SCIENTIFIC SERVICES PROJECT

(USA Track & Field)

DISCUS THROW
#2
(Women)

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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 Hoosier Dome, Suite 140, Indianapolis, IN 46225.

Bloomington, March 10, 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 women's discus throwing contains a biomechanical analysis of the techniques used by 10 of the throwers in the 1996 UC San Diego Open, 6 of the finalists in the 1994 USATF Championships, and one thrower from the 1994 National Invitational held at Indianapolis.

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 American throwers 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

Each throw was filmed 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)
Grace APIAFI	13 D96	1.85	85	54.76	54.28	53.60
Lacy BARNES-MILEHAM	37 D96	