-plus-discus system, because it helps the right foot (and during the double-support delivery, both feet) to exert on the ground the forces that are necessary for generating the angular momentum. During this part of the throw, the athlete generally has some lean toward the back of the circle. Therefore the longitudinal axis also has some backward lean, and the view shown in the graph of Figure 15 is in effect an oblique view, seen from overhead and also somewhat from the back of the circle. So the angular momentum that the second propulsive drive of the left arm helps to generate is a combination of Z angular momentum and Y angular momentum, which is exactly what the thrower is looking for.

After the landing of the right foot, the left arm should be thrown counterclockwise very fast, far from the middle of the body, and over the longest possible range of motion. As we saw for the earlier thrust of the left arm, the single mechanical factor that best measures the combination of speed, radius and range of motion may be the "integral of the angular momentum of the left arm", which we will call for this period the "second left arm action", or LAA2. The value of LAA2 is normalized for height and weight, and therefore can be compared directly across subjects.

[Note for other researchers (coaches and athletes can skip this paragraph): LAA2 is the time-integral of the angular momentum of the left arm about the longitudinal axis of the thrower-plus-discus system between the landing of the right foot and the release of the discus, normalized for the subject's height and weight.]

The value of the second left arm action (LAA2) for each throw is shown in Table 13. The larger its value, the better.

If an athlete's LAA2 value was small, it is advisable to find out what made it be small: Either the average angular momentum of the arm was small, or the combined duration of the single-support on the right foot and the delivery phase was too short. To help us to distinguish between the two, Table 13 also shows the average normalized angular momentum of the left arm about the longitudinal axis ($H_{LA-RSSDEL}$), and the combined duration of the single-support on the left foot and the delivery (t_{RSSDEL}). The product of these two factors is equal to the value of LAA2. By comparing their values in an individual subject with the mean of their values in all subjects, it is possible to see which of the two factors was mainly responsible for a small value of their product, LAA2.

Second recovery of the left arm

The second left arm action which has just been described (LAA2) helps the thrower-plus-discus system to obtain more angular momentum from the ground, and this is good. However, much of that angular momentum will be initially stored in the left arm itself, where it does not do the athlete any good. Before the discus is released, the athlete needs to transfer as much as possible of the angular momentum of the left arm to the discus. To achieve this, the athlete will generally reduce the angular momentum of the left arm during the final part of the delivery, either by slowing down its motion or by reducing the radius of its motion. This is visible in the graph in the lower right of Figure 15. The areas of the successive triangles formed by the path of the left arm c.m. about the system c.m. are roughly proportional to the angular momentum of the left arm. (Each triangle shows the area swept by the arm c.m. about the system c.m. in a 0.02-second interval.) After the landing of the right foot, the triangles became progressively larger, as was described previously. They reached their maximum size not far from the instant of landing of the left foot. (In the airborne-release throwers, such as the one shown in Figure 15, maximum angular momentum of the left arm tended to occur slightly after the landing of the left foot, while in the grounded-release throwers it tended to occur slightly *before* the landing of the left foot; the reasons for this difference are not completely clear at this time.) After reaching maximum size, the areas of the triangles decreased again. In most throwers, such as the one shown in Figure 15, the decrease in the areas of the triangles (and therefore in the angular momentum of the left arm) was primarily a result of a slowing down of the left arm, as indicated by the progressive *narrowing* of the triangles. In a few throwers, there was also a progressive decrease in the length of the long sides of the triangles (radius of the left arm c.m.), indicating that in these throwers the decrease in the angular momentum of the left arm was the combined result of a slowing down of the left arm *and* shortening of its radius.

Table 13 shows the maximum angular momentum reached by the left arm between the landing of the right foot and release (H_{MAX}), the angular momentum that the left arm still had at the instant of release of the discus (H_{REL}), and the difference between them (ΔH). For a good transfer of angular momentum from the left arm to the rest of the system (and possibly to the discus), the larger the negative value of ΔH, the better.

Torsion angles

In the course of a throw, the thrower-plus-discus system becomes wound-up, with the upper parts of the system rotated clockwise with respect to the lower parts (the hip axis is rotated clockwise with respect to the line joining the two feet, the shoulder axis is rotated clockwise with respect to the hip axis, and the right arm is rotated clockwise with respect to

Table 13

Second propulsive swinging action of the left arm, and recovery

Second left arm action (LAA2), average normalized angular momentum of the left arm about the longitudinal axis of the system ($H_{LA\text{-}RSSDEL}$) and time (t_{RSSDEL}) between the landing of the right foot and the release of the discus; maximum value of the normalized angular momentum of the left arm about the longitudinal axis of the system between right foot landing and release (H_{MAX}), its value at release (H_{REL}), and the difference between them (ΔH). Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	Left arm					
		LAA2 ($Kg{\cdot}m^2{\cdot}10^{-3}$/ $Kg{\cdot}m^2$)	$H_{LA\text{-}RSSDEL}$ ($s^{-1}{\cdot}10^{-3}$)	t_{RSSDEL} (s)	H_{MAX} ($s^{-1}{\cdot}10^{-3}$)	H_{REL}	ΔH
Bloom	41 D96	18.5	41	0.46	67	30	-37
Dumble	23 D96	18.8	49	0.38	78	23	-55
Fitzpatrick	40 U94	19.0	43	0.44	59	31	-29
Fitzpatrick	*62 D96*	*18.1*	*44*	*0.41*	*60*	*23*	*-36*
Godina	28 U94	13.7	43	0.32	57	21	-36
Gravelle	22 U94	18.6	46	0.40	55	27	-27
Hart	57 D96	23.6	56	0.42	71	38	-34
Haynes	24 D96	21.2	53	0.40	73	20	-53
Heisler	36 U94	18.3	48	0.38	63	31	-32
Johnson	10 D96	15.6	40	0.39	59	26	-33
Kirchhoff	34 D96	24.7	55	0.45	69	23	-46
McPherran	08 D96	12.4	29	0.43	48	22	-26
Mielke	22 D96	19.1	47	0.41	63	22	-41
Muse	47 D96	16.6	44	0.38	64	19	-44
Nuti	15 D96	15.7	44	0.36	61	22	-39
Patera	01 U94	11.2	34	0.33	48	13	-35
Presser	09 D96	12.6	35	0.36	42	15	-27
Schulte	59 D96	18.6	44	0.43	64	21	-44
Scott	41 U94	16.5	35	0.48	50	7	-44
Setliff	*27 U94*	*17.9*	*44*	*0.40*	*58*	*20*	*-37*
Setliff	65 D96	15.3	40	0.38	54	13	-41
Staat	25 D96	16.0	39	0.41	58	18	-39
Sullivan	06 D96	14.6	39	0.38	53	22	-31
Tveitaa	39 D96	19.3	46	0.42	64	14	-51
Washington	66 D96	18.1	51	0.36	72	23	-49
Wirtz	42 D96	21.5	57	0.38	82	31	-51
Mean		17.5	44	0.40	61	22	-39
S.D.		±3.3	±7	±0.04	±10	±7	±8

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

the shoulder axis). Then the system unwinds, and the upper parts catch up with the lower parts.

In a typical throw, there are usually two major cycles of this sort (i.e., wind-unwind-wind-unwind), as well as some minor ones. These are the major cycles: During the preliminary swing at the back of the circle, the upper parts of the system rotate clockwise relative to the lower parts, and a very wound-up position is produced at the instant that the discus reaches its most backward point. Then the system unwinds until the right foot leaves the ground or shortly afterward. After that, the lower parts of the system get ahead of the upper parts, and produce another wound-up position. This second wound-up position generally occurs before the left foot lands. Then there is a final unwinding of the system, which is associated with the transfer of angular momentum from the thrower to the discus.

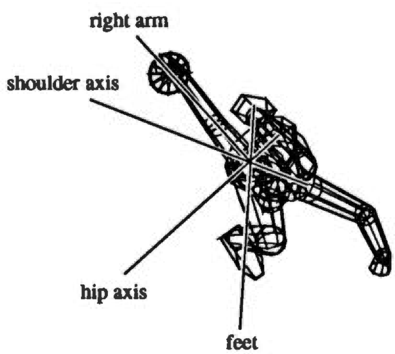

Figure 16

To find out more details about how the winding and unwinding of the system occurred, we calculated "torsion angles" between the various parts of the system. Figure 16 shows a thrower in a view along the longitudinal axis of the system. Four lines are defined: (a) feet orientation, which passes through the midpoints of both feet; (b) hip axis, which passes through the left and right hip joints; (c) shoulder axis, which passes through the left and right shoulder joints; and (d) right arm orientation, which passes through the right shoulder joint and the center of the discus. Figure 17 shows the angles between these lines: $k_{HP/FT}$ between the hip axis and the line of the feet; $k_{SH/FT}$ between the shoulder axis and the line of the feet; $k_{RA/FT}$ between the right arm and the line of the feet; $k_{SH/HP}$ between the shoulder axis and the hip axis; $k_{RA/HP}$ between the right arm and the hip axis; and $k_{RA/SH}$ between the right arm and the shoulder axis. We called them the torsion angles. They

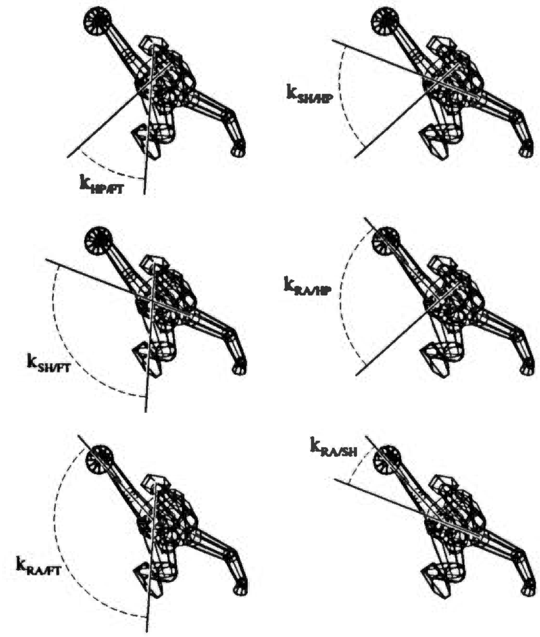

Figure 17

describe how much the system is wound, and where the main winding is.

We assigned negative values to the torsion angles when the upper parts of the system were behind (i.e., clockwise relative to) the lower parts of the system. During winding, the angles become more negative; during unwinding, they become less negative, or even positive.

Figure 18 shows how the torsion angles changed in the course of a typical throw. We will focus on the torsion angle patterns during the period between the instant of landing of the right foot (RTD)and the release of the discus (REL). During this period, the torsion angles of the hips relative to the feet, of the shoulders relative to the hips and of the right arm relative to the shoulders all reached a local maximum negative value (i.e., maximum wind-up). This was followed by the final unwinding. Table 14 shows the maximum negative values of all the torsion angles in the period between the landing of the right foot and release, and the times when they occurred. (Remember that the time t = 10.00 s was assigned in all throws to the instant when the left foot landed on the ground.) In most of the throwers (18 out of 24), maximum torsion of the hips relative to the feet was reached first ($k_{HP/FT} = -56 \pm 13°$ at $t = 9.90 \pm 0.04$ s), followed by maximum torsion of the shoulders

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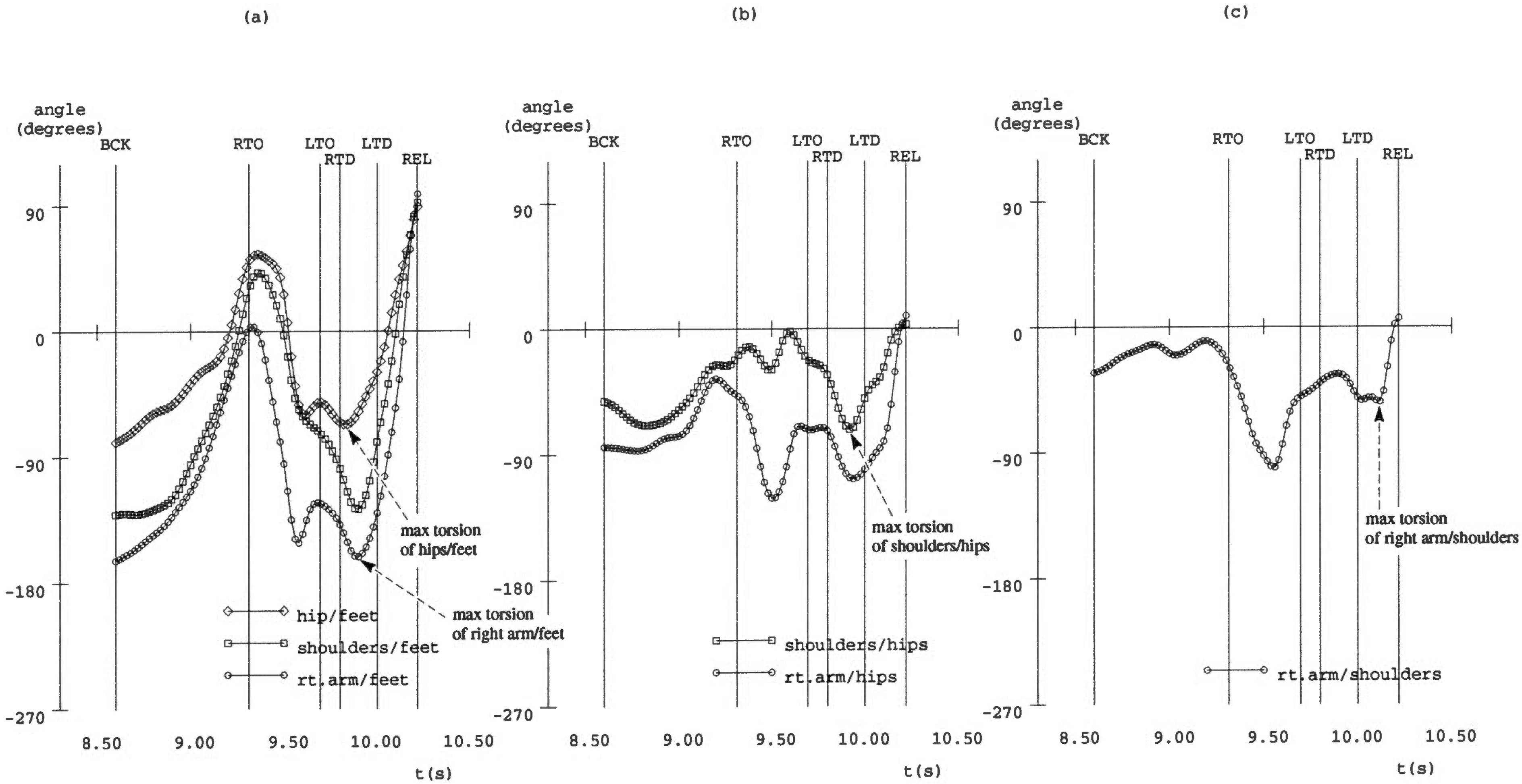


Figure 18

Table 14

Maximum individual torsion angles between the landing of the right foot and release

Maximum torsion angles of the hips relative to the feet ($k_{HP/FT}$), of the shoulders relative to the feet ($k_{SH/FT}$), of the right arm relative to the feet ($k_{RA/FT}$), of the shoulders relative to the hips ($k_{SH/HP}$), of the right arm relative to the hips ($k_{RA/HP}$) and of the right arm relative to the shoulders ($k_{RA/SH}$) between the instant of landing of the right foot and the release of the discus, and the times when these maximum torsion angles were reached ($t_{HP/FT}$, $t_{SH/FT}$, $t_{RA/FT}$, $t_{SH/HP}$, $t_{RA/HP}$ and $t_{RA/SH}$, respectively). Note: The time t = 10.00 s was assigned in all throws to the instant of landing of the left foot.

Athlete	Trial and meet (*)	Torsion Angles						Times					
		$k_{HP/FT}$ (°)	$k_{SH/FT}$ (°)	$k_{RA/FT}$ (°)	$k_{SH/HP}$ (°)	$k_{RA/HP}$ (°)	$k_{RA/SH}$ (°)	$t_{HP/FT}$ (s)	$t_{SH/FT}$ (s)	$t_{RA/FT}$ (s)	$t_{SH/HP}$ (s)	$t_{RA/HP}$ (s)	$t_{RA/SH}$ (s)
Bloom	41 D96	-61	-142	-158	-94	-115	-39	9.88	9.92	9.92	9.98	9.98	10.08
Dumble	23 D96	-74	-130	-140	-67	-82	-28	9.90	9.92	9.94	9.96	9.98	10.10
Fitzpatrick	40 U94	-65	-146	-171	-82	-107	-37	9.88	9.92	9.90	9.92	9.92	10.02
Fitzpatrick	*62 D96*	*-58*	*-148*	*-168*	*-92*	*-111*	*-28*	*9.88*	*9.90*	*9.90*	*9.92*	*9.90*	*10.04*
Godina	28 U94	-71	-121	-150	-51	-80	-40	9.90	9.92	9.92	9.92	9.94	10.00
Gravelle	22 U94	-32	-77	-121	-48	-91	-45	9.92	9.90	9.90	9.86	9.88	9.92
Hart	57 D96	-25	-88	-120	-74	-97	-59	9.96	9.90	9.94	9.80	9.90	10.06
Haynes	24 D96	-55	-93	-115	-46	-77	-39	9.88	9.90	9.96	9.94	9.98	10.08
Heisler	36 U94	-56	-102	-128	-47	-73	-38	9.96	9.96	9.96	9.94	9.98	10.04
Johnson	10 D96	-69	-128	-161	-61	-94	-38	9.90	9.90	9.90	9.92	9.92	10.00
Kirchhoff	34 D96	-47	-114	-142	-68	-97	-49	9.92	9.96	9.96	9.96	9.98	10.14
McPherran	08 D96	-51	-99	-148	-56	-106	-52	9.90	9.92	9.94	9.96	9.96	10.10
Mielke	22 D96	-45	-107	-135	-62	-92	-42	9.84	9.86	9.88	9.86	9.88	9.98
Muse	47 D96	-54	-117	-157	-70	-114	-65	9.86	9.90	9.92	9.92	9.96	10.10
Nuti	15 D96	-42	-84	-147	-55	-106	-64	9.96	9.94	9.94	9.82	9.94	9.96
Patera	01 U94	-74	-124	-136	-58	-69	-13	9.88	9.92	9.92	9.96	9.96	9.94
Presser	09 D96	-59	-98	-126	-39	-70	-39	9.94	9.94	9.98	9.94	10.00	10.00
Schulte	59 D96	-43	-107	-155	-69	-119	-62	9.90	9.92	9.94	9.94	9.96	10.12
Scott	41 U94	-53	-113	-150	-67	-103	-38	9.84	9.84	9.88	9.78	9.90	9.90
Setliff	*27 U94*	*-50*	*-113*	*-136*	*-63*	*-87*	*-52*	*9.88*	*9.88*	*9.88*	*9.88*	*9.92*	*10.00*
Setliff	65 D96	-65	-123	-168	-60	-109	-63	9.88	9.88	9.90	9.90	9.92	9.98
Staat	25 D96	-67	-115	-171	-52	-109	-58	9.94	9.94	9.96	9.98	9.98	9.98
Sullivan	06 D96	-61	-94	-138	-39	-89	- 50	9.90	9.92	9.94	9.96	9.96	9.98
Tveitaa	39 D96	-67	-128	-162	-72	-108	-54	9.84	9.90	9.90	9.92	9.94	10.12
Washington	66 D96	-60	-123	-136	-75	-92	-41	9.86	9.94	9.96	9.94	9.98	10.08
Wirtz	42 D96	-44	-99	-121	-55	-78	-28	9.94	9.96	9.96	9.96	9.96	10.06
Mean		-56	-111	-144	-61	-95	-45	9.90	9.92	9.93	9.92	9.95	10.03
S.D.		±13	±17	±17	±13	±15	±13	±0.04	±0.03	±0.03	±0.05	±0.03	±0.07

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

relative to the hips ($k_{SH/HP}$ = -61 ± 13° at t = 9.92 ± 0.05 s). In practically all the throwers (22 out of 24), the maximum torsion of the shoulders relative to the hips was followed by the maximum torsion of the right arm relative to the shoulders ($k_{RA/SH}$ = -45 ± 13° at t = 10.03 ± 0.07 s).

A pattern such as the one just described, in which the lower parts of the system start their actions before the higher parts, is very typical of throwing activities. The reasons for it are not completely clear at this time, but an interesting theory has been proposed by Alexander (1991). In the course of a throw, greater demands are solicited from the muscles of the lower parts of the system than from the muscles of the higher parts of the system. This is because the muscles of the lower parts are not only required to accelerate the lower parts, but also to support the acceleration of the upper parts, while the muscles of the upper parts are only required to accelerate the upper parts. Although the muscles of the legs are stronger than the muscles of the arms, the greater demands required of them makes them be slower in the completion of their task. Therefore, the leg muscles need to start their actions before the muscles of the arms, in order to complete their task at the same time as the muscles of the arms, which have an easier task to do in relation to their own strength. If the arm muscles are activated too early, the discus will be released before the muscles of the legs (and of the trunk) have had a chance to make a full contribution to the throw, and this would shorten the distance of the throw. (For more details, see Alexander, 1991.)

The torsion angle that we are most interested in is the angle between the line joining the feet and the orientation of the right arm ($k_{RA/FT}$). We call this angle the total torsion of the system, and it is the sum of $k_{HP/FT}$, $k_{SH/HP}$ and $k_{RA/SH}$. Figure 18 and Table 14 show that $k_{RA/FT}$ reaches a maximum negative value during the single-support on the right foot ($k_{RA/FT}$ = -144 ± 17° at t = 9.93 ± 0.03 s). Notice that this value is not quite as large as the sum of the maximum values of $k_{HP/FT}$, $k_{SH/HP}$ and $k_{RA/SH}$. This is because these angles reach their maximum negative values at different times, as pointed out previously.

Table 15 shows the values of the six torsion angles at the instant that the right arm reached its maximum torsion relative to the line joining the feet (t = 9.93 ± 0.03 s). The larger the negative value of $k_{RA/FT}$, the better. If the size of $k_{RA/FT}$ is smaller than the average, it will be useful to look at the values of $k_{HP/FT}$, $k_{SH/HP}$ and $k_{RA/SH}$, to see which of them is mainly responsible, since the sum of these three angles adds up to the torsion angle of the system ($k_{RA/FT}$).

Table 15 also shows the values of the six torsion angles at the instant of release. These angles describe how well the athlete unwound during the transfer of angular momentum from the body to the discus. The ideal should be to achieve a large positive value for $k_{RA/FT}$ at release. However, torsion angles *relative to the feet* may not be very meaningful at release for athletes whose feet are off the ground at that time. In such cases, the angle between the right arm and the hip axis may be the best way to judge how well the athlete unwound. The athlete should strive to achieve a large positive value of $k_{RA/HP}$.

Conditions at release, aerodynamic effects, and distance of the throw

The distance of a throw is determined to a great extent by the speed of the discus at release. That is why most of this report was dedicated to the analysis of the factors that ultimately affect the final speed of the discus.

Table 16 shows the resultant (i.e., total) speed of the discus at release (v_{RD} = 23.6 ± 0.6 m/s) and the initial direction of motion of the discus relative to the horizontal plane (d_{VREL} = 35 ± 3°). It also shows the breakdown of the resultant speed into horizontal speed (v_{HD} = 19.3 ± 0.8 m/s) and vertical speed (v_{ZD} = 13.6 ± 1.1 m/s).

Although the speed of the discus at release is extremely important, the path of the discus is also influenced by the aerodynamic forces exerted during the flight. Theoretical mechanical analysis of the discus flight has shown that in certain conditions these forces can greatly affect the distance of the throw (Ganslen, 1959, 1964; Cooper *et al.*, 1959; Soong, 1976; Frohlich, 1981).

Computer simulation has shown that the discus generally should be released with a tilt that initially exposes the upper side (rather than the underside) of the discus to the oncoming airflow. (See the first image of the discus on discus path #1 in the sketch shown in Figure 19.) This makes the air exert downward forces on the discus during the early part of the flight. Such forces tend to depress the path of the discus, and this not good in itself. However, in the later stages of the flight the forward and downward direction that the path of the discus follows makes the *under*side of the discus be exposed to the oncoming air. This makes the air exert an uplifting force which helps the discus to travel further forward before landing.

If the discus is released instead with a larger backward tilt, so that the underside of the discus is exposed to the oncoming air from the very beginning of the flight, this tends to lift the discus during the

Table 15

Torsion angles at the instant of maximum torsion of the system, and at release

Torsion angles of the hips relative to the feet ($k_{HP/FT}$), of the shoulders relative to the feet ($k_{SH/FT}$), of the right arm relative to the feet ($k_{RA/FT}$), of the shoulders relative to the hips ($k_{SH/HP}$), of the right arm relative to the hips ($k_{RA/HP}$) and of the right arm relative to the shoulders ($k_{RA/SH}$) at the instant of maximum torsion of the system (i.e., at the instant of largest negative value of $k_{RA/FT}$) and at release. Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	at maximum torsion of system						at release					
		$k_{HP/FT}$ (°)	$k_{SH/FT}$ (°)	$k_{RA/FT}$ (°)	$k_{SH/HP}$ (°)	$k_{RA/HP}$ (°)	$k_{RA/SH}$ (°)	$k_{HP/FT}$ (°)	$k_{SH/FT}$ (°)	$k_{RA/FT}$ (°)	$k_{SH/HP}$ (°)	$k_{RA/HP}$ (°)	$k_{RA/SH}$ (°)
Bloom	41 D96	-58	-142	-158	-84	-100	-16	71	79	85	8	14	6
Dumble	23 D96	-63	-129	-140	-66	-77	-12	58	78	87	20	29	9
Fitzpatrick	40 U94	-65	-145	-171	-80	-106	-26	73	88	88	15	15	0
Fitzpatrick	*62 D96*	*-57*	*-148*	*-168*	*-91*	*-111*	*-20*	*70*	*79*	*89*	*9*	*20*	*10*
Godina	28 U94	-70	-121	-150	-51	-79	-28	70	83	87	13	17	3
Gravelle	22 U94	-31	-77	-121	-46	-90	-44	77	92	105	15	29	14
Hart	57 D96	-25	-82	-120	-57	-95	-38	92	84	74	-8	-17	-9
Haynes	24 D96	-39	-84	-115	-45	-76	-31	61	85	87	24	26	2
Heisler	36 U94	-56	-102	-128	-47	-73	-26	72	88	98	16	26	10
Johnson	10 D96	-69	-128	-161	-60	-93	-33	57	75	84	18	27	9
Kirchhoff	34 D96	-46	-114	-142	-68	-96	-28	85	88	85	3	0	-3
McPherran	08 D96	-44	-99	-148	-54	-103	-49	93	96	83	3	-11	-13
Mielke	22 D96	-44	-105	-135	-62	-92	-30	87	86	87	-1	0	1
Muse	47 D96	-46	-116	-157	-70	-111	-41	95	92	77	-3	-18	-15
Nuti	15 D96	-40	-84	-147	-44	-106	-63	78	88	90	10	12	2
Patera	01 U94	-70	-124	-136	-53	-66	-12	76	83	99	7	23	16
Presser	09 D96	-57	-91	-126	-34	-69	-35	95	89	86	-6	-9	-4
Schulte	59 D96	-37	-106	-155	-69	-118	-49	91	101	99	10	8	-2
Scott	41 U94	-49	-112	-150	-63	-101	-38	72	83	106	11	34	23
Setliff	*27 U94*	*-50*	*-113*	*-136*	*-63*	*-87*	*-24*	*78*	*96*	*110*	*19*	*33*	*14*
Setliff	65 D96	-62	-123	-168	-60	-106	-46	58	71	77	13	19	5
Staat	25 D96	-64	-115	-171	-51	-107	-56	89	73	77	-16	-12	4
Sullivan	06 D96	-52	-91	-138	-39	-86	-47	80	88	89	8	10	1
Tveitaa	39 D96	-58	-128	-162	-70	-104	-34	88	91	97	3	9	6
Washington	66 D96	-45	-119	-136	-74	-91	-17	65	79	104	14	38	25
Wirtz	42 D96	-43	-99	-121	-55	-78	-23	58	87	105	28	47	19
Mean		-51	-110	-144	-58	-93	-34	77	85	90	9	13	5
S.D.		±12	±18	±17	±12	±14	±13	±13	±7	±9	±10	±18	±10

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

Table 16

Conditions at release, distance of the throw, and aerodynamic effects

Conditions at release: resultant speed of the discus (v_{RD}); angle between the resultant speed of the discus and the horizontal plane (d_{vREL}); horizontal speed of the discus (v_{HD}); vertical speed of the discus (v_{ZD}); height of the discus (h_{DREL}). Theoretical distance of the throw in a vacuum (D_V); actual measured distance of the throw (D); gain in the distance of the throw due to aerodynamic effects (ΔD). The height of the discus is expressed in meters, and also as a percent of the standing height of each subject. Note: Some of the values in this table may not fit perfectly with each other, because of rounding off.

Athlete	Trial and meet (*)	v_{RD} (m/s)	d_{vREL} (°)	v_{HD} (m/s)	v_{ZD} (m/s)	h_{DREL} (m)	h_{DREL} (%)	D_V (m)	D (m)	ΔD (m)	
Bloom	41 D96	23.8	30	20.5	12.0	1.72	93.0	52.65	59.18	6.53	
Dumble	23 D96	23.8	38	18.9	14.6	1.61	87.0	57.85	58.48	0.63	
Fitzpatrick	40 U94	24.2	37	19.4	14.5	1.92	100.0	59.59	59.24	-0.35	
Fitzpatrick	*62 D96*	*23.8*	*40*	*18.3*	*15.2*	*1.87*	*97.5*	*58.73*	—	—	
Godina	28 U94	23.5	42	17.6	15.6	1.78	93.0	57.38	53.26	-4.12	
Gravelle	22 U94	24.7	37	19.6	15.0	1.72	87.5	62.00	61.38	-0.62	
Hart	57 D96	24.0	33	20.2	13.1	1.60	83.0	55.87	61.92	6.05	
Haynes	24 D96	22.7	34	18.9	12.7	1.74	95.0	51.29	55.76	4.47	
Heisler	36 U94	24.6	33	20.5	13.5	1.94	101.5	58.90	58.60	-0.30	
Johnson	10 D96	24.3	37	19.5	14.5	1.77	92.0	59.72	60.82	1.10	
Kirchhoff	34 D96	23.5	31	20.0	12.3	1.68	87.0	52.54	58.54	6.00	
McPherran	08 D96	23.4	35	19.1	13.5	1.79	90.5	54.82	57.86	3.04	
Mielke	22 D96	23.7	36	19.2	14.0	1.58	83.0	56.15	59.46	3.31	
Muse	47 D96	23.7	30	20.6	11.7	1.77	96.0	51.61	55.16	3.55	
Nuti	15 D96	22.9	36	18.6	13.3	1.70	88.0	52.56	58.72	6.16	
Patera	01 U94	23.3	38	18.3	14.4	1.74	91.0	55.72	54.70	-1.02	
Presser	09 D96	23.6	32	20.0	12.7	1.69	86.0	53.76	59.04	5.28	
Schulte	59 D96	22.0	31	18.8	11.5	1.72	87.0	46.38	51.30	4.92	
Scott	41 U94	24.2	37	19.3	14.6	1.91	99.0	59.50	59.32	-0.18	
Setliff	*27 U94*	*24.0*	*33*	*20.0*	*13.2*	*1.69*	*87.5*	*55.99*	*57.44*	*1.45*	
Setliff	65 D96	23.5	35	19.2	13.6	1.61	83.5	55.01	63.32	8.31	
Staat	25 D96	22.9	40	17.4	14.8	1.64	83.0	54.23	55.52	1.29	
Sullivan	06 D96	23.6	35	19.3	13.6	1.74	94.0	55.76	57.78	2.02	
Tveitaa	39 D96	23.1	37	18.5	13.8	1.49	80.5	53.97	57.80	3.83	
Washington	66 D96	24.2	36	19.6	14.3	1.52	81.5	58.67	63.96	5.29	
Wirtz	42 D96	23.6	36	19.2	13.7	1.64	87.0	55.78	61.48	5.70	
Mean		23.6	35	19.3	13.6	1.71	89.5	55.49	58.44	2.95	(ALL THROWS)
S.D.		±0.6	±3	±0.8	±1.1	±0.11	±5.9	±3.38	±2.98	±3.02	
Mean		24.1	37	19.1	14.6	1.84	95.3	58.85	57.75	-1.10	(1994 USATF
S.D.		±0.5	±3	±0.9	±0.6	±0.09	±5.1	±1.95	±2.83	±1.38	CHAMPIONSHIPS)
Mean		23.5	35	19.3	13.3	1.67	87.6	54.37	58.67	4.30	(1996 UC SAN
S.D.		±0.5	±3	±0.8	±1.0	±0.08	±4.7	±2.98	±2.99	±2.06	DIEGO OPEN)

(*) U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

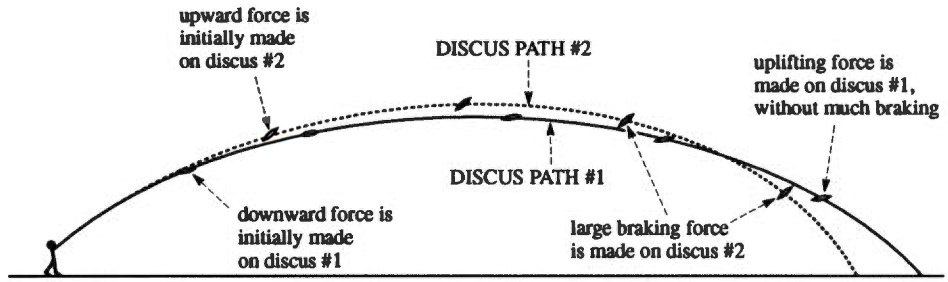


Figure 19

early part of the flight. (See the first image of the discus on discus path #2 in Figure 19.) In itself, this is good. However, in the late part of the flight the greater backward tilt of the discus also makes it face more perpendicular to the direction of the oncoming air. This slows down the speed of the discus very much, and ultimately results in a shorter throw.

Frohlich (1981) used computer simulation to calculate the optimum combinations for the release angle (d_{VREL}) and discus tilt in three different wind conditions (10 m/s tailwind, no wind, and 10 m/s headwind). The results (taken from his graphs) were as follows: For a 10 m/s tailwind, release angle = 44° and tilt angle = 47°; for zero wind, release angle = 37° and tilt angle = 27°; for a 10 m/s headwind, release angle = 32° and tilt angle = 17°. These results imply that in headwind and no-wind (as well as in mild tailwind) conditions, the forward edge of the discus should be pointing downward relative to the direction of motion of the discus at release. The relative downward tilt of the forward edge of the discus needs to be particularly marked in throws made into headwinds.

A strong tailwind will tend to produce short throws, because the air and the discus will be traveling together in the same direction. This reduces the forces that they can exert on each other, and therefore limits the assistance that the air can provide. Frohlich (1981) has also shown that it is not very critical to attain the optimum angle of tilt when there is a strong tailwind: The speed of the discus and its direction of travel at release will determine almost completely the distance of the throw; the skill of the thrower in achieving the optimum angle of tilt will only make a minor difference in the result under these conditions.

The discus will generally travel farther when throwing into a strong headwind, but in these conditions the distance of the throw will be greatly affected by the angle of tilt of the discus (Frohlich, 1981). When throwing into a headwind, it is particularly important to use an angle of tilt that is very close to the optimum. Only the throwers who are able to attain an angle of tilt that is close to the optimum will obtain full benefit from the wind, and those who are not very near the optimum will be at a great disadvantage. A computer simulation experiment at our lab has shown that a deviation of only 7-10° from the optimum angle of tilt when throwing into a 10 m/s headwind can produce a loss of about 7 meters in a 60-meter throw.

From the position of the discus and its horizontal and vertical speeds at release, we calculated the distance that each of the analyzed throws would have reached if the discus had been thrown in a vacuum (D_V = 55.49 ± 3.38 m). A comparison of this theoretical vacuum distance with the actual distance of the throw (D = 58.44 ± 2.98 m) shows that the aerodynamic forces exerted by the air on the discus during its flight produced an average improvement of 2.95 ± 3.02 m (ΔD) in the distance of the throws. Estimates of the distance gained or lost by male discus throwers through aerodynamic forces (ΔD) had only been reported previously in two publications. In a study that used two-dimensional film analysis, Terauds (1978) found a small negative average effect of the aerodynamic forces on the distance of the throw, but with a large amount of variability among subjects (ΔD = -0.58 ± 4.58 m). In a 3D analysis of throws pooled from two men's competitions, the results of Hay and Yu (1995) were similar to ours: an average positive contribution of the aerodynamic forces to the distance of the throw, with a large variability among subjects (ΔD = 2.42 ± 3.29 m).

[Note for other researchers (coaches and athletes can skip this paragraph): Researchers should be wary of possible errors in the calculation of the speed and angle of release of the discus (v_{RD}

and d_{VREL} respectively, in Table 16). Errors in these values will produce errors in the predicted vacuum distance (D_V), and consequently in the value that shows the gain or loss due to aerodynamic effects (ΔD). To minimize these errors in our project, we did not use derivatives taken directly from the X, Y and Z locations of the discus at the instant of release. Instead, we fitted straight lines through the X and Y (horizontal) and a parabola of second derivative equal to -9.81 m/s² through the Z (vertical) discus locations versus time in the first 4-8 frames (i.e., the first 0.08-0.16 s) after release. The equations of the lines and of the parabola were then used to calculate the X, Y and Z velocities (and locations) of the discus at release. The cage usually hides the discus partly or completely in some of the film frames. Digitized data taken from such frames can occasionally produce marked distortions in the fitted equations, and can therefore produce important errors in the results. To avoid this problem, we omitted any such frames from the data used for the calculation of the equations. The paper by Hay and Yu (1995) was reported in a scientific journal, and the description of the methods used was very detailed. The methods appeared to be sound. However, Teraud's (1978) results were reported in a coaching journal, and due to the nature of the journal the description of the methods was less detailed. Because of this, it is more difficult to judge the validity of his results.]

As pointed out previously, the data of the present report were obtained at two separate competitions: the 1994 USA Track & Field Championships and the 1996 UC San Diego Open. We believe that the wind conditions were very different in these two meets. Because of this, we would lose important information if we kept all the throws pooled together. To improve our understanding of the aerodynamic effects on the analyzed throws, we will now examine separately the data from the two competitions.

At the 1994 USA Track & Field Championships, the actual distance of the throws (D = 57.75 ± 2.83 m) was shorter than the distance predicted for a vacuum (D_V = 58.85 ± 1.95 m); the effect of the aerodynamic forces was ΔD = -1.10 ± 1.38 m. The negative value of ΔD, together with the poor general results of this meet in comparison with previous years, strongly suggests that there was a tailwind during the competition. This is also supported by the small size of the standard deviation of ΔD (±1.38 m), which indicates that the (generally negative) effect of the air was similar for most throwers. In this competition, the ability or inability of a thrower to attain a tilt angle close to the optimum probably did not have much effect on the results.

The 1996 UC San Diego Open was very different. The average distance of the throws (D = 58.67 ± 2.99 m) was longer than the predicted distance in a vacuum (D_V = 54.37 ± 2.98 m); the effect of the aerodynamic forces was ΔD = 4.30 ± 2.06 m. The large positive value of ΔD, together with the outstanding results of the meet (11 of the 19 athletes analyzed in this competition broke their personal records during the meet), strongly suggests that there was a headwind during this competition. (Although there had been a noticeable headwind earlier, during the women's competition, it seemed to calm down for the men's competition. However, these were perceptions at ground level. The above results strongly suggest that a headwind lingered at the higher levels of the discus flight during the men's competition.) The presence of a strong headwind is also supported by the large size of the standard deviation of ΔD (±2.06 m), which indicates that the effect of the aerodynamic forces was very different for different throwers at this competition: At the extremes, one thrower gained only 0.63 m, while another gained 8.31 m. In this competition, the ability or inability of a thrower to attain a tilt angle close to the optimum seemed to play a tremendous role in the results.

[Note for other researchers (coaches and athletes can skip this paragraph): We had not originally planned to measure the 3-D tilt of the discus in the analyzed throws, but we tried after we saw the large effects of the aerodynamic forces on the distance of the throws at the UC San Diego Open. However, the measurements were not accurate enough for our purposes. In that meet, our cameras were not positioned in the best locations to facilitate such measurements. Both were shooting from the back of the circle, about 45° on either side of the line that cut the circle into right and left halves. It probably would have been better to have one camera shoot directly from the back of the circle and another one from the right side, which is what we usually do. However, buildings located next to the throwing site did not allow this. We are not sure if our usual camera set-up would have been good enough either; it is possible that measuring the tilt of the discus with the necessary accuracy may require marking the discus with colored paint or with thin tape of some sort.]

The effect of the wind on the distance of a throw is affected by the angle of tilt of the discus, and also by the intensity of the wind. It is possible that fluctuations in the speed of the wind may have contributed in part to the large differences between throws with respect to the value of ΔD during the

1996 UC San Diego Open competition. However, it is also necessary to keep in mind, as pointed out earlier, that a deviation of only 7-10° from the optimum angle of tilt when throwing into a 10 m/s headwind can produce a loss of about 7 meters in a 60-meter throw. This makes it very possible that the differences in the value of ΔD were due to different amounts of deviation from the optimum angle of tilt.

Discus throwers should strive to release the discus with an optimum angle of tilt. This generally means a downward tilt of the forward edge of the discus relative to the direction of motion of the discus at release. (We might think of this as a "thumb-down" position.) The use of an optimum angle of tilt will be particularly important in meets where the discus is thrown into a headwind.

SPECIFIC RECOMMENDATIONS FOR INDIVIDUAL ATHLETES

Andy BLOOM

Trial 41 was Bloom's third-best throw at the 1996 UC San Diego Open (59.18 m, 2½ meters off from his best throw of the meet). We could not film Bloom's 61.64 m best throw nor his 59.50 m second-best throw at San Diego, but trial 41 was probably reasonably representative of his best throwing that day.

At the back of the circle, Bloom shifted the system c.m. toward his left foot. Then, he drove with the left leg against the ground. By the time that the left foot lost contact with the ground, the thrower-plus-discus system had a good amount of horizontal speed (v_{HLTO} = 2.6 m/s), and the direction of travel of the system c.m. was almost perfectly in the forward direction (i.e., not diagonal) (a_{LTO} = 1°). After the landing of the right foot, the loss of horizontal speed during the single-support was larger than in most other throwers (Δv_{SSR} = -0.7 m/s). This still left Bloom with a reasonable amount of horizontal speed at the instant that the left foot landed (v_{HLTD} = 1.9 m/s).

During the double-support delivery, Bloom made a forward and downward force on the ground. The backward horizontal reaction force reduced his horizontal speed (for the period of the last quarter-turn of the discus) to an amount which was somewhat conservative, although not terribly small either (v_{HQ} = 1.2 m/s). Due to Bloom's very direct-forward general direction of travel across the throwing circle, the c.m. of the system was still traveling almost perfectly forward (a_Q = -3°). Although the ultimate direction of motion of the discus at release pointed somewhat too far toward the right (d_{HREL}= 14°), the divergence angle between the directions of motion of the system and of the discus was still quite small (c_Q = -16° —this number is correct; the 1° discrepancy from the 17° difference expected from the previous two values is just the result of rounding-off). Because of the small size of the divergence angle, the contribution of the horizontal speed of the system to the horizontal speed of the discus (v_{HCON} = 1.1 m/s) was almost as large as the value of v_{HQ} itself. The value of v_{HCON} was similar to the average for the throwers in our sample.

The downward force that Bloom made against the ground during the double-support delivery was very large, and the upward vertical reaction to this force gave the system a good amount of vertical speed which contributed to increase the vertical speed of the discus (v_{ZCON} = 1.6 m/s). The overall combination of all the actions described up to here was reasonably good.

The swinging action of the right leg at the back of the circle was somewhat weak (RLA = 22.3 $\cdot 10^{-3}$ Kg·m²/Kg·m²). The swinging action of the left arm was extremely weak (LAA = 26.8 $\cdot 10^{-3}$ Kg·m²/Kg·m²). This was due to the fact that at the instant that the discus reached its most backward position at the end of the last preliminary swing, the position of the shoulders was not very clockwise-rotated, and also the left arm was more or less aligned with the shoulder axis, and not in front of the chest. This left a reduced range of motion for the subsequent counterclockwise swing of the left arm. Because of the weak individual actions of the right leg and particularly of the right arm, their combined action was also very weak (RLLAA = 49.1 $\cdot 10^{-3}$ Kg·m²/Kg·m²). At the instant of landing of the left foot in the front of the circle, the system had only 73% of the Z angular momentum (counterclockwise rotation in a view from overhead) that it would eventually reach at release. This was much lower than in any other thrower. Of course, Bloom then proceeded to "make up for lost ground", and gained a very large amount of Z angular momentum during the double-support delivery phase. The main question here is whether he was able to fully compensate during the double-support delivery for the previous "lost ground". (See the long jump analogy in pages 7-8 and in page 24.) We think that maybe he was not.

The recovery actions of the legs in the middle of the throw ($r_{LAVG-NSRSS}$ = 9.9% of standing height) were near the average, and therefore we consider them to be reasonably good. The recovery action of the left arm was very good (H_{LA-NS} = 21 $\cdot 10^{-3}$ s^{-1}): Bloom slowed down this arm very well during the non-support phase in the middle of the throw. It is too bad that, due to its previous weak swinging action in the back of the circle, it did not have more angular momentum to yield to the rest of the body at this time.

The second propulsive swing of the left arm (LAA2 = 18.5 $\cdot 10^{-3}$ Kg·m²/Kg·m²), the maximum angular momentum that this arm reached (H_{MAX} = 67 $\cdot 10^{-3}$ s^{-1}) and its subsequent slowing down (ΔH = -37 $\cdot 10^{-3}$ s^{-1}) were all reasonably good, not very different from those of the average thrower in our sample.

At release, the Z angular momentum of the discus was 31.9 Kg·m²/s, almost identical to the average value for the whole sample of throwers (31.8 Kg·m²/s). Since the contribution of the horizontal speed of the system to the horizontal speed of the discus was also near average (v_{HCON} = 1.1 m/s, as we saw before), we expected the horizontal speed of the discus at release to be more or less average also. However, the horizontal speed of the discus in Bloom's throw was one of the largest in the sample, much larger than the average (Bloom v_{HD} = 20.5 m/s; average = 19.3 m/s). We think that part of the explanation for this apparent discrepancy lies in Bloom's lean. In the view from the back, Bloom was leaning somewhat toward the left at the instant of release. This shifted the right shoulder toward the left, and in the view from overhead brought the discus nearer to the system c.m. For a given amount of Z angular momentum of the discus, the shorter the distance (in the view from overhead) between the system c.m. and the extension of the line of travel of the discus (which is roughly forward at release, in the view from overhead), the faster the horizontal speed of the discus. By tilting his body toward the left near the instant of release, Bloom shortened the distance between the c.m. and the discus (in effect, he shortened the radius of motion of the discus), and thus increased the horizontal speed of the discus. (Yes, we realize that discus throwers are generally told to maintain the longest possible radius for the discus during the entire throw. However, we feel that this advice needs to be modified. We agree that the radius of the discus should be maintained at the longest possible length during most of the throw. But we think that it should be shortened for a brief period of time *immediately prior to release*, because this will increase the speed of the discus. It is important that this shortening occur only near the release, and not sooner. At this time, we are not going to go out of our way to instruct discus throwers to do such a thing, because more research is needed on this question —notice that we did not include it in the main body of the report; we had to refer to it here in order to explain how Bloom managed to give a very large horizontal speed to the discus with only a moderate amount of Z angular momentum.)

At release, in the view from the back of the circle the counterclockwise angular momentum of the thrower-plus-discus system (H_{YS} = 51.4 Kg·m²/s) was somewhat larger than average. However, Bloom only transfered a very small fraction of it to the discus (27% of the total). Therefore, the Y angular momentum of the discus at release was very small (H_{YD} = 13.7 Kg·m²/s). In spite of the good contribution of the vertical speed of the system c.m. to the vertical speed of the discus (v_{ZCON} = 1.6 m/s, as we saw before), the small Y angular momentum of the discus resulted in a very small vertical speed of the discus at release (v_{ZD} = 12.0 m/s), and this shortened the distance of the throw. The poor transfer of Y angular momentum from the body to the discus is illustrated in the back view sequence of the throw: Between t = 10.18 s and t = 10.24 s, the right arm seemed to lag too far behind the counterclockwise tilting of the trunk, not able to catch up and overtake the trunk as quickly as it should have. We are not sure what caused this problem. One possibility is that the orbit of the discus may not have been tilted enough during the last 3/4 of a turn: not high enough at the high point (t = 9.88/9.94 s), and not low enough at the low point (t = 10.16 s). However, we are not sure of this. Another possibility is that Bloom simply may not have used the deltoid muscle of his right shoulder strongly enough during the final acceleration of the discus, either through error or through a relative weakness of that muscle.

Bloom achieved a well wound-up position in the single-support over the right foot ($k_{RA/FT}$ = -158°). This was good, because the subsequent unwinding helped him to transfer angular momentum from the body to the discus. The main advantage of Bloom with respect to the average thrower at the instant of maximum torsion of the system was in the torsion of the shoulders relative to the hips, which was extremely large (Bloom $k_{SH/HP}$ = -84°; average = -58°). This and the reasonable torsion of the hips relative to the feet (Bloom $k_{HP/FT}$ = -58°; average = -51°) more than compensated for the weak torsion of Bloom's right arm relative to the shoulders (Bloom $k_{RA/SH}$ = -16°; average = -34°).

Bloom made very good use of aerodynamic forces (ΔD = 6.53 m).

Summary

The horizontal translation of the system c.m. was very direct forward. The contribution of the horizontal speed of the system to the horizontal speed of the discus was slightly smaller than average, while the contribution of the vertical speed of the system to the vertical speed of the discus was slightly larger than average. Therefore, this part of his technique was overall reasonably good. The combined swinging actions of the right leg and left arm at the back of the circle were weak. The amount of Z angular momentum generated at the back of the circle was very small. This was followed by a large increase at the front of the circle. Bloom gave a very large amount of horizontal speed to the discus. The recovery actions of the legs after the takeoff of the left foot from the ground were reasonably good. The recovery action of the right arm was very good. The second swing and recovery of the left arm were average. During the single-support on the right foot and the double-support delivery, Bloom obtained a reasonably large amount of Y angular momentum, but he did not transfer enough of it to the discus. This made the vertical speed of the discus at release be very small. Bloom achieved a well wound-up position in the single-support on the right foot, thanks primarily to the large torsion of his shoulders relative to his hips. The subsequent unwinding probably helped Bloom in the transfer of Z angular momentum to the discus. Bloom's use of aerodynamic forces was very good.

Recommendations

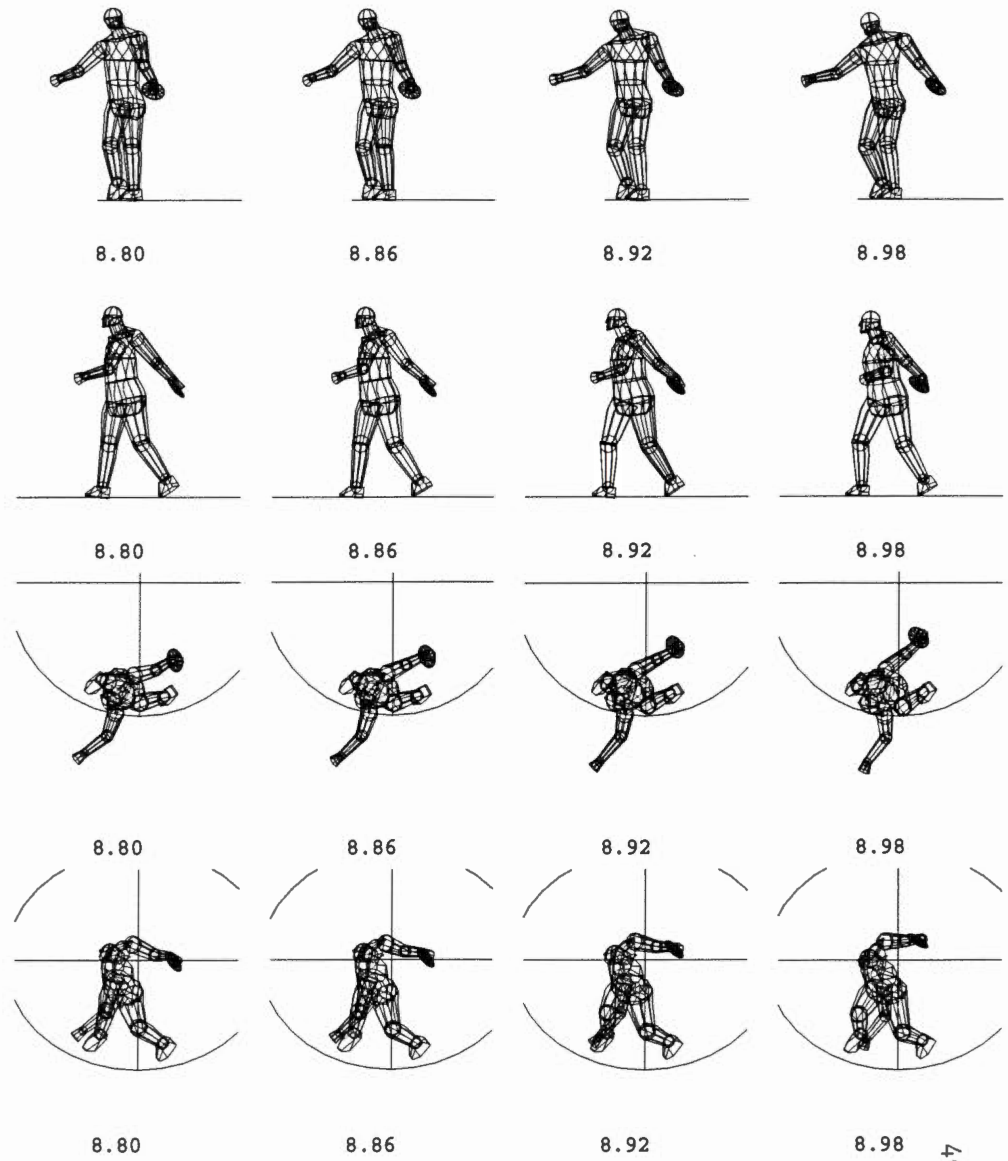
In throw 41, Bloom generated a relatively small amount of Z angular momentum in the back of the circle, and then added a large amount to that through his actions in the front of the circle. If Bloom had generated a larger amount of Z angular momentum in the back of the circle, the amount that he would have been able to add in the front would have been smaller than in throw 41. However, we think that the ***total*** amount might have been larger. In other words, we think that in throw 41 he may have fallen too far behind in his generation of Z angular momentun at the back of the circle, and then was not quite able to catch up at the front, in spite of the tremendous increase of Z angular momentum that he achieved at the front.

To correct this very likely problem, at the back of the circle Bloom should keep both arms higher (at shoulder level) during the last preliminary swing. At the time that the discus reaches its most backward position, Bloom should have much more torsion in his body, with the shoulders rotated markedly clockwise relative to the hips, and the left arm should be in front of the chest. (For example, see the position reached by Setliff at that instant.) Then, Bloom should throw the left arm strongly counterclockwise during the double-support phase and the single support phase on the left foot, without any bend at the elbow. He should also swing the right leg harder counterclockwise during the single-support on the left foot. All this will help him to generate more Z angular momentum at the back of the circle. We think that the final result will be a larger amount of Z angular momentum in the system at the end of the delivery than in throw 41. This will make it easier for Bloom to transfer more Z angular momentum to the discus, which in turn will help to increase the horizontal speed of the discus.

The other main problem in Bloom's technique was the small amount of Y angular momentum that he transfered to the discus during the second half of the double-support delivery phase. This resulted in a very small vertical speed of the discus at release. To correct this important problem, we think that he should start off by establishing a more tilted plane of motion for the discus during the final turn. For this, he should lift the discus higher at the high point of the orbit (see the sequence at about t = 9.88/9.94 s), and then bring the discus down to a lower position at the low point of the orbit (see the sequence at about t = 10.16 s). Finally, he should concentrate on propelling the discus forward but also ***more upward*** during the final part of the delivery.

The torsion angle of the hips relative to the feet was reasonable good at the instant of maximum torsion of the system during the single-support on the right foot, and the torsion angle of the shoulders relative to the hips was excellent. However, Bloom should try to increase the torsion angle of the *right arm relative to the shoulder axis*, by keeping the right arm farther back. This will increase the overall torsion of the system —it will produce a more wound-up position. The subsequent unwinding of the system will then allow Bloom to drive the discus over a longer range of motion during the final acceleration, and thus to impart more speed to the discus, which in turn will result in a longer throw.

BLOOM #41 59.18 M 033096



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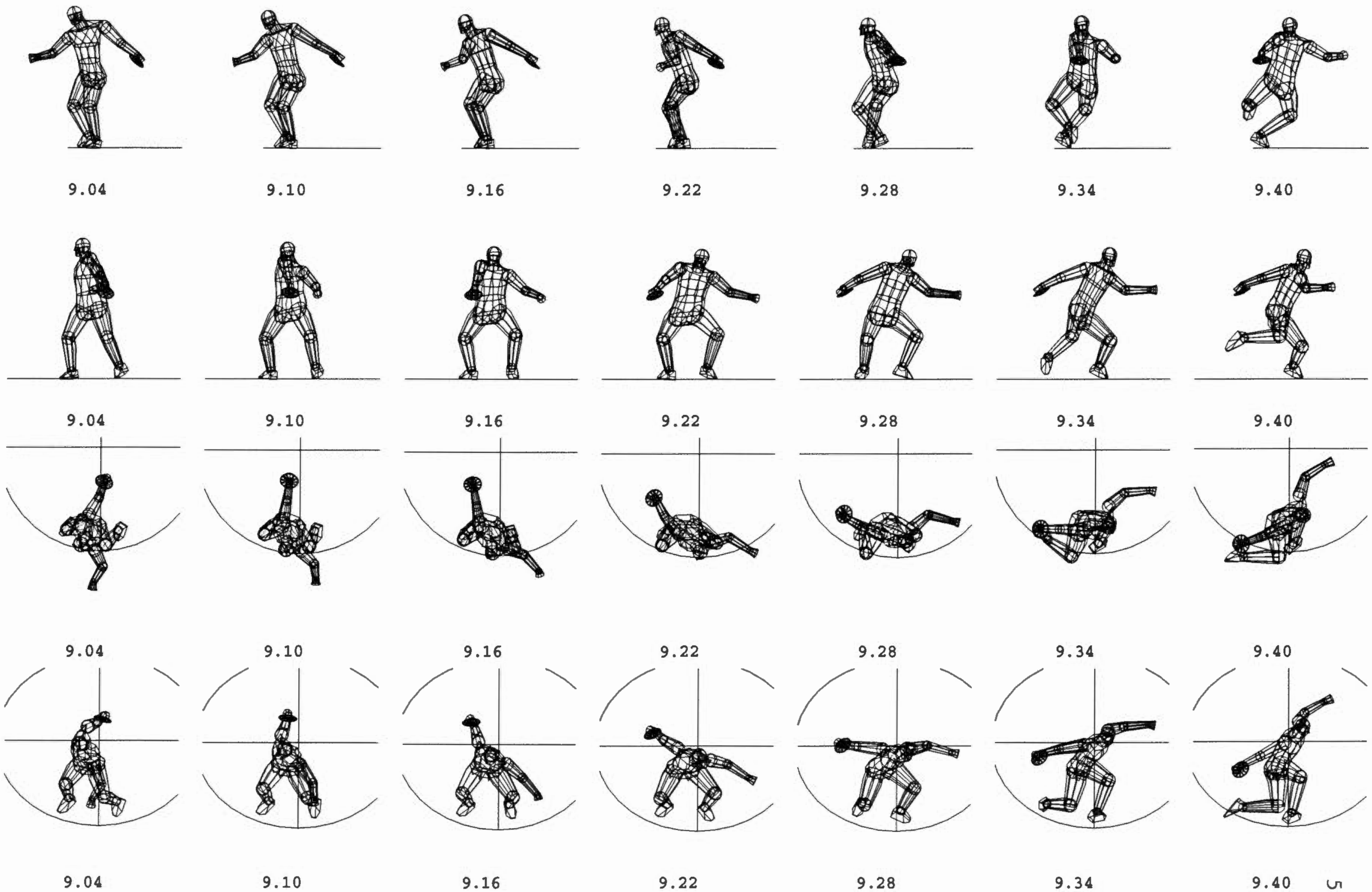

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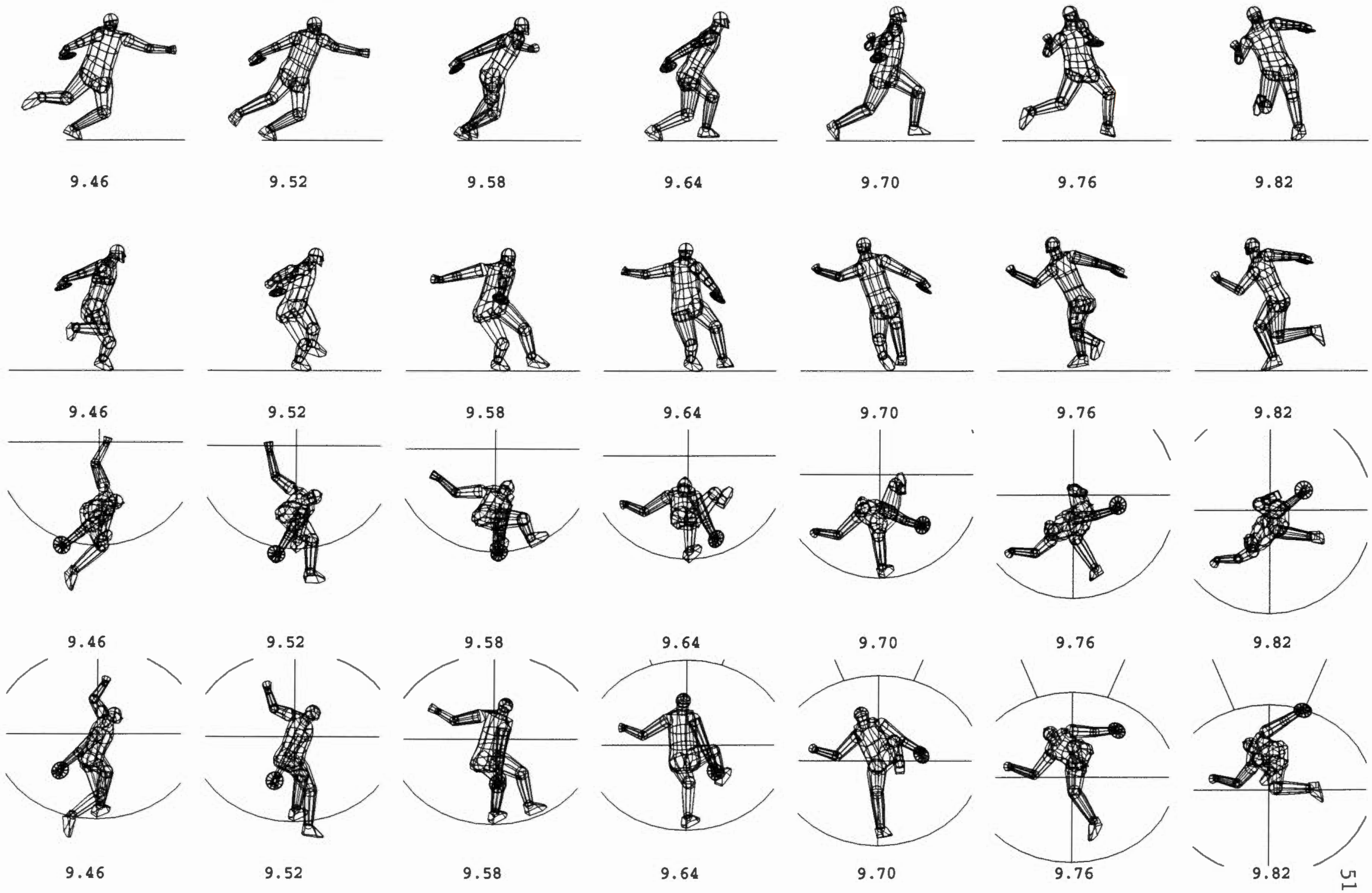

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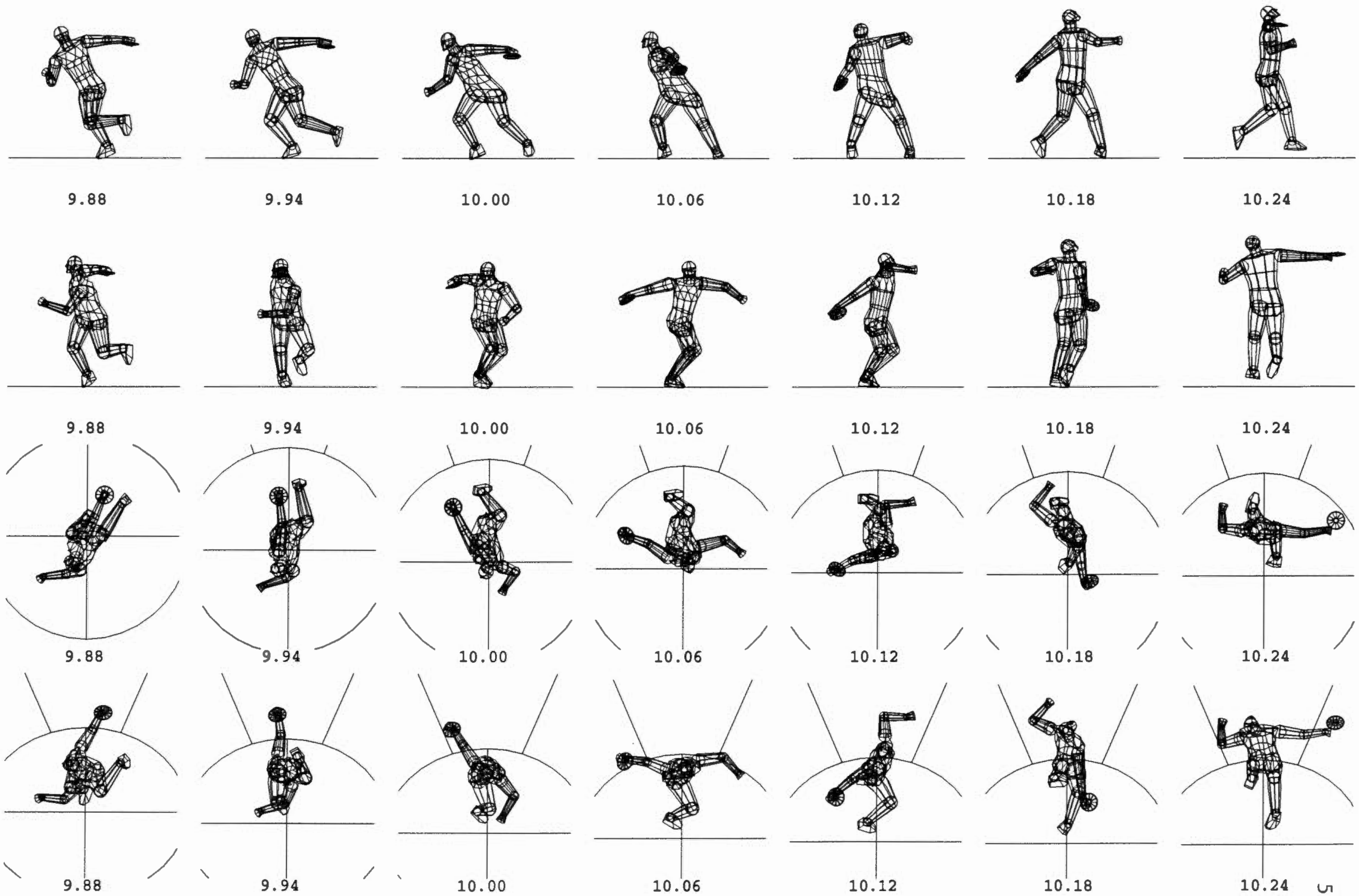

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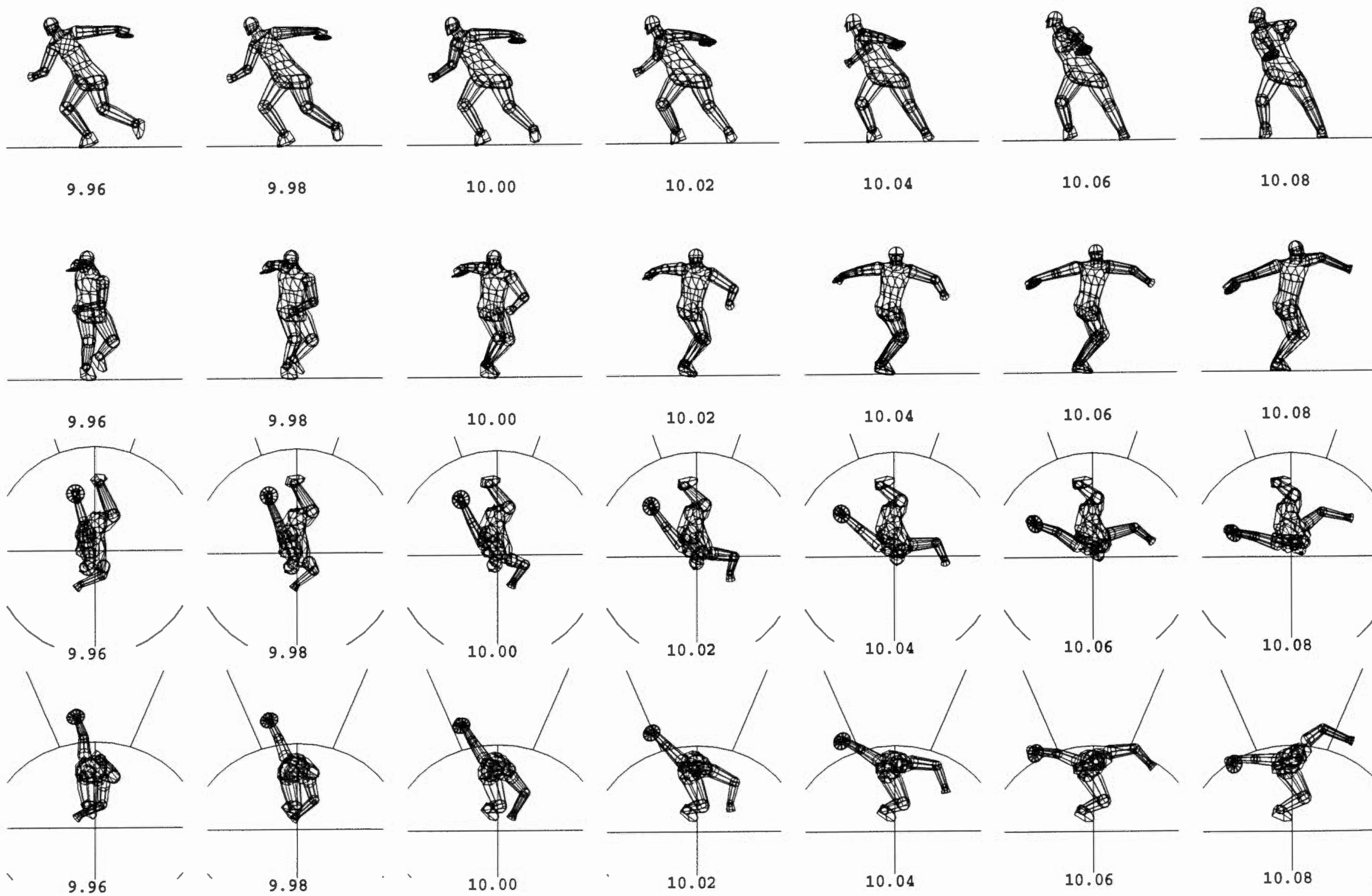

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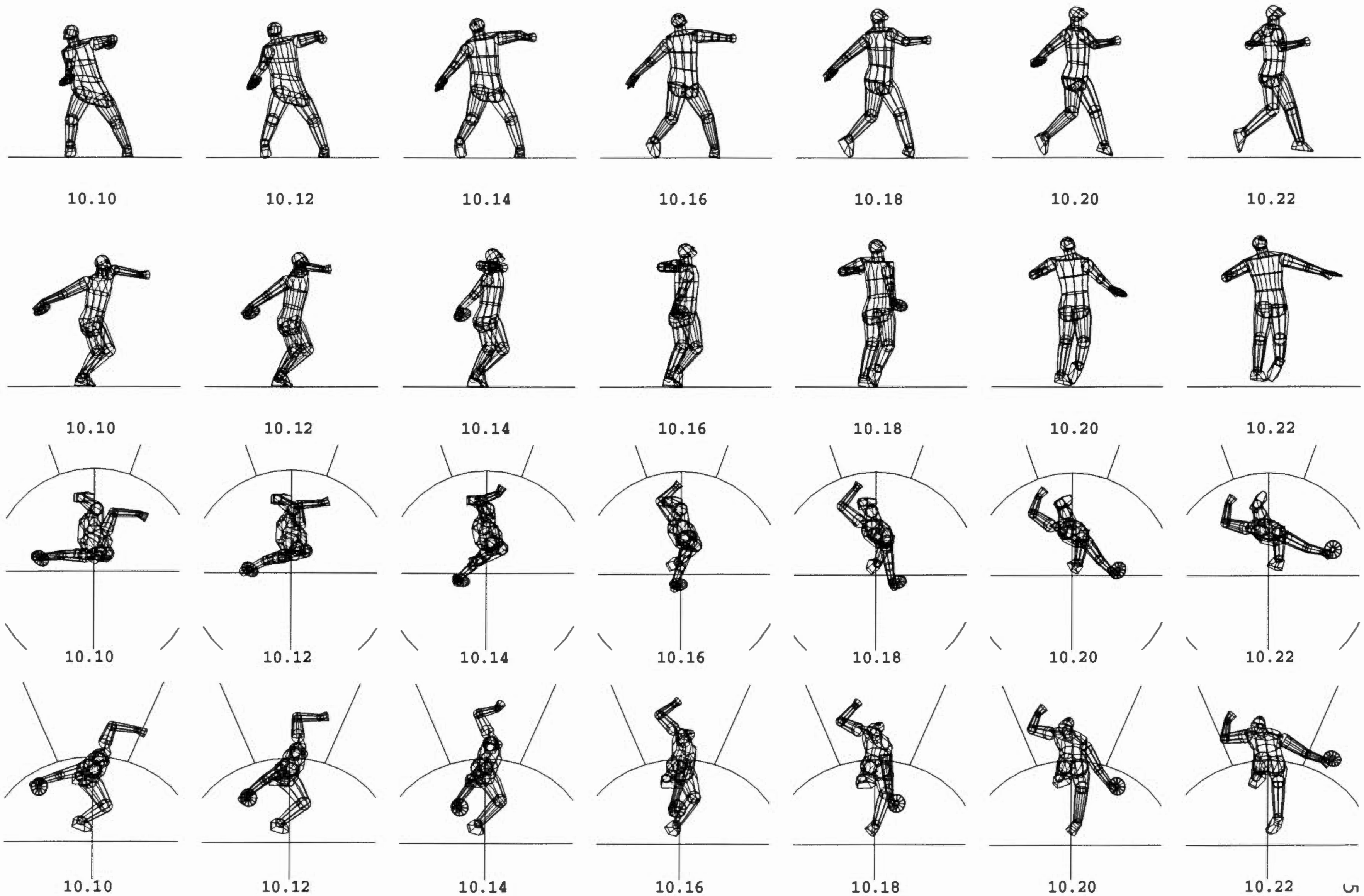

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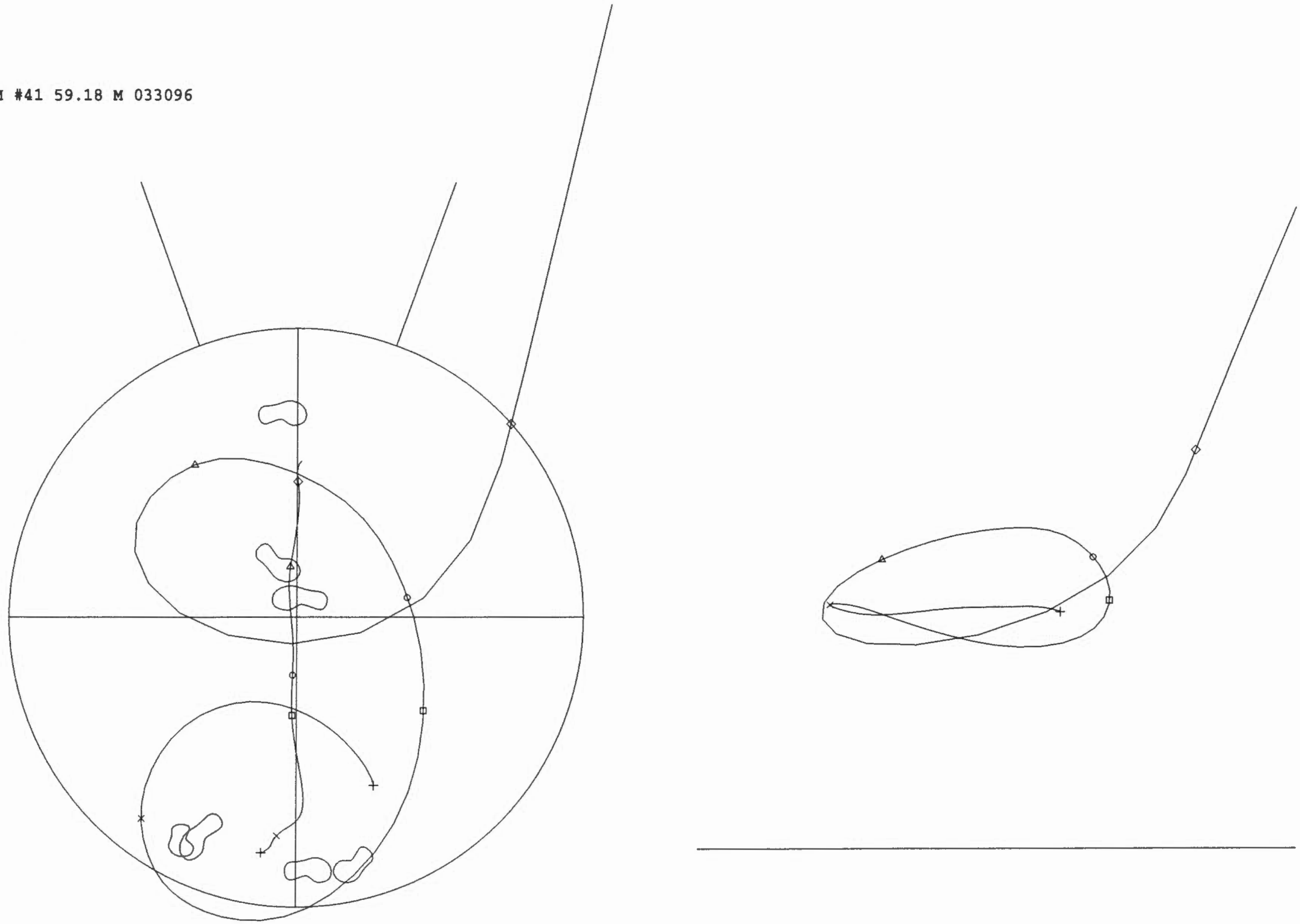

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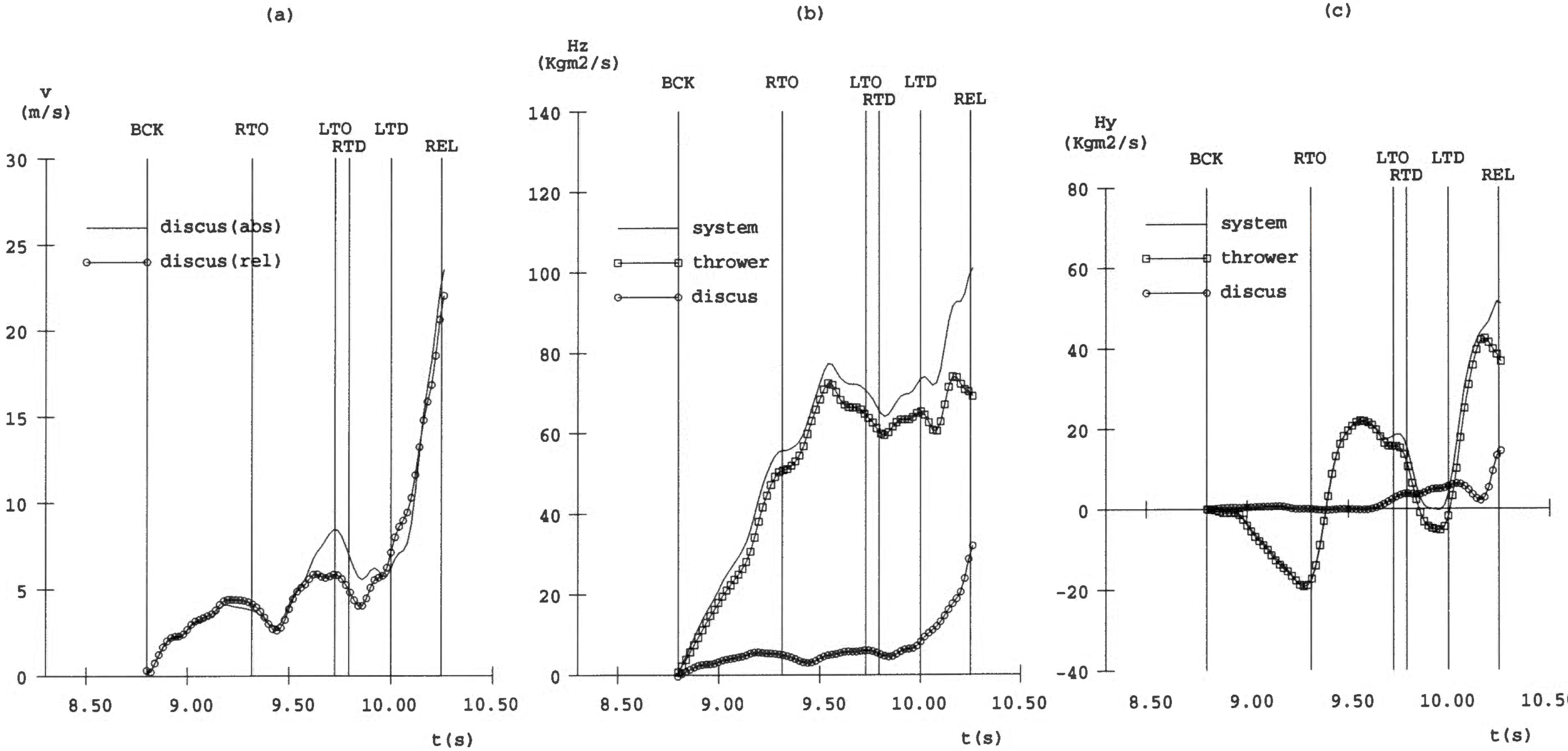
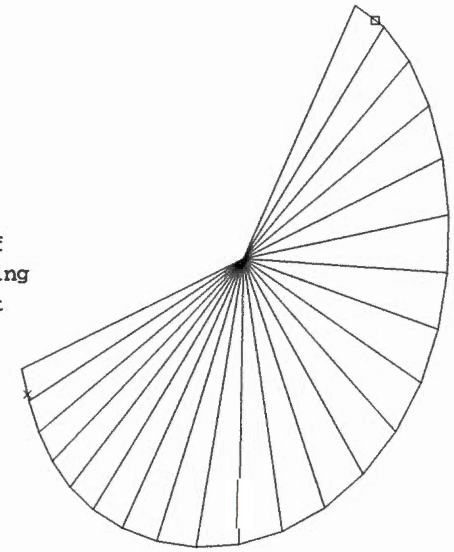
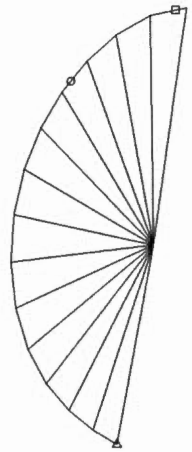


BLOOM #41 59.18 M 033096

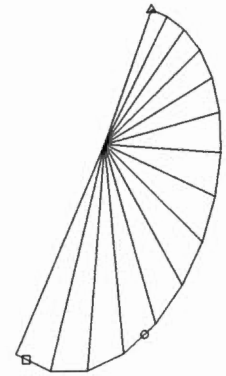
25% of
standing
height



drive of right leg

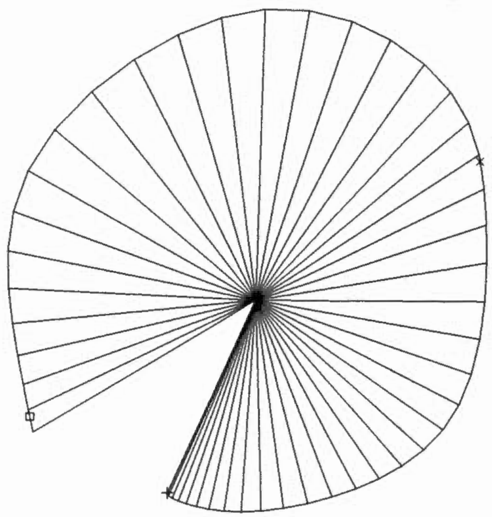


recovery of right leg

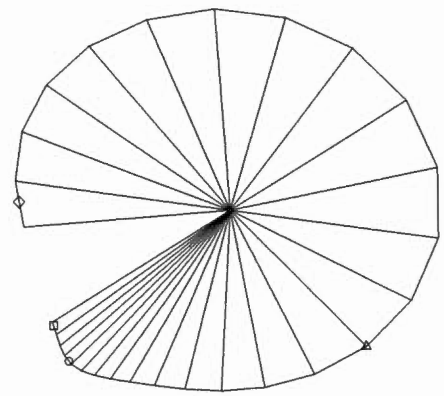


recovery of left leg

50% of
standing
height

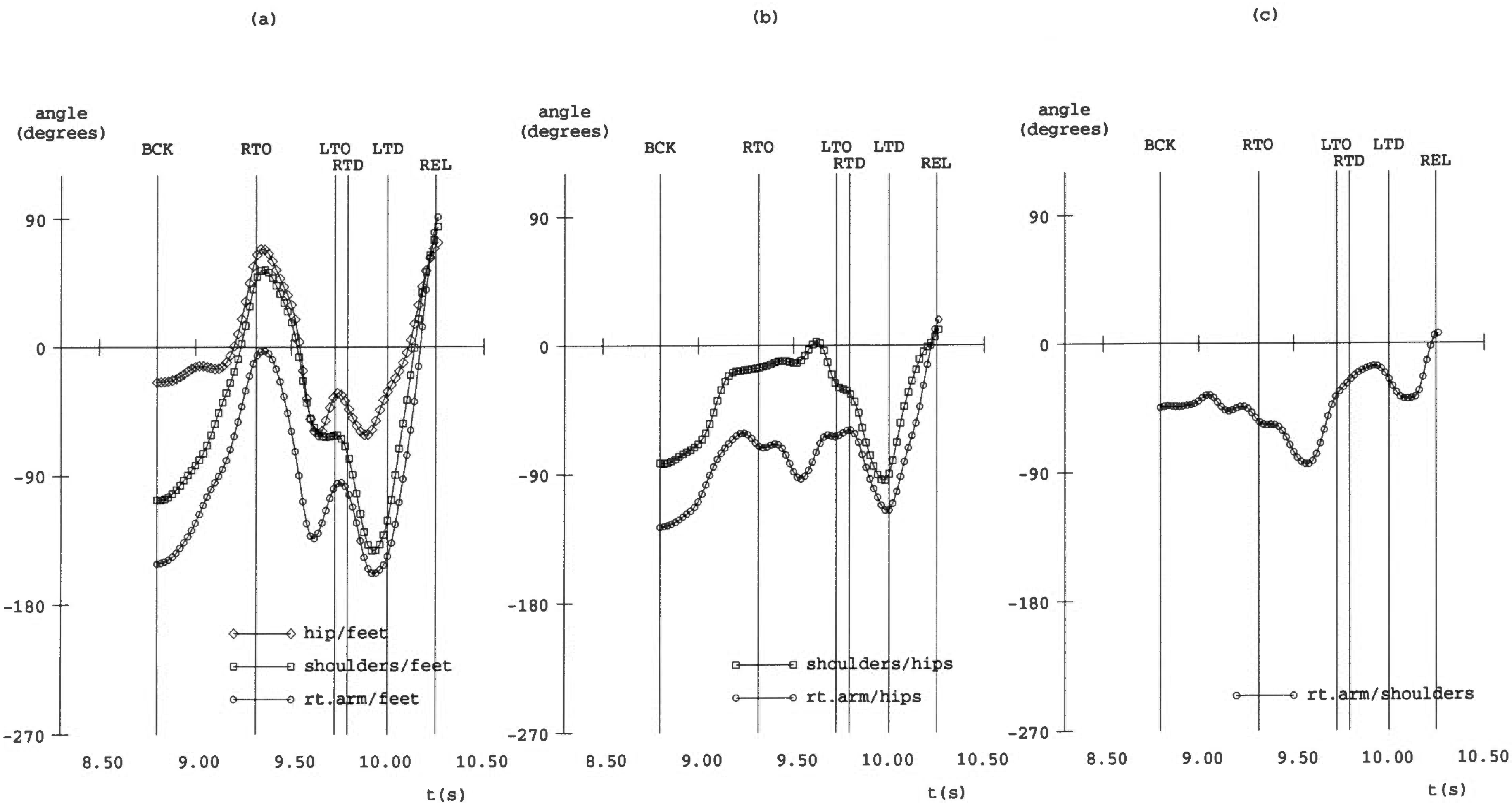


drive of left arm



recovery of left arm, and action during
right foot single-support and delivery

BLOOM #41 59.18 M 033096



Gregg HART

Trial 57 was Hart's personal record, 61.92 m, thrown at the 1996 UC San Diego Open.

At the back of the circle, Hart did not shift his c.m. enough toward his left foot. This made him follow a very diagonal path across the throwing circle (a_{LTO} = -31°; a_{LTD} = -28°). His horizontal speed across the circle was somewhat slow (v_{HLTO} = 2.2 m/s; v_{HLTD} = 1.9 m/s). The markedly diagonal direction of the path ultimately led to a large divergence angle between the directions of motion of the system and of the discus (c_Q = -31°). A large divergence angle tends to produce a large reduction in the contribution of the horizontal motion of the system to the horizontal speed of the discus. However, this contribution was fairly large in Hart's throw (v_{HCON} = 1.3 m/s). This was because the forward horizontal force that Hart made on the ground during the double-support delivery was small, and thus allowed the thrower-plus-discus system to retain a large amount of its horizontal speed for the last quarter-turn of the discus (v_{HQ} = 1.5 m/s). To a great extent, the rather large horizontal speed of the system compensated for the large divergence angle, and allowed the system to make a good contribution (v_{HCON} = 1.3 m/s) to the horizontal speed of the discus. However, the size of the vertical force made on the ground during the double-support delivery phase is generally linked to the size of the horizontal force made on the ground during that same period; therefore, the vertical force that Hart made on the ground during the double-support delivery was small. As a result, the vertical speed of the system during the last quarter-turn (and therefore the contribution of the vertical motion of the system c.m. to the vertical speed of the discus) was very small (v_{ZCON} = 0.9 m/s). In summary, Hart pushed weakly on the ground during the delivery phase, both in the horizontal and vertical directions. This allowed him not to lose very much horizontal speed, but it also made him unable to generate much vertical speed.

The swinging actions of the right leg and of the left arm at the back of the circle were reasonably good (RLA = 23.5 · 10^{-3} Kg·m²/Kg·m²; LAA = 36.2 · 10^{-3} Kg·m²/Kg·m²; RLLAA = 59.7 · 10^{-3} Kg·m²/Kg·m²). At the instant of landing of the left foot in the front of the circle, the system had 89% of the Z angular momentum (counterclockwise rotation in a view from overhead) that it would eventually reach at release. All this suggests that Hart's *rotational* efforts in the back of the circle were good.

The recovery actions of the legs were not good. The legs remained spread out too far apart in the middle part of the throw after the takeoff of the left foot ($r_{LAVG-NSRSS}$ = 10.8% of standing height). In comparison with other throwers, the left leg was particularly far from the longitudinal axis of the system ($r_{LL-NSRSS}$ = 10.1% of standing height). The counterclockwise path followed by this leg around the body from the instant when it took off from the ground until its landing in the front of the circle was too wide. (Compare with the leg recovery actions of Johnson or Setliff, who did this very well.) The wide paths followed by Hart's legs contributed to slow down their counterclockwise rotation, which in turn decreased the rotational lead of the feet over the hips (and, vice versa, the amount of torsion of the hips relative to the feet) at the instant of maximum torsion of the system ($k_{HP/FT}$ = -25°, much smaller than the average value of -51°). Although the torsion of the shoulders relative to the hips ($k_{SH/HP}$ = -57°) and the torsion of the right arm relative to the shoulders ($k_{RA/SH}$ = -38°) were similar to those of other throwers, the total torsion ($k_{RA/FT}$ = -120°) was much smaller than average (-144°), due mainly to the small torsion of Hart's hips relative to his feet.

The recovery of Hart's left arm was not good either (H_{LA-NS} = 52 · 10^{-3} s^{-1}, which was too large). The left arm was kept very far out during the non-support phase, and it did not slow down its rotation enough. This means that it did not make available (i.e., did not transfer) much of its own angular momentum to the rest of the system, and therefore it did not contribute much to the rotation of the lower body during the non-support phase. In contrast, Hart's second propulsive swing of this arm was one of the very best (LAA2 = 23.6 · 10^{-3} Kg·m²/Kg·m²), and the arm reached a large maximum angular momentum (H_{MAX} = 71 · 10^{-3} s^{-1}). However, it still had too much of that angular momentum left at release (H_{REL} = 38 · 10^{-3} s^{-1}), which implies that Hart did not slow this arm down enough: ΔH = -34 · 10^{-3} s^{-1}, close to average, but not nearly as good as the excellent second swing of this arm might have led us to expect.

At release, the discus had 34% of the total Z angular momentum of the thrower-plus-discus system. This was well within normal bounds, and suggests that Hart did a good job transfering Z angular momentum from the thrower's body to the discus. He was able to give a very good amount of horizontal speed to the discus (v_{HD} = 20.2 m/s).

The initial path of the discus at release was rather shallow (d_{VREL} = 33°). In part, this was due to the large horizontal speed of the discus, which was good. But in part it was also due to the rather small size of the vertical speed of the discus (v_{ZD} = 13.1 m/s), which was not so good. To some extent, the small vertical speed of the discus at release was due to the small vertical speed of the system c.m. which we discussed previously. However, most of it was due to an insufficient transfer of Y angular momentum from the body to the discus during the final part of the delivery: At release, the thrower-plus-discus system had a reasonably good amount of counterclockwise angular momentum in the view from the back of the circle (H_{YS} = 51.5 Kg·m²/s), but too much of it (H_{YT} = 34.3 Kg·m²/s, or 67% of the total) was in the thrower, and too little (H_{YD} = 17.2 Kg·m²/s, or 33% of the total) in the discus.

Hart's use of aerodynamic forces was very good (ΔD = 6.05 m).

Summary

Hart did not shift his c.m. enough toward the left foot at the back of the circle, and this made him follow a very diagonal path across the throwing circle. During the double-support delivery, he did not push very hard on the ground with his legs, which allowed him to retain more of his horizontal speed, but prevented him from generating much vertical speed. Hart's rotational actions at the back of the circle were good. He kept his legs too far apart after the takeoff of the left foot in the middle of the throw. This decreased the speed of rotation of the legs, and thus decreased the torsion of the system. The second swing of the left arm was good, but it did not slow down enough before release. The transfer of Z angular momentum to the discus was good, but the transfer of Y angular momentum was weaker. Hart's use of aerodynamic forces was very good.

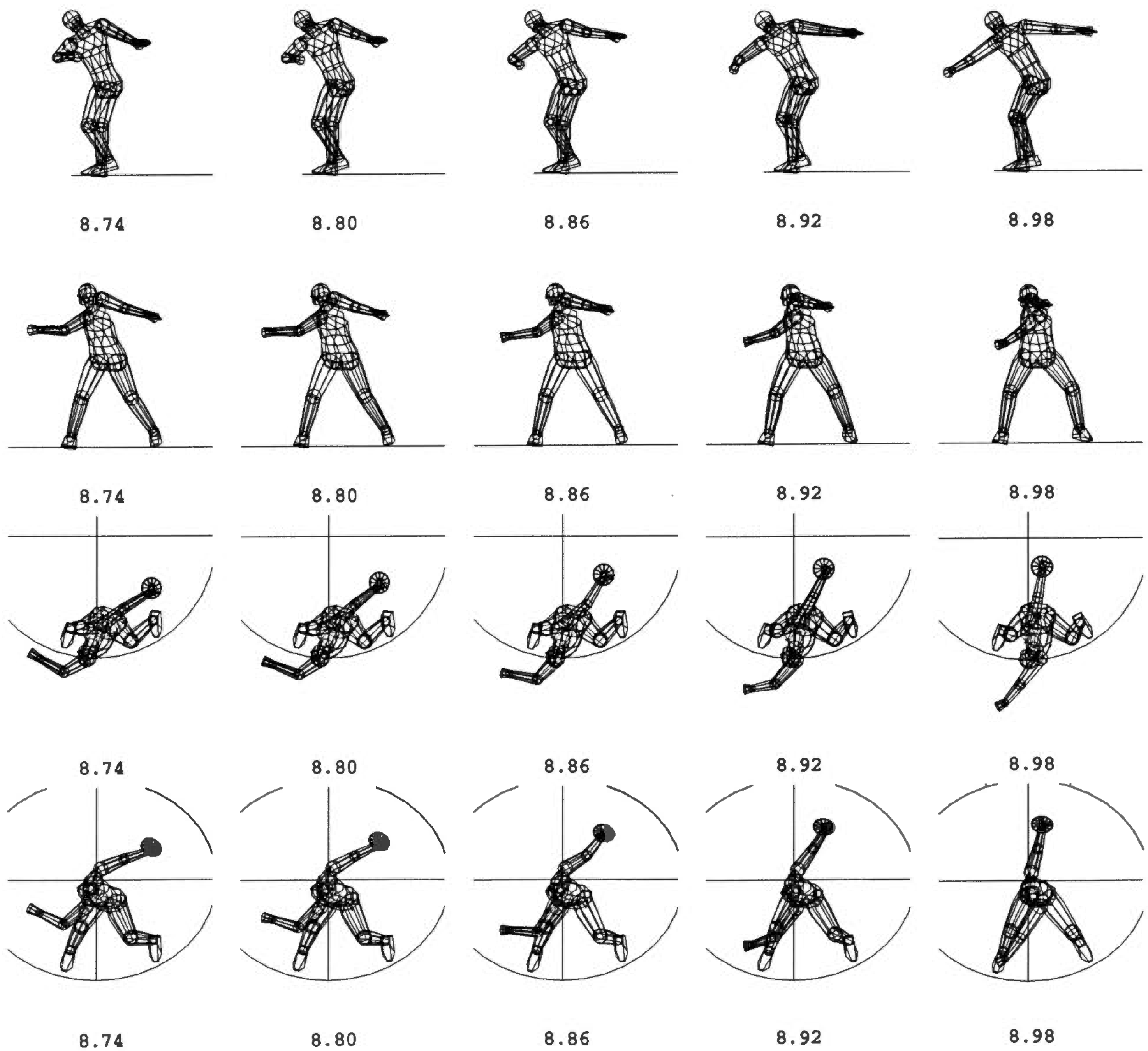
Recommendations

Ultimately, the source of Hart's difficulties in generating vertical speed for the system during the double-support delivery may have been the insufficient shift of his c.m. toward the left foot at the back of the circle before the main drive of the left leg. At the back of the circle, Hart "sat" backward too much before starting to shift the system c.m. toward his left foot. (See the overhead view of the path of the system c.m.) We think that this may have forced him to start prematurely the main push with the left foot before the c.m. was close enough to the vertical of that foot. To avoid this problem, Hart should *first* shift the system c.m. toward the left foot, with very little "sitting back". That will allow the c.m. to get closer to the vertical of the left foot. These changes should then allow him to drive his body more directly *forward* across the circle. He should also push *harder* across the circle. Later on, in the front of the circle, Hart should push very hard forward and downward with his left leg, and he should also try to extend his right leg. These actions will make him lose more horizontal speed than in throw 57 (but he will *need* to lose more horizontal speed than in that throw anyway, because otherwise his new larger horizontal speed will make him foul), and they will leave him with just about the right amount of horizontal speed to provide help for the horizontal speed of the discus in the last quarter-turn, and still avoid fouling. This will be about the same speed that Hart had left in throw 57 (v_{HQ} = 1.5 m/s), but through the more active use of his legs, he will be able to generate a larger amount of vertical speed for the system c.m., which will contribute to increase the vertical speed of the discus.

After the takeoff of the left foot in the middle of the throw, the left leg should be brought very quickly to a position below the body, and from there follow an almost direct line to the point where the left foot is to be planted on the ground. The compact configuration of the legs in the view from overhead will help the lower body to rotate ahead of the upper body, and should allow Hart to reach a more wound-up position at the time that the final acceleration of the discus starts during the single-support on the right foot. This should allow him to drive the discus over a longer path during the final acceleration, which should produce a larger release speed for the discus, and a longer throw.

During the delivery, Hart should give more vertical speed to the discus. In part this can be achieved through the stronger downward and forward actions of the legs against the ground, but in part it will need to be achieved through a greater activity of the deltoid muscle of the right arm (i.e., by throwing the right arm more upward during the last part of the delivery). It will also be greatly facilitated by a marked slowing down and/or a reduction in the radius of the left arm shortly before the release of the discus.

HART #57 61.92 M 033096



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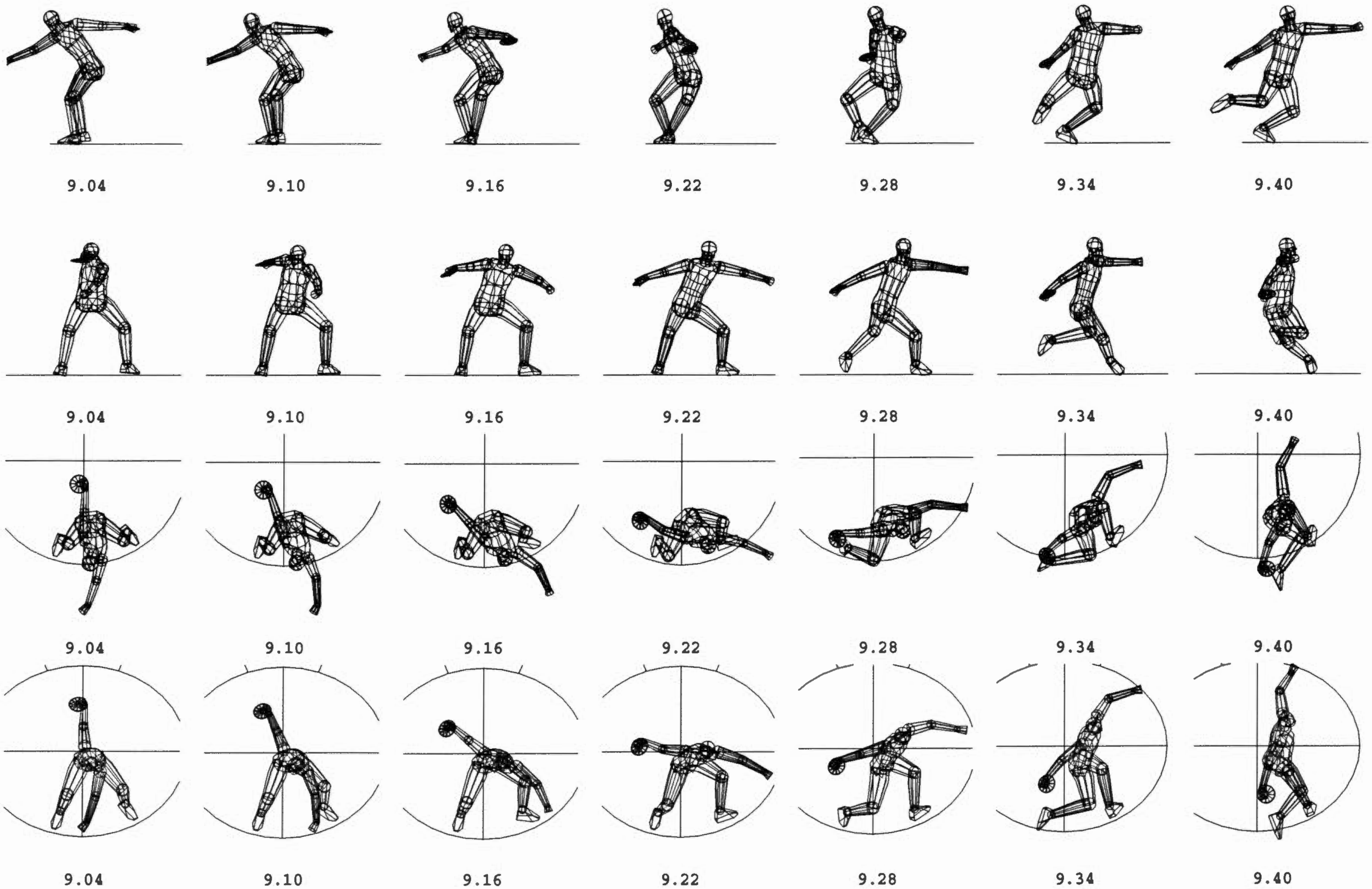

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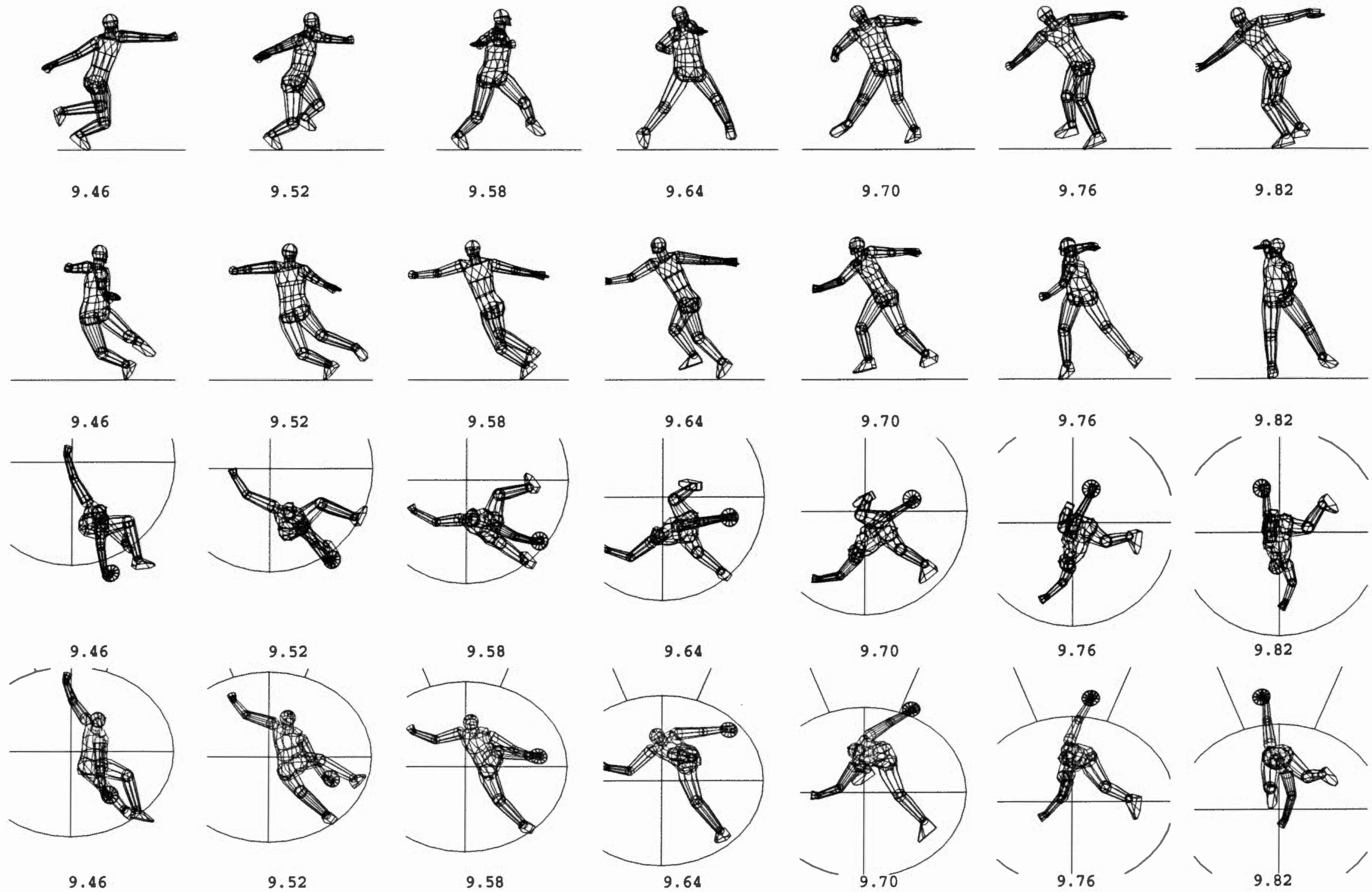

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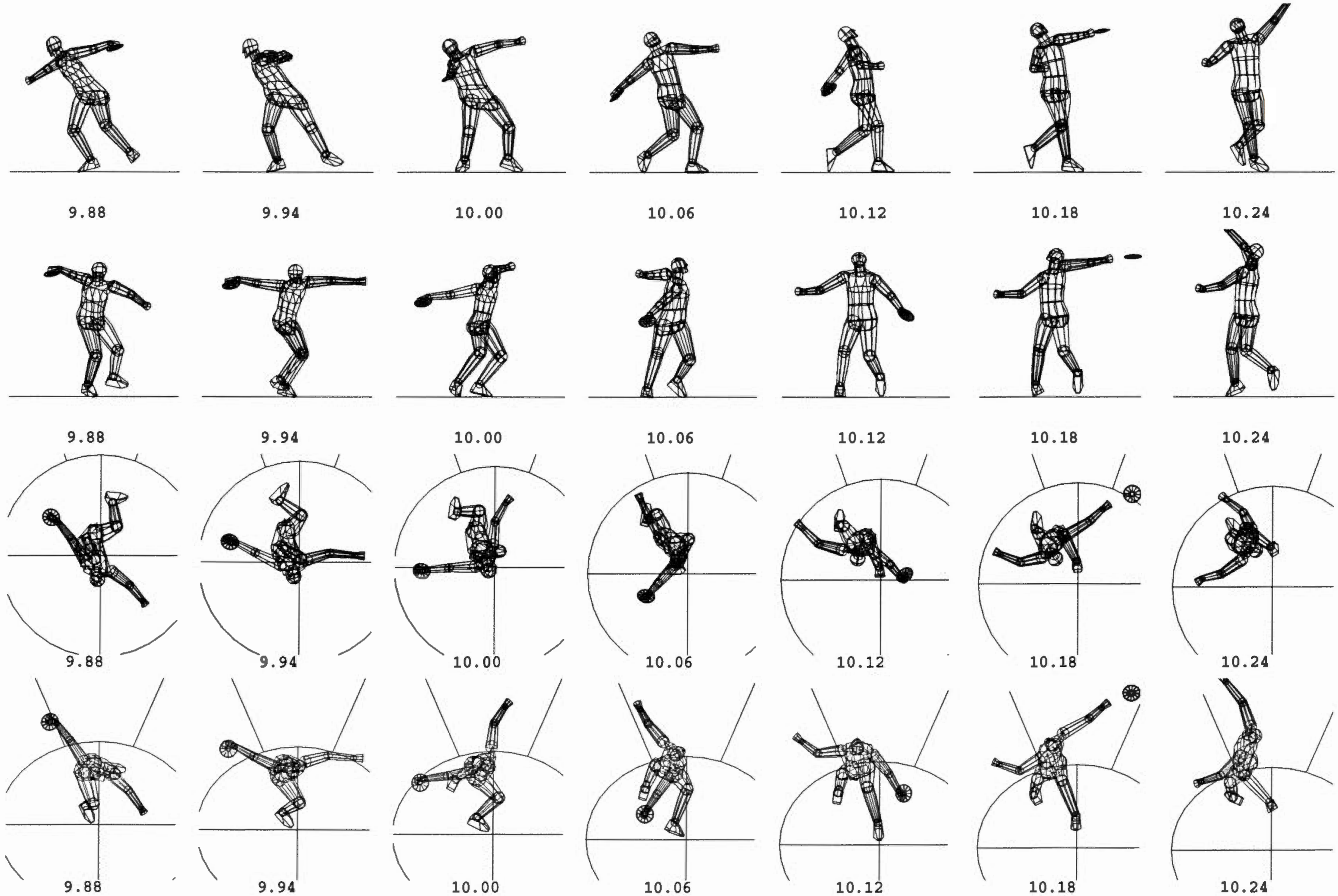

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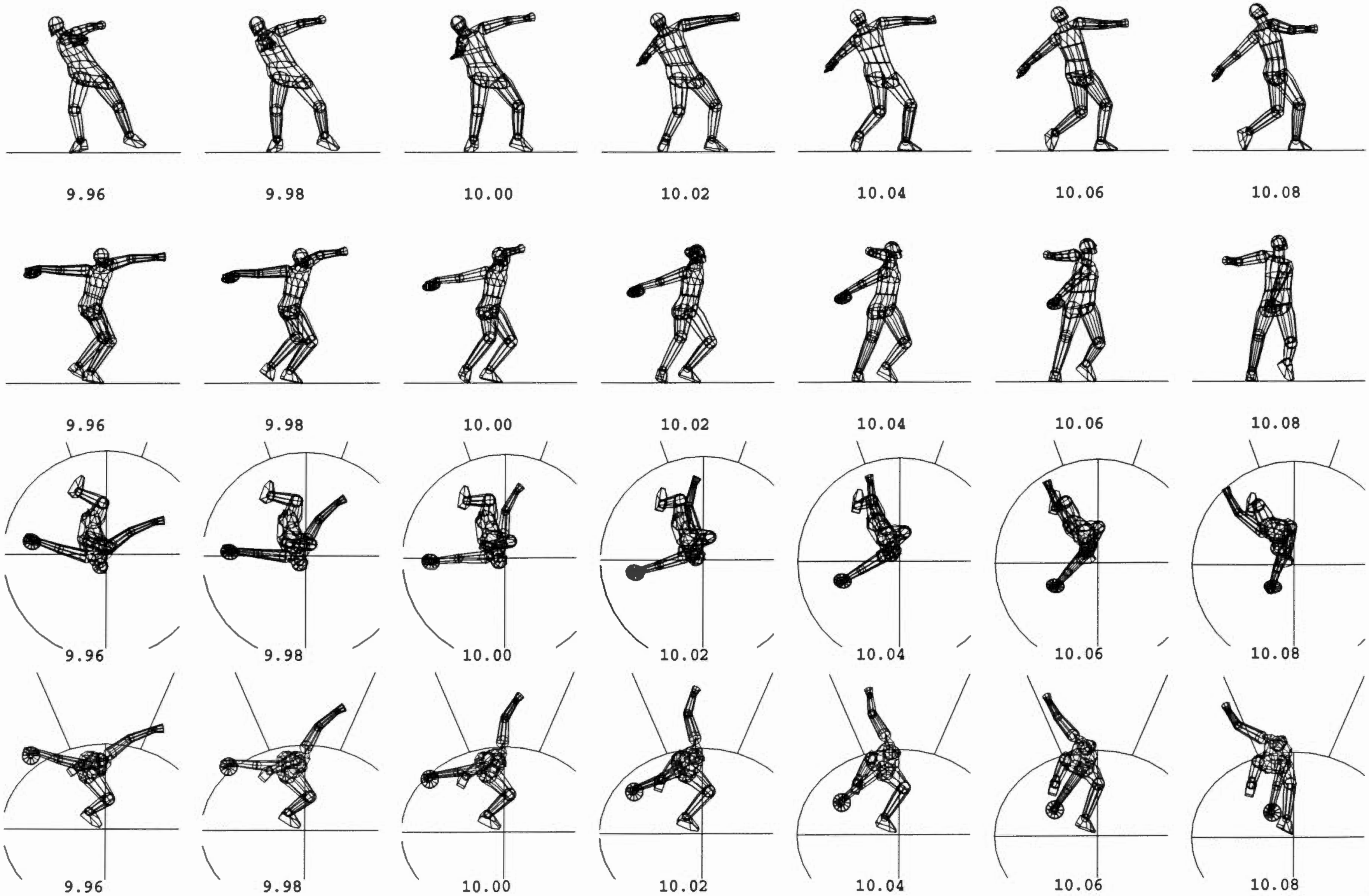

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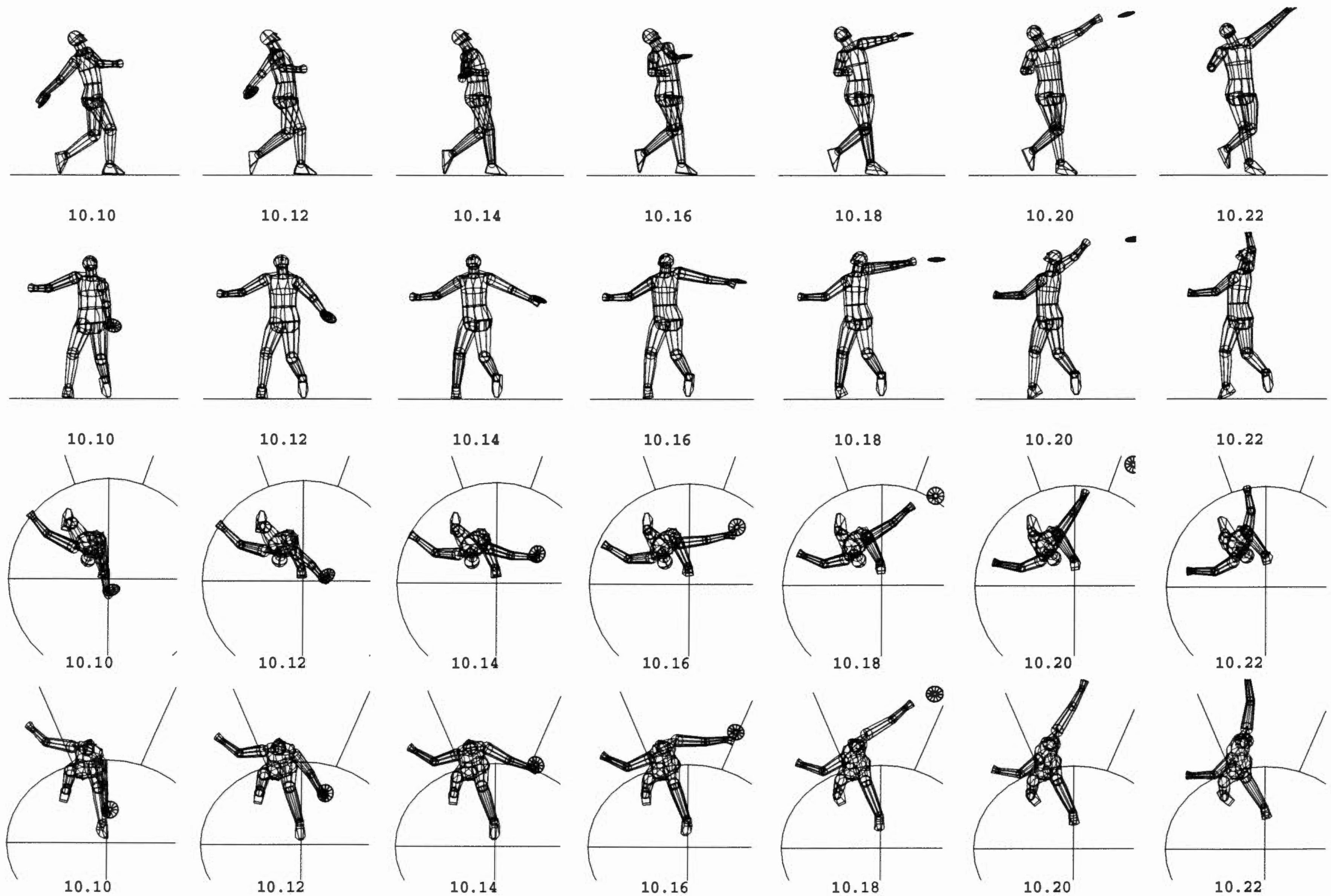

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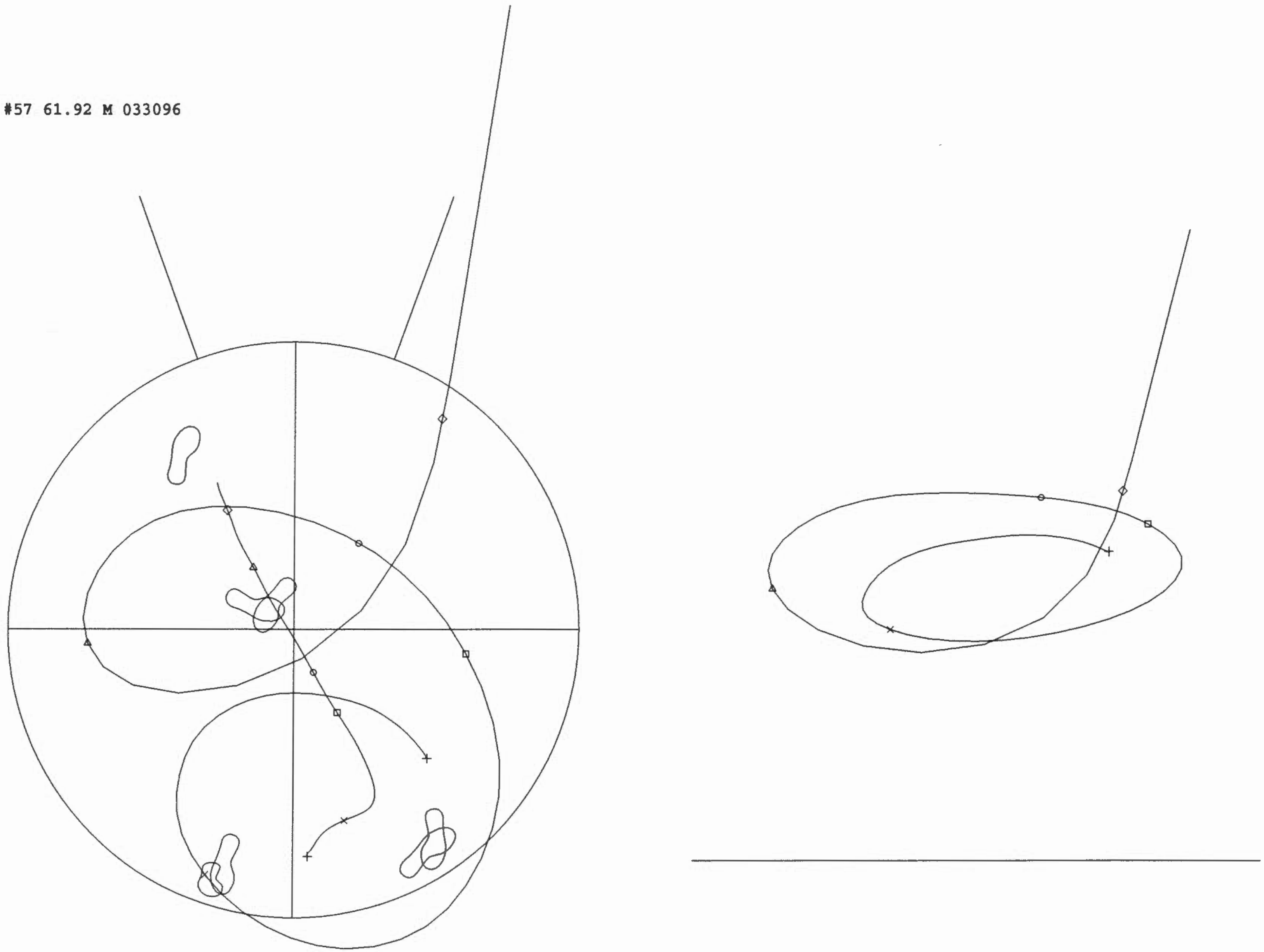

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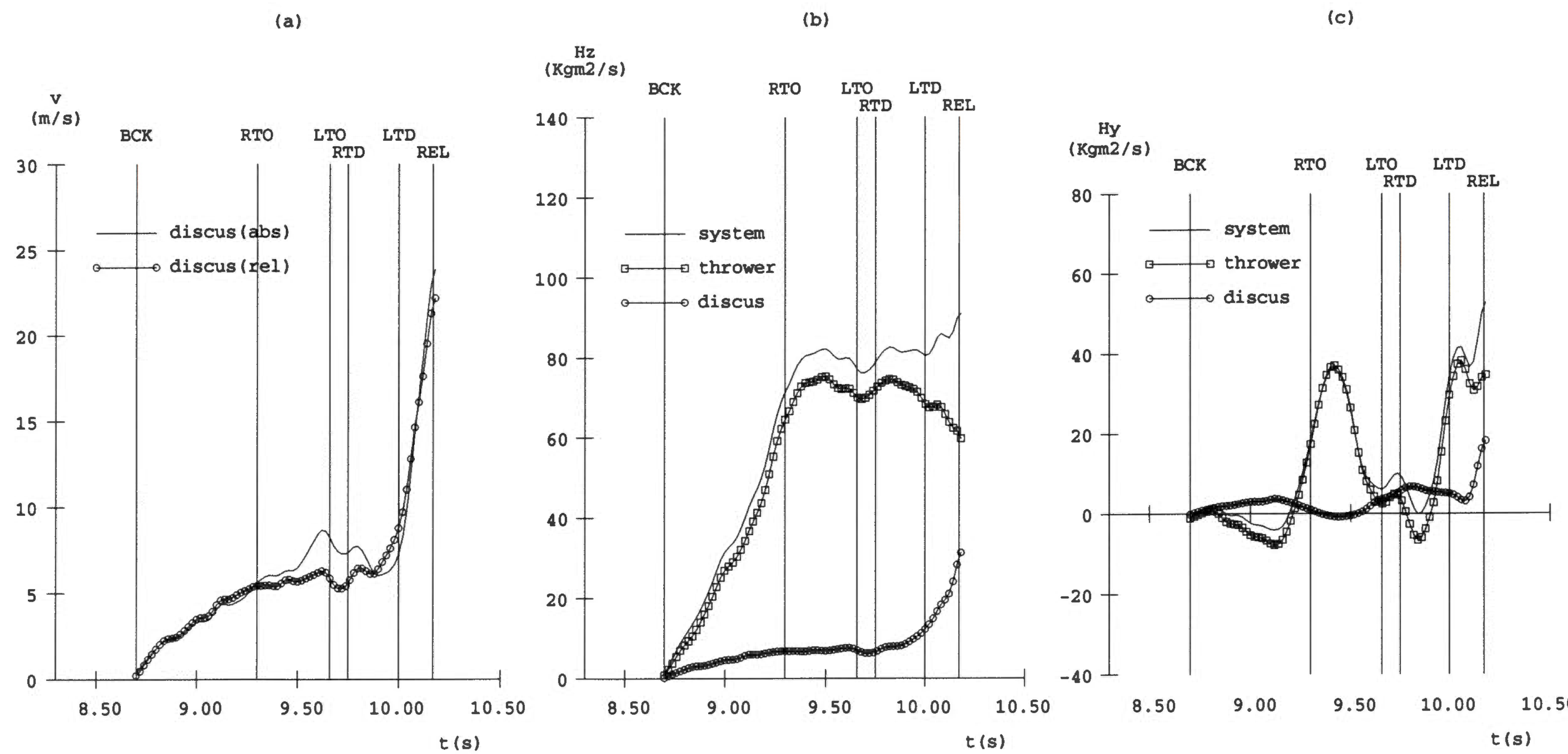

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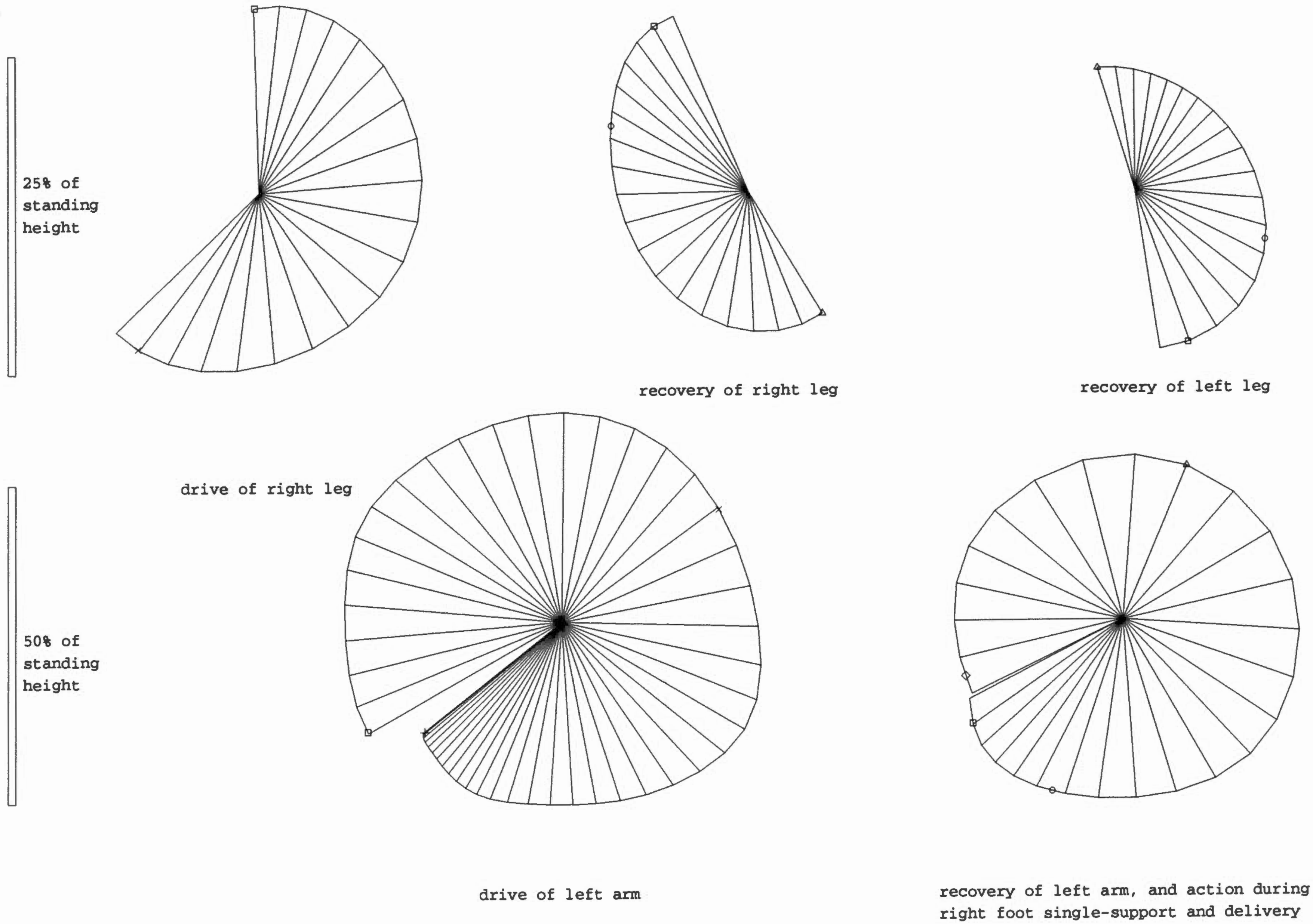

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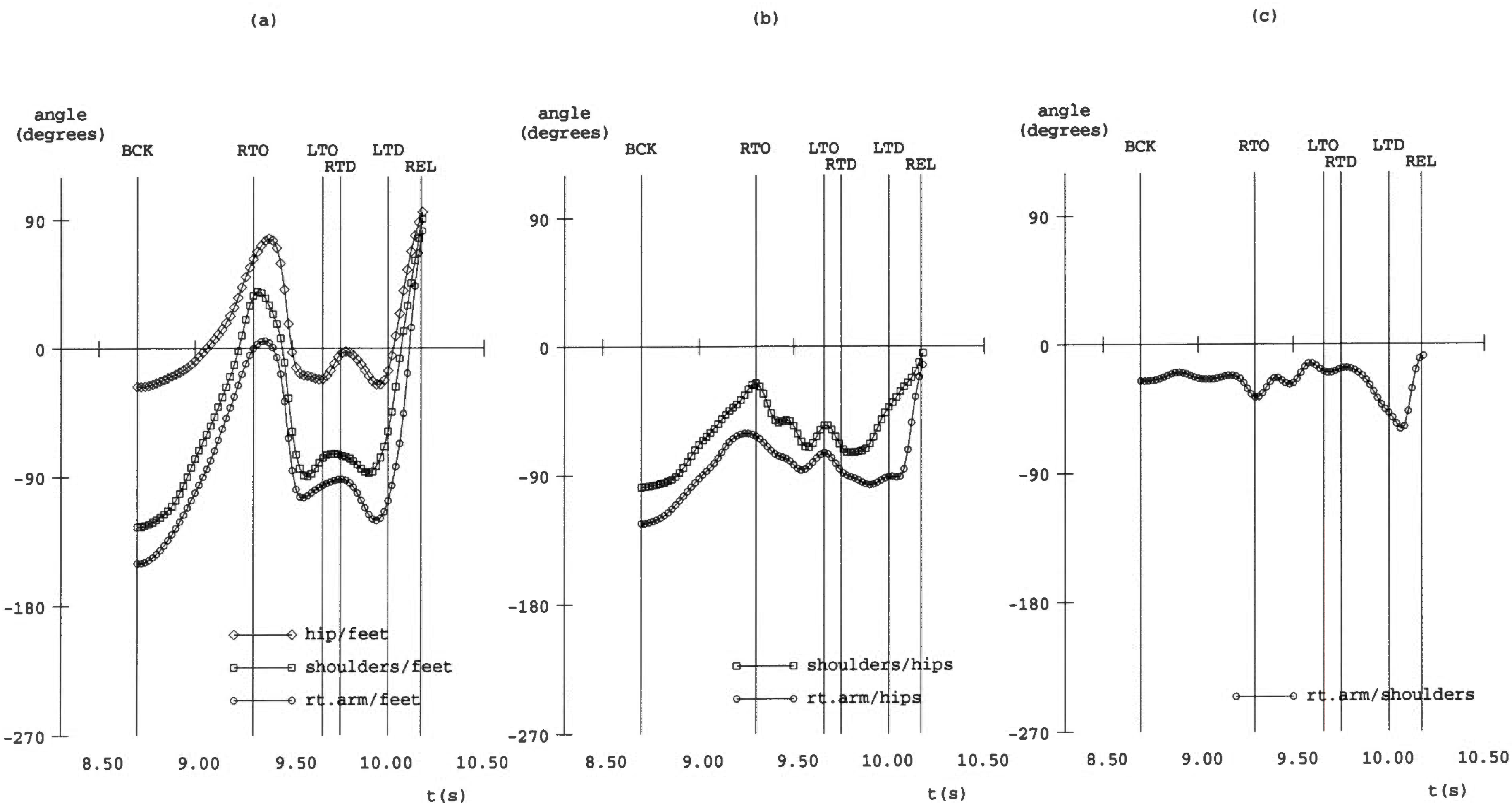

Erik JOHNSON

Trial 10 was Johnson's personal record, 60.82 m, thrown at the 1996 UC San Diego Open.

Johnson's horizontal translation across the circle was not very different from the horizontal translation of the average subject. At the back of the circle, he shifted the system c.m. toward his left foot. Then, he drove with the left leg against the ground, and traveled moderately fast across the throwing circle (v_{HLTO} = 2.4 m/s; v_{HLTD} = 2.0 m/s), with a diagonal deviation from the forward direction that may have been slightly excessive (a_{LTO} = -34°; a_{LTD} = -19°). During the double-support delivery, he made a forward and downward force on the ground. The backward horizontal reaction force reduced his horizontal speed to an amount which was somewhat conservative, although not terribly small either (v_{HQ} = 1.3 m/s). The divergence angle between the directions of motion of the system and of the discus was somewhat larger than would have been desirable, but not extremely bad either (c_Q = -32°). Therefore, the contribution of the horizontal speed of the system to the horizontal speed of the discus was not too far from average (v_{HCON} = 1.1 m/s). The downward force that Johnson made against the ground during the double-support delivery was very large, and the reaction to it gave the system a very good vertical speed which contributed to increase the vertical speed of the discus (v_{ZCON} = 1.7 m/s). Overall, these actions were fairly good. The only possible criticism is that maybe at the back of the circle Johnson should have shifted the system c.m. further toward his left before making the main push with the left foot.

The swinging action of the right leg at the back of the circle was somewhat weak (RLA = 23.0 · 10^{-3} Kg·m²/Kg·m²), but the swinging action of the left arm was fairly strong (LAA = 36.7 · 10^{-3} Kg·m²/Kg·m²). Therefore, their combination was reasonably good (RLLAA = 59.7 · 10^{-3} Kg·m²/Kg·m²). At the instant of landing of the left foot in the front of the circle, the system had 81% of the Z angular momentum (counterclockwise rotation in a view from overhead) that it would eventually reach at release. In comparison with other throwers, this was a rather small fraction of the total, but we still think that it was adequate, so we felt that Johnson's generation of angular momentum in the back of the circle was reasonably good.

The recovery actions of the legs were excellent. The small average radius of the legs ($r_{LAVG\text{-}NSRSS}$ = 8.8% of standing height) shows that Johnson brought both legs very close together below his body. The recovery action of the left arm was also very good ($H_{LA\text{-}NS}$ = 27 · 10^{-3} s^{-1}).

In contrast, the second propulsive swing of the left arm (LAA2 = 15.6 · 10^{-3} Kg·m²/Kg·m²), the maximum angular momentum that it reached (H_{MAX} = 59 · 10^{-3} s^{-1}) and its subsequent slowing down before the release of the discus by the right arm (ΔH = -33 · 10^{-3} s^{-1}) were all somewhat weaker than average.

At release, the discus had 37% of the total Z angular momentum of the thrower-plus-discus system. This was larger than average, and suggests that Johnson did a good job transfering Z angular momentum from his body to the discus.

At release, in the view from the back of the circle the thrower-plus-discus system had a very large amount of counterclockwise angular momentum (H_{YS} = 60.0 Kg·m²/s). Although the fraction of it that Johnson transfered to the discus was rather small (34% of the total), it still amounted to H_{YD} = 20.2 Kg·m²/s, a reasonably large value in absolute terms. Together with the large contribution of the vertical speed of the system (v_{ZCON} = 1.7 m/s), this resulted in a good vertical speed of the discus at release (v_{ZD} = 14.5 m/s).

Johnson achieved an extremely wound-up position in the single-support over the right foot ($k_{RA/FT}$ = -161°). This was very good, because the subsequent unwinding helped him to transfer angular momentum from the body to the discus. The main advantage of Johnson with respect to the average thrower at the instant of maximum torsion of the system was in the torsion of the hip relative to the feet (Johnson $k_{HP/FT}$ = -69°; average = -51°).

Based on the speed and direction of motion of the discus at release, Johnson's throw was excellent. In a vacuum, it would have reached D_V = 59.72 m, farther than the vacuum distances for the analyzed throws made by Setliff or Washington at the 1996 UC San Diego Open (D_V = 55.01 and D_v = 58.67, respectively). If aerodynamics did not play a role in discus throwing, Johnson probably would have won the meet. However, aerodynamics does play a role in discus throwing, particularly when throwing against the wind, and Johnson's use of aerodynamic forces was very poor. While Setliff and Washington used the headwind to increase the distance of their throws by ΔD = 8.31 m and ΔD = 5.29 m, respectively, Johnson was only able to obtain an additional ΔD = 1.10 m from the wind.

Summary

The horizontal translation of the system c.m. and its contribution to the speed of the discus were very similar to those of the average subject, but Johnson generated more vertical speed for the system c.m., and therefore this part of his technique was overall fairly good. The combined swinging actions of the right leg and left arm at the back of the circle were also reasonably good. The amount of Z angular momentum generated at the back of the circle was somewhat small, but still probably alright. The recovery actions of the legs and of the right arm after the takeoff of the left foot from the ground were very good. The second swing and recovery of the left arm were somewhat weak. During the single-support on the right foot and the double-support delivery, he obtained a large amount of Y angular momentum, and he transfered enough of it to the discus during the second half of the delivery to give a good vertical speed to the discus. The transfer of Z angular momentum from the body to the discus was good. It was probably helped by Johnson's achievement of a very wound-up position in the single-support on the right foot, followed by very active unwinding. Johnson's use of aerodynamic forces was very poor, by far the most important defect in his technique.

Recommendations

If we leave out the aerodynamic aspects of the throw, Johnson's technique was very good. The only minor adjustments that would be advisable would be the following:

(a) At the back of the circle, Johnson "sat" backward too much before starting to shift the system c.m. toward his left foot. (See the overhead view of the path of the system c.m.) We think that this may have forced him to start prematurely the main push with the left foot before the c.m. was close enough to the vertical of the left foot. To avoid this problem, Johnson should *first* shift the system c.m. toward the left foot, with very little "sitting back". That will allow the c.m. to get closer to the vertical of the left foot. By doing this, Johnson will then be able to follow a more direct forward path across the circle. This will produce a smaller divergence angle in the front of the circle, and therefore a larger contribution of the horizontal speed of the system to the horizontal speed of the discus.

(b) After the right foot lands in the middle of the circle, Johnson should swing the left arm very hard counterclockwise, and without much flexion at the elbow. Then, he should stop the counterclockwise rotation of this arm and/or bring it closer to the body before the discus leaves the right hand.

Those are the only problems that we found in the process that Johnson followed to achieve a good speed and direction for the discus at release. However, Johnson's main problem, by far, was in the aerodynamics of the throw. It would be advisable for Johnson to concentrate on making the forward edge of the discus point downward ("thumb-down") relative to the direction of motion of the discus at release. This will not make much difference when throwing with a tailwind, but it will produce a great improvement in the distance of a throw made into a headwind.

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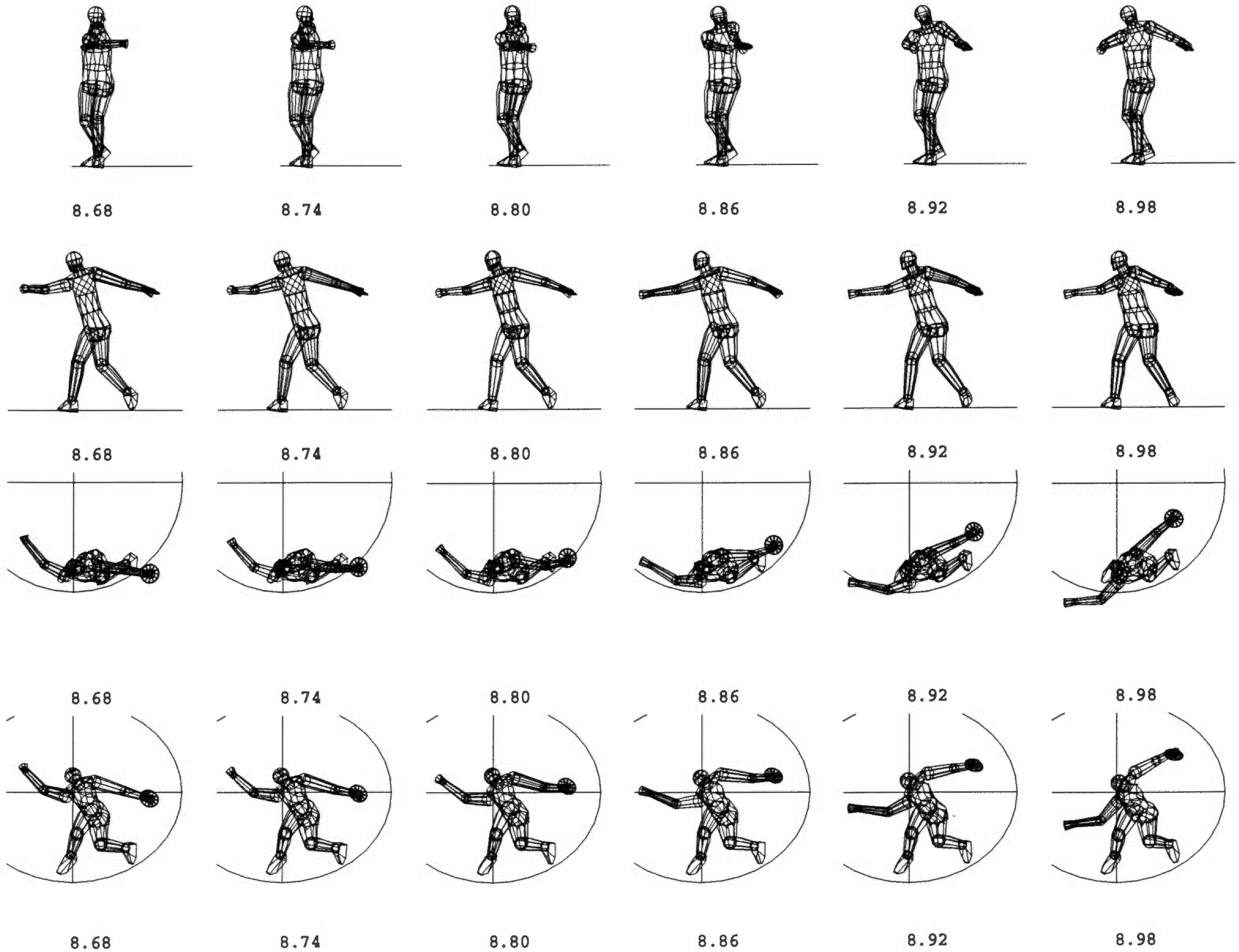

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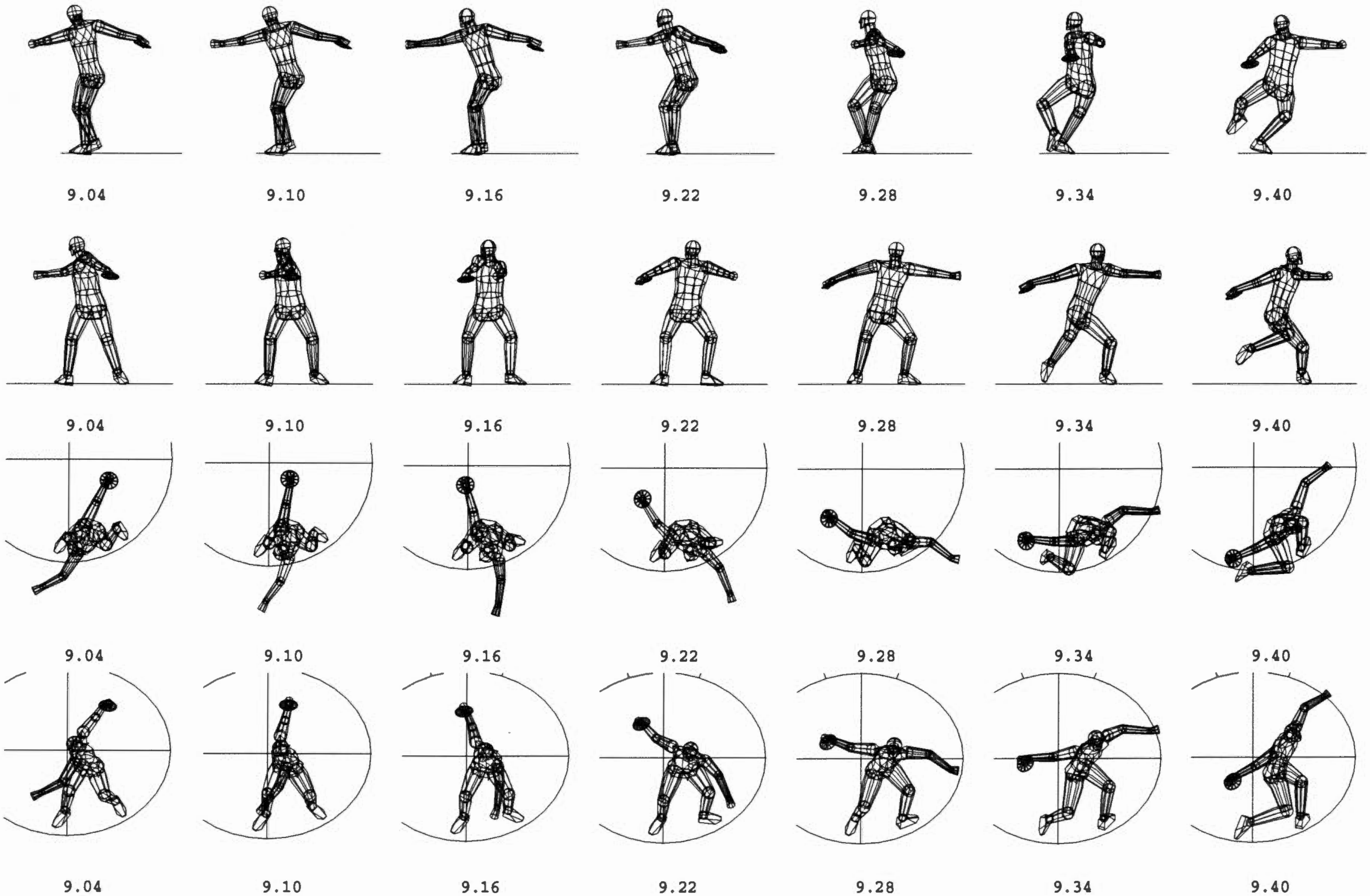

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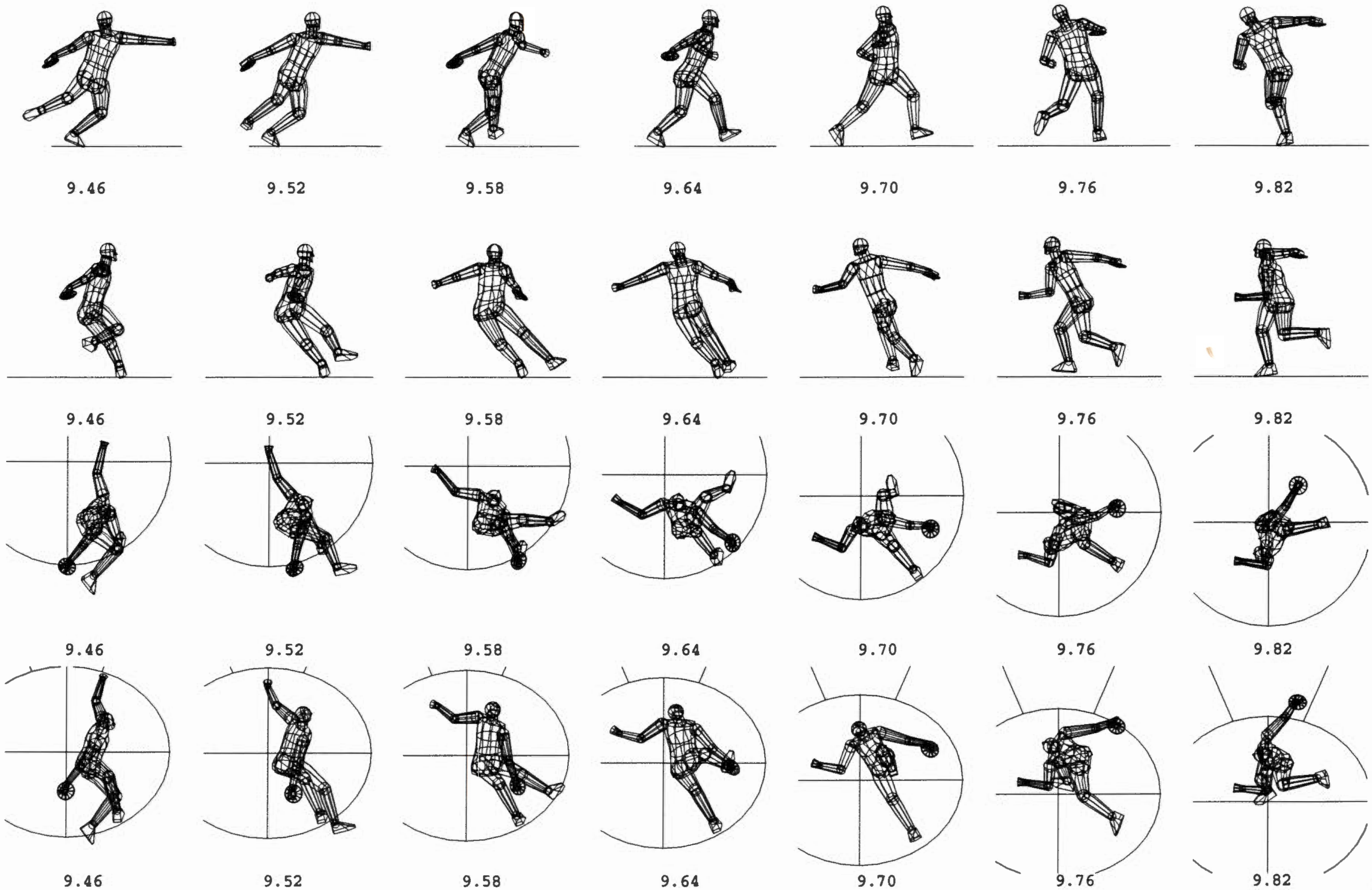

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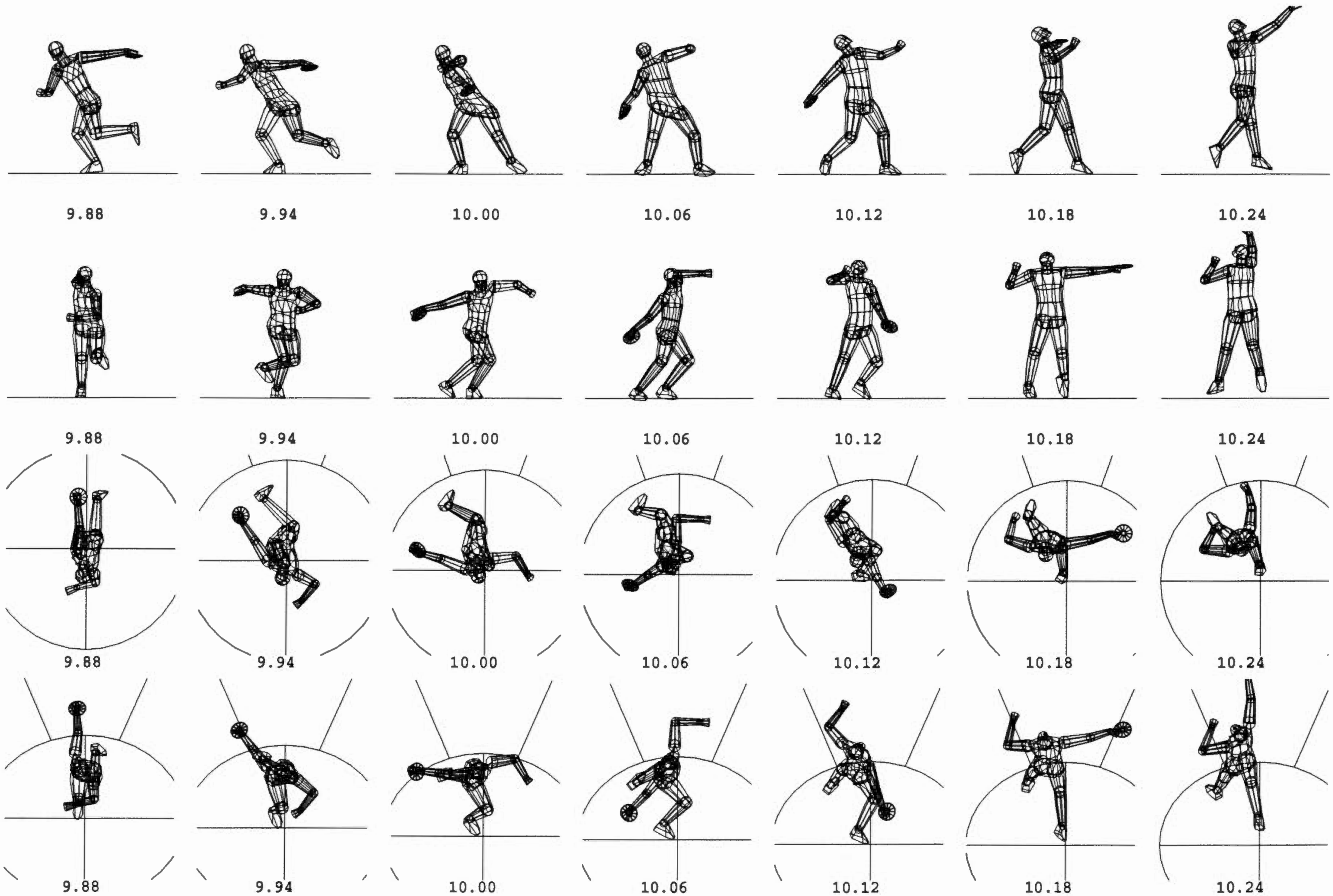

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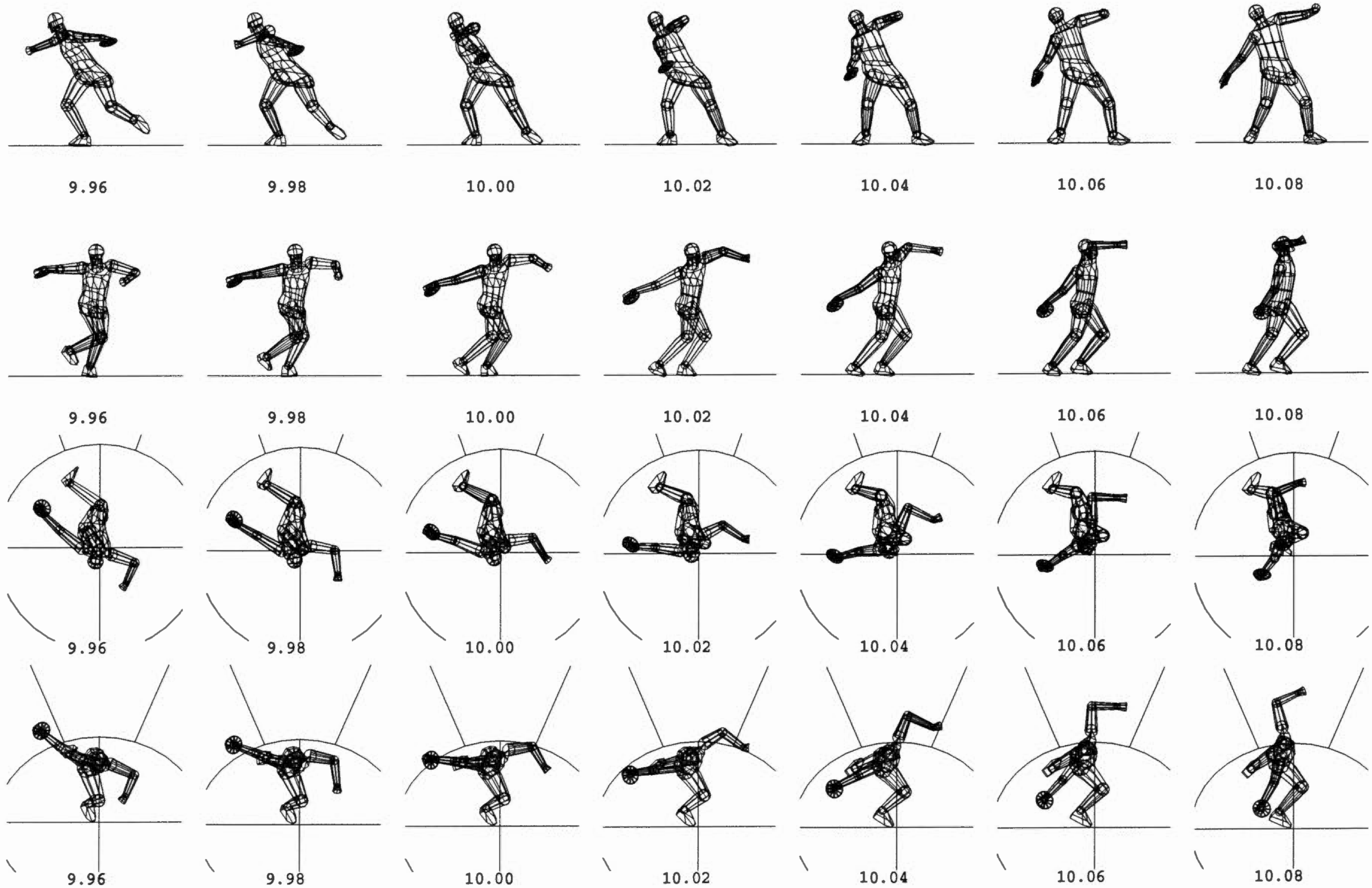

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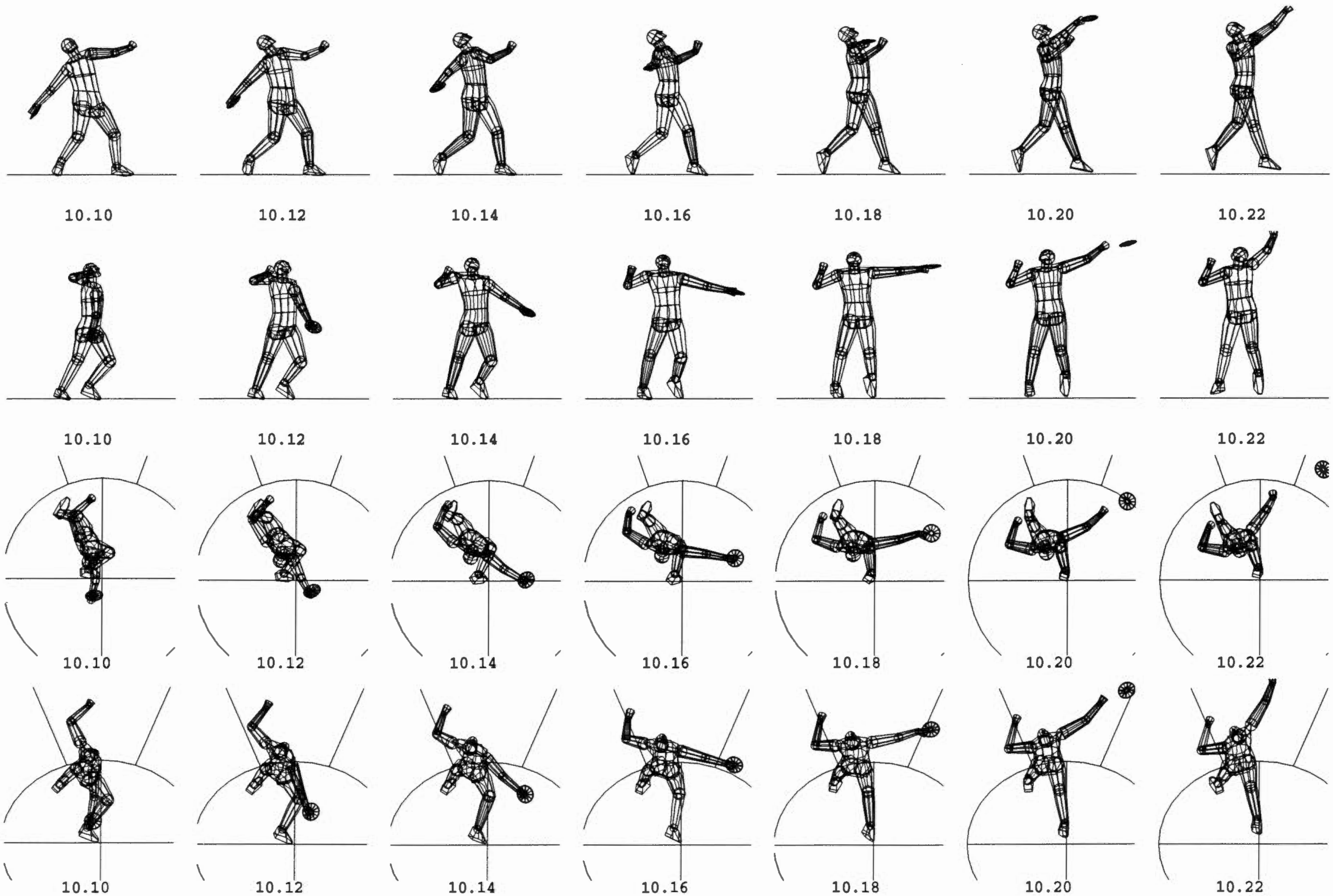

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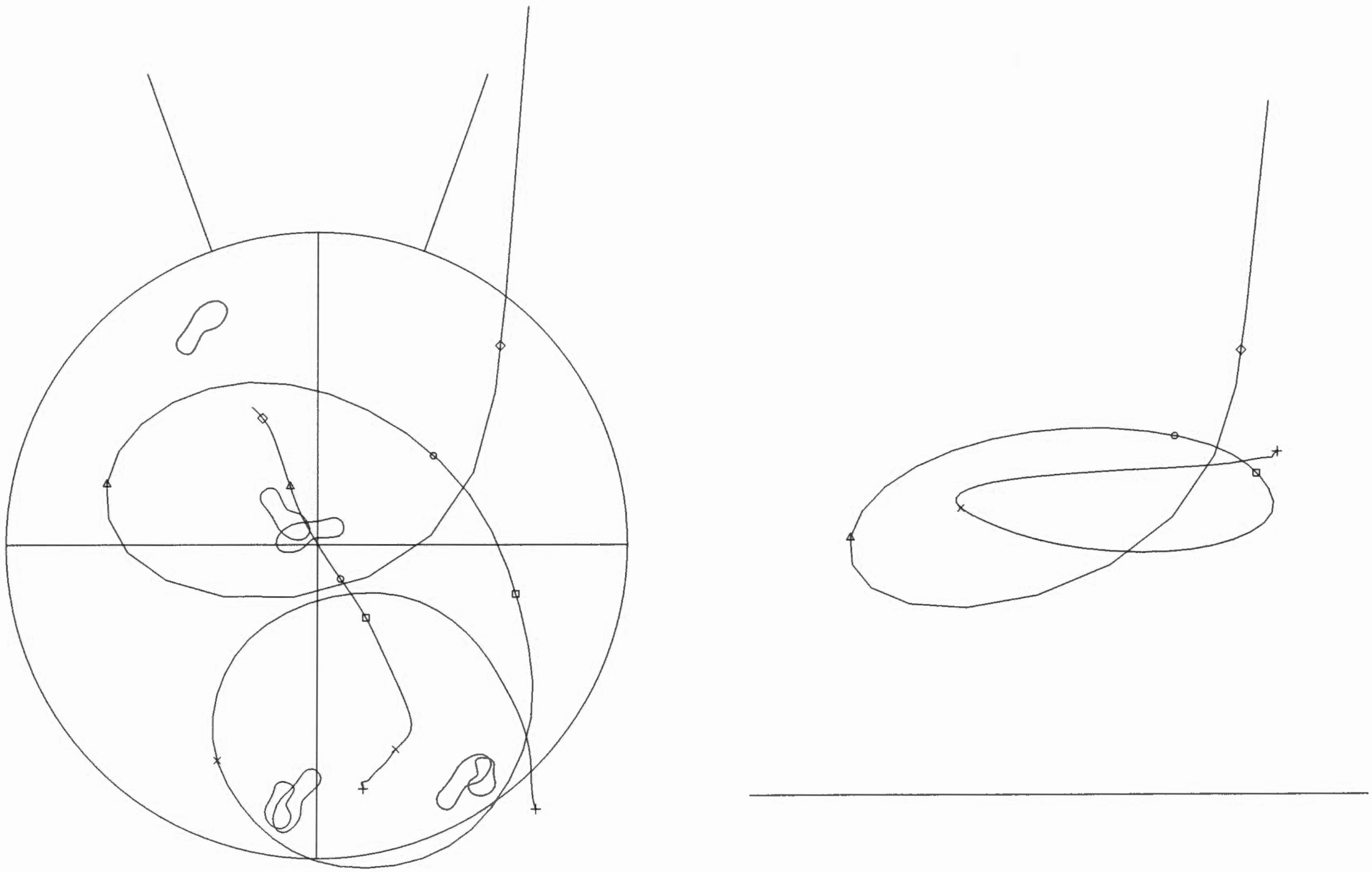

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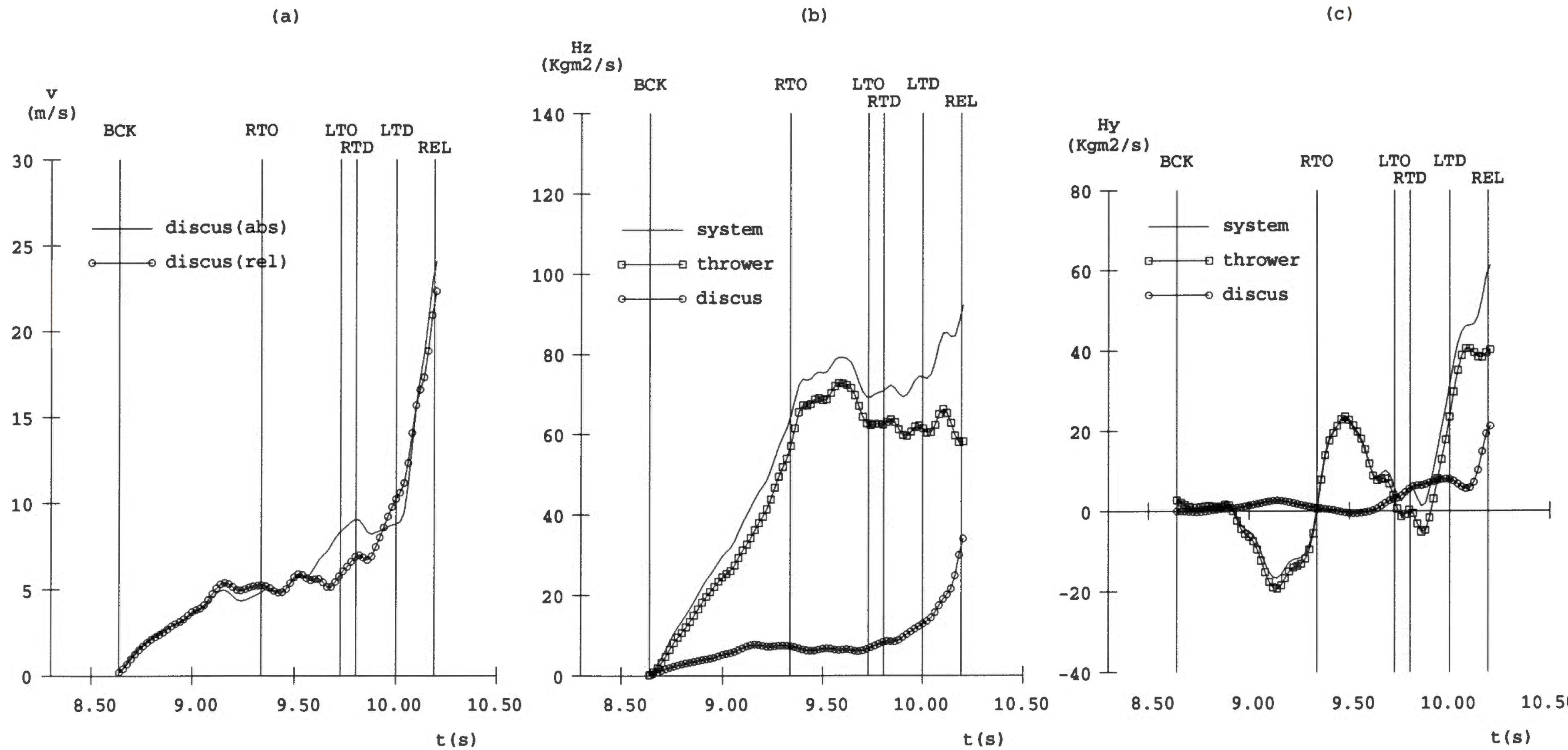
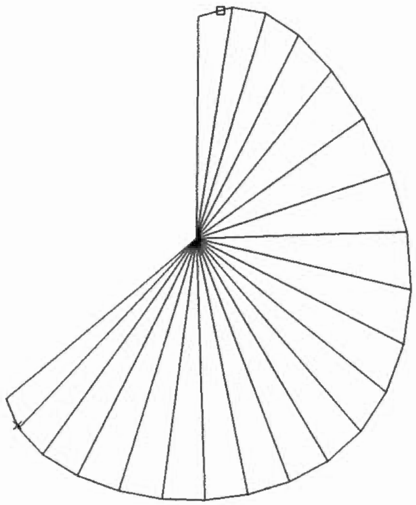
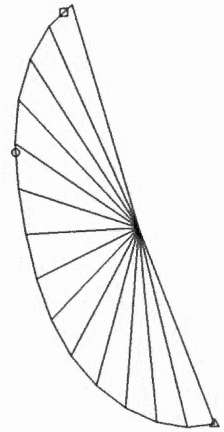


JOHNSON #10 60.82 M 033096

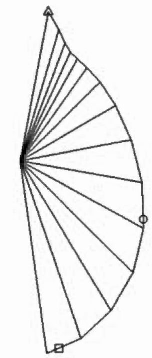
25% of
standing
height



drive of right leg

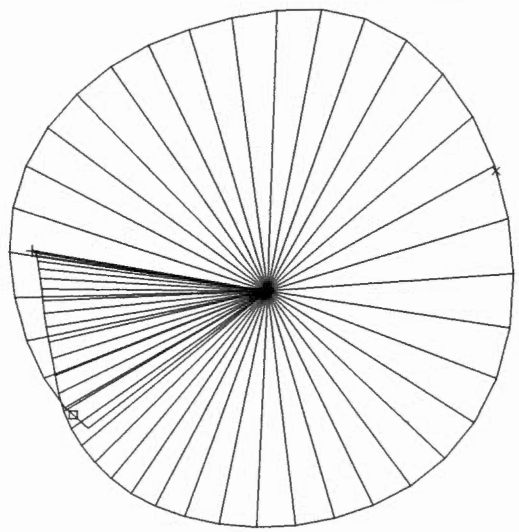


recovery of right leg

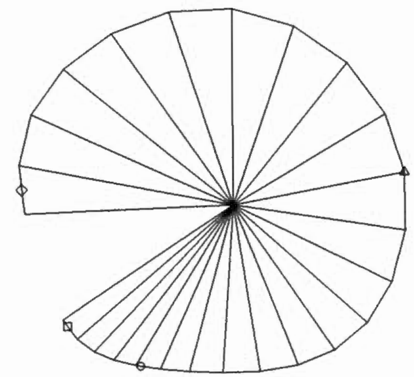


recovery of left leg

50% of
standing
height

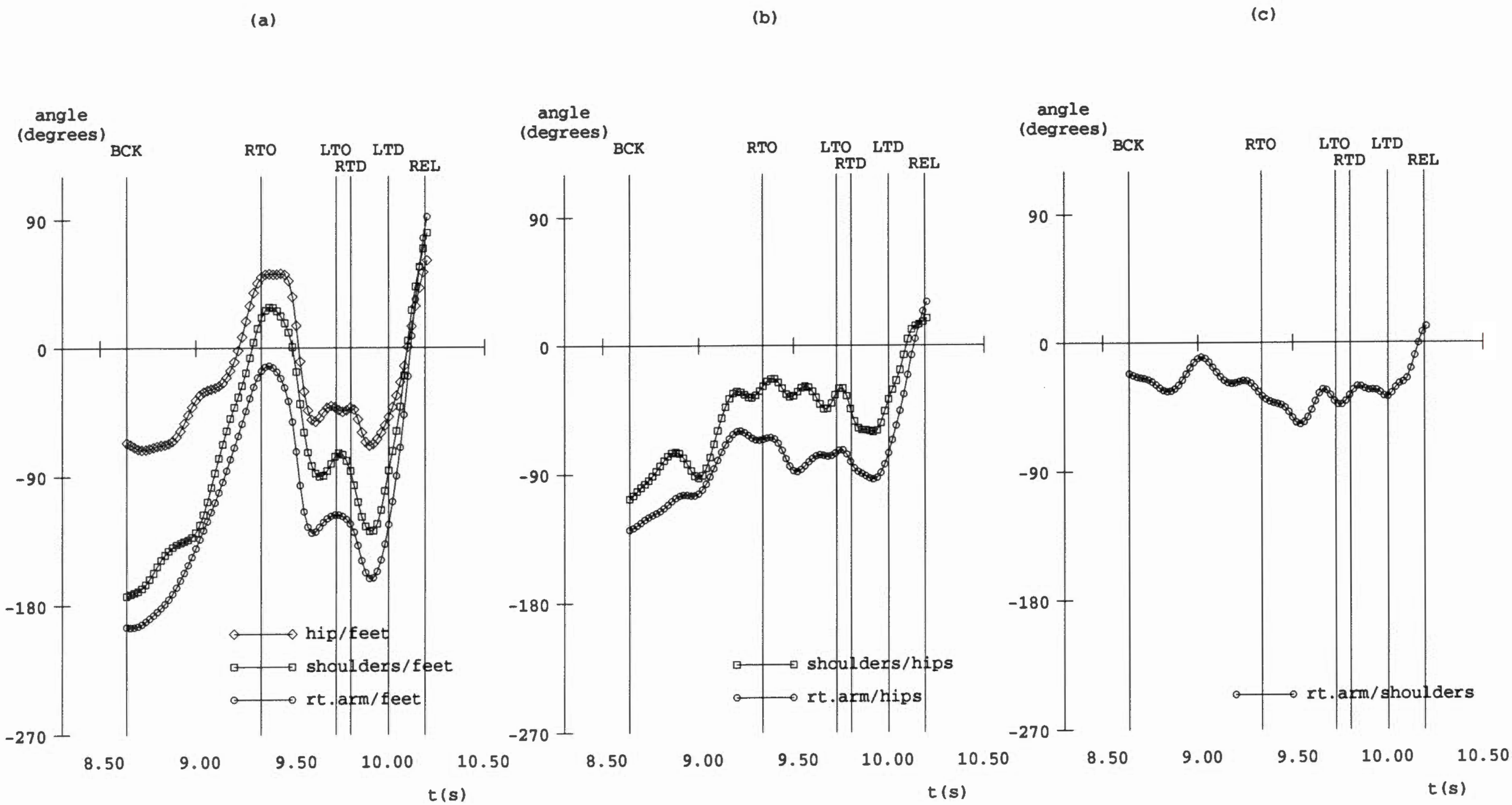


drive of left arm



recovery of left arm, and action during
right foot single-support and delivery

JOHNSON #10 60.82 M 033096



Mike MIELKE

Trial 22 was Mielke's personal record, 59.46 m, thrown at the 1996 UC San Diego Open.

At the back of the circle, Mielke did not shift his c.m. enough toward his left foot. This made the thrower-plus-discus system follow a very diagonal path across the throwing circle (a_{LTO} = -31°; a_{LTD} = -27°). However, this did not pose a problem for Mielke, in part because he corrected his path slightly toward a more forward direction by the time that the discus was on its last quarter-turn (a_Q = -18°), and in part because the final direction of motion of the discus was slightly toward the left (d_{HREL} = -8°). The combination of these two factors made the divergence angle between the paths of the system c.m. and of the discus be very small (c_Q = -10°). Therefore, most of the horizontal speed that the system had during the last quarter-turn of the discus (v_{HQ} = 1.5 m/s) contributed to the horizontal speed of the discus (v_{HCON} = 1.5 m/s also). Overall, this was good. The problem lay in what Mielke had to do to get the horizontal speed of the system to be as large as it was during the last quarter-turn (v_{HQ} = 1.5 m/s), as we will see next.

The horizontal push of Mielke's left foot from the back of the circle was weak, and therefore his horizontal speed across the circle was very slow (v_{HLTO} = 2.2 m/s; v_{HLTD} = 1.7 m/s). A slow horizontal speed of the system c.m. during the last quarter-turn of the discus limits the contribution of the horizontal motion of the system to the horizontal speed of the discus. To maximize the horizontal speed of the system in the last quarter-turn, the forward force that Mielke made on the ground during the double-support delivery was extremely small. This allowed the thrower-plus-discus system to retain almost all of its horizontal speed for the last quarter-turn of the discus (v_{HQ} = 1.5 m/s, almost no change from v_{HLTD} = 1.7 m/s). Together with the small divergence angle, this allowed the system to make a good contribution (v_{HCON} = 1.5 m/s) to the horizontal speed of the discus, as we saw previously. However, the size of the vertical force made on the ground during the double-support delivery phase is generally linked to the size of the horizontal force made on the ground during that same period; therefore, the vertical force that Mielke made on the ground during the double-support delivery was very small. As a result, the vertical speed of the system during the last quarter-turn (and therefore the contribution of the vertical motion of the system c.m. to the vertical speed of the discus) was very small (v_{ZCON} = 0.6 m/s). In summary, Mielke pushed very weakly on the ground during the push-off from the back of the circle. Then, he pushed also very weakly on the ground during the delivery phase, both in the horizontal and vertical directions. This allowed him not to lose hardly any horizontal speed, but it also made him unable to generate hardly any vertical speed either. This whole process was detrimental for the result of the throw, because it did not allow vertical motion of the system c.m. to make much contribution to the vertical speed of the discus.

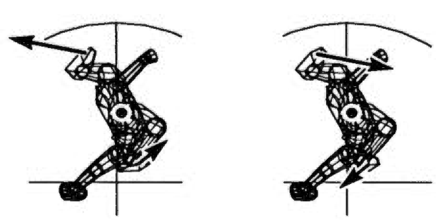
The swinging actions of the right leg and of the left arm at the back of the circle were reasonably good (RLA = 26.4 · 10^{-3} Kg·m²/Kg·m²; LAA = 34.4 · 10^{-3} Kg·m²/Kg·m²; RLLAA = 60.8 · 10^{-3} Kg·m²/Kg·m²), and at the instant of landing of the left foot in the front of the circle the system had a good amount of Z angular momentum (counterclockwise rotation in a view from overhead): $H_{ZS\text{-}LTD}$ = 87.2 Kg·m²/s. (It is very convenient for us that Mielke's standing height and weight were very similar to those of the average subject. It allows us to compare his *non-normalized* angular momentum values with those of the average subject.) All this indicated that Mielke did a good job generating Z angular momentum in the back of the circle.

However, the system then *lost* a large part (15%) of its Z angular momentum during the double-support delivery. In theory, this might be interpreted in two opposite ways: (1) Maybe an unrealistically large amount of angular momentum had been generated for the system in the back of the circle, and it was unavoidable to lose some of it during the double-support in the front of the circle, because nobody can coordinate properly the motions of the delivery when the system has such a large amount of angular momentum; or (2) maybe the system had a normal, good, amount of angular momentum at the instant that the left foot landed in the front of the circle, but something went wrong during the double-support delivery, which made the system lose a large amount of this valuable angular momentum. We tend to lean more toward option #2, for two reasons: (a) The system's Z angular momentum at the instant of landing of the left foot in Mielke's throw (87.2 Kg·m²/s) was not an outlandishly large value. Yes, it was one of the largest for that instant, but there were several other throwers who had similar or larger amounts of Z angular momentum in the thrower-plus-discus system than Mielke at the instant of landing of the left foot (even if we do not count

Carlos Scott's value, which was due to his large weight), and those other throwers generally went on to *gain* more Z angular momentum during the double-support delivery. (b) The Z angular momentum of Mielke's system at the instant of release (75.9 Kg·m²/s) was clearly the smallest of any thrower in our sample.

In our opinion, the reason for the tremendous loss of Z angular momentum during the double-support delivery in Mielke's throw was not that the angular momentum was already so large that it was unmanageable, but that Mielke's legs were too passive during the double-support delivery. At the instant of landing of the left foot, he was rotating counterclockwise very fast, because of the very good amount of Z angular momentum that he had. In those conditions, the feet should ***try very actively*** to push on the ground in a clockwise direction (i.e., the left foot pushing forward and toward the right, and the right foot pushing backward and toward the left, as shown in Figure 8). Otherwise, there will be a tendency for the passive feet to make on the ground forces similar to the ones shown in the left side of the drawing below. The ground reaction forces (shown in the right side of the drawing) will then make the system lose counterclockwise Z angular momentum.

This is not good.



forces made on ground

reaction forces made by ground on feet

Going back to the analogy of the child traveling on a fast-moving scooter (page 7), if the child allows the foot to drop passively to the ground, the foot will tend to make a forward ("dragging") force on the ground; the ground reaction force will point backward, and the scooter will tend to slow down. We think that this is what happened to Mielke: His legs were too passive during the double-support delivery, and instead of contributing to increase the Z angular momentum of the system, they made it decrease.

During the double-support delivery, Mielke managed to transfer a reasonably large amount of Z angular momentum from his body to the discus. However, he had to do this in very difficult conditions. As explained in page 24, the slower the counterclockwise rotation of the thrower, the more difficult it is to transfer angular momentum from the thrower to the discus. Mielke's initial rotation at the instant of landing of the left foot was fast, because of the initial large Z angular momentum of the system. However, apart from the normal losses of angular momentum from the body to the discus, the body also lost angular momentum to the ground, contrary to the normal influx of Z angular momentum that most throwers obtain from the ground during the delivery. Therefore, the counterclockwise rotation of Mielke's body became slow very soon, and this made the further transfer of angular momentum to the discus very difficult. The fact that Mielke managed to transfer a very respectable amount of Z angular momentum to the discus in these circumstances is a credit to his outstanding physical condition. It shows that he could produce exceptionally good throws if he corrects his technical problems. If he were able to avoid the loss of Z angular momentum, or better yet, *increase* his Z angular momentum during the double-support delivery, he would be able to transmit a much larger amount of Z angular momentum to the discus.

The vertical speed of the discus at release was reasonably large (v_{ZD} = 14.0 m/s), in spite of the very small contribution that the vertical motion of the system c.m. made to it (v_{ZCON} = 0.6 m/s). The reason for this success was that the Y angular momentum of the thrower-plus-discus system (counterclockwise rotation in the view from the back of the circle) was larger in Mielke's throw (H_{YS} = 63.1 Kg·m²/s) than in any other throw of our sample. Although the fraction of it that Mielke transfered to the discus was somewhat small (37% of the total), it still amounted to H_{YD} = 23.1 Kg·m²/s, quite a large value in absolute terms. This is what allowed Mielke to give to the discus a good amount of vertical speed at release.

Other aspects of Mielke's technique (torsion angles, recoveries of the legs and of the left arm, second drive of the left arm) were not too different from those of the average thrower, and therefore we will not devote any further attention to them.

Mielke's use of aerodynamic forces was rather poor (ΔD = 3.31 m).

Summary

Mielke did not shift the system c.m. enough toward the left foot at the back of the circle, and this made him follow a very diagonal path across the throwing circle. However, it did not create a problem for him. He pushed off very weakly from the back of the circle, which set off a chain of events that prevented Mielke from acquiring much vertical speed for the system during the double-support delivery. He produced a good amount of Z angular momentum in the back of the circle, but his legs were very passive in the front of the circle, which made the system lose a large amount of its Z angular momentum. In spite of the great disadvantage that this produced, he was still able to transfer a good amount of Z angular momentum from his body to the discus. During the single-support on the right foot and the double-support delivery, he obtained a large amount of Y angular momentum, and he transfered enough of it to the discus during the second half of the delivery to give a good vertical speed to the discus.

Recommendations

Mielke's main problem was the passiveness of his legs in the front of the circle, which affected both his translation and his rotation. By pushing too weakly downward on the ground during the delivery, the system obtained very little vertical speed. The small size of the vertical speed of the system limited the vertical speed that Mielke was able to give to the discus. By pushing (passively) on the ground toward the left with the left foot and toward the right with the right foot during the delivery, the legs made the system lose a large amount of counterclockwise Z angular momentum. This loss limited the amount of Z angular momentum that Mielke was able to transfer to the discus, which in turn limited the horizontal speed of the discus. (Mielke still managed to transfer a good amount of Z angular momentum to the discus, but he could have transfered still much more if his body had not slowed down so much during the double-support delivery.)

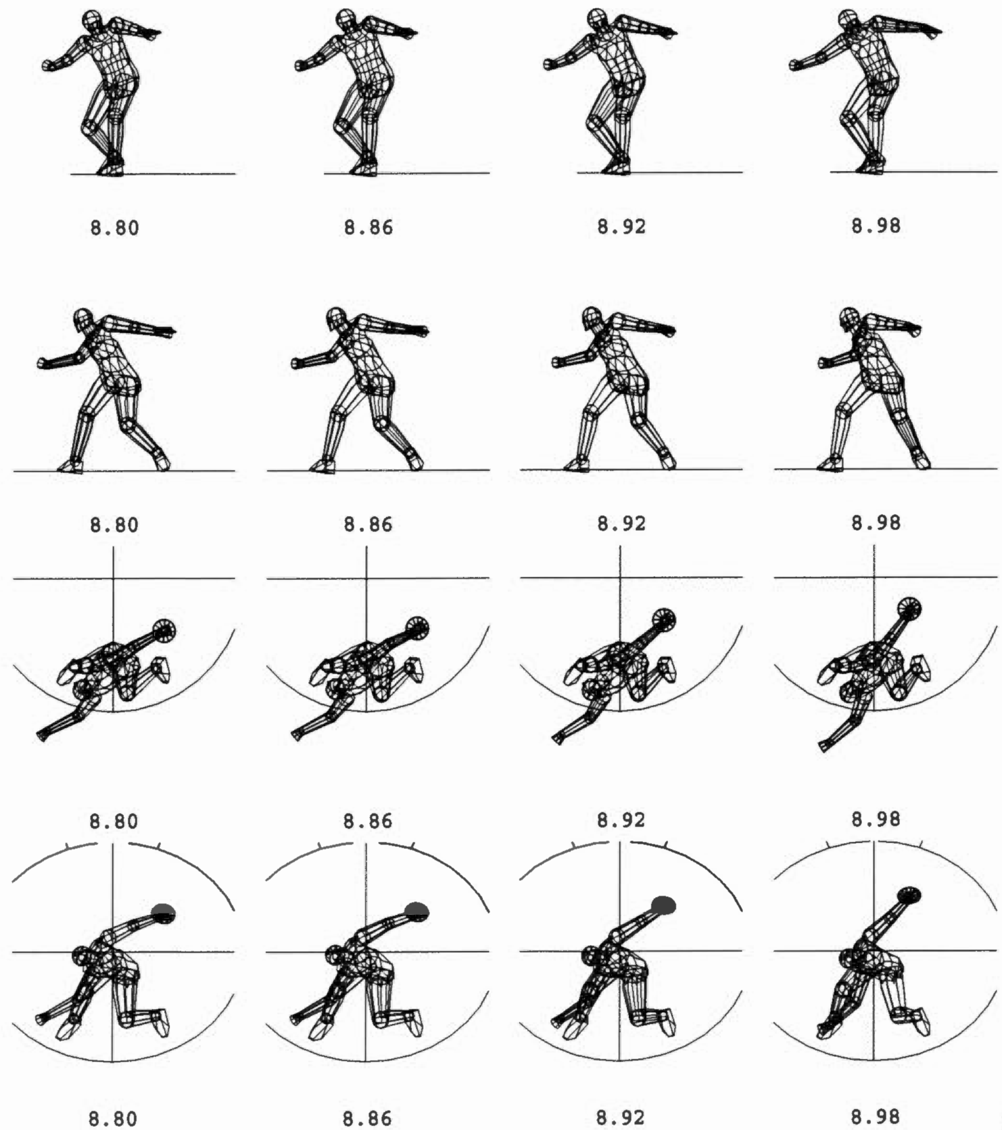
Mielke's pull-push forces at the back of the circle were very good, and he should not change this aspect of his technique. However, he should make a much harder horizontal push with his left foot (perhaps after a greater shift of the system c.m. toward the left foot). Then, in the front of the circle, he should push explosively downward and forward against the ground with his feet, especially with his left foot. This will slow down the larger horizontal speed of the system (enough to prevent fouling), and it will give the system a good vertical speed which will contribute to the vertical speed of the discus.

During the double-support delivery, Mielke should concentrate particularly on pushing on the ground forward, downward ***and toward the right*** with his left foot. (See Figure 8.) If he can produce an increase in the counterclockwise Z angular momentum of the system during the double-support delivery, or even maintain it, the counterclockwise speed of rotation of his body will be faster. This will allow Mielke to transfer a larger amount of Z angular momentum to the discus, which will increase the horizontal speed of the discus and the distance of the throw.

The muscular actions of Mielke's trunk and right arm which produced the unwinding of the body during the double-support delivery in throw 22 were excellent, and Mielke should not make any changes in them. What was missing in throw 22 was the appropriate contribution of the legs in the push-off of the left foot from the back of the circle, and particularly during the double-support delivery. This should be the focus of Mielke's attention.

With respect to the use of aerodynamic forces, Mielke had a disadvantage of 5 meters relative to Setliff, and 1-3 meters relative to several other throwers. We are not sure if these differences were due to changes in the speed of the wind or to differences in the tilt of the discus at release. In any case, it would be advisable for Mielke to concentrate on making the forward edge of the discus point downward ("thumb-down") relative to the direction of motion of the discus at release. This will not make much difference when throwing with a tailwind, but it will produce a great improvement in the distance of a throw made into a headwind.

MIELKE #22 59.46 M 033096



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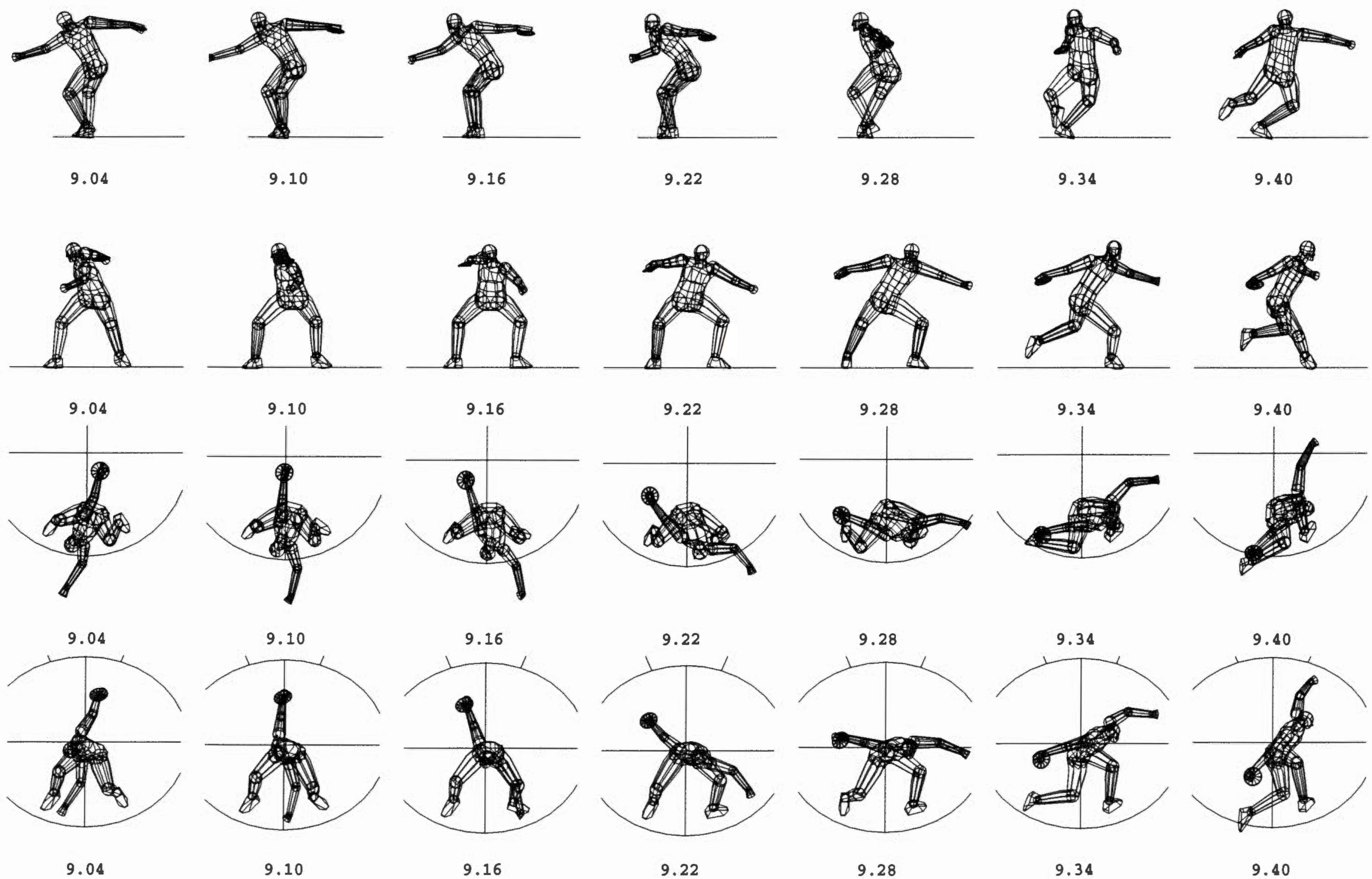

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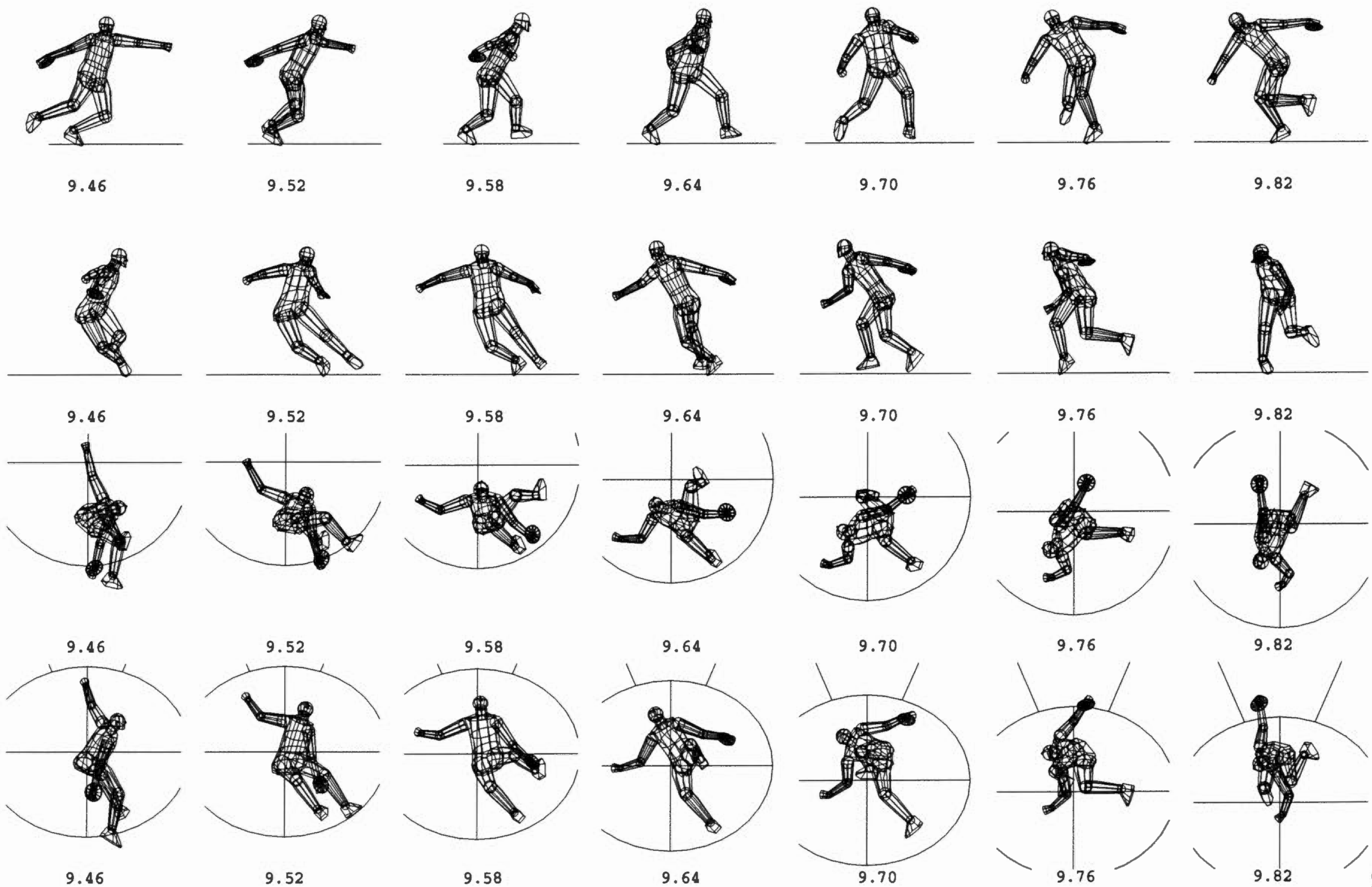

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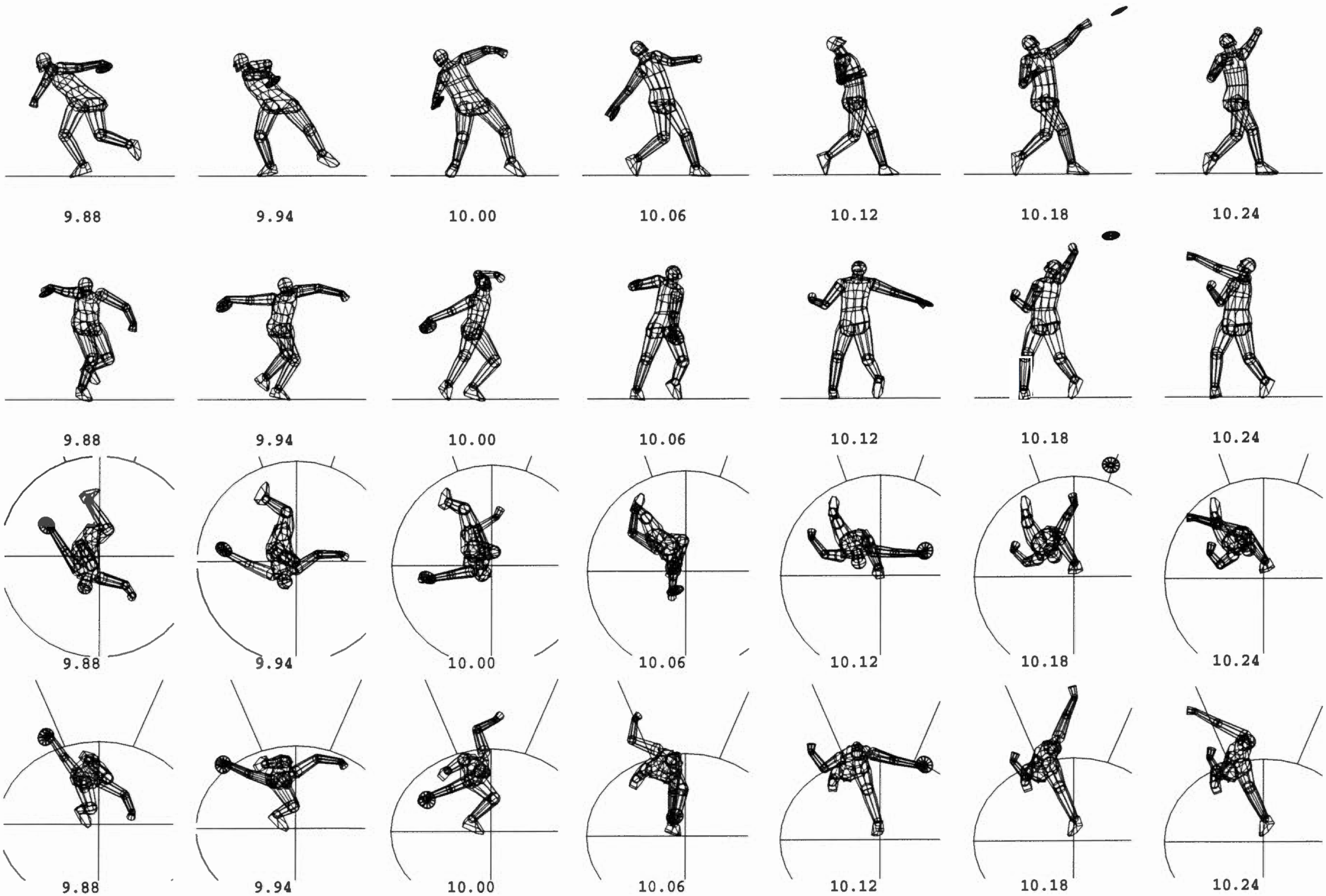

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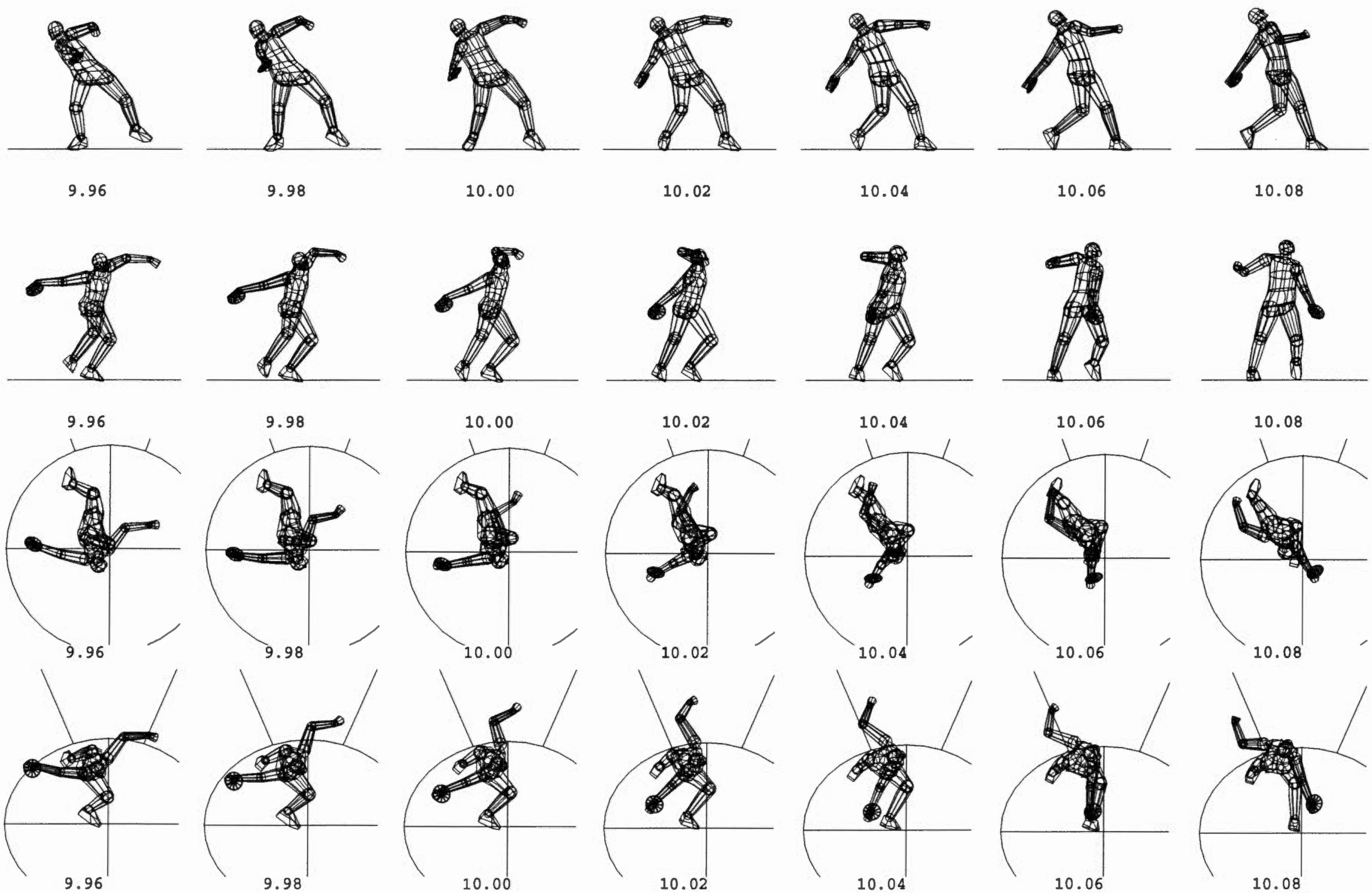

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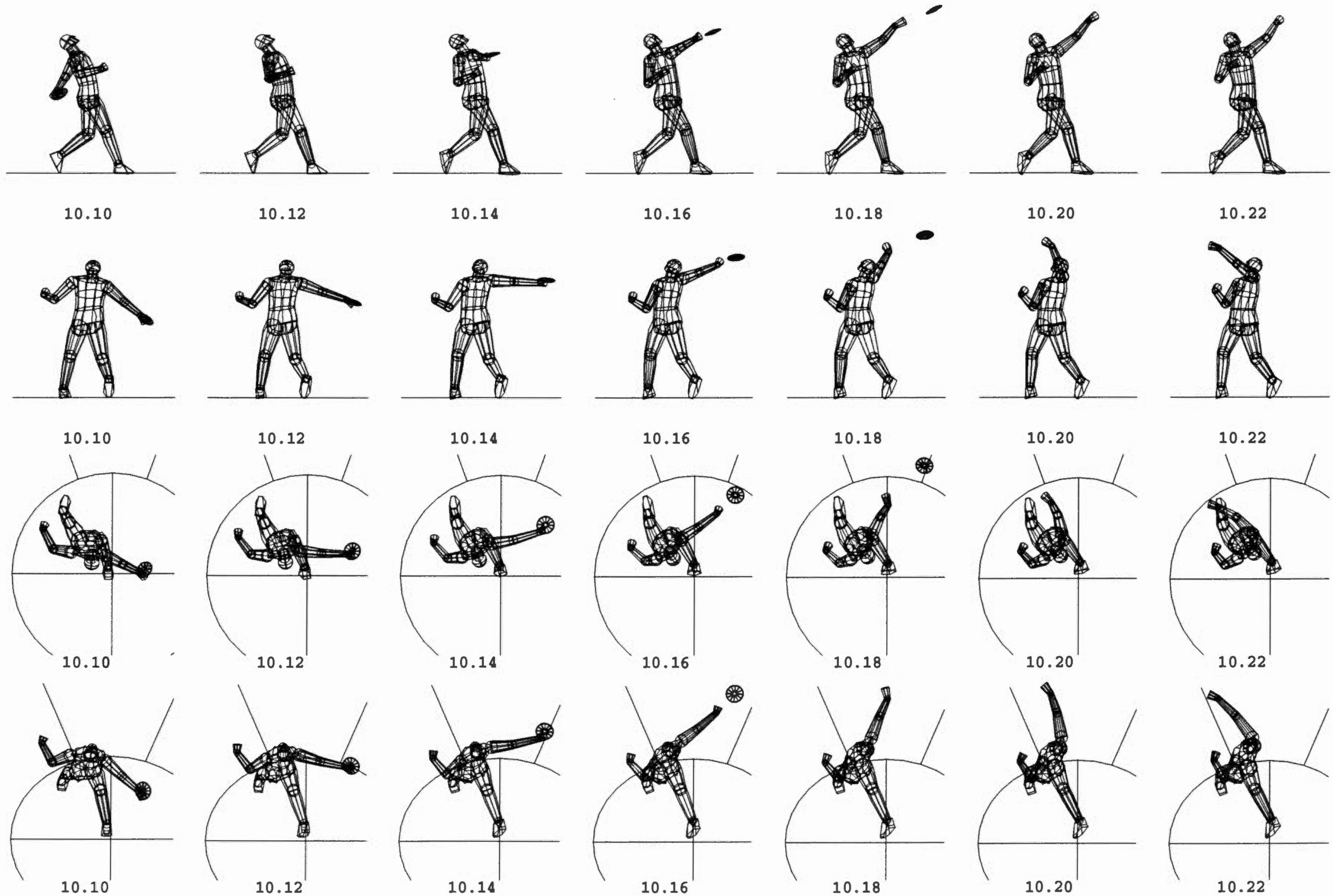

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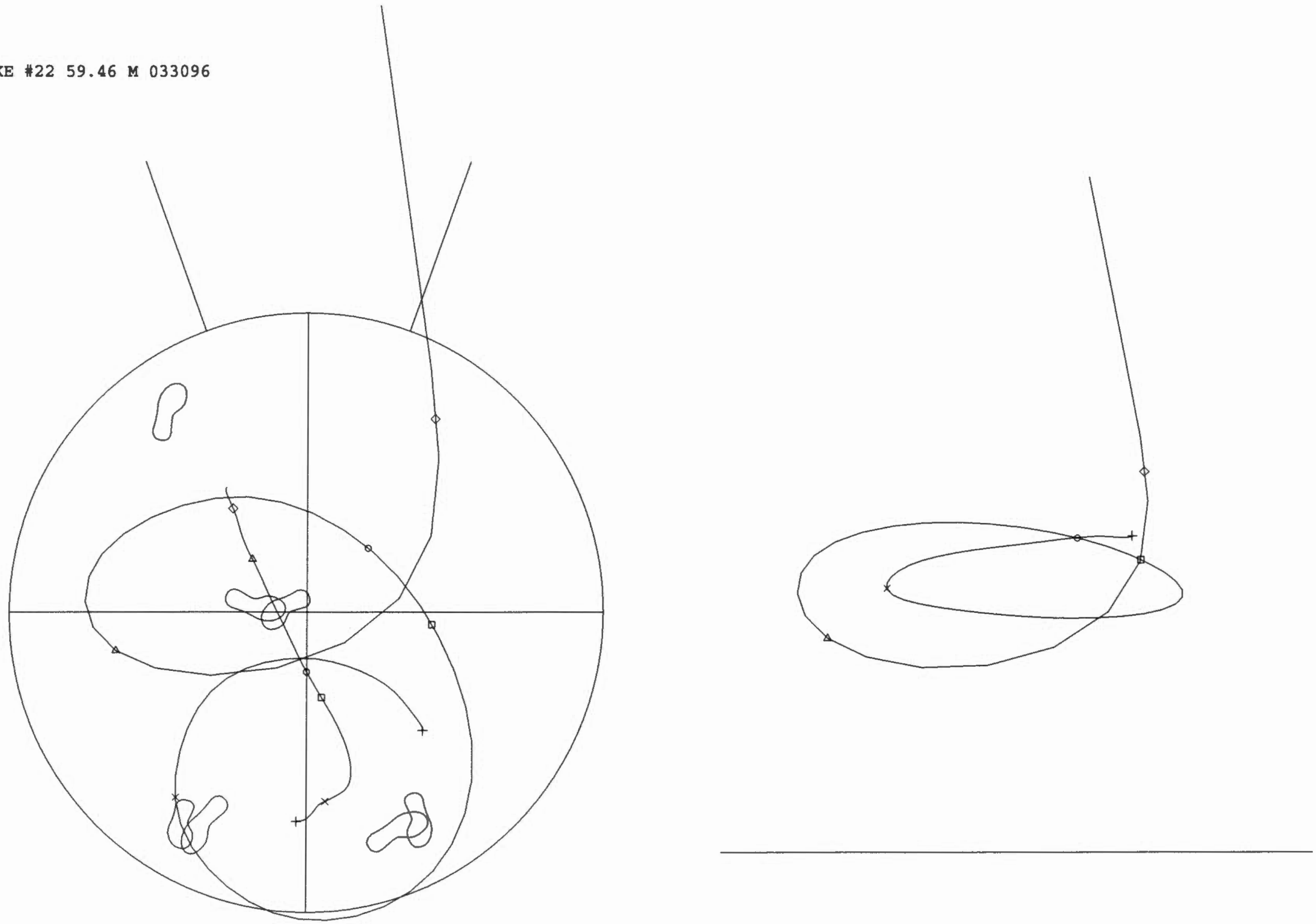

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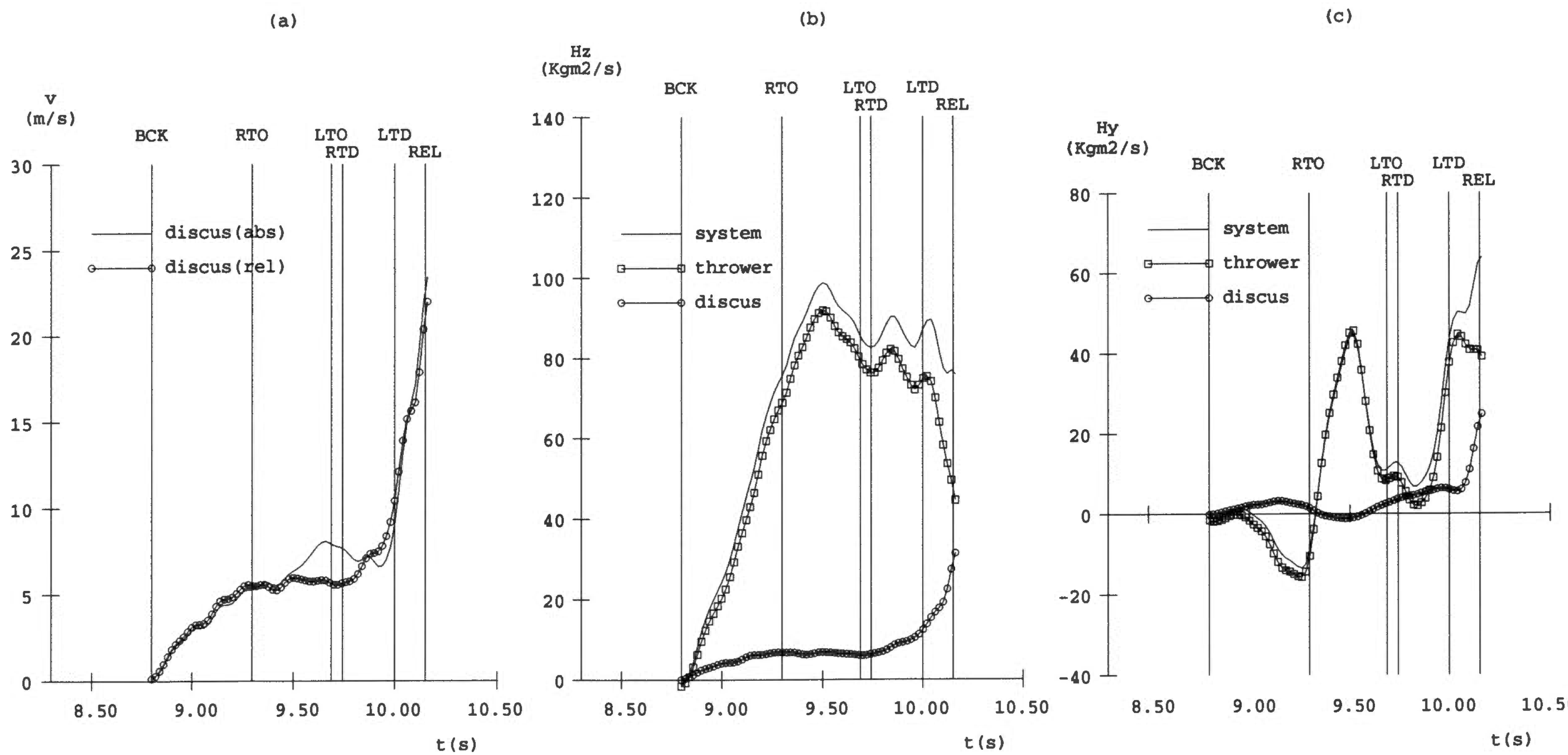
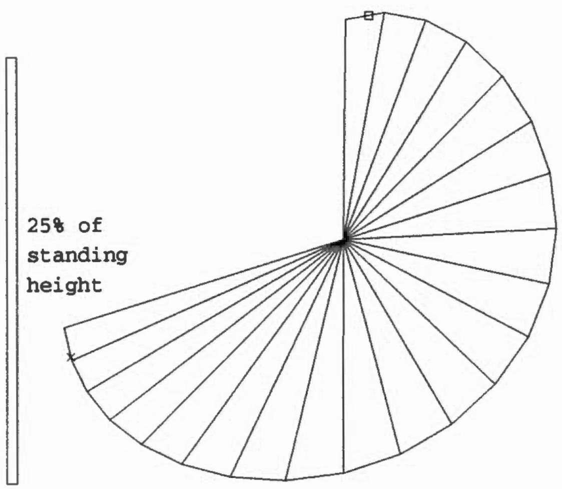
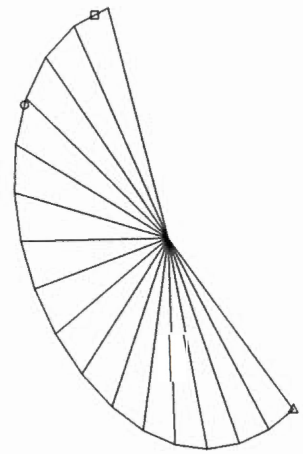
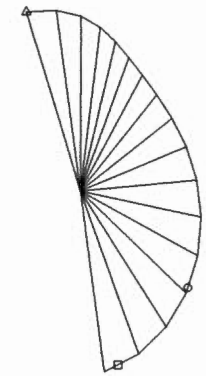




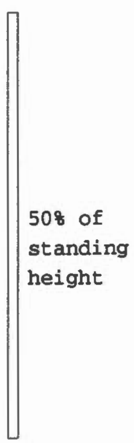
drive of right leg

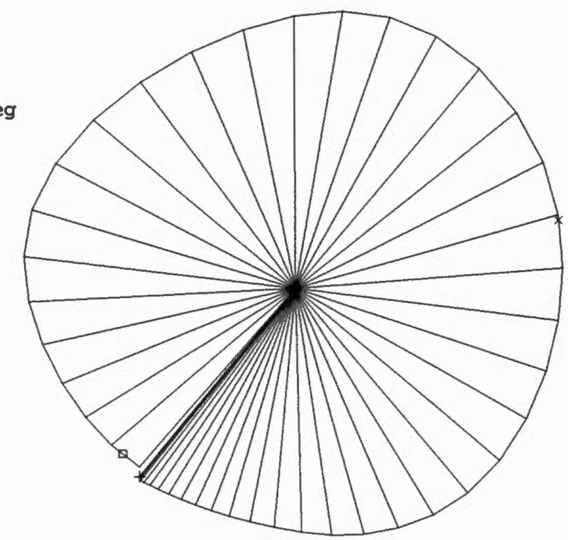


recovery of right leg

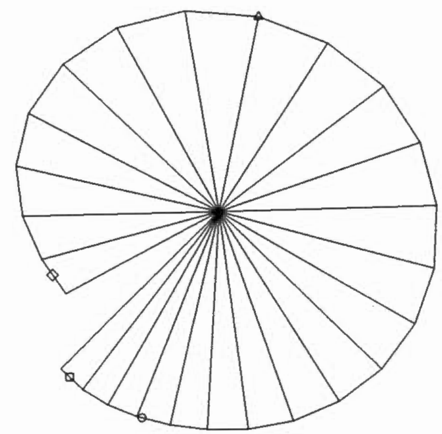


recovery of left leg



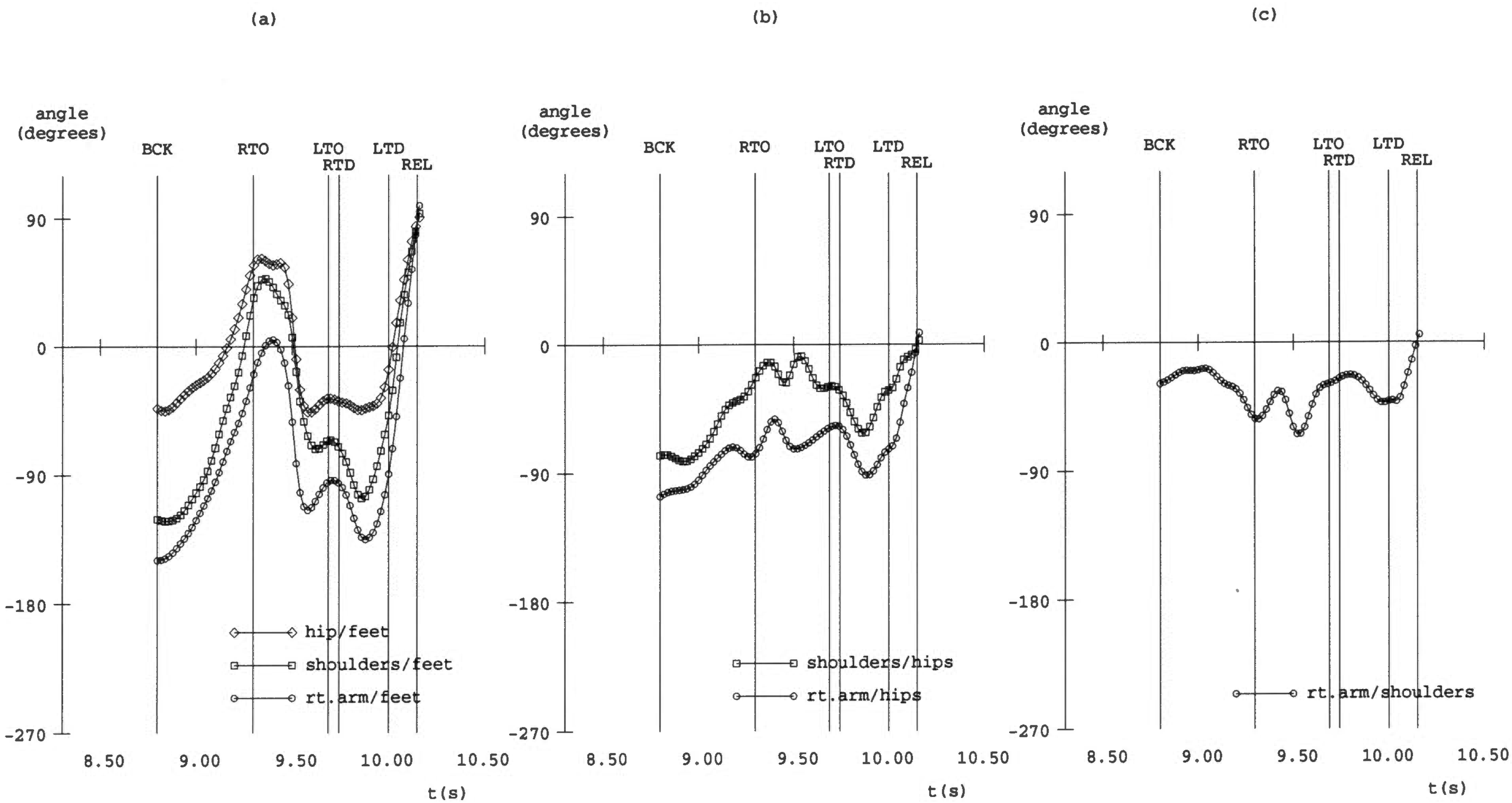


drive of left arm



recovery of left arm, and action during right foot single-support and delivery

MIELKE #22 59.46 M 033096



Jamie PRESSER

Trial 9 was Presser's second-best throw at the 1996 UC San Diego Open (59.04 m, one meter off from his best throw of the meet). We could not film Presser's 60.06 m best throw at San Diego, but trial 9 was probably reasonably representative of his best throwing that day.

The horizontal and vertical translations of the c.m. of Presser's system and their contributions to the speed of the discus were very similar to those of the average subject, and reasonably good. At the back of the circle, Presser shifted the system c.m. toward his left foot. Then, he drove with the left leg against the ground, and traveled moderately fast across the throwing circle (v_{HLTO} = 2.5 m/s; v_{HLTD} = 2.0 m/s), not excessively deviated from directly forward (a_{LTO} = -25°; a_{LTD} = -18°). During the double-support delivery, he made a forward and downward force on the ground. The backward horizontal reaction force reduced his horizontal speed to an amount which was somewhat conservative, although not terribly small either (v_{HQ} = 1.2 m/s). The divergence angle between the directions of motion of the system and of the discus was not excessive, although "borderline" (c_Q = -28°). Therefore, the contribution of the horizontal speed of the system to the horizontal speed of the discus was not far from average (v_{HCON} = 1.1 m/s). The downward force that Presser made against the ground during the double-support delivery was of a moderate size, and the ground reaction to it gave the system a moderate vertical speed which contributed to increase the vertical speed of the discus (v_{ZCON} = 1.5 m/s). There was nothing wrong in any of this; Presser's technique was basically sound. However, there was also nothing extremely good in it either.

The swinging action of the right leg at the back of the circle was better than average (RLA = 27.4 · 10^{-3} Kg·m²/Kg·m²), but the swinging action of the left arm was weaker than average (LAA = 29.7 · 10^{-3} Kg·m²/Kg·m²). Therefore, their combination was very close to average (RLLAA = 57.1 · 10^{-3} Kg·m²/Kg·m²). At the instant of landing of the left foot in the front of the circle, the system had a large amount (94%) of the Z angular momentum (counterclockwise rotation in a view from overhead) that it would eventually reach at release. All this suggests that Presser's generation of angular momentum in the back of the circle was good.

The recovery actions of the legs and of the left arm ($r_{LAVG-NSRSS}$ = 9.4% of standing height; H_{LA-NS} = 35 · 10^{-3} s^{-1}) were very near the average, and therefore we consider them to be reasonably good.

The second propulsive swing of the left arm was very weak (LAA2 = 12.6 · 10^{-3} Kg·m²/Kg·m²), and the maximum angular momentum reached by the arm was very small (H_{MAX} = 42 · 10^{-3} s^{-1}). This is the first important problem that we found in Presser's technique. It seemed to result from the combination of a slow rotation of the left arm and a short radius due to a large degree of flexion at the elbow. Of course, since the arm never obtained much angular momentum, there was also not much to transfer through its slowing down (ΔH = -27 · 10^{-3} s^{-1}) before the release of the discus by the right arm. This was overall a very weak use of the left arm.

At release, the discus had 38% of the total Z angular momentum of the thrower-plus-discus system. This was larger than average, and suggests that Presser did a good job transfering Z angular momentum from his body to the discus.

At release, in the view from the back of the circle the thrower-plus-discus system had a rather small amount of counterclockwise angular momentum (H_{YS} = 38.4 Kg·m²/s). However, a rather large fraction of it (50%) was in the discus, and in absolute terms this constituted a reasonably large amount (H_{YD} = 19.2 Kg·m²/s). Based on this and on the reasonably good contribution that the vertical speed of the system made to the vertical speed of the discus (v_{ZCON} = 1.5 m/s), we expected a moderate vertical speed of the discus at release. However, we found that the vertical speed of the discus was very small in Presser's throw (v_{ZD} = 12.7 m/s). As in Setliff's throw, we think that part of the explanation for this apparent discrepancy lies in Presser's *lean* (which was opposite to that of Setliff). In the view from the back, Presser was leaning markedly toward the right at the instant of release. This shifted the right shoulder toward the right, and took the vertical of the discus farther from the vertical of the system c.m. For a given amount of Y angular momentum of the discus, the longer the distance (in the view from the back) between the system c.m. and the extension of the line of travel of the discus (which is roughly vertical at release, in the view from the back), the ***slower*** the speed of the discus. (Yes, please read on!) By tilting his body toward the right near the instant of release, Presser produced a long distance between the system c.m. and the discus (in effect, he lengthened the radius of motion of the discus), and thus decreased the vertical speed of the discus. (We realize that discus throwers are generally told to maintain the longest possible radius for the discus during the entire throw. However, we feel that this advice needs to be modified. We agree that the radius of the discus should be maintained at the longest possible length during most of the throw. However, we think that it should be shortened for a brief period of time *immediately prior to release*, because this will increase the speed of the discus. It is important that this shortening occur only near the release, and not sooner. At this time, we are not going to go out of our way to instruct discus throwers to do such a thing, because more research is needed on this question —notice that we did not include it in the main body of the report; we had to refer to it here in order to explain why the vertical speed of the discus was so small in Presser's throw.)

Another weakness of Presser's technique was the maximum torsion that he achieved in the front of the circle, which was too small ($k_{RA/FT}$ = -126°), clearly smaller than average (-144°). The main disadvantage that Presser had with respect to the average thrower in the sample at the instant of maximum torsion of the system was the smaller torsion of his shoulders relative to his hips (Presser $k_{SH/HP}$ = -34°; average = -58°).

Presser's use of aerodynamic forces was very good (ΔD = 5.28 m).

Summary

The horizontal and vertical translations of the system c.m. and their contributions to the speed of the discus were very similar to those of the average subject, and therefore reasonably good, but not extremely good either. The combined swinging actions of the right leg and left arm at the back of the circle were also similar to those of the average subject. The generation of Z angular momentum at the back of the circle was good. The recovery actions of the legs and of the right arm after the takeoff of the left foot from the ground were also adequate. The second swing and recovery of the left arm were very weak. The vertical speed of the discus at release was small, due to Presser's excessive lean toward the right at release. The transfer of Z angular momentum from the body to the discus was good, but it might have been even better if Presser had reached a more wound-up position in the single-support on the right foot. Presser's use of aerodynamic forces was very good.

Recommendations

In many respects, Presser's technique is very similar to the technique of the average thrower in the sample. That means that in most ways it is basically sound, and needs only gradual improvements. For instance, in the back of the circle Presser should "sit back" less, and first shift the system c.m. a little bit further toward his left foot, then drive a little harder and also less diagonally across the circle; push a little bit harder forward and downward on the ground during the double-support delivery; swing the left arm a little bit harder at the back of the circle. All these are small changes which will add up to produce a noticeable increase in the distance of the throw.

But there are also clear technique defects which need correction. After the right foot lands in the middle of the circle, Presser should swing the left arm very hard counterclockwise, and without much flexion at the elbow. Then, he should stop the counterclockwise rotation of this arm and/or bring it closer to the body before the discus leaves the right hand.

With respect to Presser's lean toward the right at release, we think that it is a disadvantage, and that he should bring the body to a more erect position just before release. This will increase the vertical speed of the discus (as well as its horizontal speed). We realize that many coaches will disagree with this advice, but we still feel that this is what should be done!

We advise Presser to produce a greater degree of torsion between the right arm and the feet at the instant when the final acceleration of the discus is about to begin during the single-support on the right foot. To achieve this, he will need to use the muscles of his trunk to make the hips rotate counterclockwise further ahead of the shoulders (or to make the shoulders rotate more clockwise relative to the hips —from a mechanical standpoint, both are the same thing!). A more wound-up configuration of the body during the single-support on the right foot should allow Presser to drive the discus over a longer range of motion during the final acceleration, and thus to impart more speed to the discus, which in turn will result in a longer throw.

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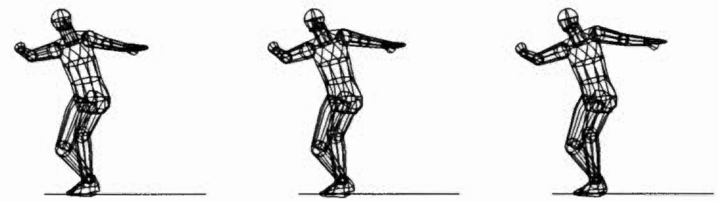

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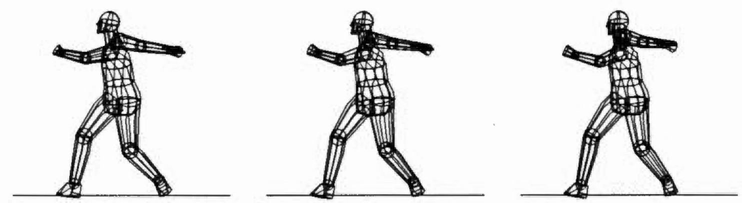

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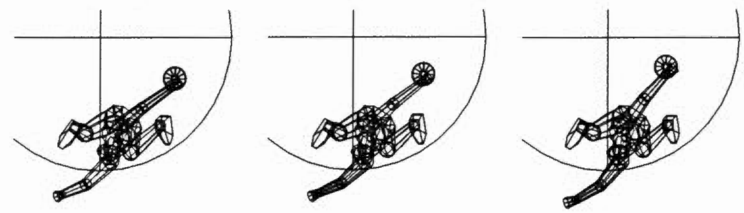

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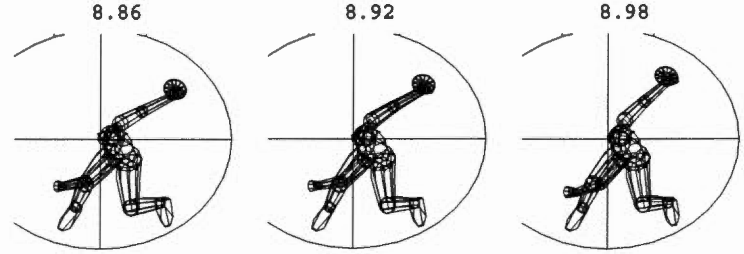

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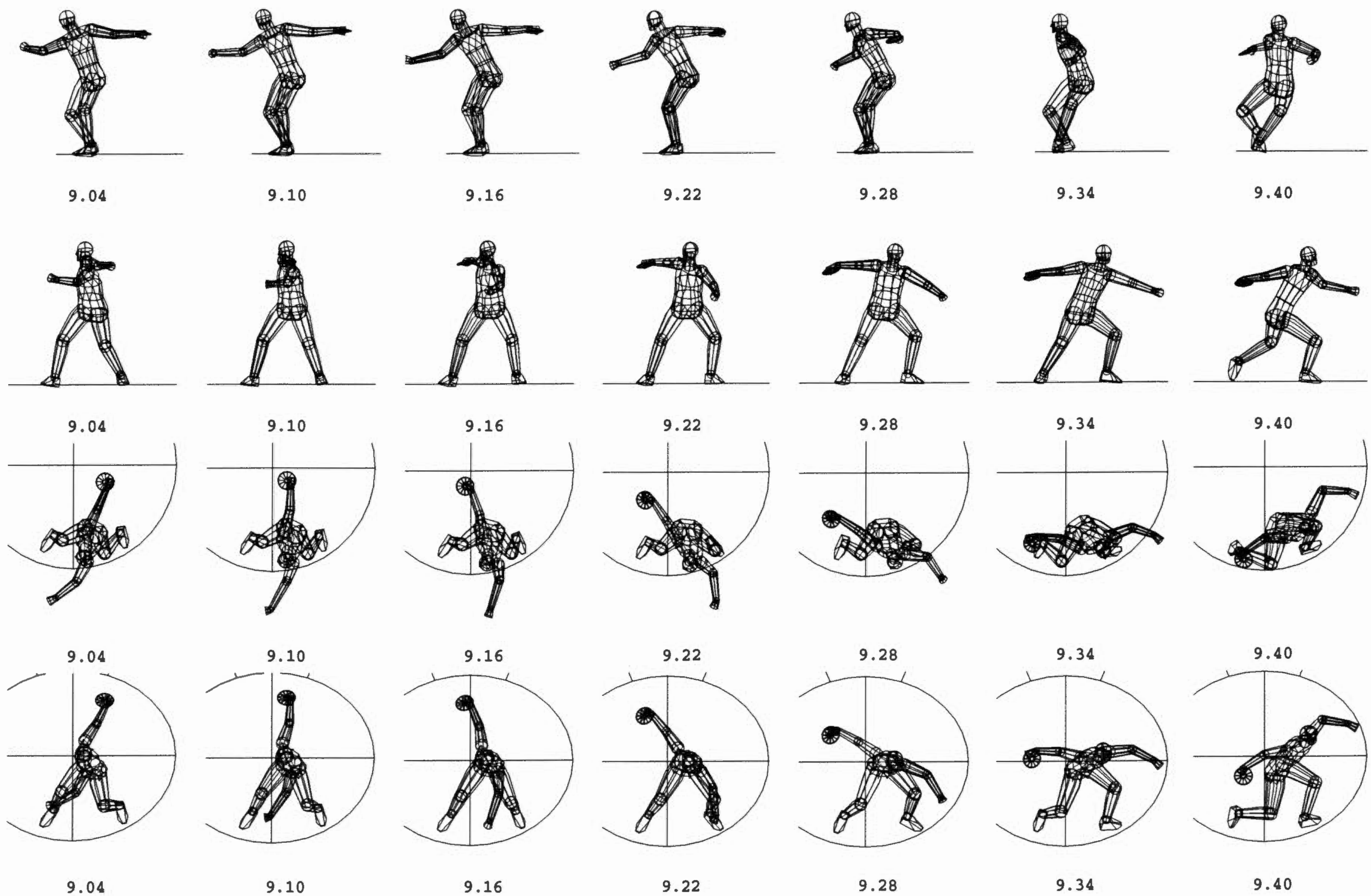

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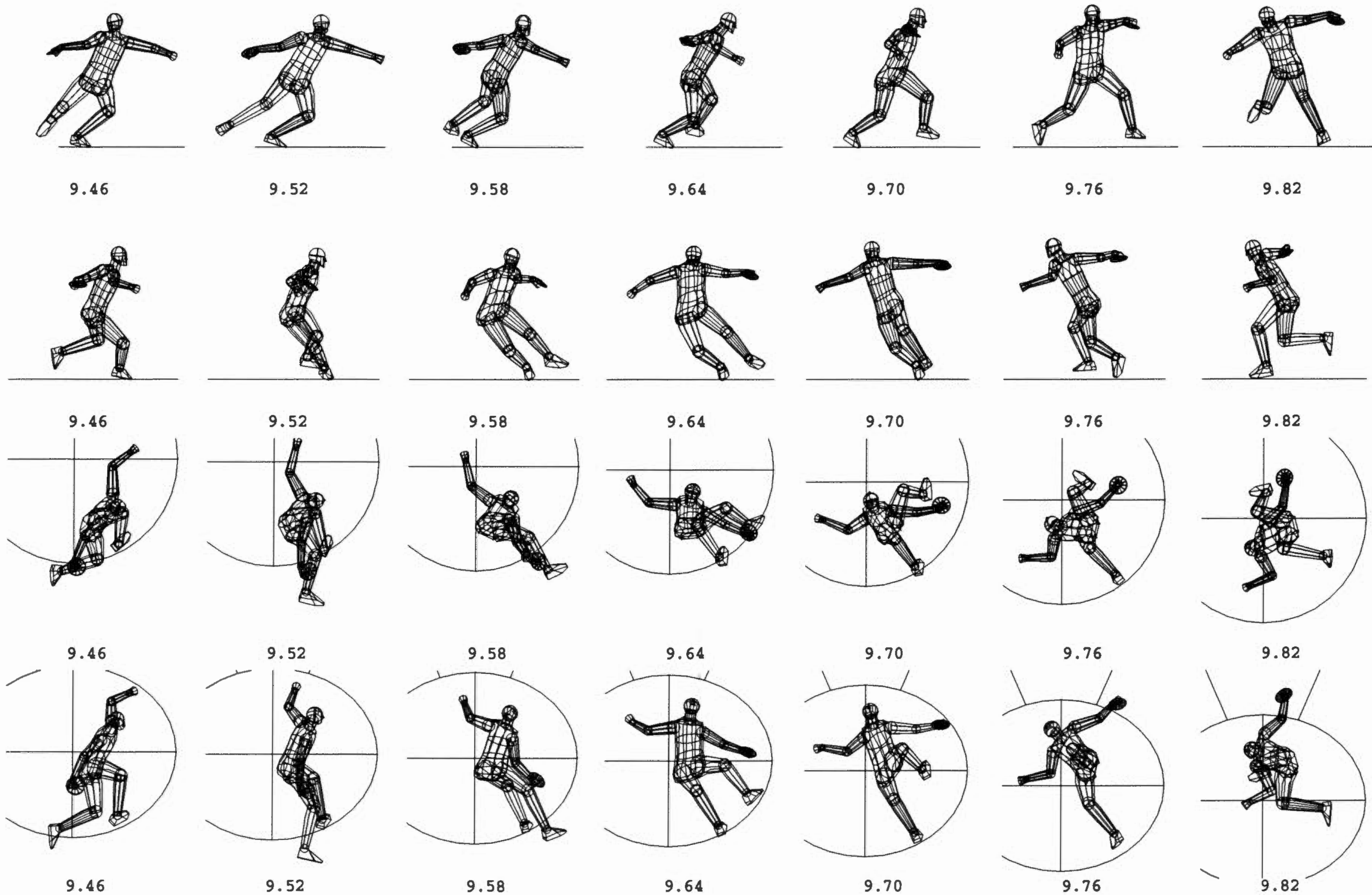

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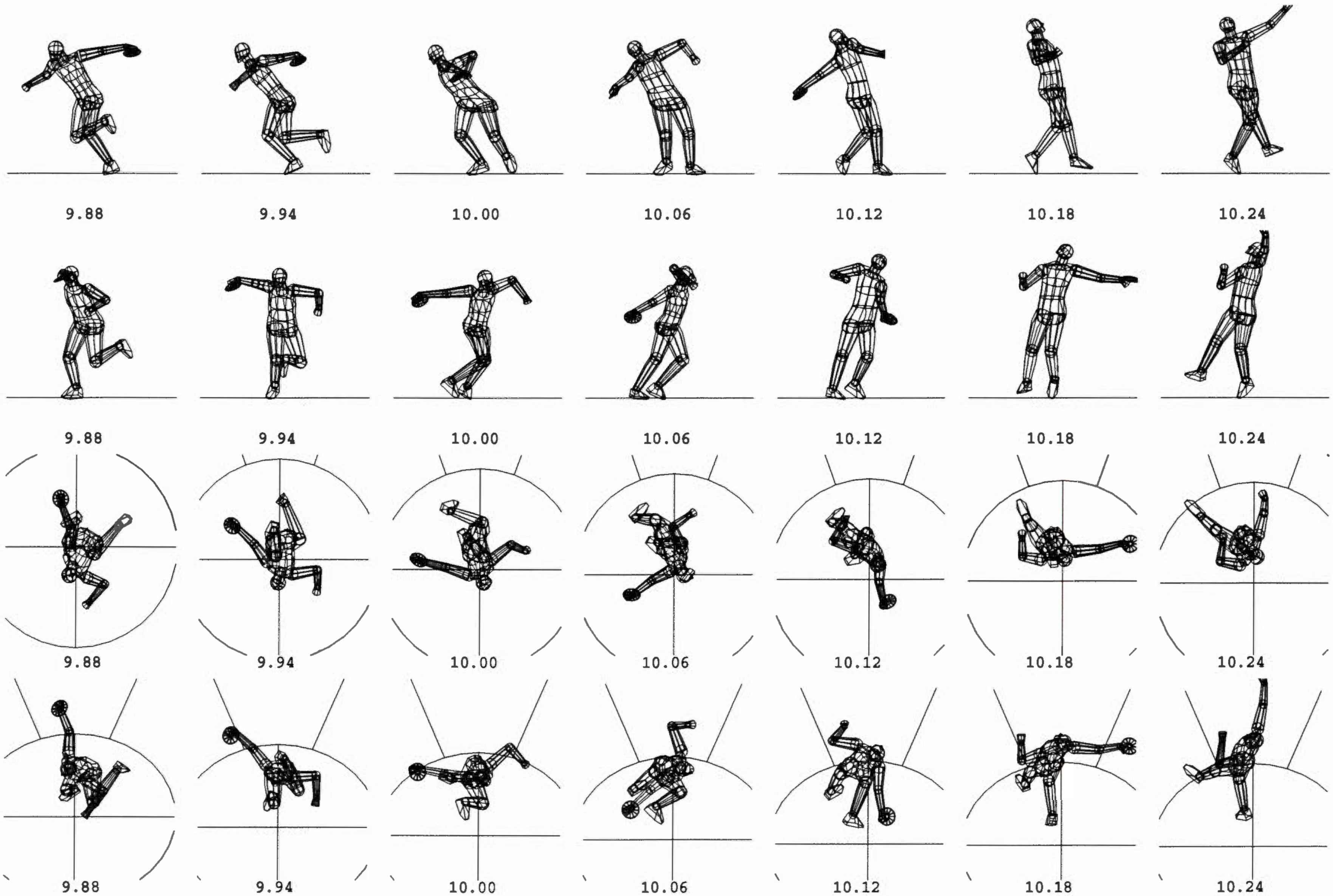

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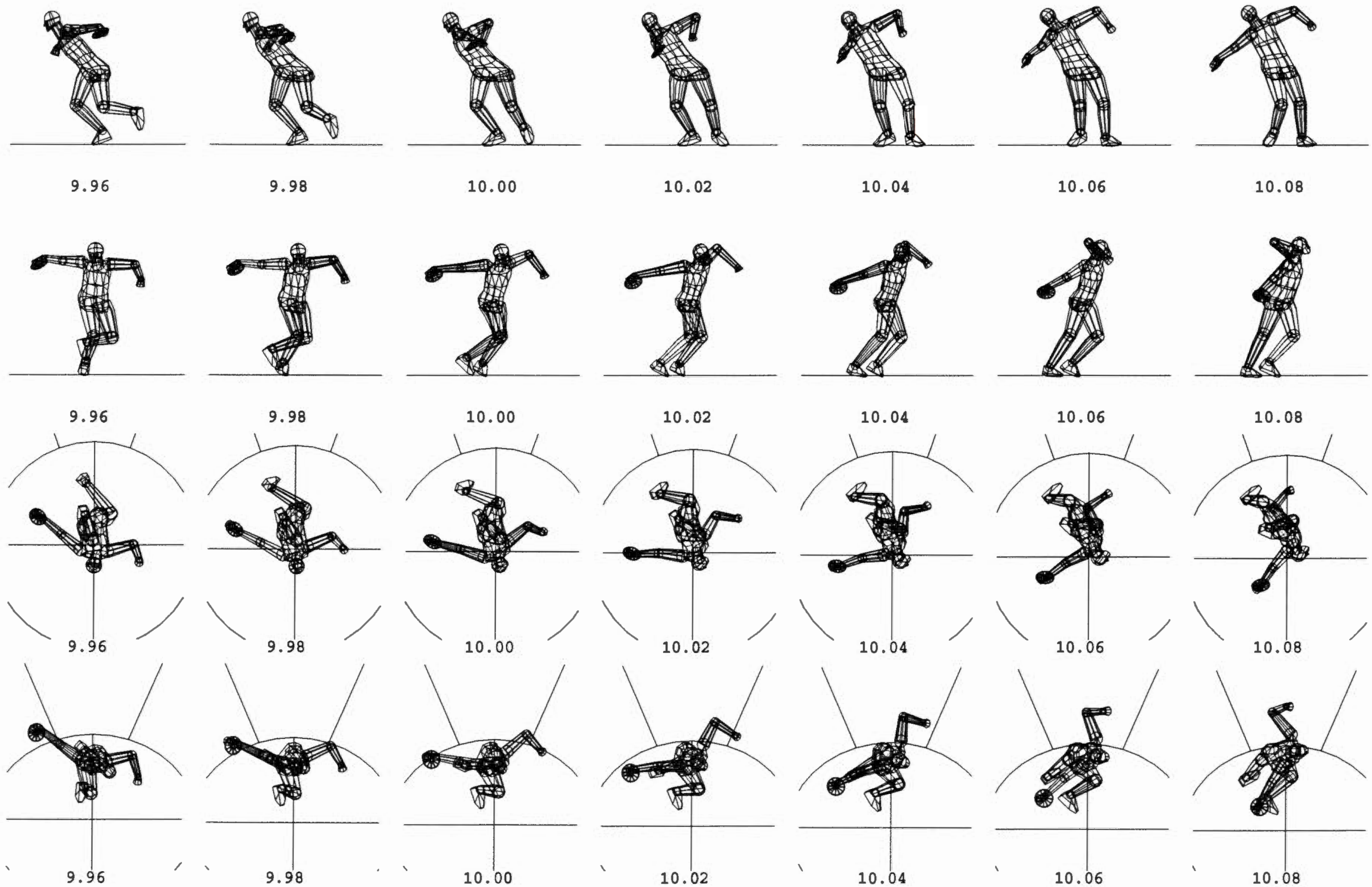

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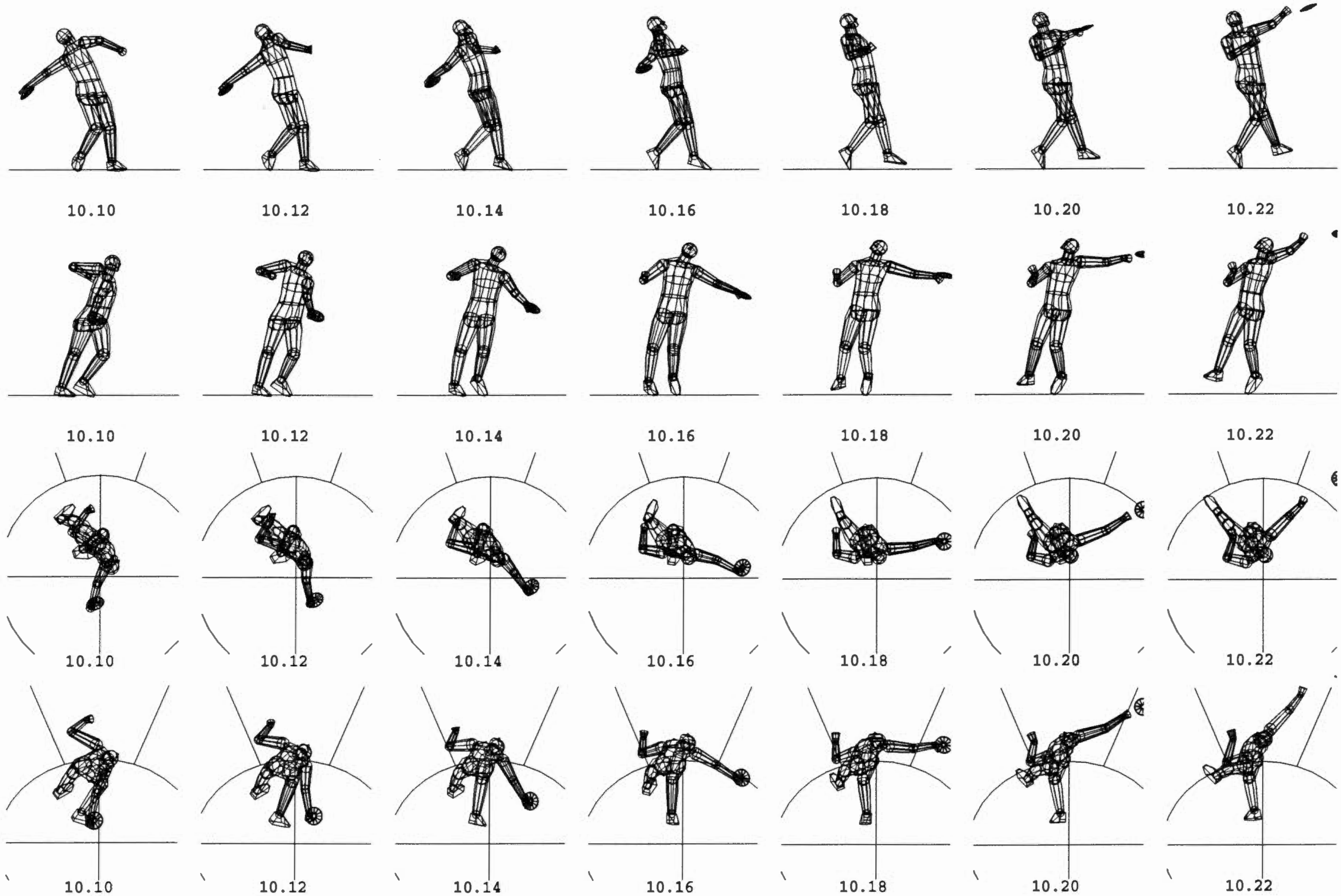

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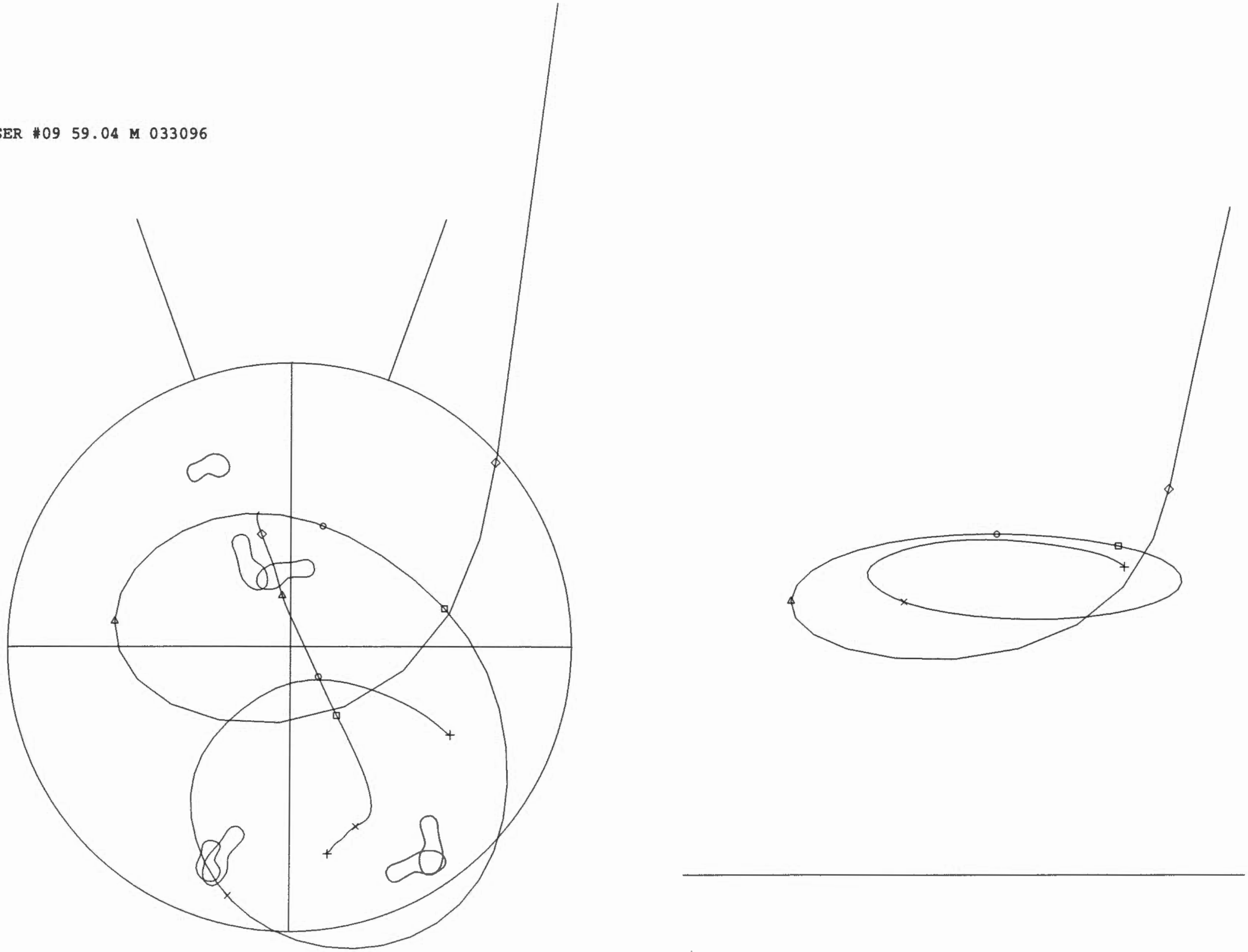

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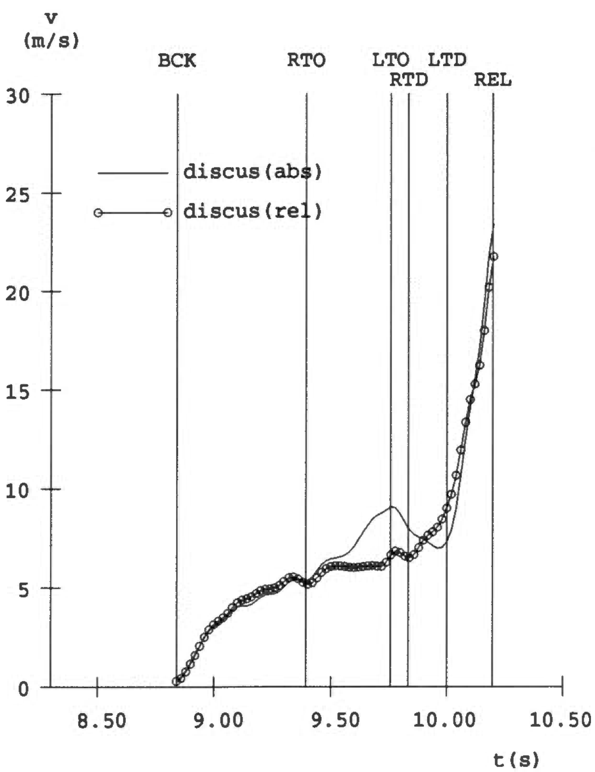

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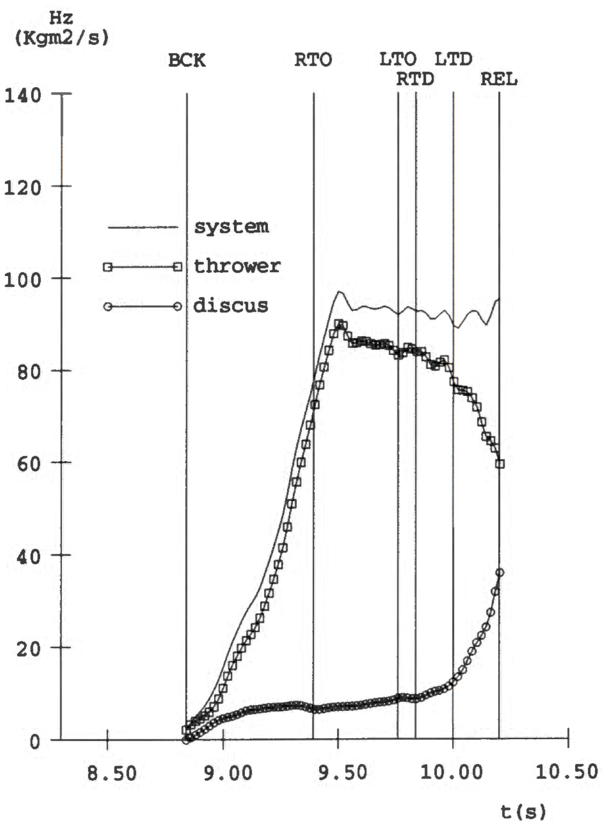

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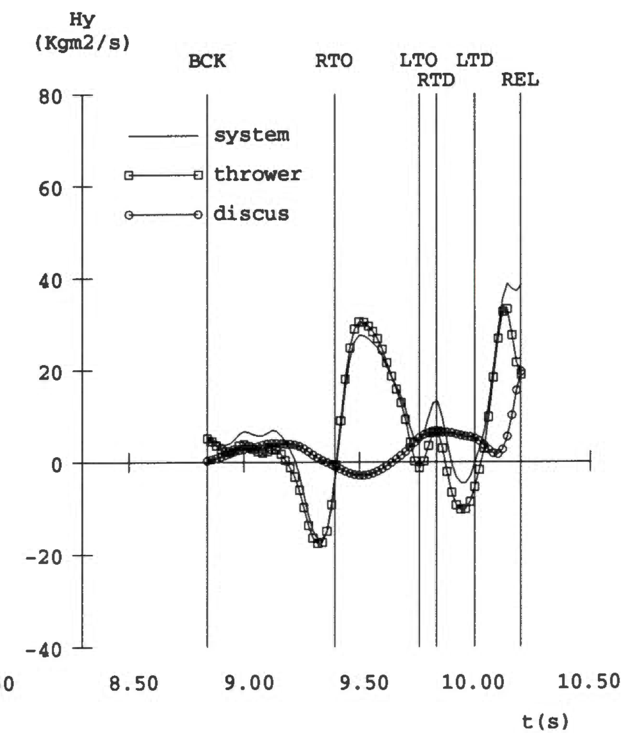

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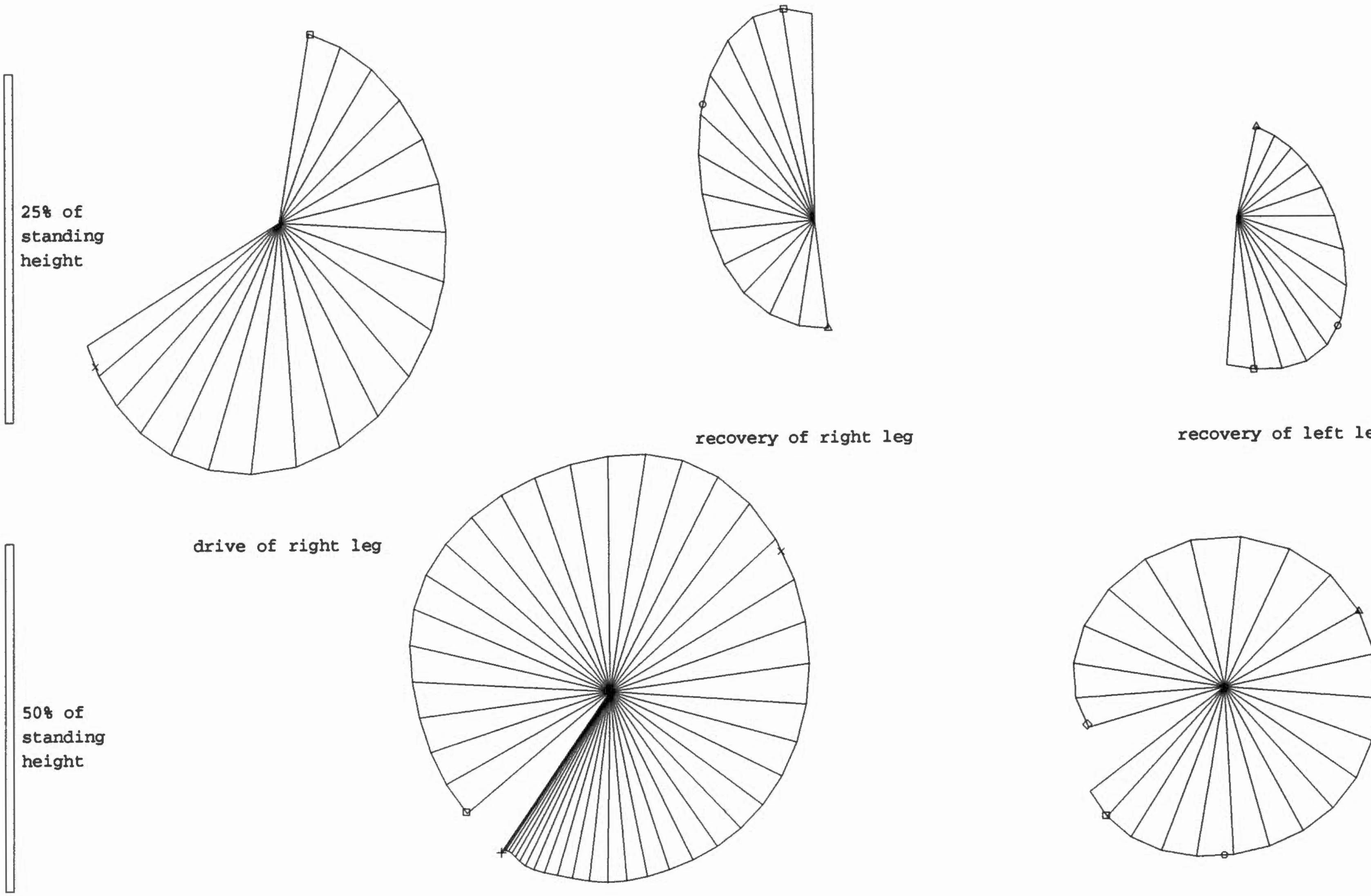

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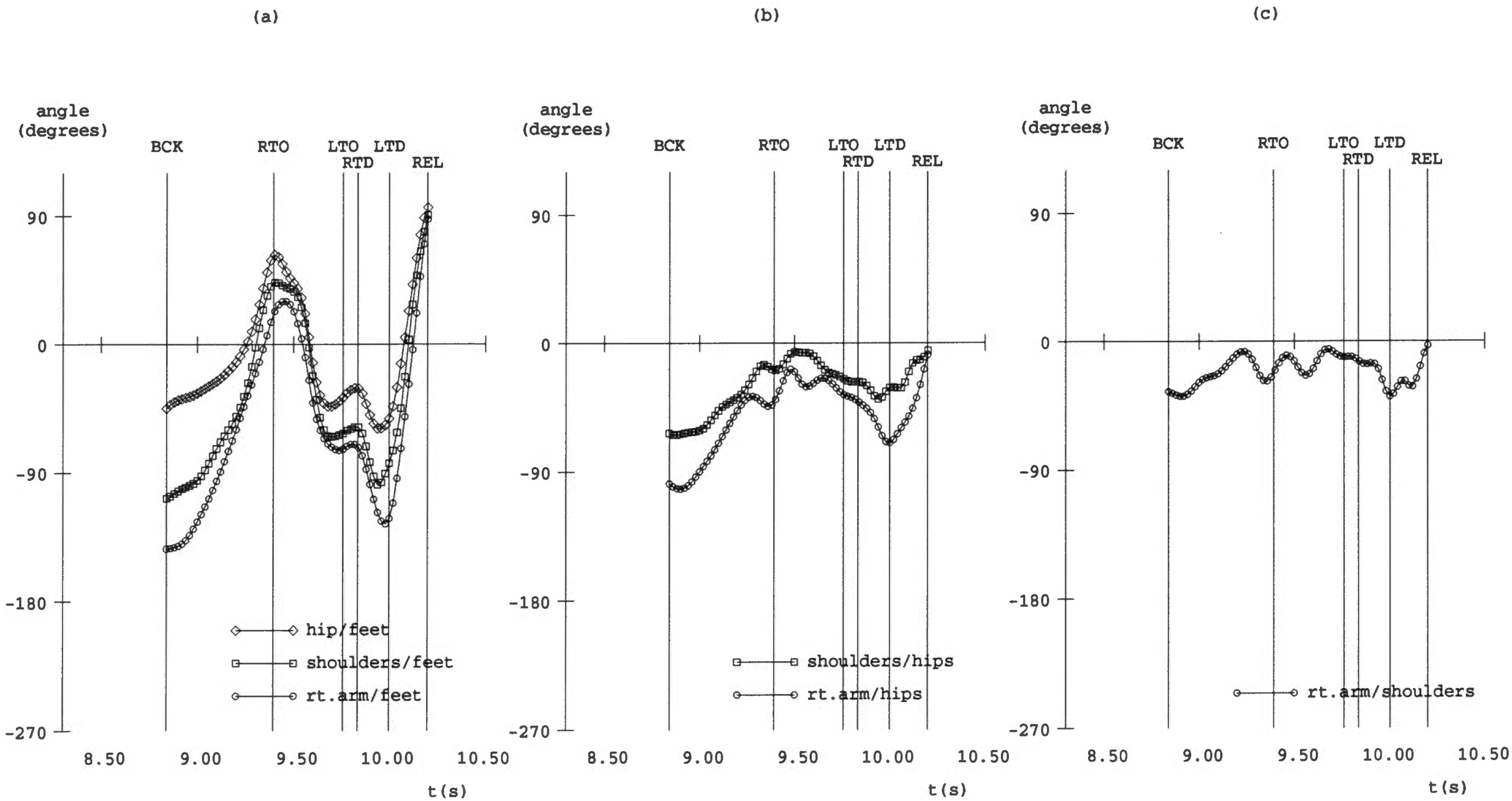

Adam SETLIFF

Trial 27 was Setliff's best throw at the 1994 USATF Championships (57.44 m). Trial 65 was his second-best throw at the 1996 UC San Diego Open (63.32 m, two meters off from his winning throw). We could not film Setliff's 65.24 m personal record throw at San Diego, but trial 65 was probably reasonably representative of his best throwing that day.

It is important to realize that the differences between the distances of throws 27 and 65 were due almost exclusively to the differences in the wind conditions at the two competitions. In a vacuum, trial 27 would have reached 55.99 m, and trial 65 would have reached 55.01 m. (See Table 16.) Taking into account that our calculations are imperfect, we should consider the two throws as essentially equal in this respect. The aerodynamic forces then contributed an additional ΔD = 1.45 m to throw 27, and ΔD = 8.31 m (!) to throw 65. So most of the difference in the distances of the two throws was due to the differences in the wind conditions, which were more advantageous in the 1996 meet than in the 1994 meet. It would be a mistake to think of throw 65 as the "good" throw, and throw 27 as the "bad" throw; throw 27 was not intrinsically inferior to throw 65.

We also need to keep in mind that, up to the instant of release, throw 65 was not very remarkable in comparison with other throws from the 1996 UC San Diego Open. What made this throw exceptional was the skillful use that Setliff made of the interaction between the discus and the wind.

We will dedicate most of our attention here to throw 65, because it is the most recent, but we will also make some references to throw 27 where they are relevant.

At the back of the circle, Setliff shifted his c.m. very well toward his left foot. Then, he drove with the left leg against the ground. By the time that the left foot lost contact with the ground, the thrower-plus-discus system had a reasonably fast horizontal speed (v_{HLTO} = 2.5 m/s), and the direction of travel of the system c.m. was not too diagonal (a_{LTO} = -17°). After the landing of the right foot, the system lost quite a bit of horizontal speed during the single-support (Δv_{SSR} = -0.9 m/s), which left it with only a small amount of horizontal speed at the instant that the left foot landed (v_{HLTD} = 1.6 m/s). It is not clear what made Setliff lose so much horizontal speed during the single-support on the right foot, but throw 27 may give us some useful clues. In throw 27, Setliff lost only a reasonable amount of horizontal speed during the single-support on the right foot (Δv_{SSR} = -0.5 m/s). Also, during the early and middle parts of the throw he was in a higher position in throw 27 than in throw 65. (Compare the views from the back of the circle and from the side in the sequences of throws 27 and 65 from the beginning of the throw until the landing of the left foot in the front of the circle: They show that Setliff was much lower in throw 65 than in throw 27.) Maybe the greater degree of flexion of the right knee in throw 65 during the single-support on the right leg was too uncomfortable, and was what made Setliff lose a large amount of horizontal speed during this period in that throw; we can't be sure if this was the cause, but it seems reasonable. It is conceiveable that the low position of Setliff in the early and middle parts of throw 65 may provide other advantages, but *this* is a disadvantage.

During the double-support delivery phase, the forward horizontal force that Setliff made on the ground was small, and thus allowed the thrower-plus-discus system to retain most of its horizontal speed for the period in which the discus made its last quarter-turn (v_{HQ} = 1.4 m/s). This was a reasonably large amount of horizontal speed.

Unfortunately, the c.m. path deviated quite a bit toward the left during the double-support delivery, and as a result the average direction of motion of the system c.m. during the last quarter-turn of the discus was very oblique with respect to the forward direction (a_Q = -33°). (It is not clear why the c.m. deviated its path so much toward the left. Maybe as the left foot pushed on the ground toward the right of the circle the left foot failed to push on the ground hard enough toward the left. That would make the net force exerted by the feet on the ground point toward the right part of the circle, and the net reaction force exerted by the ground on the feet point toward the left. The result would be a deviation of the c.m. path toward the left. However, we do not know if this is how it actually happened; all we know for sure is that the path of the system c.m. deviated toward the left.) Since the direction of travel of the discus after release was toward the right in throw 65 (d_{HREL} = 13°), the divergence angle between the directions of motion of the system and of the discus was very large (c_Q = -46°). Because of this, the contribution of the horizontal speed of the system to the horizontal speed of the discus was very small (v_{HCON} = 0.9 m/s).

The size of the vertical force made on the ground during the double-support delivery phase is generally linked to the size of the horizontal force made on the ground during that same period; therefore, the vertical force that Setliff made on the ground during the double-support delivery was small. As a result, the vertical speed of the system during the last quarter-turn (and therefore the contribution of the vertical motion of the system c.m. to the vertical speed of the discus) was also small (v_{ZCON} = 1.1 m/s).

The swinging actions of the right leg and of the left arm at the back of the circle were excellent (RLA = 31.8 · 10^{-3} Kg·m²/Kg·m²; LAA = 37.0 · 10^{-3} Kg·m²/Kg·m²), and of course, so was their sum (RLLAA = 68.8 · 10^{-3} Kg·m²/Kg·m²). At the instant of landing of the left foot in the front of the circle, the system had a reasonably large amount (87%) of the Z angular momentum (counterclockwise rotation in a view from overhead) that it would eventually reach at release. All this suggests that Setliff's generation of angular momentum in the back of the circle was good.

The recovery actions of the legs were very good. The small average radius of the legs ($r_{LAVG-NSBSS}$ = 9.1% of standing height) shows that Setliff brought both legs very close together below his body.

The recovery of Setliff's left arm was not quite so good (H_{LA-NS} = 43 · 10^{-3} s^{-1}, which was slightly large). The arm was kept far out during the non-support phase, but the main problem was that it did not slow down its rotation enough. This made the arm travel counterclockwise too far during the non-support phase, which limited the range of motion available for the second propulsive swing of the arm. The second propulsive swing of the left arm was somewhat weaker than in the average thrower of our sample (LAA2 = 15.3 · 10^{-3} Kg·m²/Kg·m²), and so was the maximum angular momentum that this arm reached (H_{MAX} = 54 · 10^{-3} s^{-1}). However, the slowing down of the arm was about average (i.e., better) (ΔH = -41 · 10^{-3} s^{-1}).

At release, the discus had 35% of the total Z angular momentum of the thrower-plus-discus system. This was within normal bounds, and suggests that Setliff did a good job transfering Z angular momentum from his body to the discus.

At release, in the view from the back of the circle the thrower-plus-discus system had only a modest amount of counterclockwise angular momentum (H_{YS} = 36.1 Kg·m²/s). A reasonably large proportion of that (46%) was in the discus, but in absolute terms the Y angular momentum of the discus was still rather small (H_{YD} = 16.5 Kg·m²/s). Since the contribution of the vertical speed of the system to the vertical speed of the discus was small (v_{ZCON} = 1.1 m/s), and the Y angular momentum of the discus was also rather small, we expected the vertical speed of the discus at release to be small. However, it was average (v_{ZD} = 13.6 m/s). We think that part of the explanation for this apparent discrepancy lies in Setliff's lean. In the view from the back, Setliff was leaning slightly toward the left at the instant of release. This shifted the right shoulder toward the left, and brought the vertical of the discus nearer to the vertical of the system c.m. For a given amount of Y angular momentum of the discus, the shorter the distance (in the view from the back) between the system c.m. and the extension of the line of travel of the discus (which is roughly vertical at release, in the view from the back), the faster the vertical speed of the discus. By tilting his body toward the left near the instant of release, Setliff shortened the distance between the c.m. and the discus (in effect, he shortened the radius of motion of the discus), and thus increased the vertical speed of the discus. (Yes, we realize that discus throwers are generally told to maintain the longest possible radius for the discus during the entire throw. However, we feel that this advice needs to be modified. We agree that the radius of the discus should be maintained at the longest possible length during most of the throw. However, we think that it should be shortened for a brief period of time *immediately prior to release*, because this will increase the speed of the discus. It is important that this shortening occur only near the release, and not sooner. At this time, we are not going to go out of our way to instruct discus throwers to do such a thing, because more research is needed on this question —notice that we did not include it in the main body of the report; we had to refer to it here in order to explain how Setliff managed to give a reasonably large vertical speed to the discus with only a rather small amount of Y angular momentum.)

Setliff achieved an extremely wound-up position in the single-support over the right foot ($k_{RA/FT}$ = -168°). This was very good, because the subsequent unwinding helped him to transfer angular momentum from the body to the discus. The main advantages of Setliff with respect to the average thrower at the instant of maximum torsion of the system were in the torsion of the hip relative to the feet (Setliff $k_{HP/FT}$ = -62°; average = -51°) and of the right arm relative to the shoulders (Setliff $k_{RA/SH}$ = -46°; average = -34°).

Setliff obtained much more benefit from the wind at the 1996 UC San Diego Open ($\Delta D = 8.31$ m) than any other thrower analyzed at that meet. This was an outstanding use of the aerodynamic forces. We do not think that it was by accident, since Setliff also made best use of the aerodynamic forces at the 1994 USATF Championships (where the wind conditions were less advantageous: $\Delta D = 1.45$ m).

Summary

In throw 65, Setliff shifted his c.m. very well toward his left foot at the back of the circle, and then produced a reasonably fast horizontal speed which pointed almost directly forward across the circle. However, this horizontal speed of the system c.m. was slowed down too much during the single-support on the right foot, and the direction of travel of the system c.m. deviated too much toward the left during the double-support delivery phase. The horizontal and vertical forces that Setliff made on the ground during the double-support delivery were small. Therefore, the system only reached a small vertical speed. The system also retained a large horizontal speed, but the divergence angle between the directions of motion of the system and of the discus was large. In consequence, the contributions to the vertical and horizontal speeds of the discus were small. The actions of Setliff's right leg and left arm in the back of the circle were excellent, and the generation of Z angular momentum was good. The recovery actions of his legs after the takeoff of the left foot in the middle of the throw were good. The recovery of the left arm was not so good. It traveled counterclockwise somewhat too far during the non-support phase, and this may have limited the second drive of the left arm to some extent. Setliff achieved an extremely wound-up position in the single-support on the right foot. He used the aerodynamic forces better than anyone else in the sample.

Recommendations

Most aspects of Setliff's technique were very good. The swings of the right leg and left arm in the back of the circle, the recovery actions of the legs after the takeoff of the left foot in the middle part of the throw, the very wound-up position achieved during the single-support on the right foot, and the extremely effective use that he made of the aerodynamic forces were all excellent aspects of Setliff's technique.

The only flaws that we found were the low forward and upward speeds of the system c.m. during the last quarter-turn of the discus and, to a lesser degree, the recovery and second drive of the left arm. We will now propose ways in which these problems might be overcome.

Three corrections should alleviate or fix the first problem: (a) pass over the single-support on the right foot without losing so much horizontal speed; (b) prevent the marked deviation of the system c.m. toward the left during the double-support delivery; (c) push forward and downward explosively against the ground during the double-support delivery.

(a) The large loss of horizontal speed that occurred in throw 65 during the single-support on the right foot may have been due to discomfort associated with Setliff's much lower position in comparison with throw 27. Although the system c.m. was in a lower position during the early and middle parts of throw 65, by the time that the left foot landed in the front of the circle to start the delivery, it had been raised to approximately the same height as in throw 27. This makes us think that the lower position of the c.m. may not have produced any advantage for Setliff, while creating difficulties in maintaining the horizontal speed of the system during the single-support on the right foot. If Setliff is not able to maintain a larger amount of his horizontal speed with his c.m. in the low position of throw 65, it is possible that he might be better off returning to the old, higher, position of the c.m. during the early and middle parts of the throw.

(b) During the double-support delivery, Setliff should push on the ground harder toward the left part of the circle with his right foot. This will help to prevent the deviation of the path of the system c.m. toward the left, and therefore it will reduce the divergence angle between the paths of the system c.m. and of the discus. The result will be a larger contribution of the forward motion of the system c.m. to the horizontal speed of the discus, and therefore to the distance of the throw.

(c) During the double-support delivery, Setliff should push explosively forward and downward against the ground with his left leg. This will reduce the forward speed of the system c.m., but that is alright, because the system will have more horizontal speed than in throw 65, and he will *need* to lose more of it to avoid fouling. But the main effect that we are looking for is the large increase of the vertical speed of the system c.m. which will result from the large upward vertical force that the body will receive as a reaction to the large downward force that the left foot is making on the ground. The increased vertical speed of the system will make a larger contribution to the vertical speed of the discus, and therefore to the distance of the throw.

After the left foot takes off from the ground in the middle of the throw, Setliff should slow down momentarily the counterclockwise motion of his left arm. This will leave a larger range of motion available for this arm during the single-support on the right foot and the double-support delivery phase. During these phases, he should again accelerate the left arm counterclockwise very strongly, keeping the elbow well extended. Then, he should try to stop the counterclockwise rotation of the left arm and/or bring the left arm closer to the body before the discus leaves the right hand.

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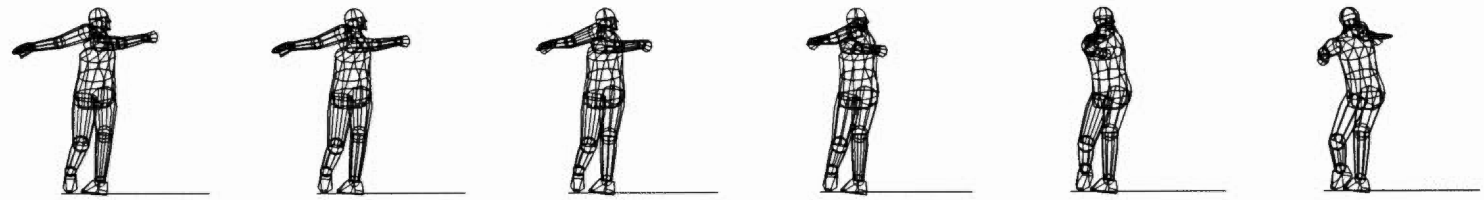

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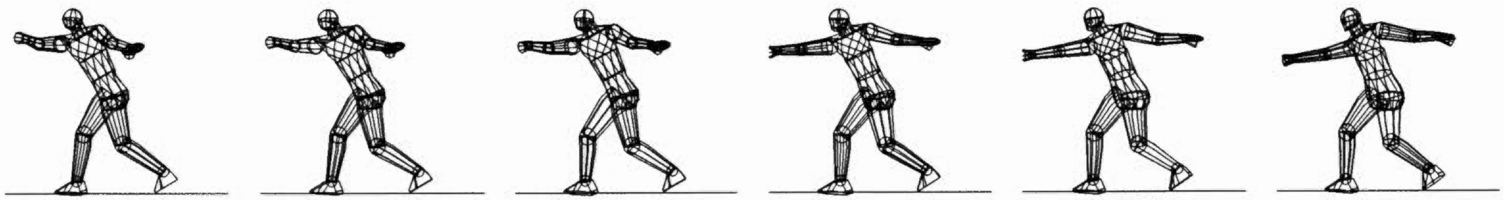

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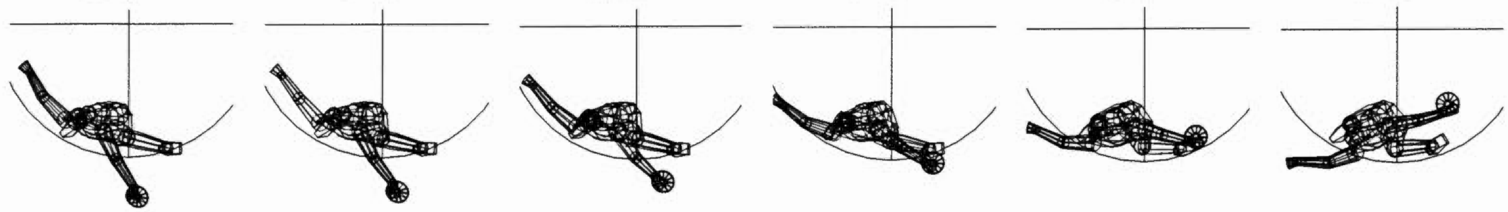

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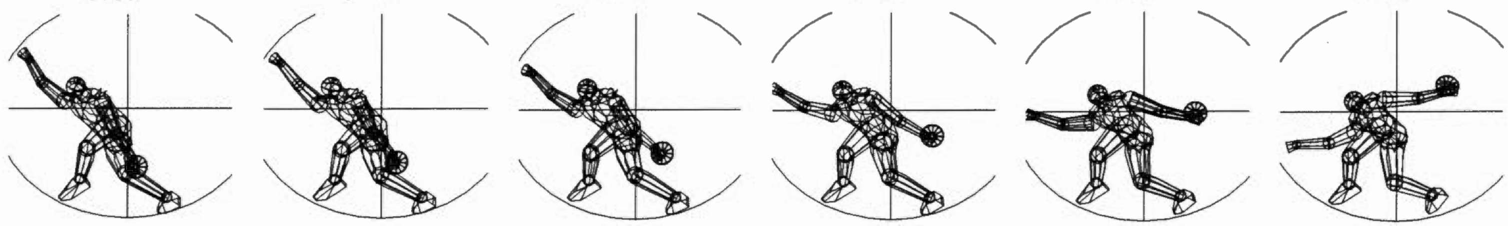

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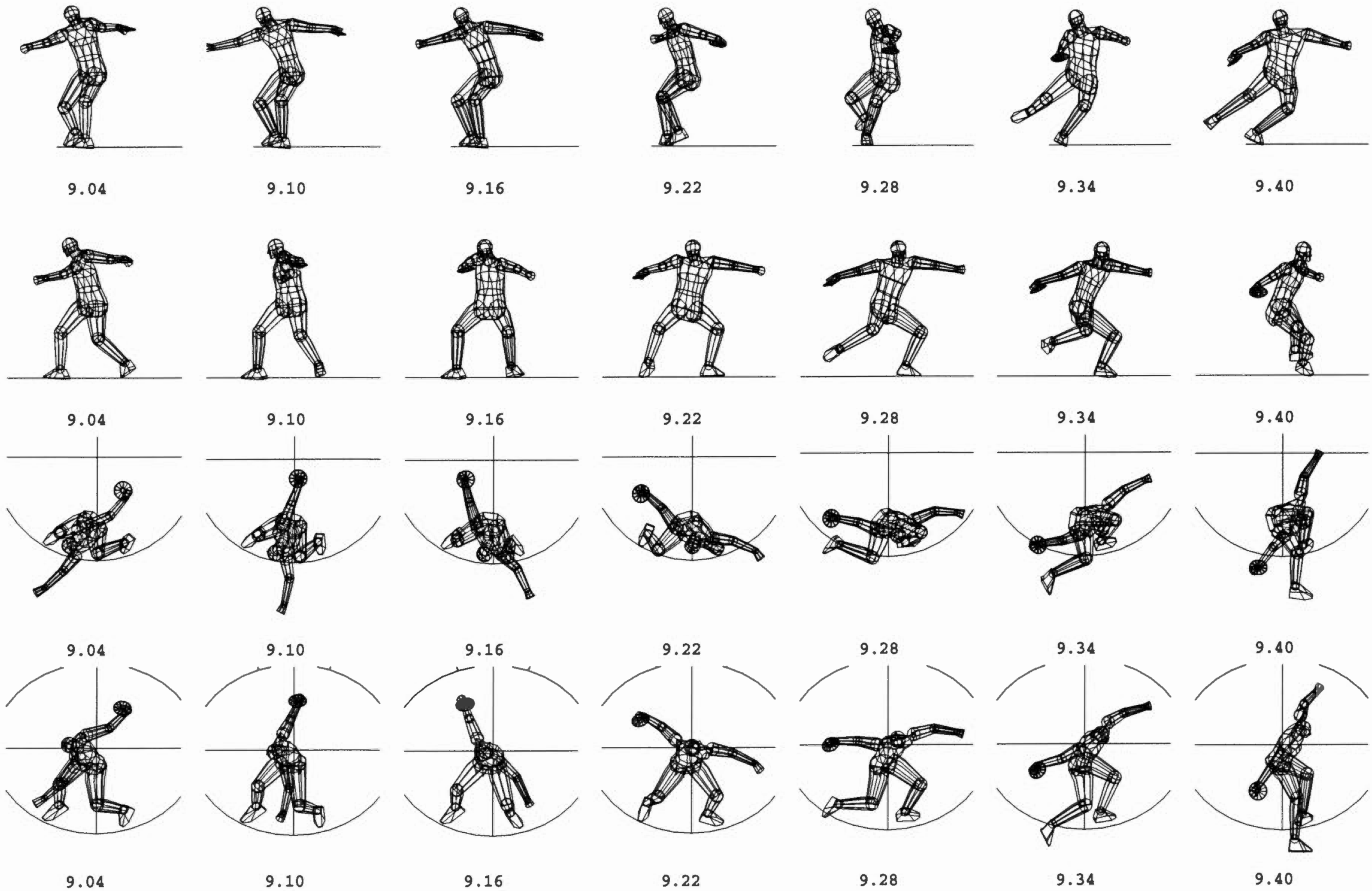

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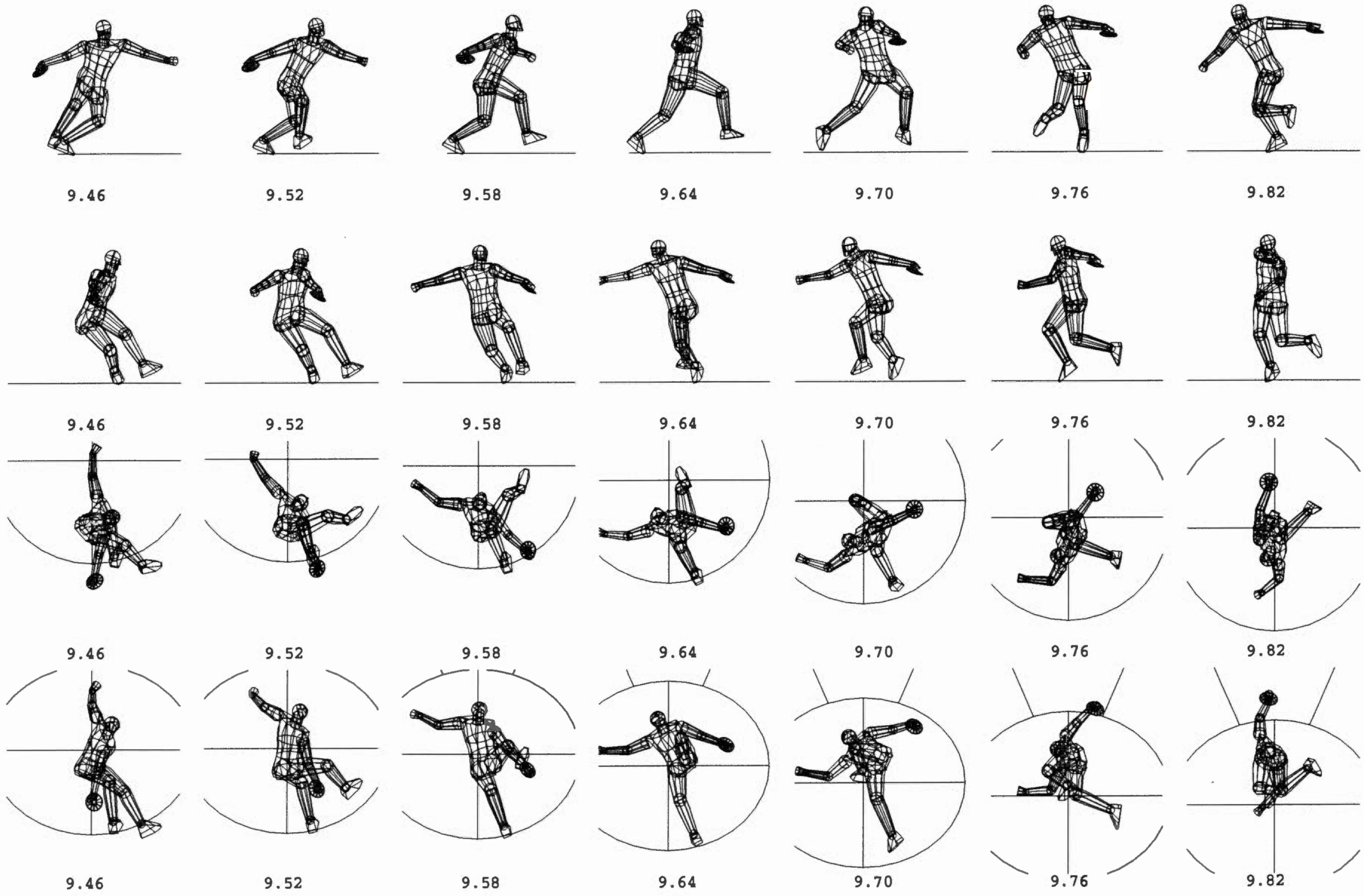

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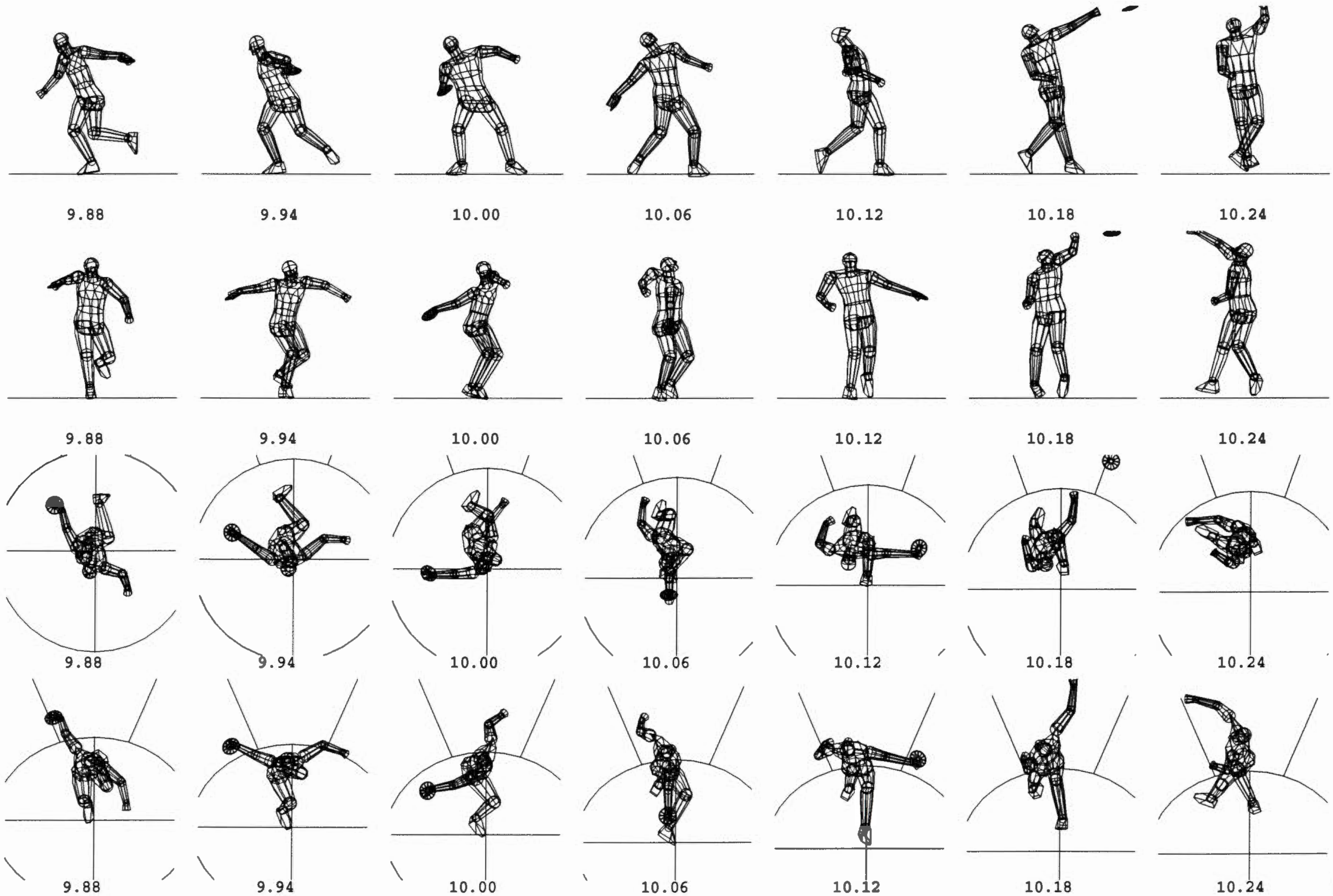

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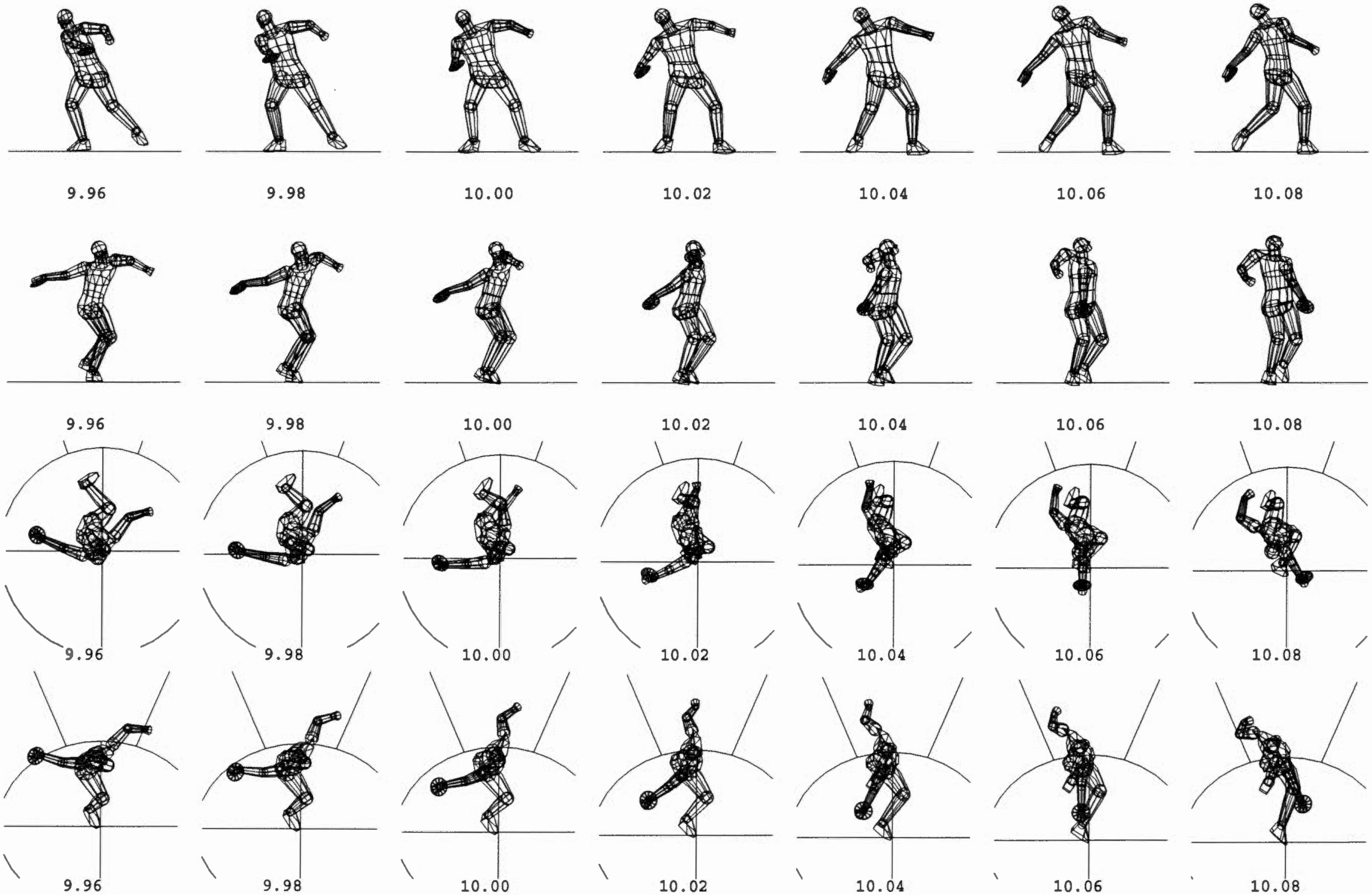

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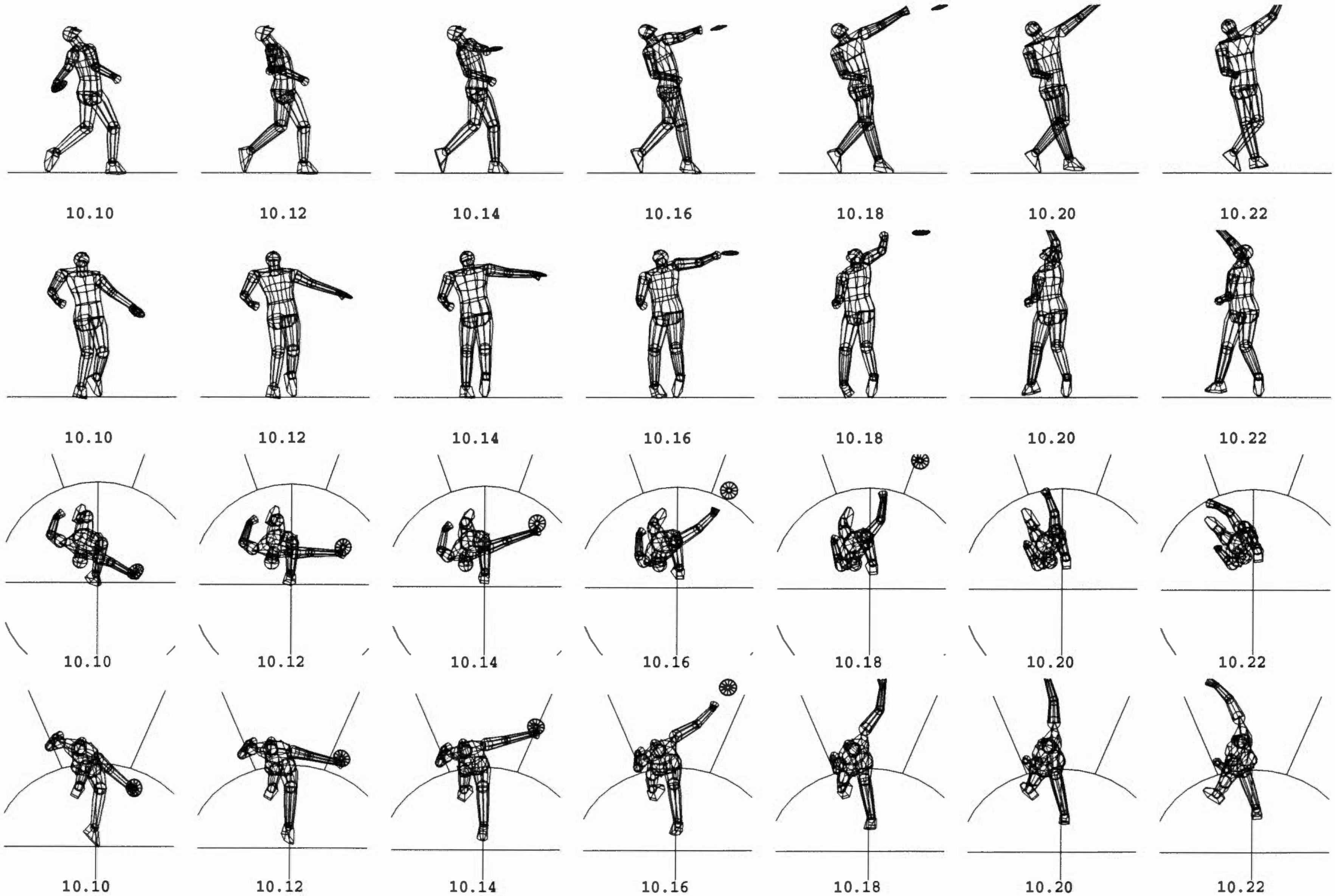

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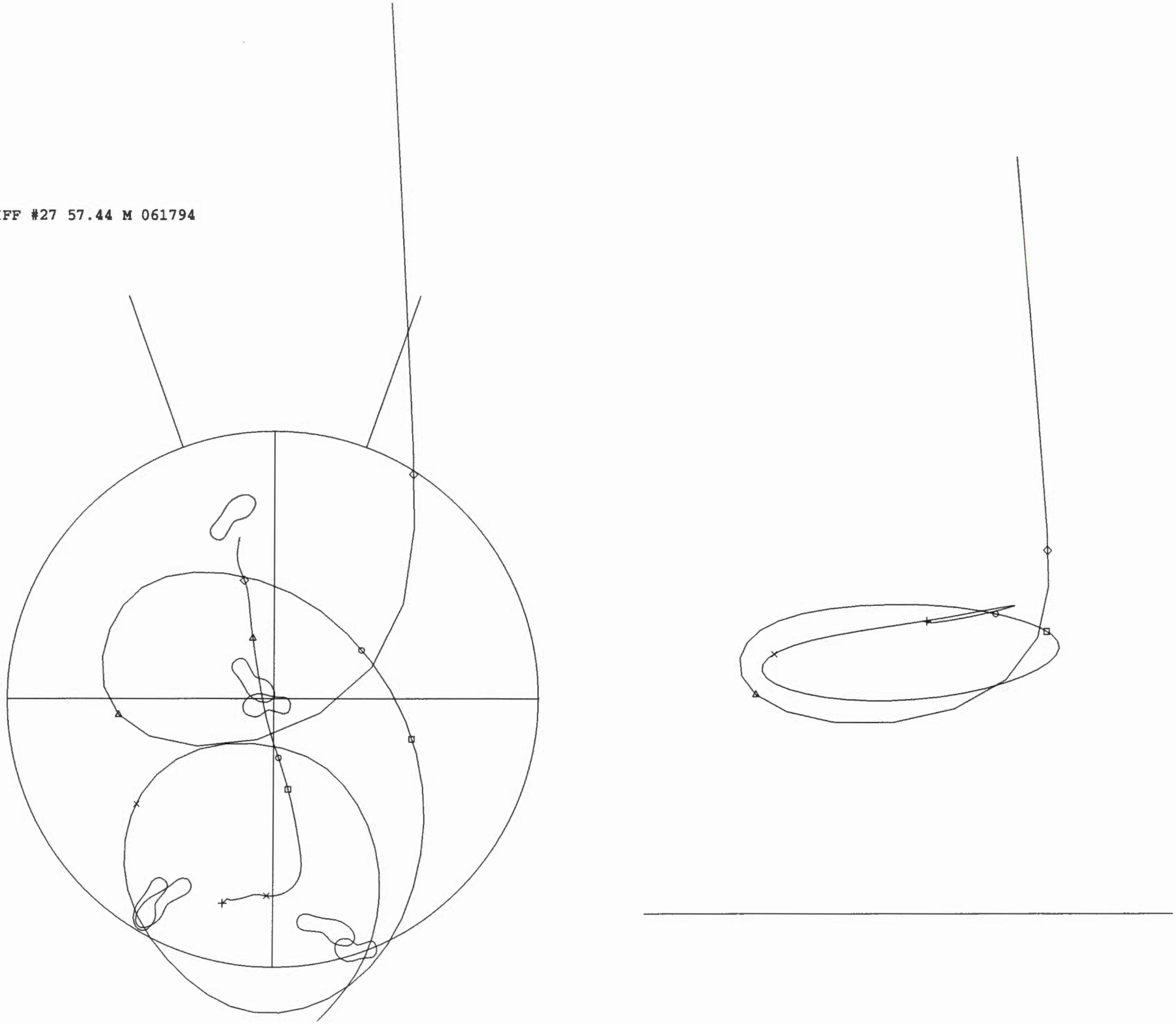

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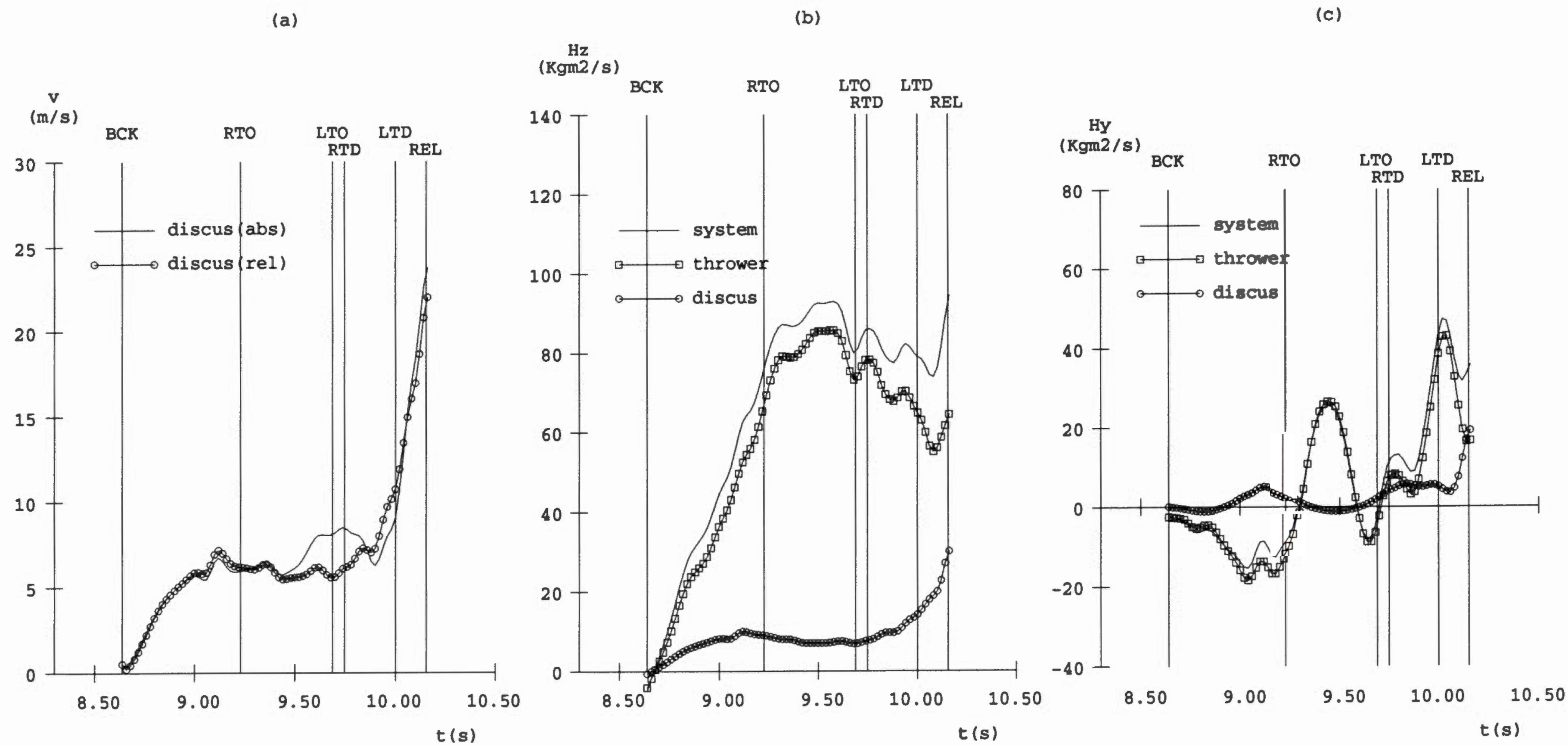

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25% of
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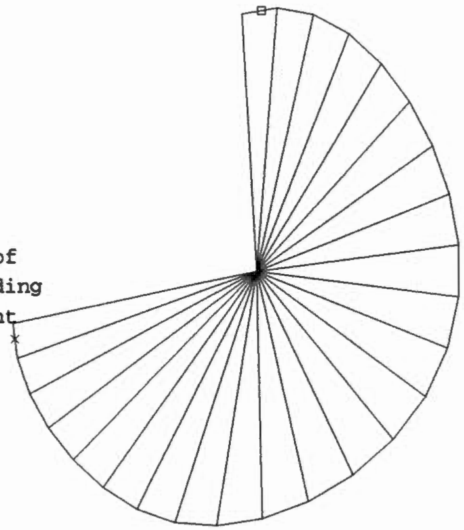
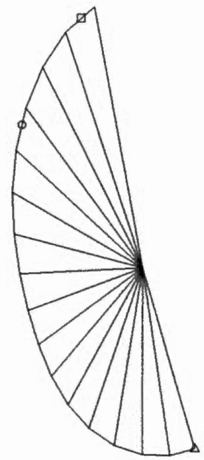
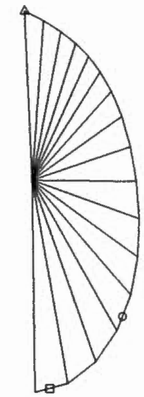
height





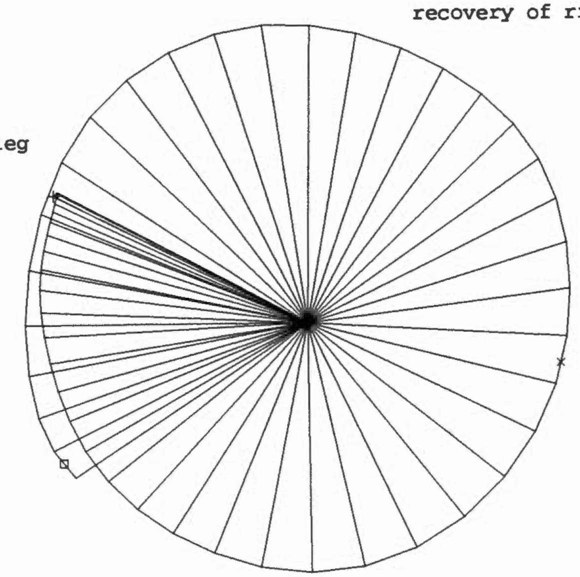
recovery of right leg



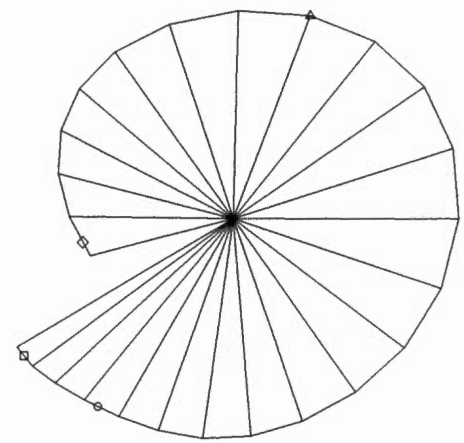
recovery of left leg

drive of right leg

50% of
standing
height



drive of left arm



recovery of left arm, and action during
right foot single-support and delivery

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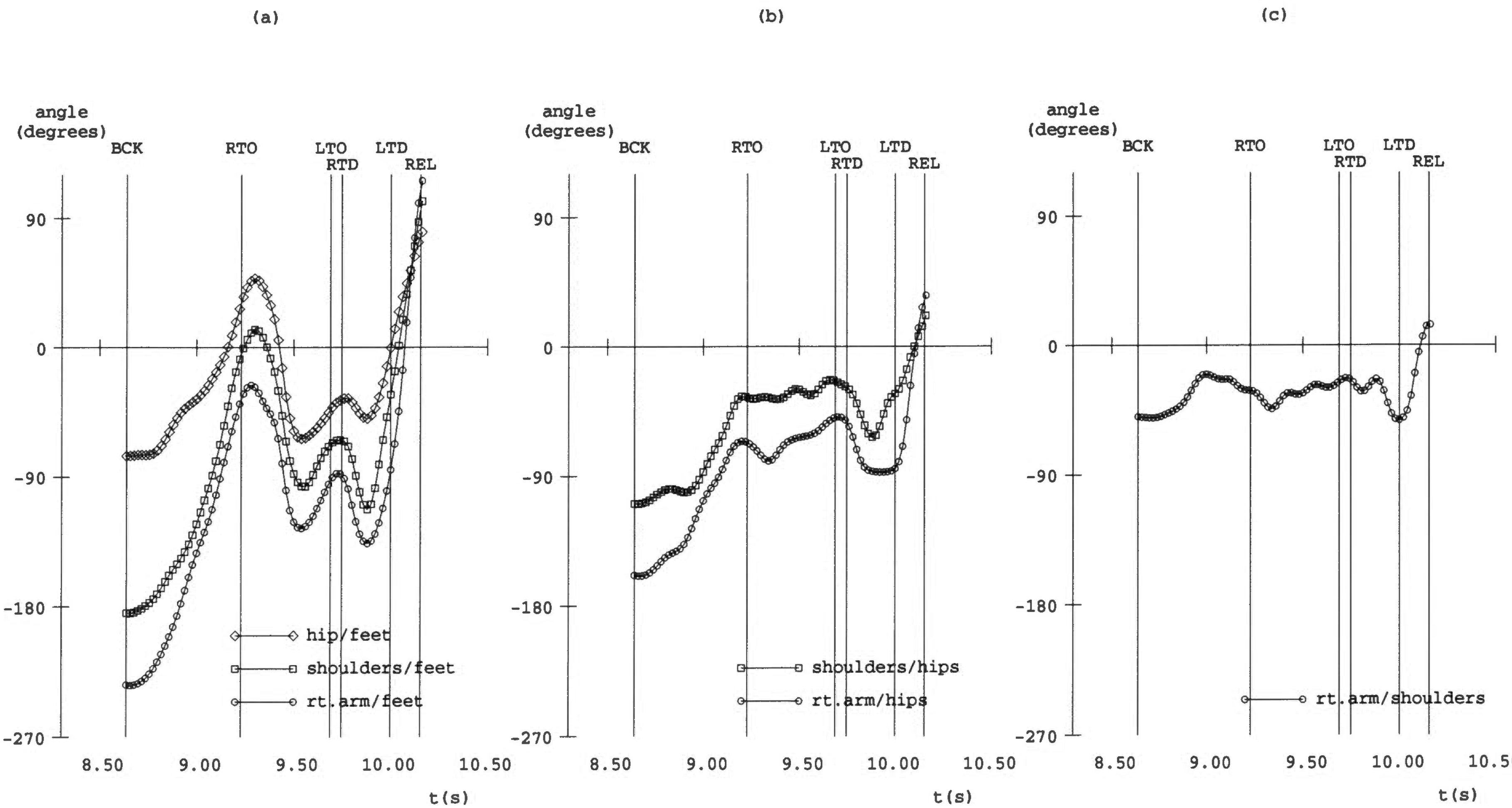

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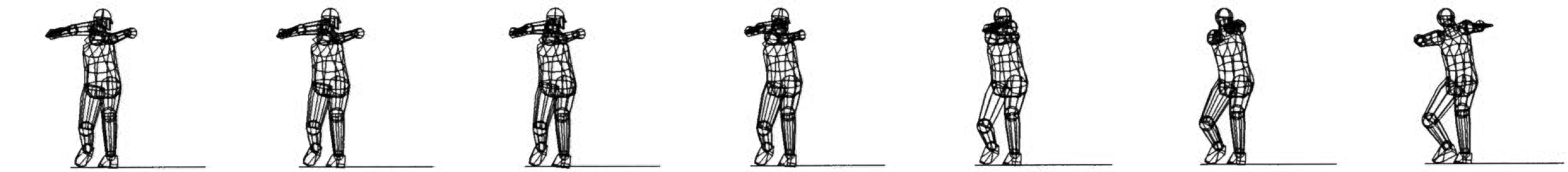

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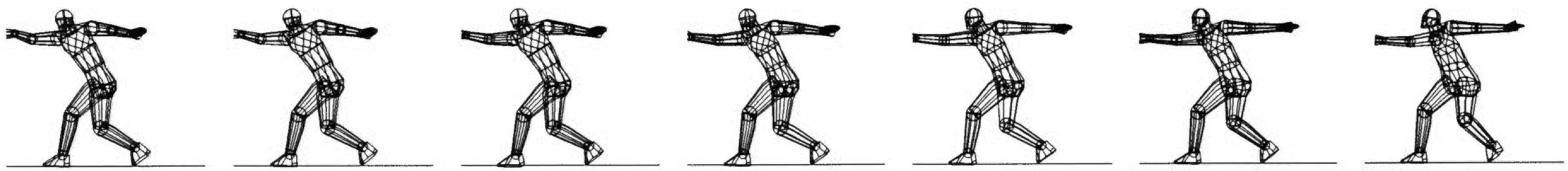

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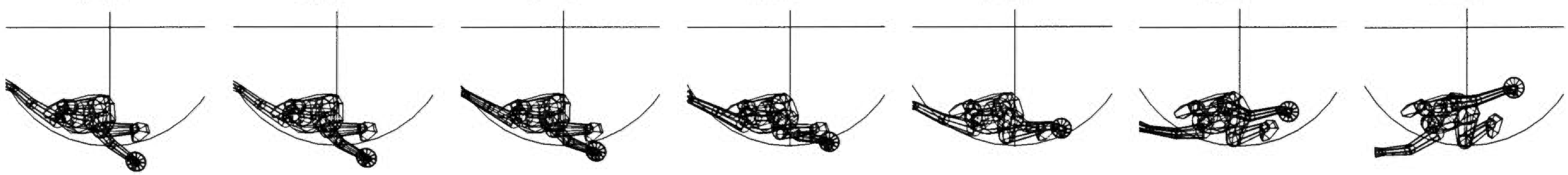

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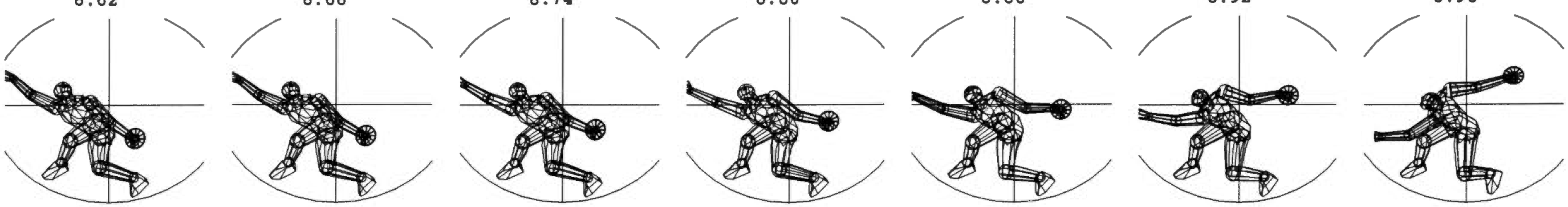

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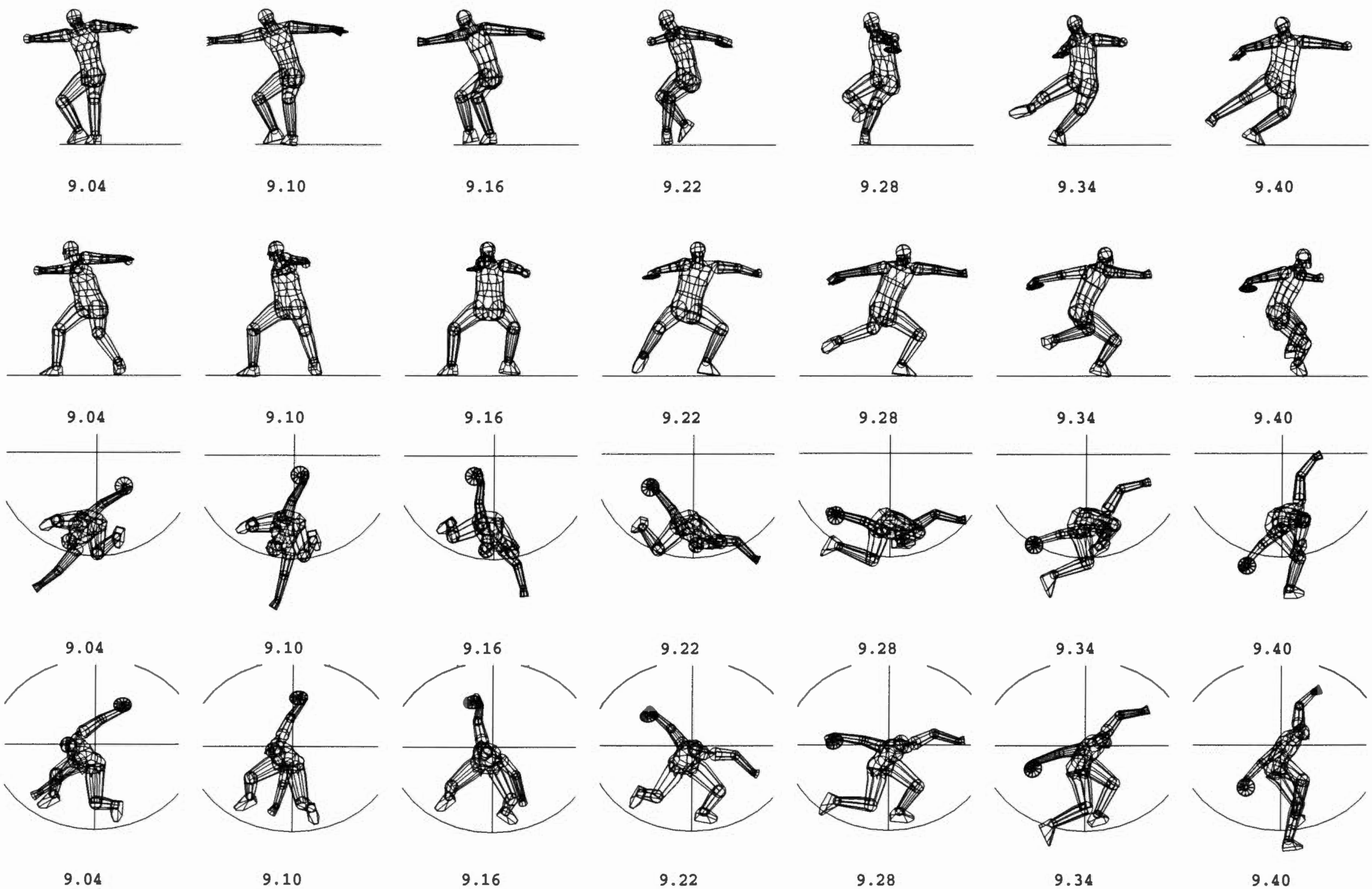

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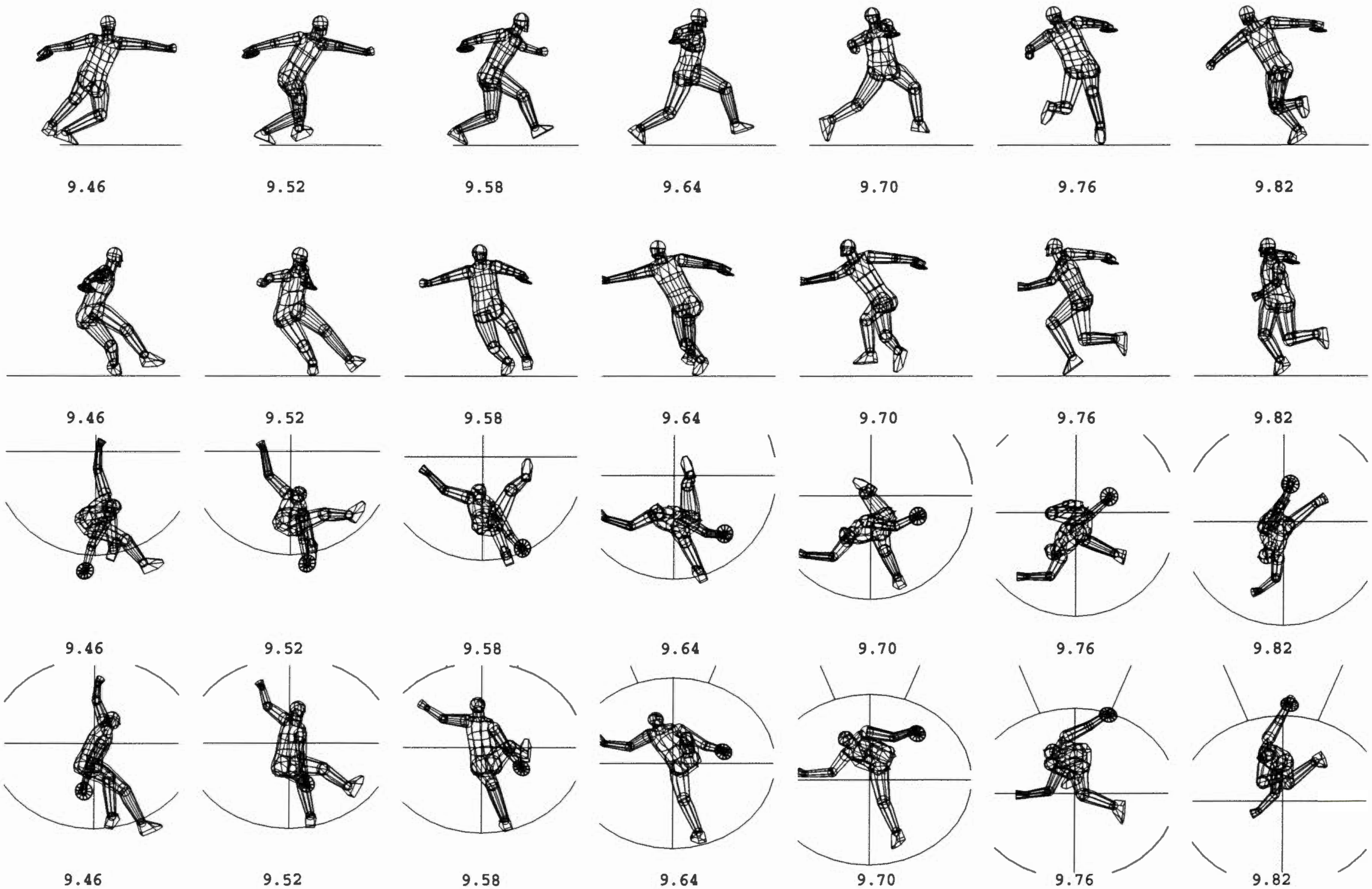

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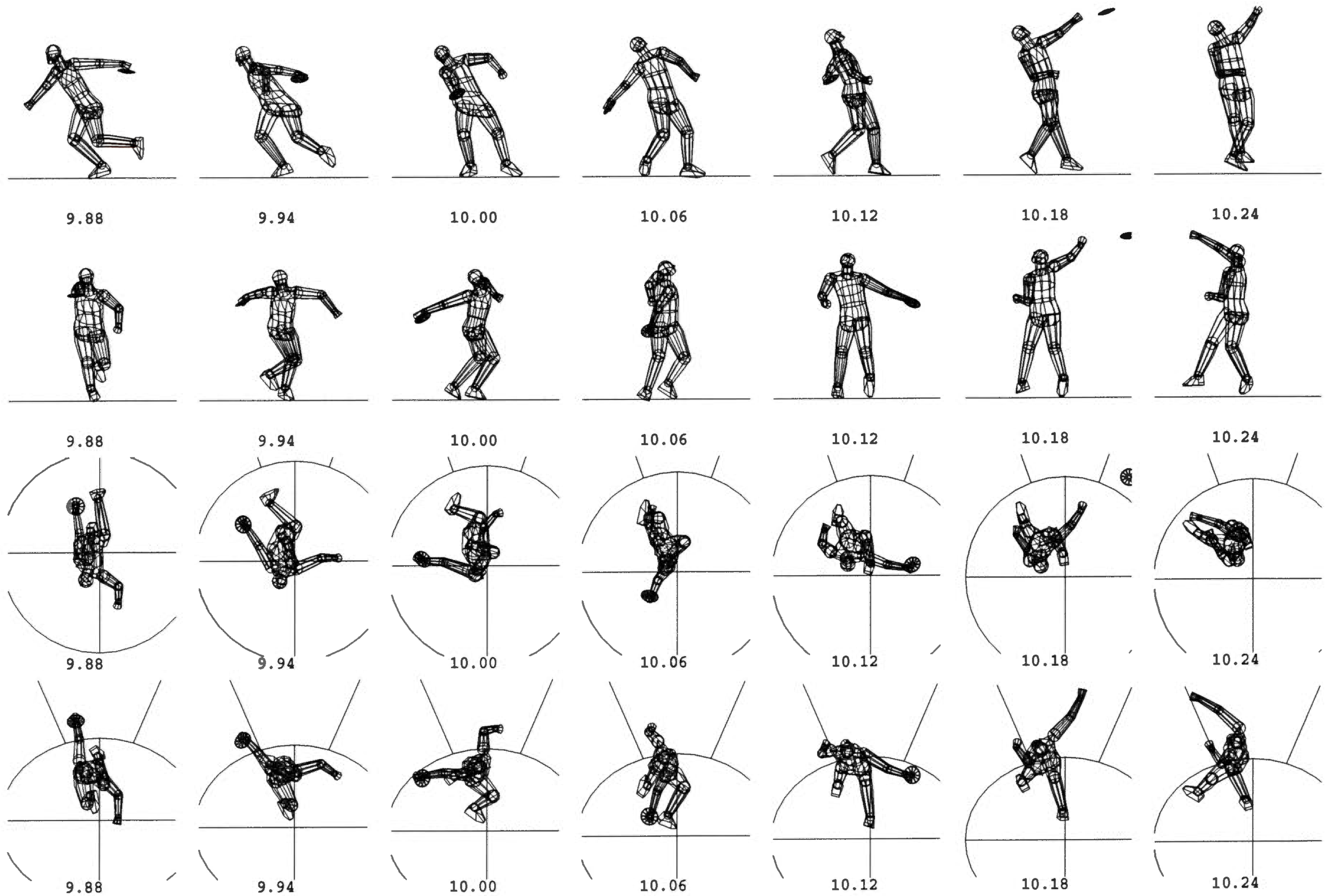

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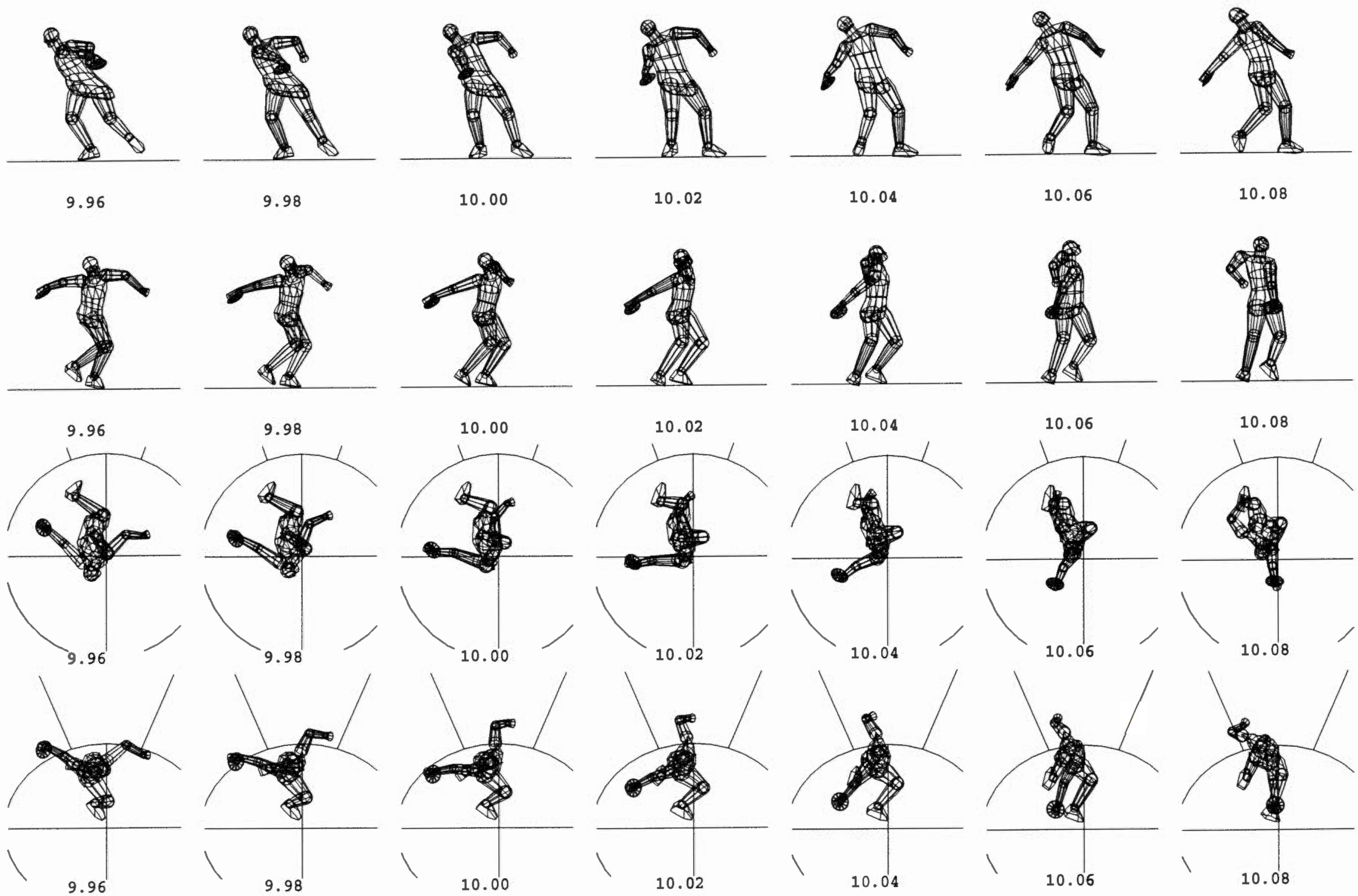

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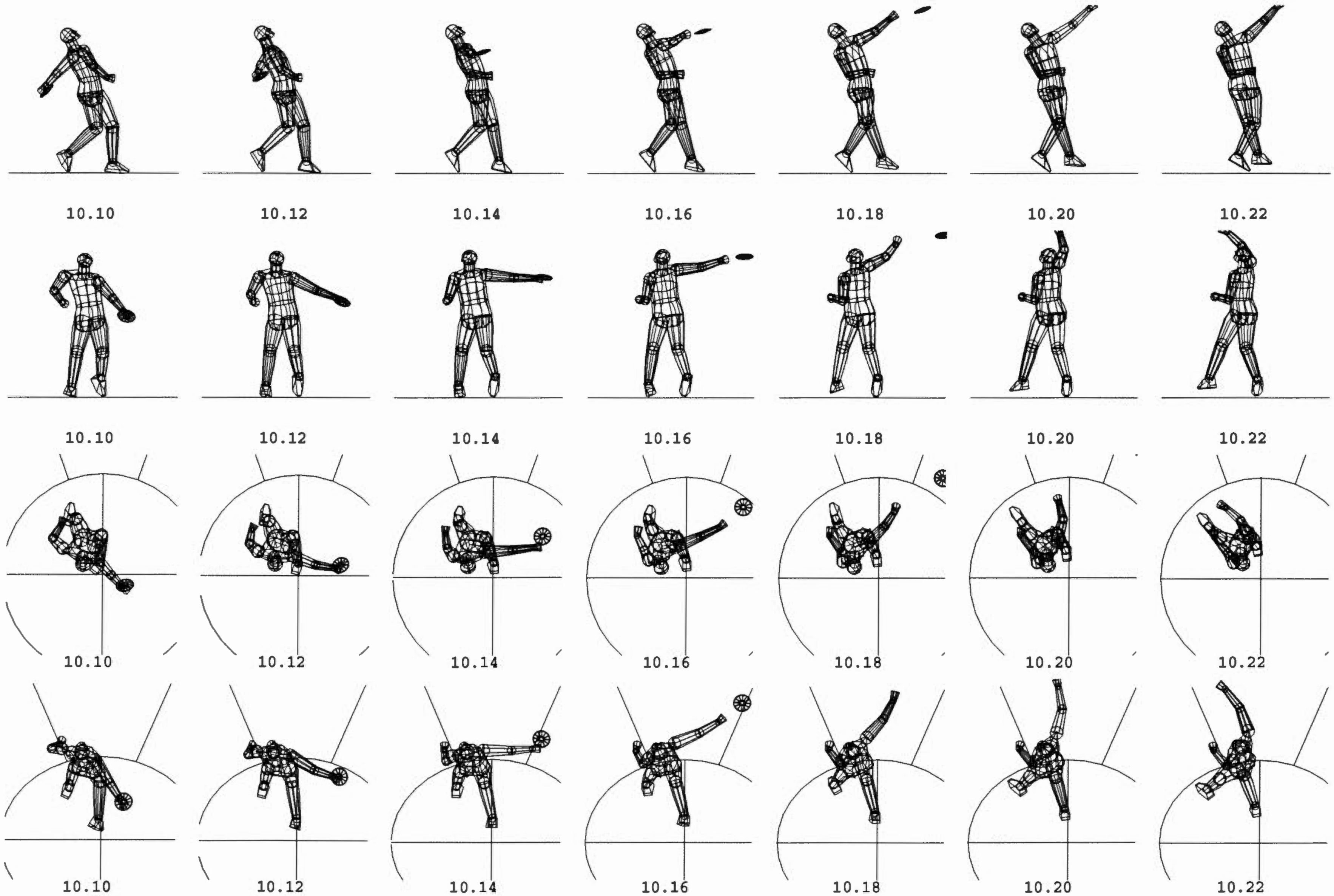

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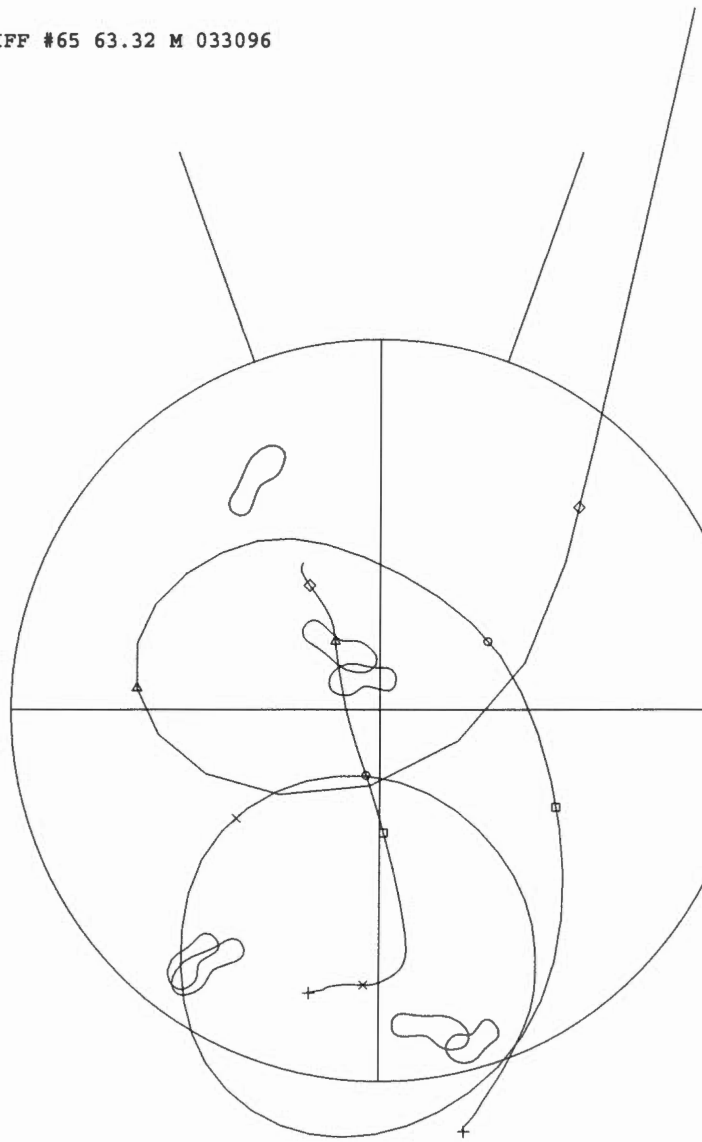

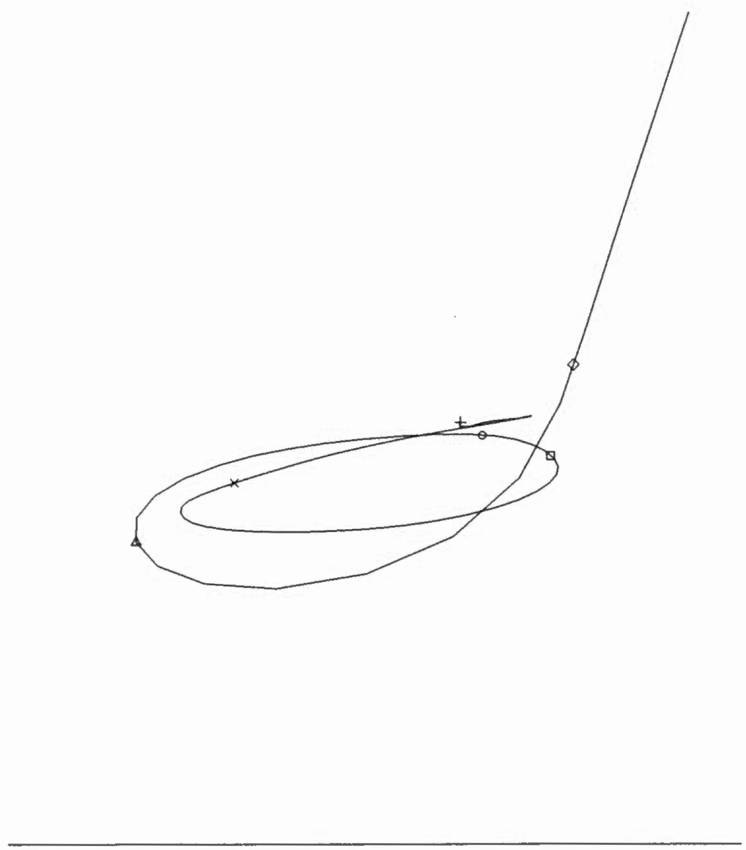

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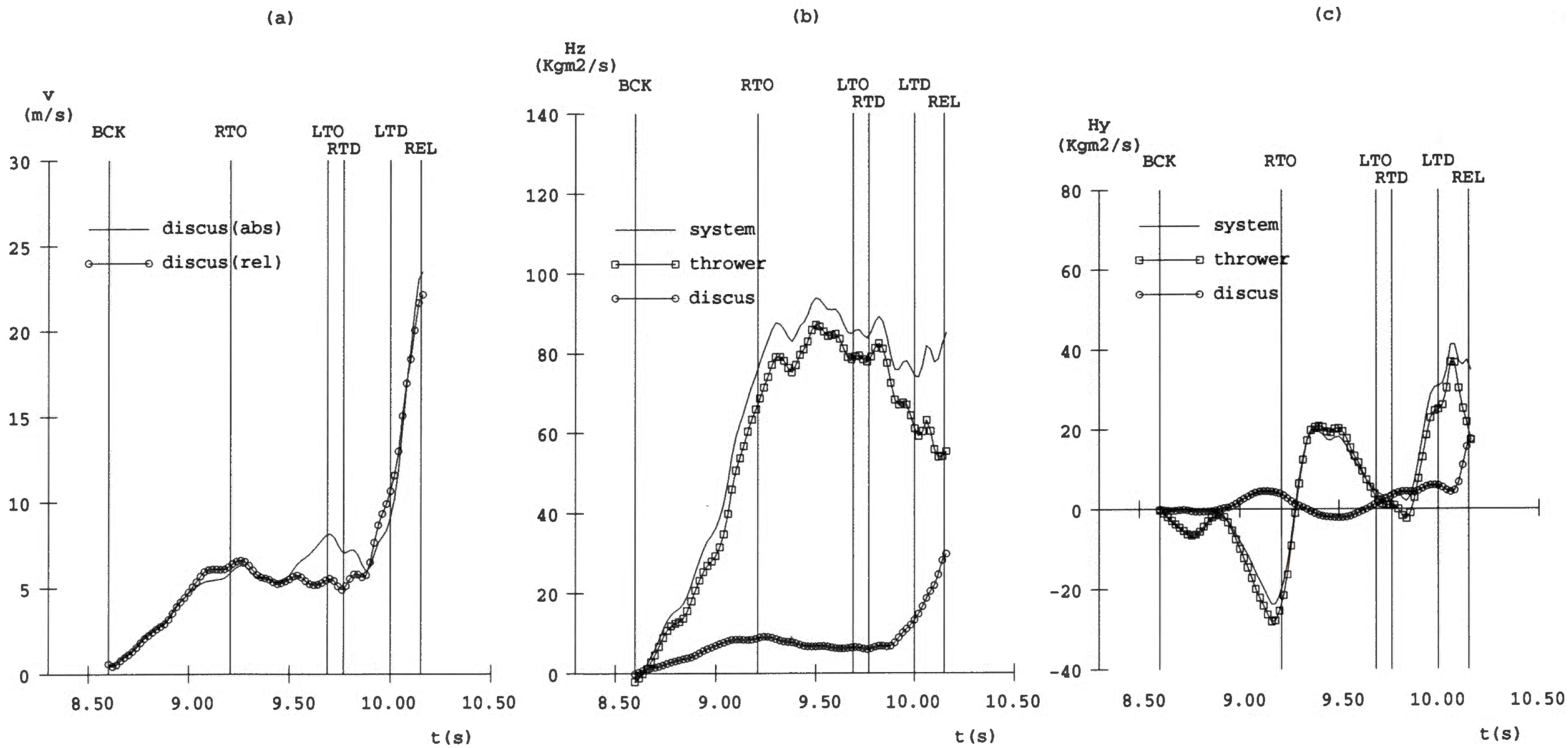

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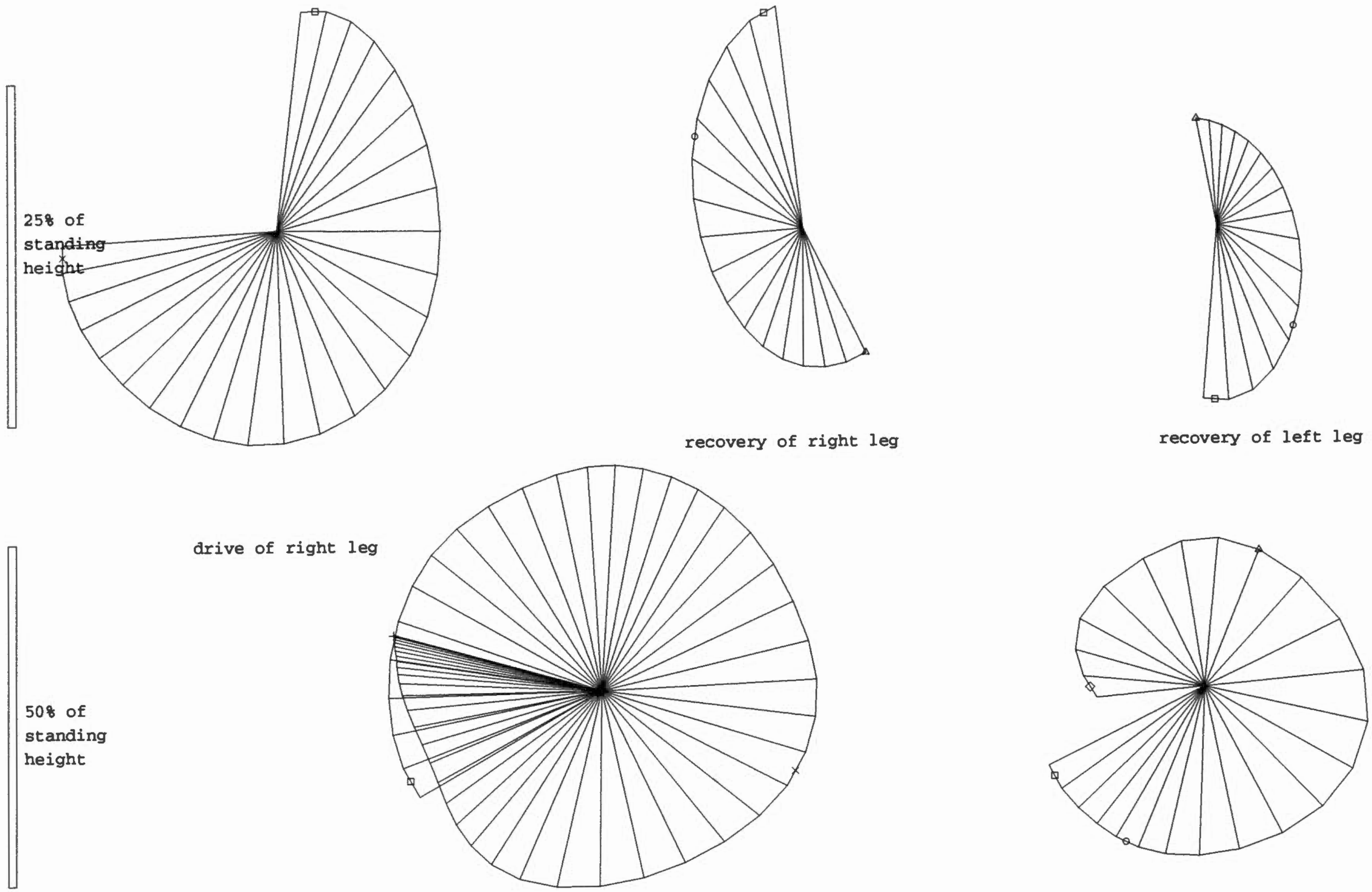

drive of left arm

recovery of left arm, and action during right foot single-support and delivery

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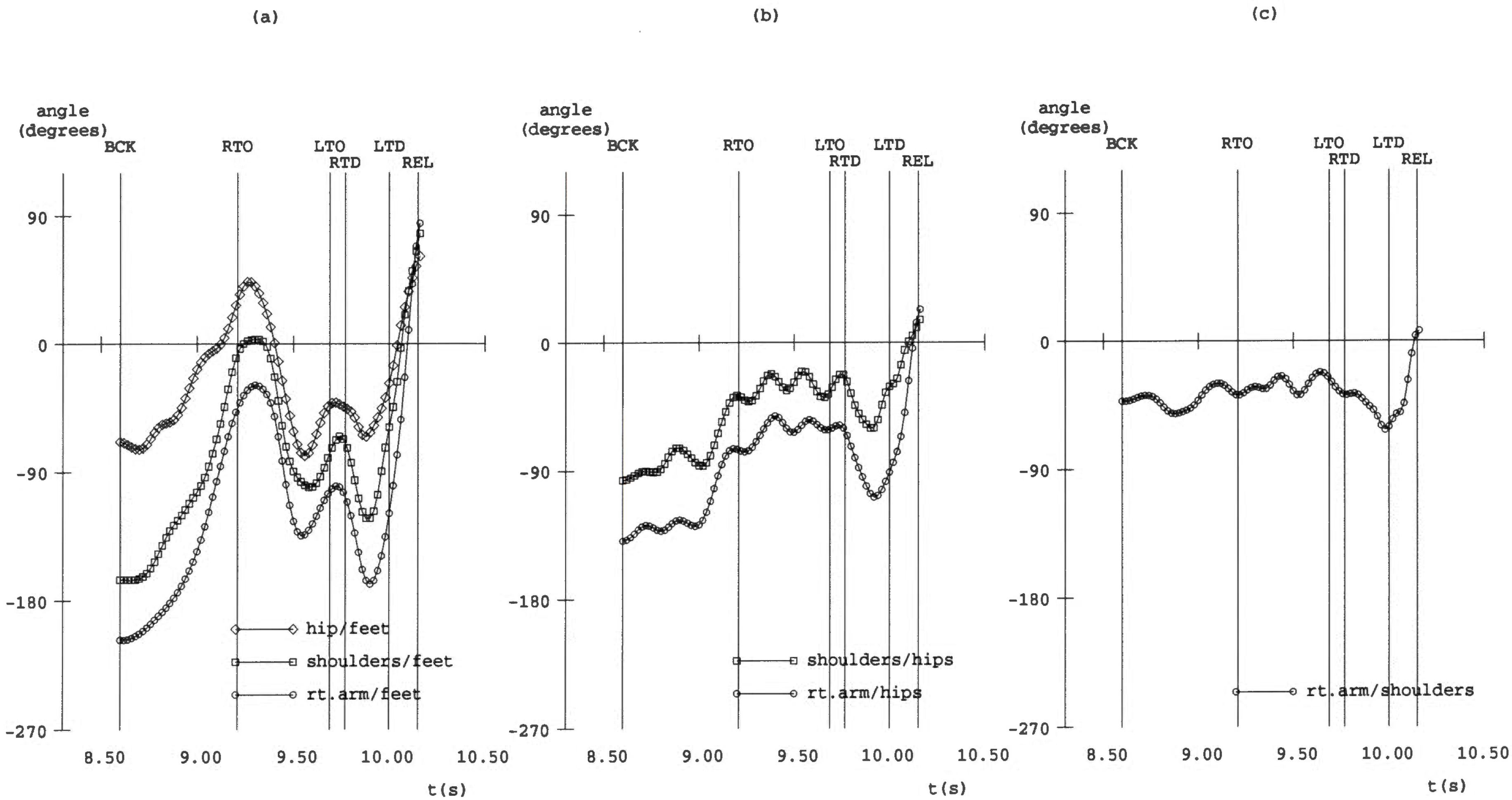


Anthony WASHINGTON

Trial 66 was Washington's second-best throw at the 1996 UC San Diego Open (63.96 m). We could not film his 64.18 m best throw at San Diego. However, this did not matter much, since trial 66 reached almost the same distance.

At the back of the circle, Washington did not shift the c.m. enough toward his left foot. This made the c.m. of the system follow a very diagonal path across the throwing circle (a_{LTO} = -42°; a_{LTD} = -40°). Fortunately, the final direction in which the discus was thrown was slightly left from forward (d_{HREL} = -2°), and this limited the divergence between the direction of motion of the discus and the direction of motion of the system c.m. during the period of the last quarter-turn of the discus (a_Q = -30°). The divergence angle was c_Q = -28°, not very good, but also not terrible.

At the back of the circle, Washington did not push very hard with his left foot against the ground. Because of this, the horizontal speed of the thrower-plus-discus system across the circle was slow (v_{HLTO} = 2.1 m/s; v_{HLTD} = 1.8 m/s). During the double-support delivery phase, Washington made a forward and downward force on the ground. All throwers do this, but the force that Washington made pointed more downward and less forward than in most other throwers. This was good. The reaction to the horizontal force reduced his already small horizontal speed. However, because of the moderate size of the force, the loss of speed was not very large, and the remaining speed (v_{HQ} = 1.2 m/s) was only slightly slower than in the average thrower. The combination of this remaining speed with the divergence angle (see above) determined the contribution of the horizontal speed of the system c.m. to the horizontal speed of the discus (v_{HCON} = 1.1 m/s). This was smaller than in the average thrower, but only slightly smaller.

As we mentioned previously, during the double-support delivery Washington somehow managed to combine a large vertical downward push on the ground with his moderate horizontal push. As a result, he obtained a very large vertical speed (v_{ZCON} = 1.7 m/s) for the system c.m. without losing very much horizontal speed.

Overall, these actions turned out quite well in the end: The potential for trouble which stemmed from Washington's markedly diagonal initial direction of travel and his slow horizontal speed did not materialize, because (a) the discus was not thrown toward the right, and (b) Washington was (somehow!) able to obtain a large vertical speed without losing too much horizontal speed.

The swinging action of the right leg at the back of the circle was weak (RLA = 20.9 $\cdot 10^{-3}$ Kg·m²/Kg·m²), while the swinging action of the left arm was somewhat stronger than average (LAA = 35.0 $\cdot 10^{-3}$ Kg·m²/Kg·m²); the combination of the two was slightly weaker than average (RLLAA = 56.0 $\cdot 10^{-3}$ Kg·m²/Kg·m²). At the instant of landing of the left foot in the front of the circle, the system had 94% of the Z angular momentum (counterclockwise rotation in a view from overhead) that it would eventually reach at release. This suggests that Washington's rotational efforts in the back of the circle were good.

The recovery actions of the legs and of the left arm ($r_{LAVG-NSRSS}$ = 9.3% of standing height; H_{LA-NS} = 39 $\cdot 10^{-3}$ s^{-1}) were near average, and therefore we consider them to be reasonably good.

The second propulsive swing of the left arm was only slightly stronger than average (LAA2 = 18.1 $\cdot 10^{-3}$ Kg·m²/Kg·m²), mainly due to the fact that the arm was somewhat too advanced by the time that the right foot landed. This implies that the arm probably did not make an outstanting contribution to the generation of angular momentum for the system during this period. However, Washington rotated the arm counterclockwise very fast (H_{MAX} = 72 $\cdot 10^{-3}$ s^{-1}), and then slowed it down very much (ΔH = -49 $\cdot 10^{-3}$ s^{-1}) before the discus left the right hand. This was a very good transmission of angular momentum from the arm to the rest of the system, and it probably helped to increase the speed of the discus.

At release, the discus had 36% of the total Z angular momentum of the thrower-plus-discus system. This was slightly larger than average, and suggests that Washington did a good job transfering Z angular momentum from his body to the discus.

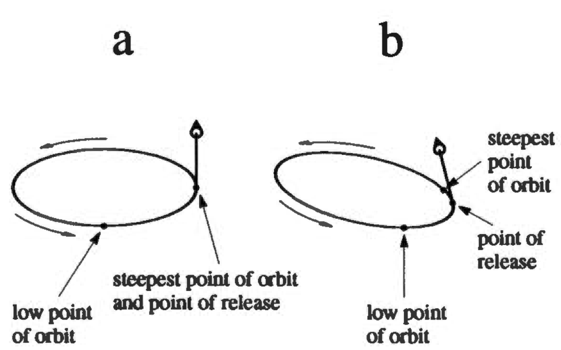
At release, in the view from the back of the circle the counterclockwise angular momentum of the thrower-plus-discus system was only moderate (H_{YS} = 45.5 Kg·m²/s). (In part, this was probably due to the fact that Washington was one of the smallest throwers in the sample.) However, a rather large part of this angular momentum (48%) was in the discus, and in absolute terms this constituted a reasonably large amount (H_{YD} = 21.9 Kg·m²/s). Together with the large contribution of the vertical speed of the system (v_{ZCON} = 1.7 m/s), this resulted in a good vertical speed of the discus at release (v_{ZD} = 14.3 m/s).

With respect to the maximum torsion achieved in the front of the circle, Washington was not very different from the average thrower in our sample (Washington $k_{RA/FT}$ = -136°; average = -144). In comparison with the average thrower, at the instant of maximum torsion Washington had more torsion of the shoulders relative to the hips (Washington $k_{SH/HP}$ = -74°; average = -58°), but less torsion of the right arm relative to the shoulders (Washington $k_{RA/SH}$ = -17°; average = -34°).

Washington made very good use of aerodynamic forces (ΔD = 5.29 m).

A discussion of Washington's technique needs to include a description of the unusual orbit followed by the discus in his throws. (Note: At this point, we have not yet been able to devise a satisfactory way to quantify the tilt or orientation of the orbit followed by the discus around the athlete. Therefore, the comments that follow are based on rough general observations rather than on hard quantitative data.)

In most throwers, the low point of the orbit is near the back end of the throwing circle. In a view from the back, the orbit has an elliptical shape, and the long axis of the ellipse is horizontal. This is shown in idealized form in sketch "a" below. The discus is released near the steepest point, "half-way up the hill".

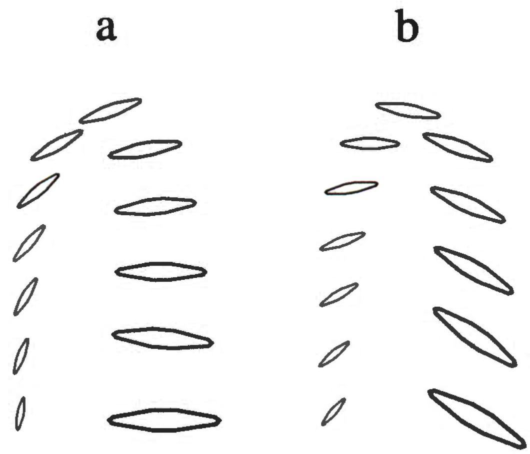


(views from the back of the throwing circle)

In Washington's throws, the low point of the orbit seems to be farther to the right, somewhere between the back and right ends of the throwing circle. Therefore, in a view from the back the orbit also has an elliptical shape, but the long axis of the ellipse appears tilted, with the right end lower than the left end (sketch "b"). (This difference is noticeable in the computer-generated graphs that show the back view of the path of the discus. For each throw, this graph is on the right side of the page that shows the footprints and the view from overhead; see Figure 11.) If Washington released the discus near the steepest point, "half-way up the hill", the final direction of motion of the discus would point too far toward the left, and this might produce a sector foul. Therefore, Washington needs to release the discus earlier. To compensate for the fact that the discus is released before the steepest point of the orbit, Washington probably uses a more tilted orbit than other throwers. (And he may still need to release the discus slightly toward the left, as shown in sketch "b".)

The orbit that we have just described is a typical characteristic of Washington's throws. At this time, we are not sure of the implications of such a technique. Jay Silvester, the national coordinator for the discus throw, has described it as "throwing the discus like a bowling ball". This is an exaggeration, of course, but very graphical. Based on his many years of experience with the discus, Silvester thinks that the discus can be accelerated very well using such a technique (Jay Silvester, personal communication). We believe that Washington's orbit requires the use of somewhat different musculature than a standard throw, and speculate that it might be better suited to the particular natural strengths of Washington's musculature. Or maybe Washington started to throw this way by accident, and then through the repetition of many throws the strengths of his musculature adapted to such a technique.

It is also possible that Washington's unusual orbit might give him an aerodynamic advantage in the discus flight. The description of aerodynamic effects given in the main part of this report was purely two-dimensional, and dealt exclusively with the degree of backward tilt of the discus. However, the aerodynamic effects on a discus are actually three-dimensional: In a view from the back of the circle, the discus can also tilt toward the right or toward the left. In general, it tends to tilt more and more toward the left as the flight progresses, particularly if the discus is thrown into a headwind. This tilt is caused by a gyroscopic effect —for more details, see Frohlich (1981). Because of the changing left/right tilt, if the discus is flat at release (in the view from the back), it may reach a very large degree



(views from the back of the circle)

of tilt toward the left in the late stages of the flight. (See sketch "a" above.) This will reduce very much the lift force provided by the air, and the discus will slide down toward the ground. However, if the discus is tilted toward the right at release (sketch "b"), this tilt will gradually decrease, the discus will eventually become level, and finally it will acquire a tilt toward the left. However, the discus will never reach such a great tilt toward the left as in the throw shown in sketch "a". It is possible that the type of throw shown in sketch "b" might allow the discus to fly farther. Jay Silvester thinks that there may be some advantage in releasing the discus with the outside edge lower than the inside edge. We think that the reason may be this aerodynamic effect. It is possible that Washington's technique may make it easier to produce a throw in which the outside edge of the discus is lower than the inside edge at release, and this might be an advantage.

At this time, we are not sure if the peculiar orbit that the discus follows in Washington's throws gives him an advantage or not, but we would advise him to continue using it.

Summary

Washington did not shift the system c.m. enough toward his left foot at the back of the circle, and this made him follow a very diagonal path across the throwing circle. He did not push off hard enough from the back of the circle with his left foot, and therefore the horizontal speed of the system c.m. was slow. The path of the discus after release pointed slightly toward the left, which limited the problem posed by the diagonal path of the system c.m. During the delivery phase, Washington made on the ground a moderate horizontal force and a large vertical force. This allowed him to retain a reasonable amount of horizontal speed, and to generate a large amount of vertical speed. Thus, Washington compensated for the problems created at the back of the circle. The combined swinging actions of the right leg and left arm at the back of the circle were somewhat weak. The amount of Z angular momentum generated at the back of the circle was good. The recovery actions of the legs and of the right arm after the takeoff of the left foot from the ground in the middle of the throw were adequate. The left arm was somewhat too advanced in its counterclockwise rotation at the time that the right foot landed. This limited the range of motion available for the second propulsive swing of this arm. However, its action was still very forceful, and then the arm slowed down very well. During the single-support on the right foot and the double-support delivery, Washington obtained a reasonable amount of Y angular momentum, and he transfered a large part of it to the discus during the second half of the delivery to give a good vertical speed to the discus. The transfer of Z angular momentum from the body to the discus was good, even though the maximum torsion of the system during the single-support on the right foot was only moderate. Washington's use of aerodynamic forces was very good. The discus followed a peculiar orbit during the throw; the reasons and the consequences of this are not clear.

Recommendations

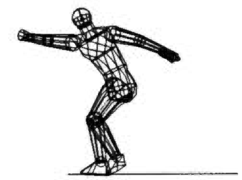
The divergence angle between the directions of motion of the discus and of the system c.m. in throw 66 was near the borderline of what should be considered acceptable. If the discus were released toward the right half of the landing sector in any throw, the combination of such a direction with the marked diagonal direction of motion of the system c.m. toward the left would produce a very large divergence angle, and therefore an excessive loss of horizontal speed for the discus. To prevent such a problem, we would advise Washington to drive more directly forward across the throwing circle.

The origin of the problem was at the back of the circle, when Washington "sat" backward too much before starting to shift the system c.m. toward his left foot. (See the overhead view of the path of the system c.m.) We think that this may have forced him to start prematurely the main push with the left foot before the c.m. was close enough to the vertical of that foot. To avoid this problem, Washington should *first* shift the system c.m. toward the left foot, with very little "sitting back". That will allow the c.m. to get closer to the vertical of the left foot. By doing this, Washington will then be able to follow a more direct forward path across the circle. This will produce a smaller divergence angle in the front of the circle, and therefore a larger contribution of the horizontal speed of the system to the horizontal speed of the discus.

Once the c.m. reaches a position near the vertical of the left foot, Washington should drive much *harder* with his left foot against the ground than in throw 66. This will give the system a larger horizontal speed across the throwing circle, and will allow Washington to have a larger amount of horizontal speed left over for the period of the last quarter-turn of the discus. This will also contribute to increase the horizontal speed of the discus. In throw 66, the horizontal speed of the system during the last quarter-turn of the discus was 1.2 m/s; ideally, it should be around 1.5/1.7 m/s. Smaller values produce a loss in the contribution to the horizontal speed of the discus; larger values are likely to produce a foul.

It would also be advisable for Washington to increase the torsion of the system during the single-support on the right foot, since the torsion in throw 66 was somewhat weaker than the torsion of the average thrower in our sample. In throw 66, the torsion of the hips relative to the feet was aceptable, and the torsion of the shoulders relative to the hips was excellent. What Washington needs to concentrate on is the *angle between the shoulder axis and the right arm.* He should keep the right arm further back. This will produce a more wound-up position of the right arm relative to the feet during the single-support on the right foot. The subsequent unwinding of the system will then allow Washington to drive the discus over a longer range of motion during the final acceleration, and thus to impart more speed to the discus, which in turn will result in a longer throw.

WASHINGTON #66 63.96 M 033096



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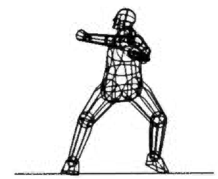

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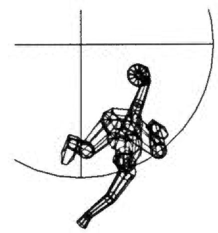

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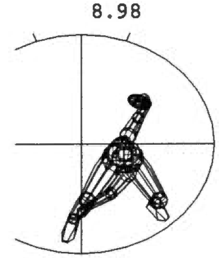

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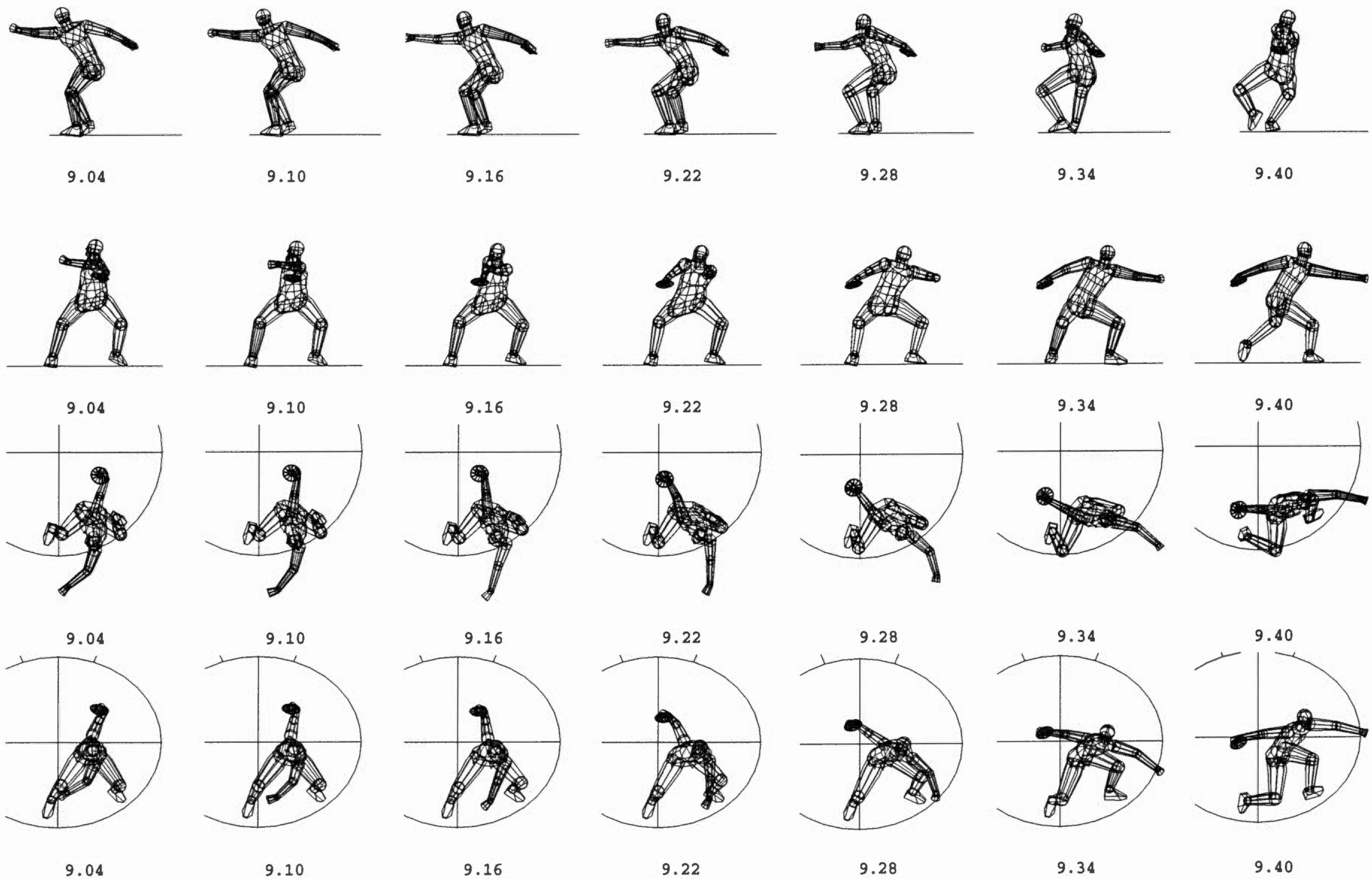

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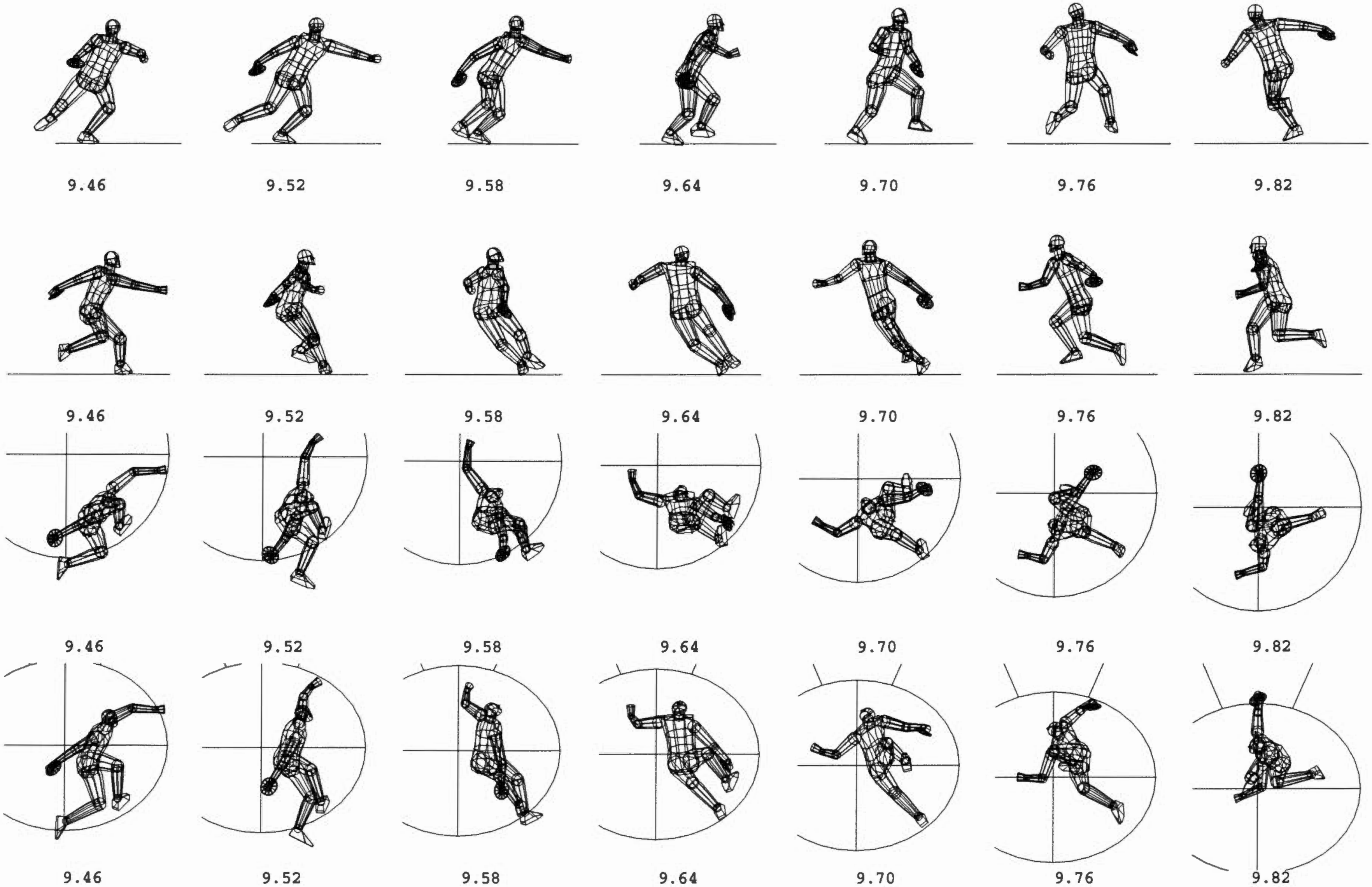

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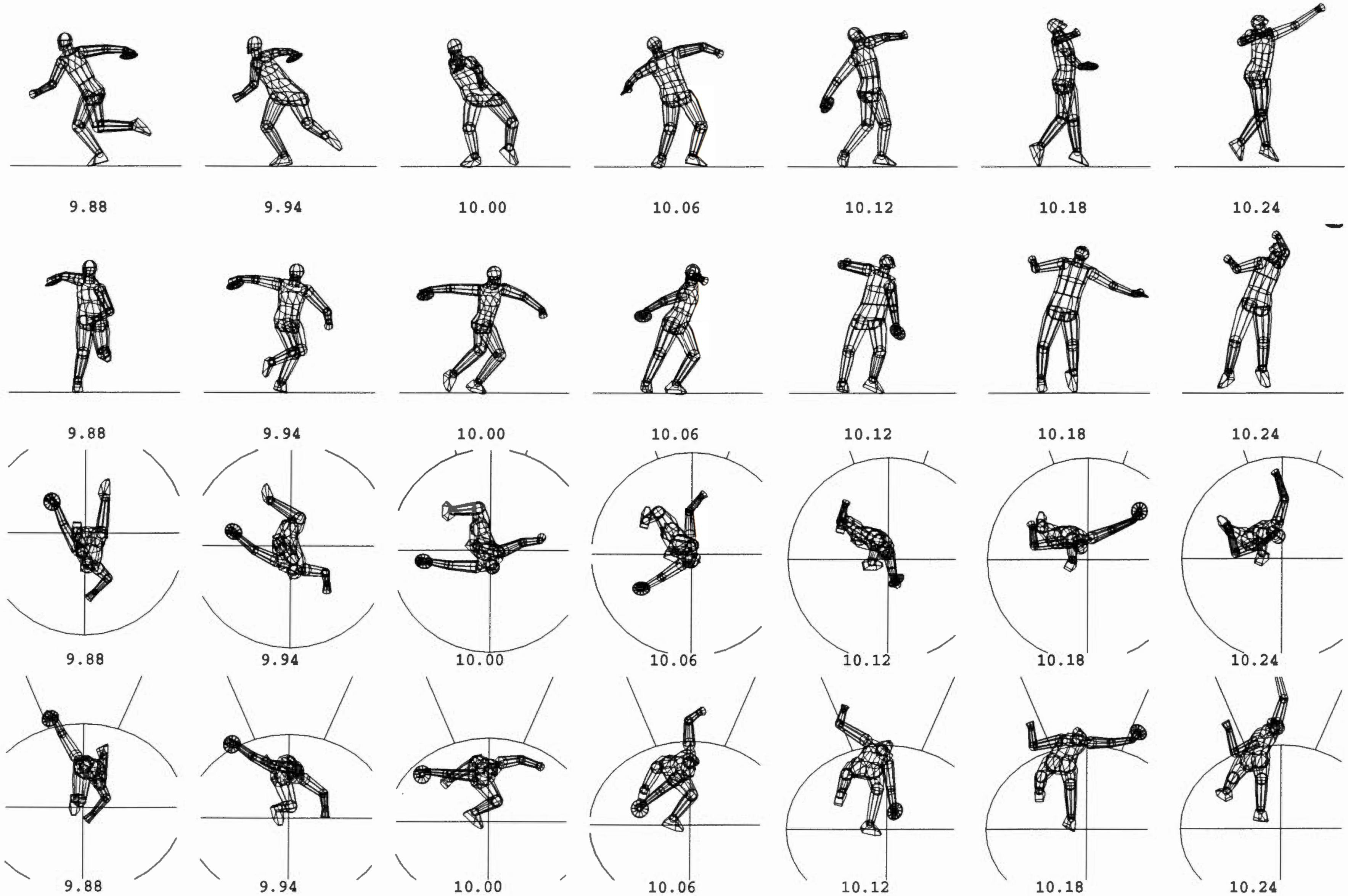

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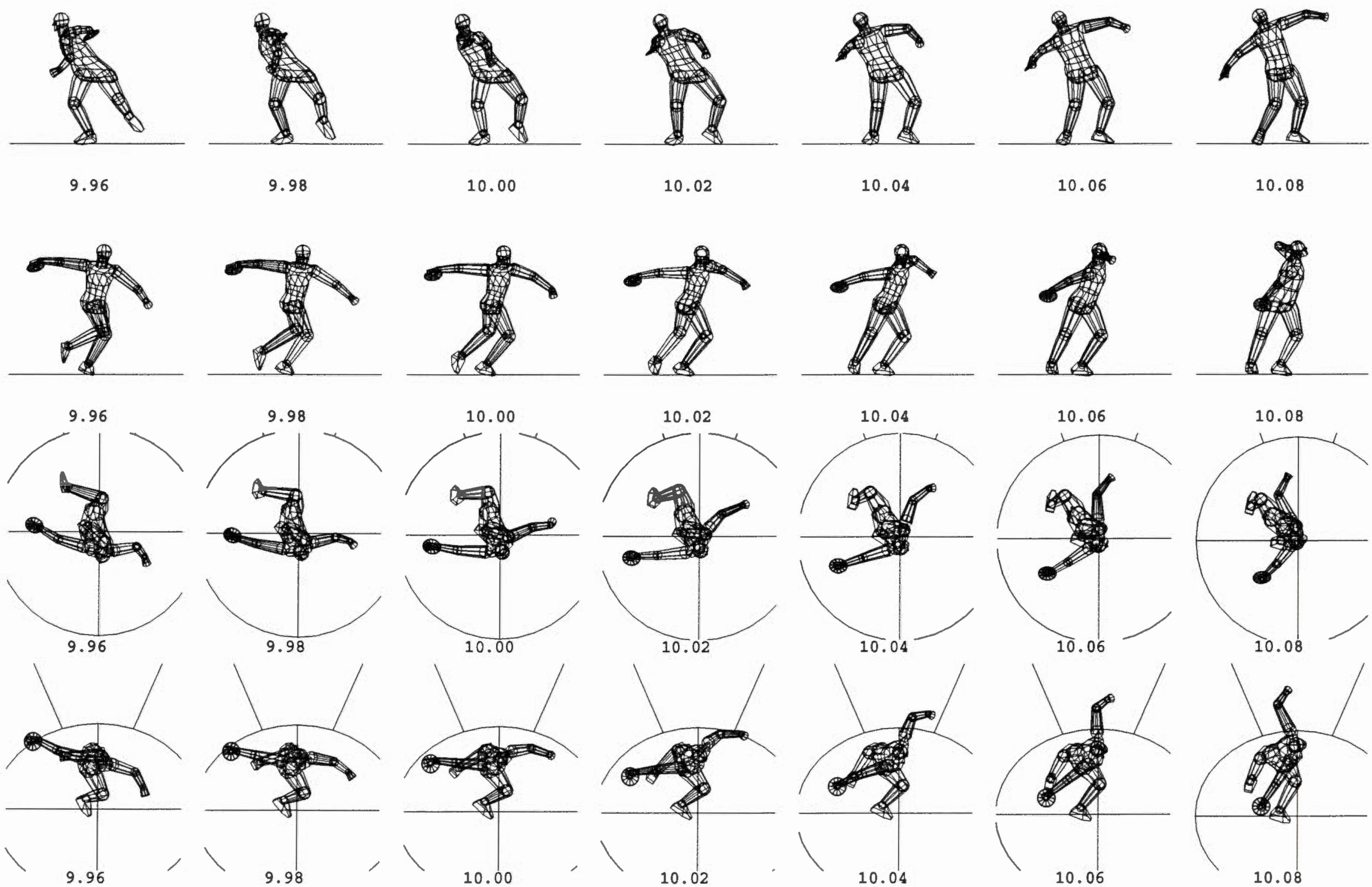

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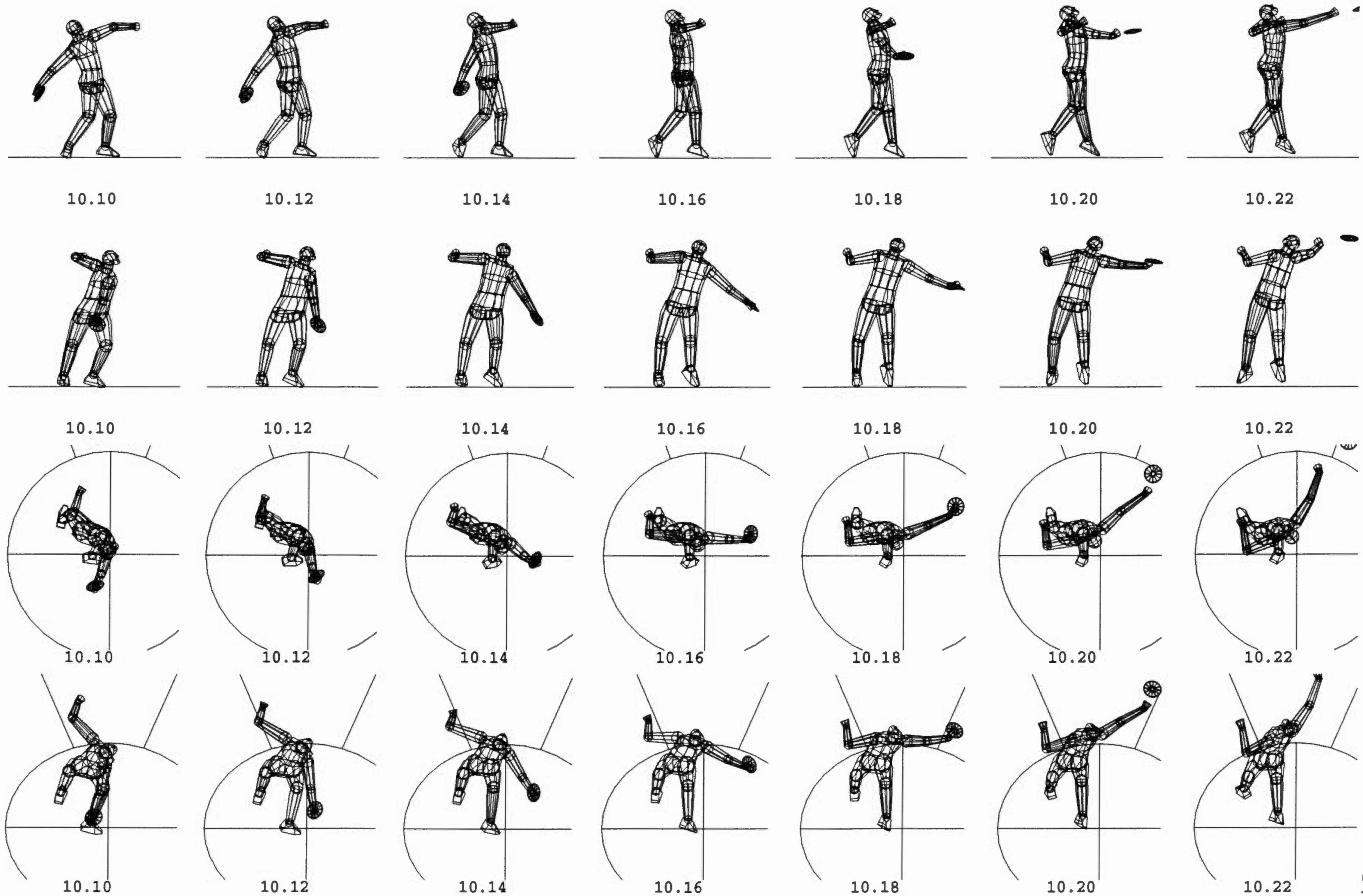

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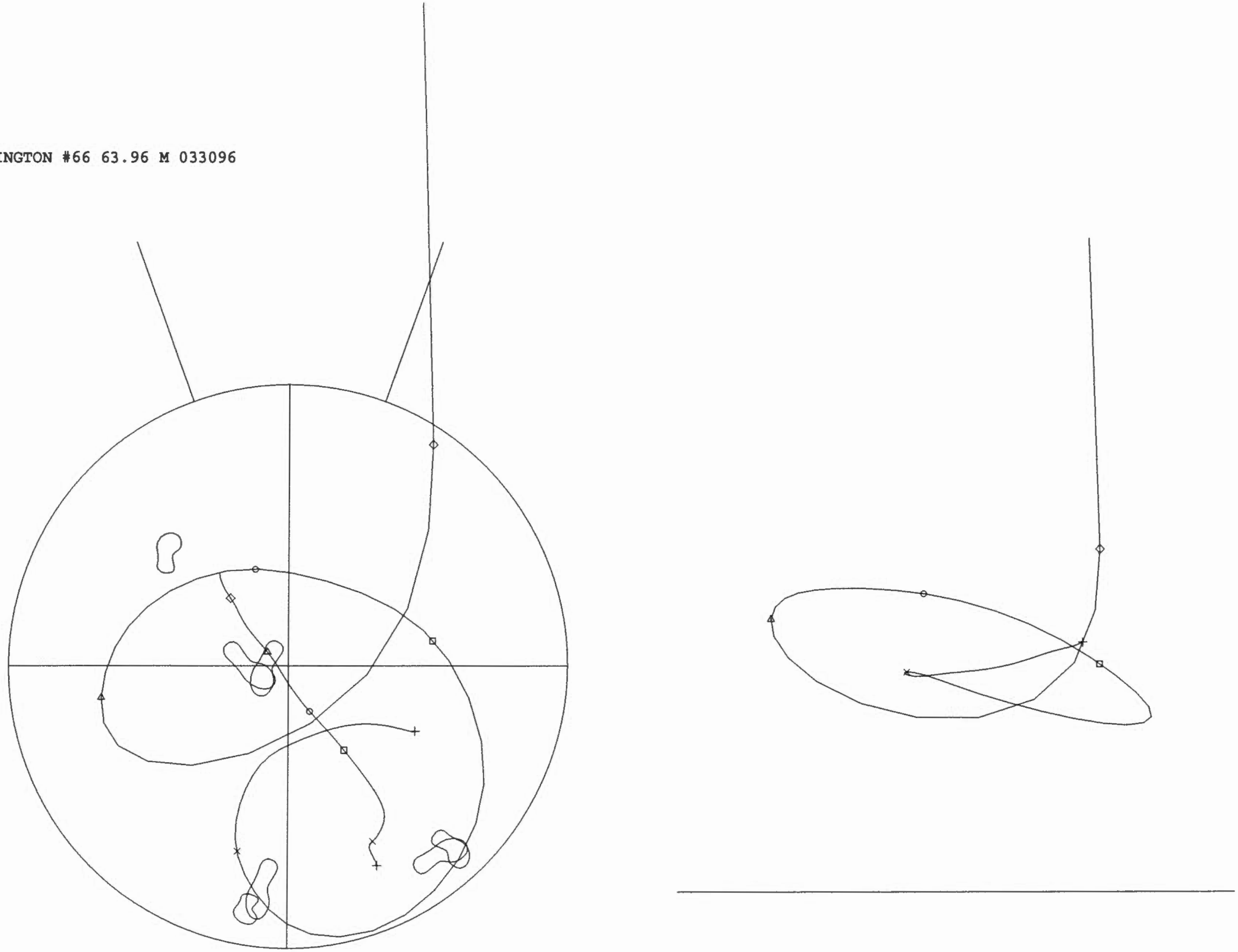

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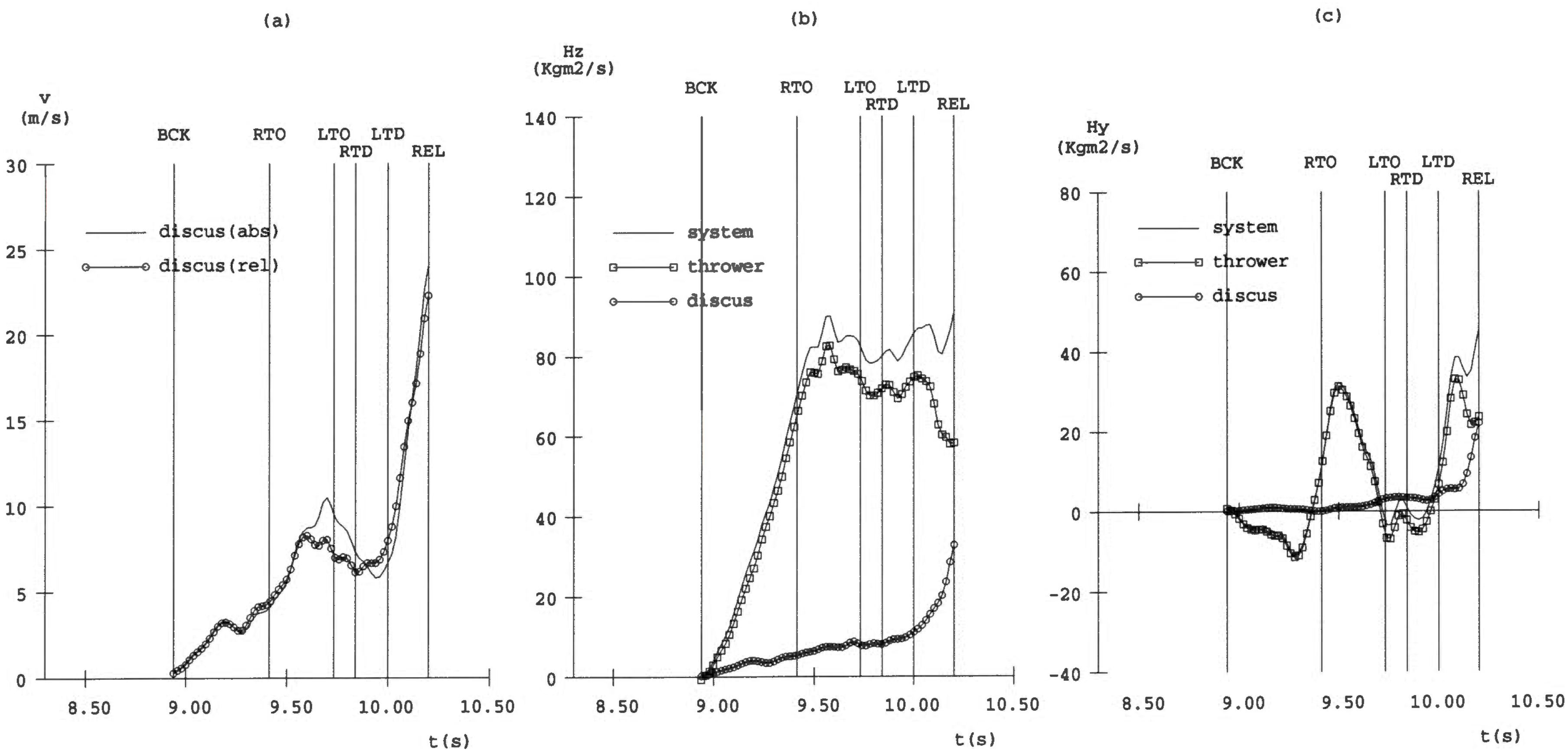
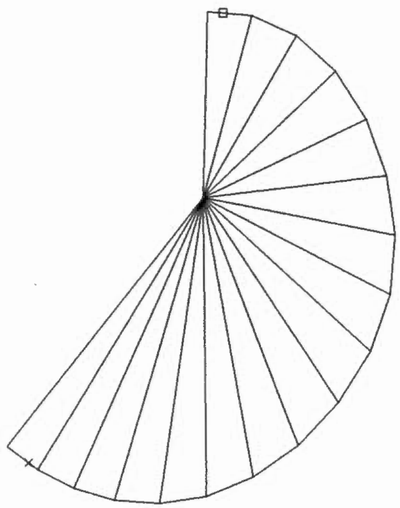
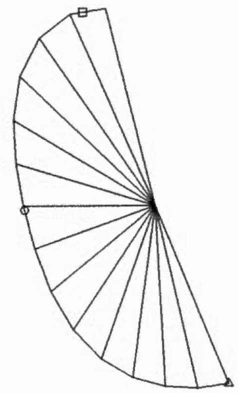


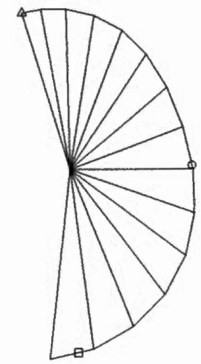
25% of
standing
height



drive of right leg

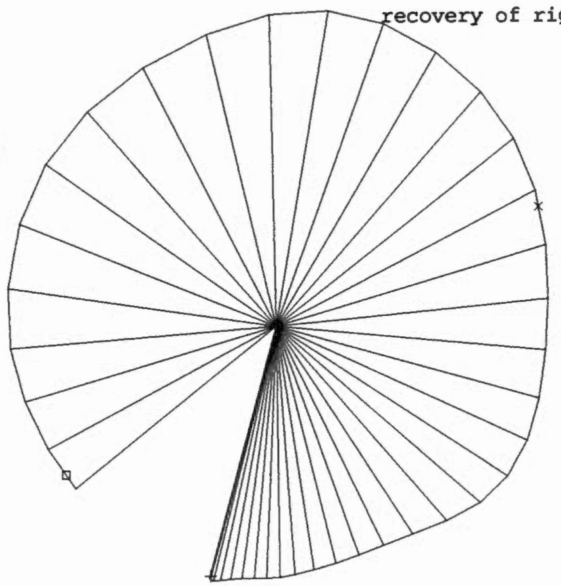


recovery of right leg

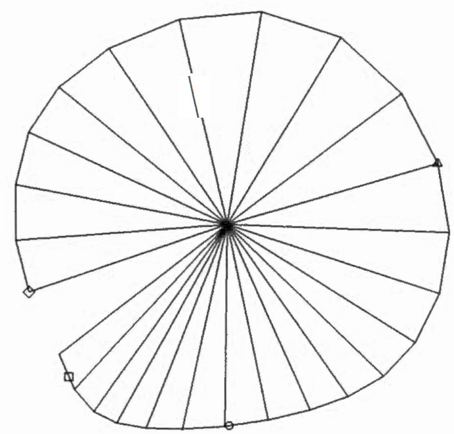


recovery of left leg

50% of
standing
height

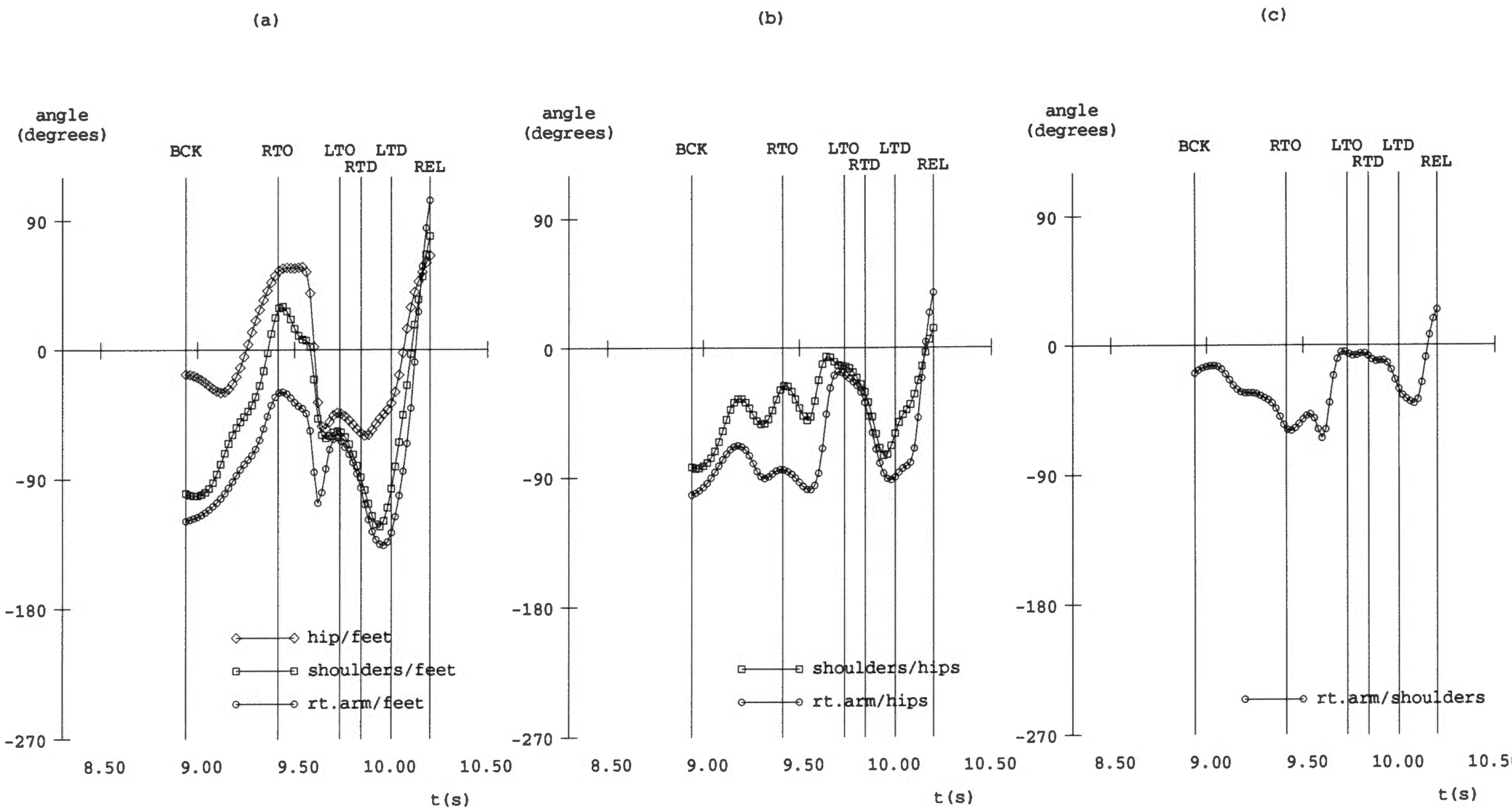


drive of left arm



recovery of left arm, and action during
right foot single-support and delivery

WASHINGTON #66 63.96 M 033096



John WIRTZ

Trial 42 was Wirtz' second-best throw at the 1996 UC San Diego Open (61.48 m). We could not film his 61.64 m best throw at San Diego, a personal record. However, this did not matter much, since trial 42 reached an almost identical distance.

At the back of the circle, Wirtz shifted the system c.m. very well toward his left foot. Then, he made a strong drive with the left leg against the ground, which made him travel very fast, and almost directly forward across the throwing circle (v_{HLTO} = 2.7 m/s; v_{HLTD} = 2.3 m/s; a_{LTO} = -17°; a_{LTD} = -6°). This was very good.

During the double-support delivery, Wirtz made a large forward and downward force on the ground. The backward horizontal reaction force reduced his horizontal speed to an amount (v_{HQ} = 1.4 m/s) which was still large enough to make a good contribution to the horizontal speed of the discus, but small enough to avoid a foul. Due to the very forward (i.e., not very diagonal) direction of motion of the system c.m., the divergence angle between the directions of motion of the system and of the discus was very small (c_Q = -13°). Therefore, practically all the horizontal speed of the system contributed to the horizontal speed of the discus (v_{HCON} = 1.4 m/s). All this was very good.

The size of the vertical force made on the ground during the double-support delivery phase is generally linked to the size of the horizontal force made on the ground during the same period. Wirtz was no exception: Like the horizontal force, the vertical downward force that he made on the ground during the double-support delivery was large, and the vertical upward ground reaction to this force gave the thrower-plus-discus system a large vertical speed which contributed to increase the vertical speed of the discus (v_{ZCON} = 1.6 m/s). This was also very good.

The swinging action of the left arm at the back of the circle was reasonably good (LAA = 33.3 · 10^{-3} Kg·m²/Kg·m²), and the swinging action of the right leg was very good (RLA = 28.3 · 10^{-3} Kg·m²/Kg·m²). Therefore, the combination was also good (RLLAA = 61.6 · 10^{-3} Kg·m²/Kg·m²). At the instant of landing of the left foot in the front of the circle, the system had a reasonably large amount (87%) of the Z angular momentum (counterclockwise rotation in a view from overhead) that it would eventually reach at release. All this suggests that the generation of angular momentum by Wirtz in the back of the circle was good.

The recovery actions of the legs and of the left arm were not too far from average, and therefore we consider them to be reasonably good ($r_{LAVG-NSRSS}$ = 10.0% of standing height; H_{LA-NS} = 37 · 10^{-3} s^{-1}).

The second propulsive swing of the left arm was one of the very best (LAA2 = 21.5 · 10^{-3} Kg·m²/Kg·m²). The arm reached a very large maximum angular momentum (H_{MAX} = 82 · 10^{-3} s^{-1}). Then, Wirtz slowed the left arm down very much (ΔH = -51 · 10^{-3} s^{-1}) before the release of the discus by the right arm. This was an excellent use of the left arm.

At release, the discus had 36% of the total Z angular momentum of the thrower-plus-discus system. This was within normal bounds, and suggests that Wirtz did a good job transfering Z angular momentum from his body to the discus.

At release, the thrower-plus-discus system had a reasonably good amount of counterclockwise angular momentum in the view from the back of the circle (H_{YS} = 49.2 Kg·m²/s), and a reasonable amount of it (H_{YD} = 21.2 Kg·m²/s, or 43% of the total) was in the discus. This suggests that Wirtz made good use of Y angular momentum for the generation of vertical speed for the discus.

The only clear weakness that we found in the technique used by Wirtz was in the maximum torsion of the system ($k_{RA/FT}$ = -121°), which was clearly smaller than average (-144°). The main disadvantages that Wirz had with respect to the average thrower in the sample were the smaller torsion of the hips relative to the feet (Wirtz $k_{HP/FT}$ = -43°; average = -51°), and of the right arm relative to the shoulders (Wirtz $k_{RA/SH}$ = -23°; average = -34°).

Wirtz made very good use of aerodynamic forces (ΔD = 5.70 m).

Summary

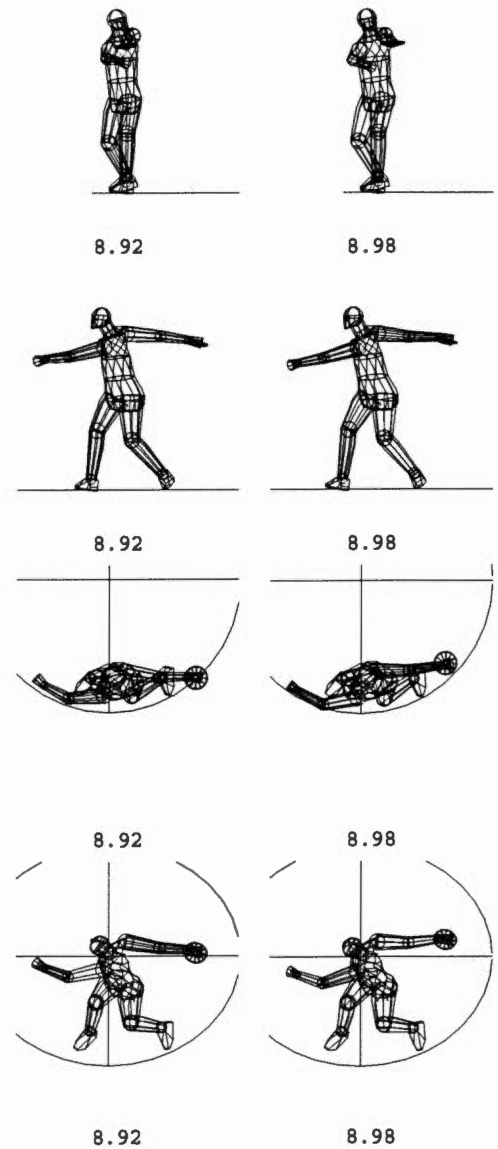
Wirtz shifted his c.m. well toward his left foot, and then made a strong drive almost directly forward across the circle. During the double-support delivery, he made large forward and downward forces on the ground. The ground reactions to these forces reduced his large horizontal speed and increased his vertical speed. The final forward and upward motion of the system c.m. made good contributions to the horizontal and vertical speeds of the discus. The generation of angular momentum by Wirtz at the back of the circle was good. The recovery actions of the legs and of the left arm were reasonably good. The second swing of the left arm was very good, and it was followed by a marked slowing down of this arm prior to the release of the discus by the right arm. The transfer of Y angular momentum from the body to the discus was good. The main weakness in the technique used by Wirtz was the small degree of torsion that he had during the single-support on the right foot. Wirtz used the aerodynamic forces very well.

Recommendations

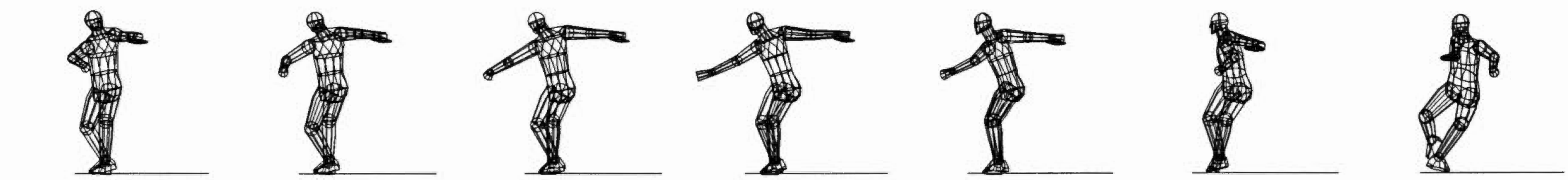
We do not have much advice to give to Wirtz. As far as we can tell, he used a technique that was very good in most respects.

We advise Wirtz to produce a greater degree of torsion between the right arm and the feet at the instant when the final acceleration of the discus is about to begin, during the single-support on the right foot. To achieve this, he will need to use his leg muscles to make the feet rotate counterclockwise further ahead of the hips, and his shoulder muscles to keep the right arm and discus farther back than in throw 42. A more wound-up configuration of the body during the single-support on the right foot should allow Wirtz to drive the discus over a longer range of motion during the final acceleration, and thus to impart more speed to the discus, which in turn will result in a longer throw.

WIRTZ #42 61.48 M 033096



WIRTZ #42 61.48 M 033096



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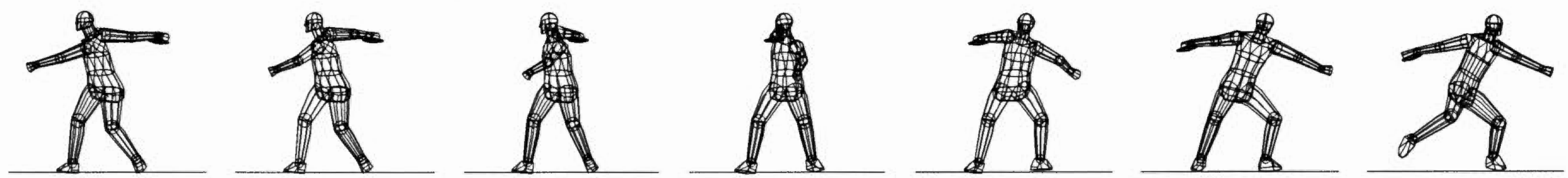

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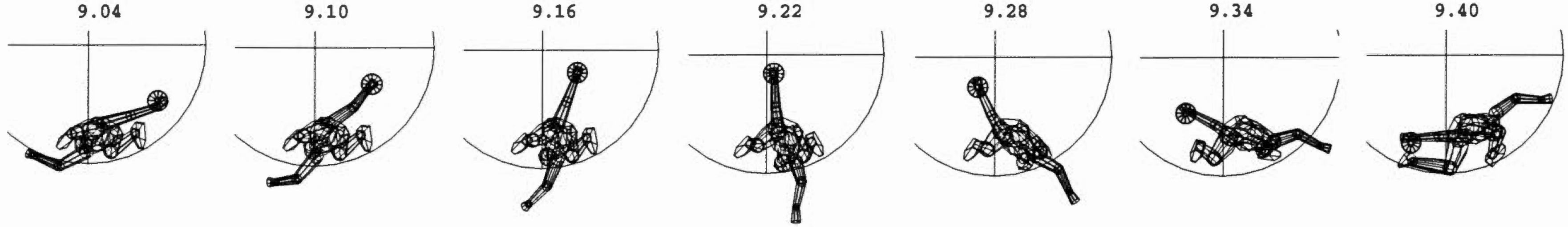

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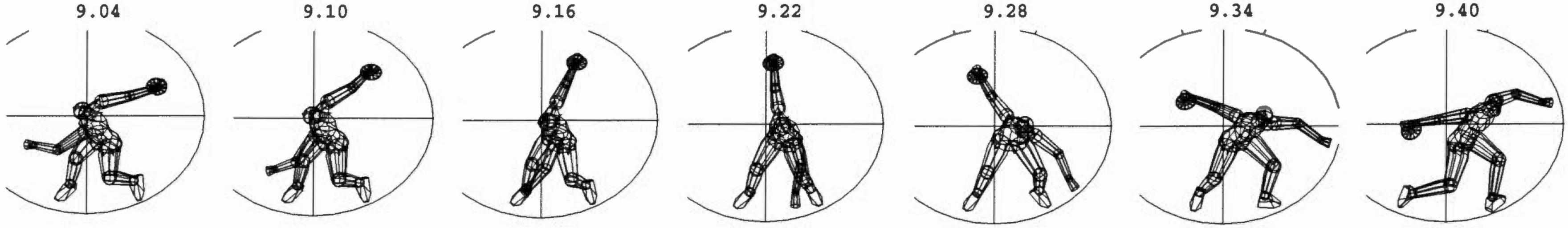

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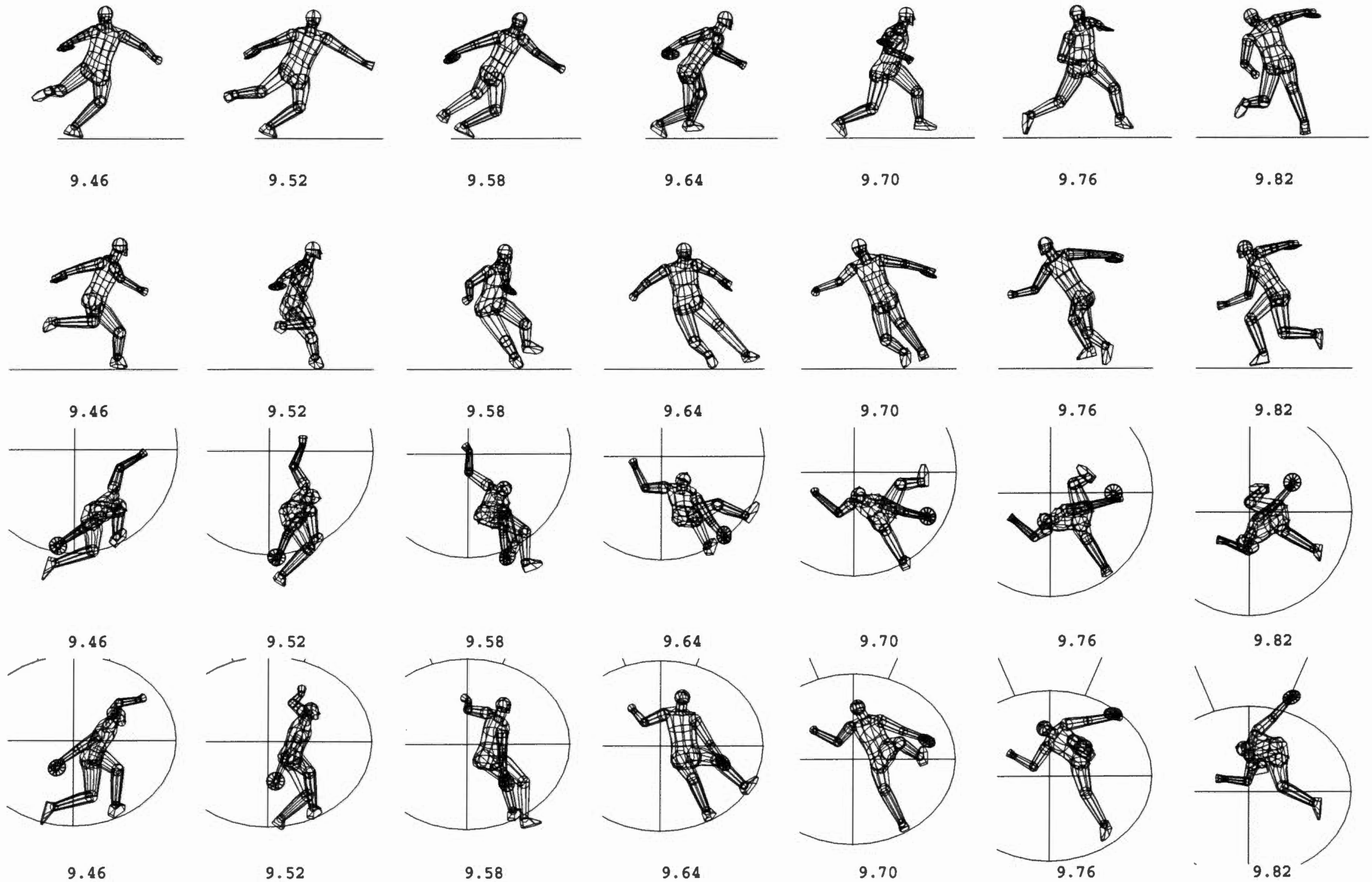
WIRTZ #42 61.48 M 033096



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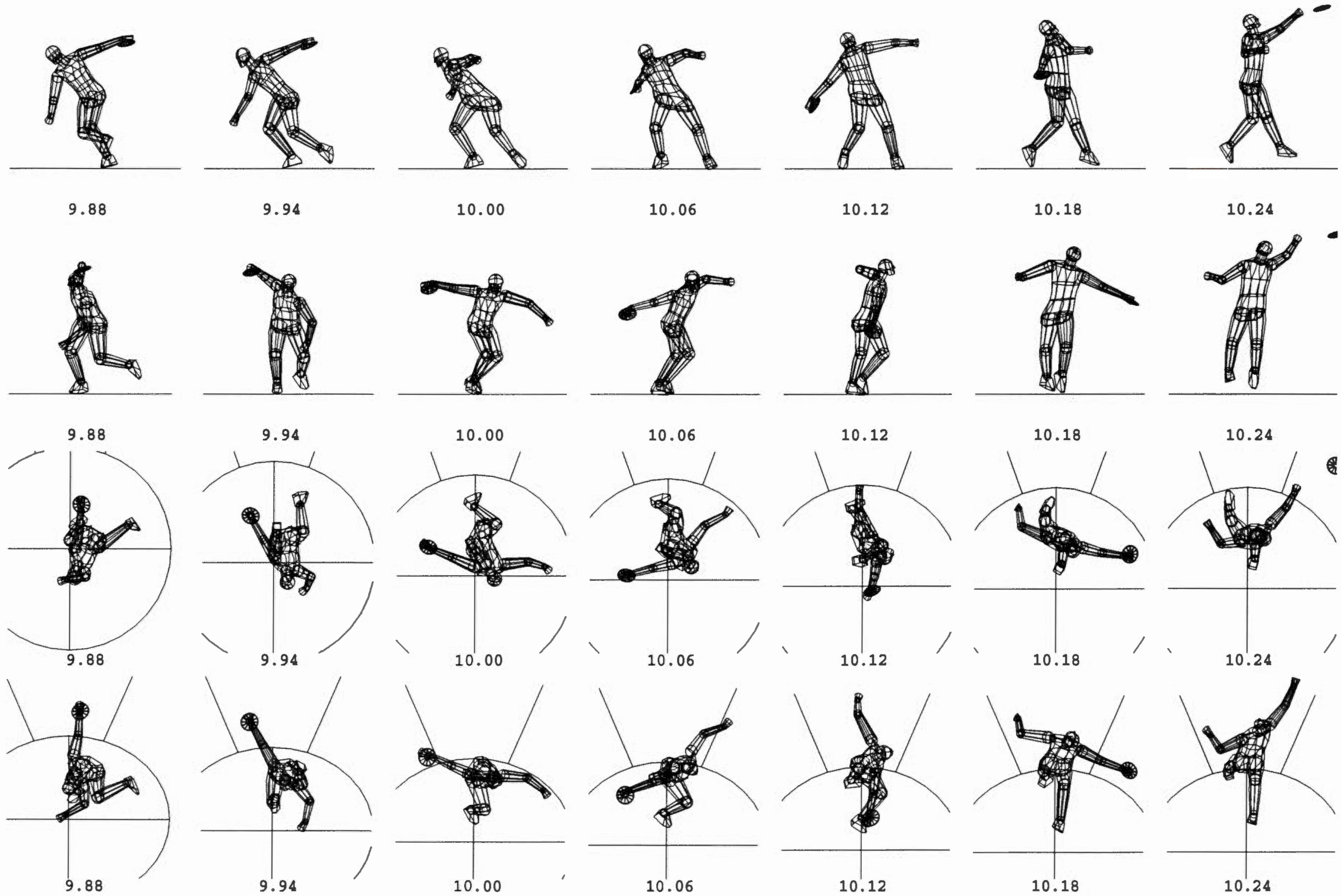

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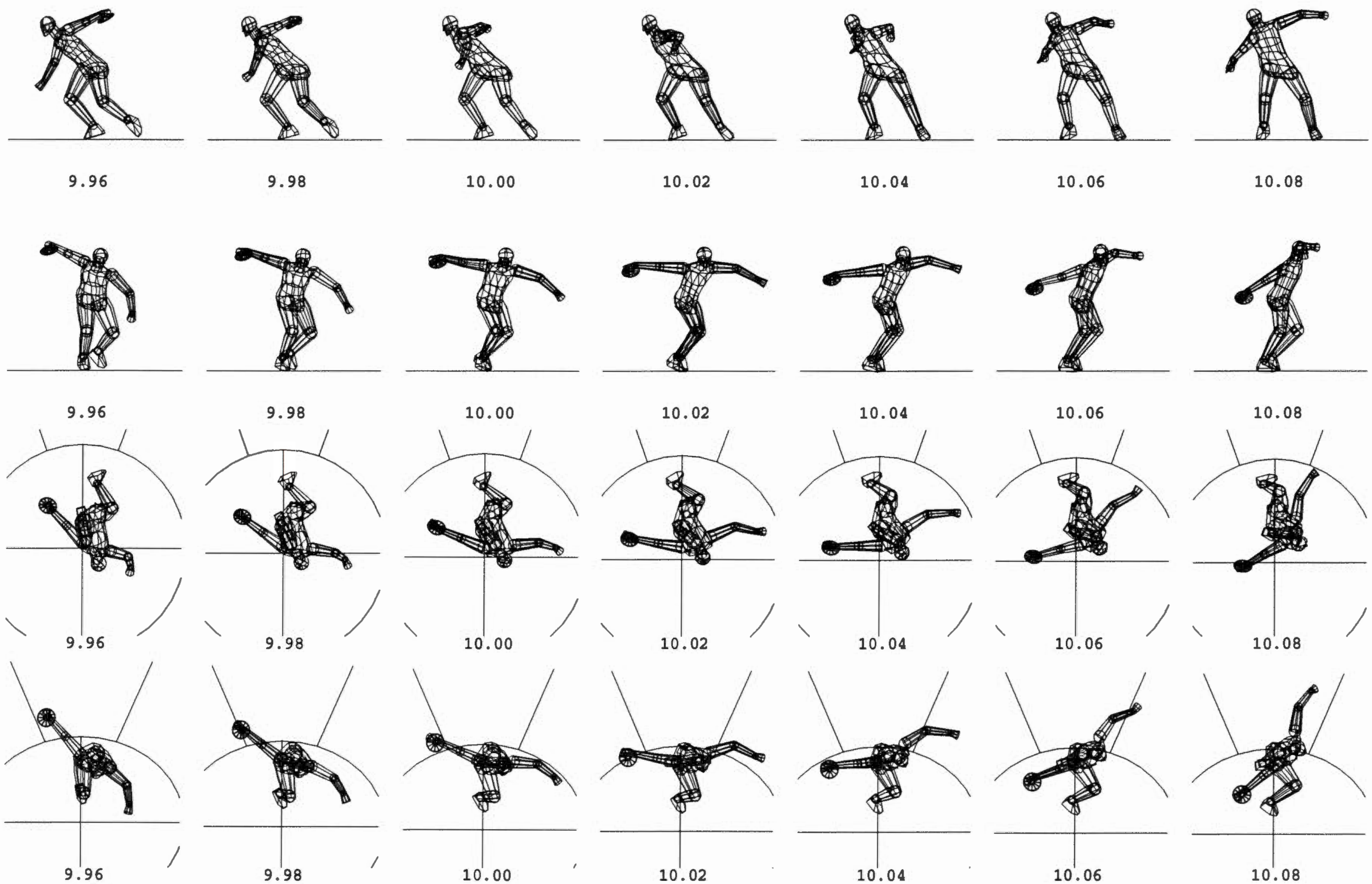

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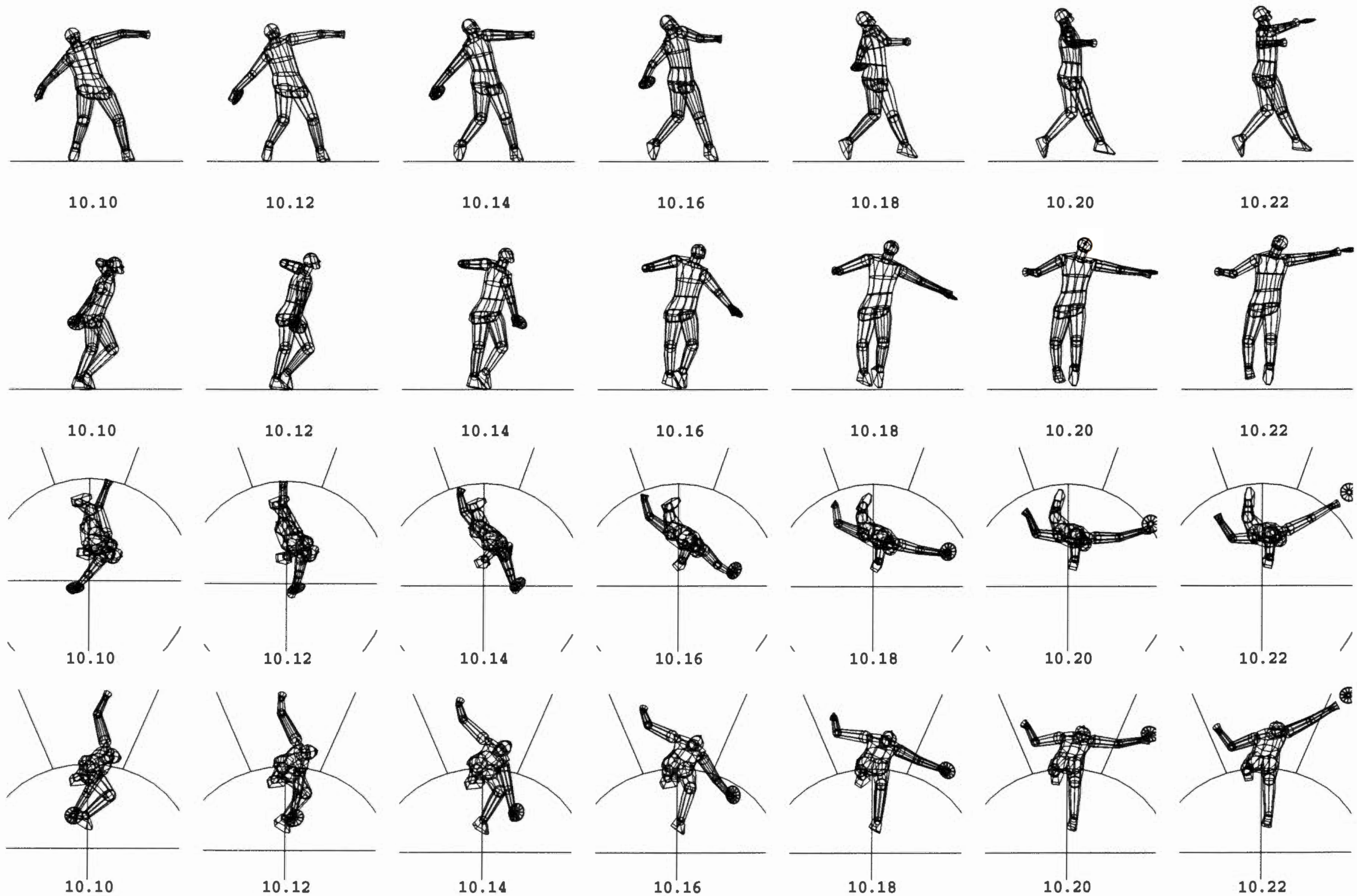

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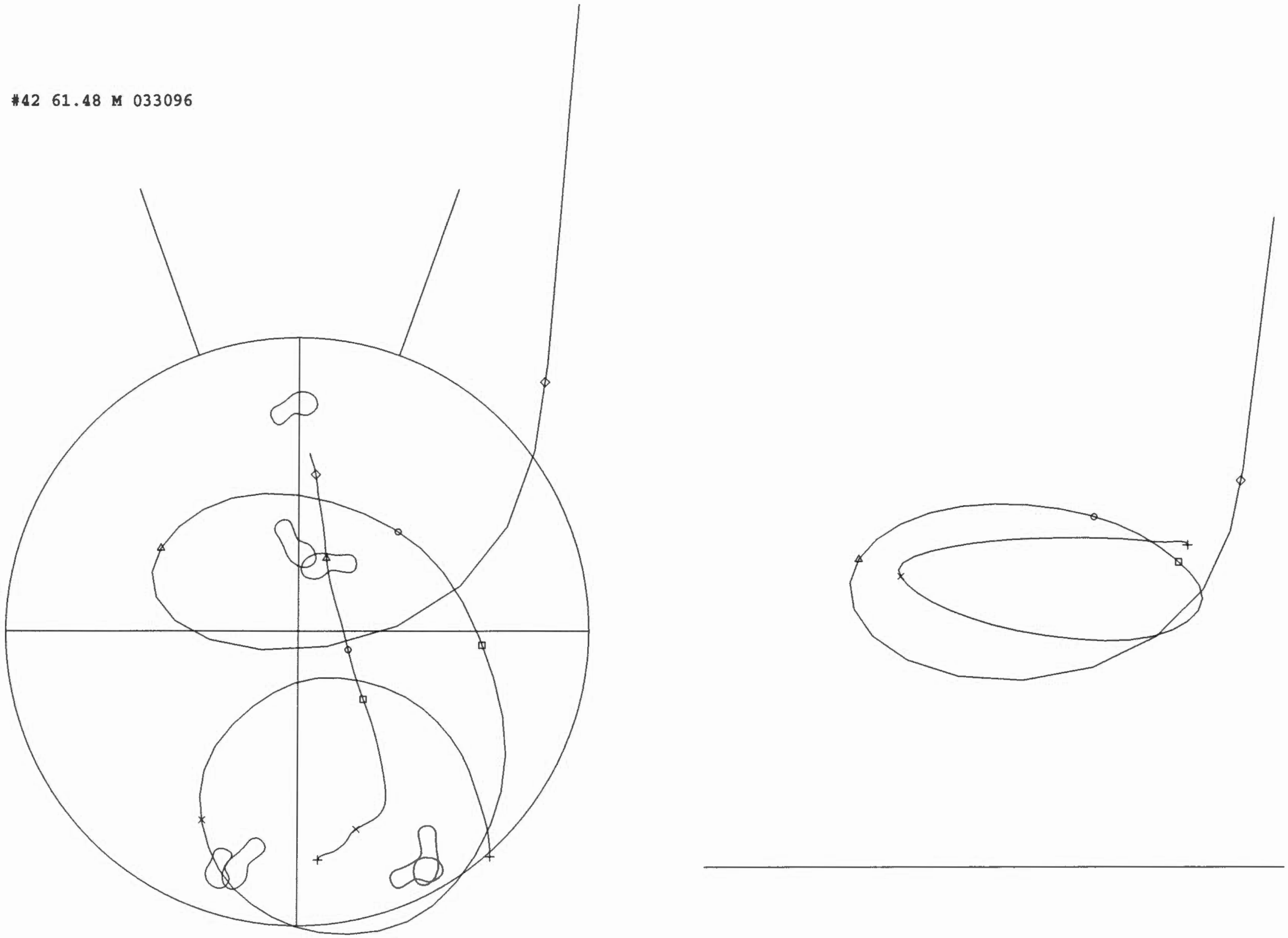

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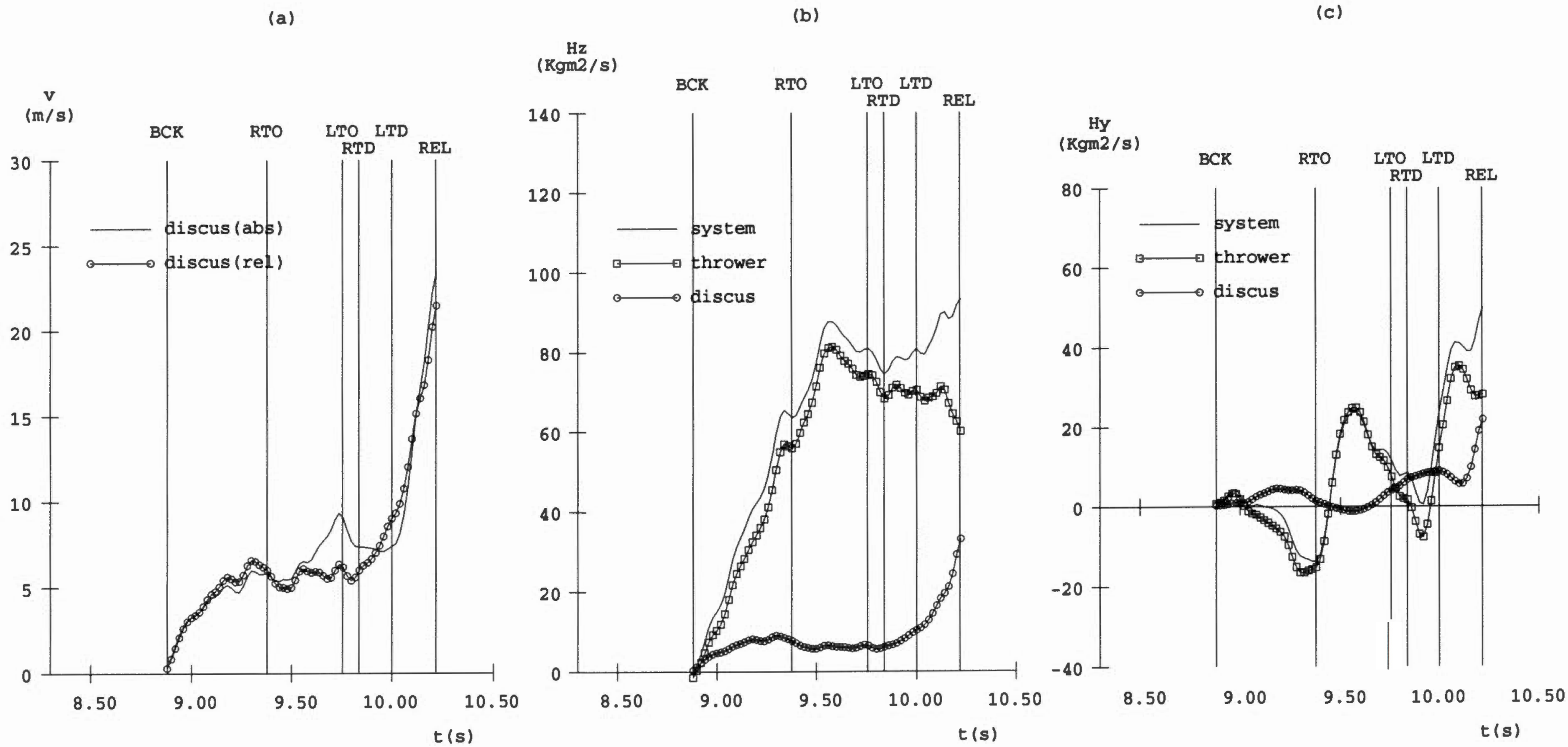

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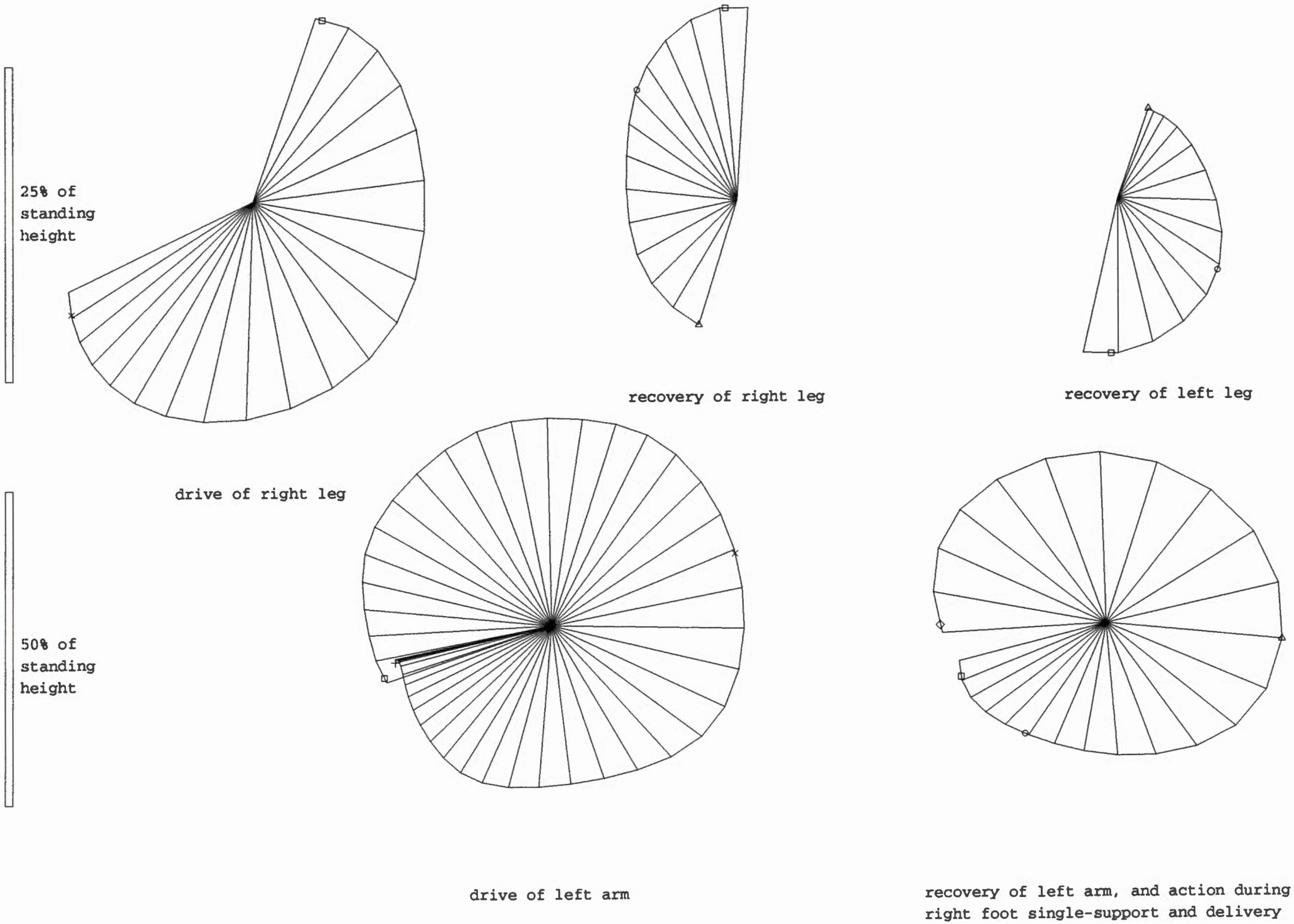

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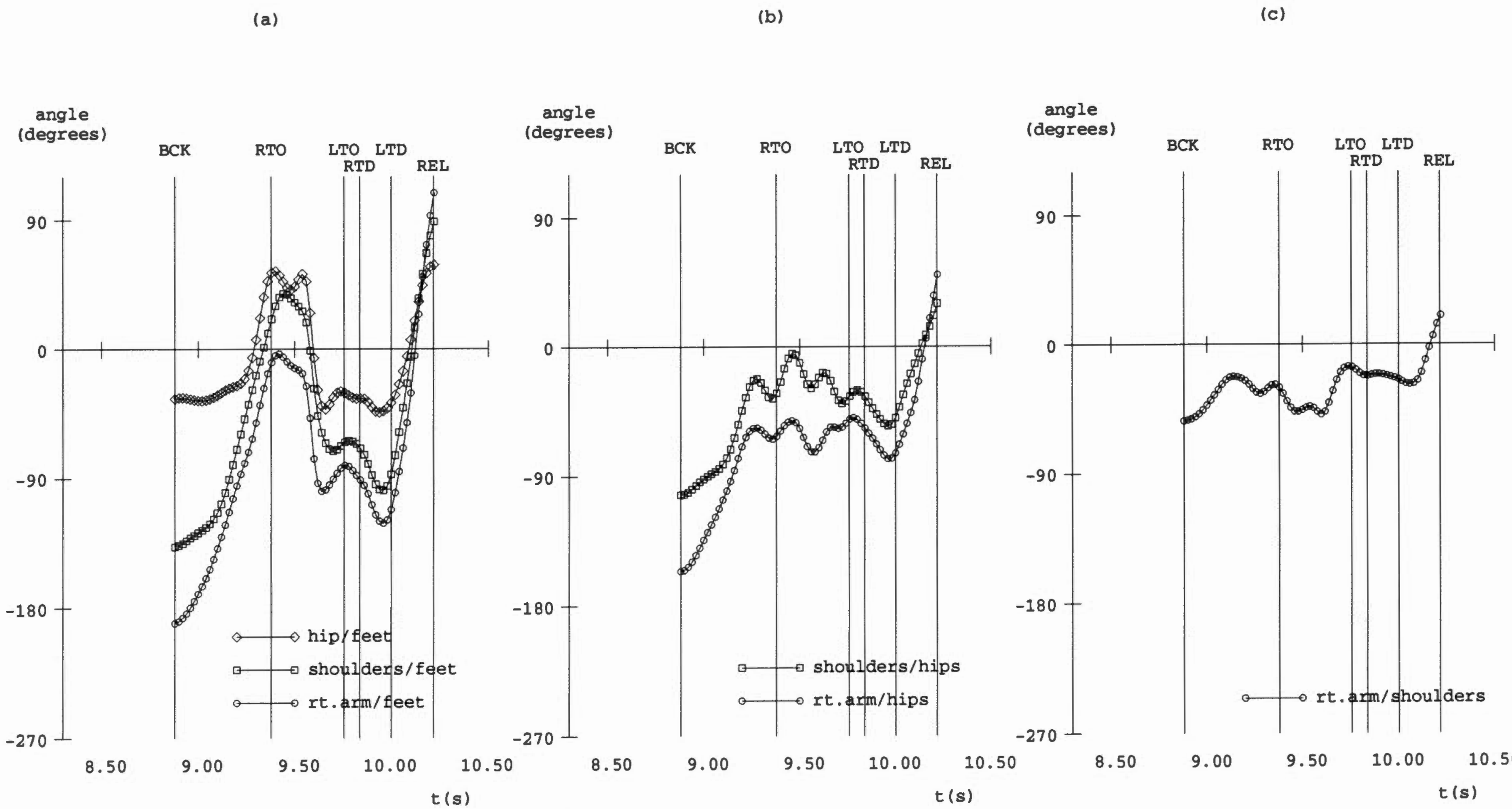

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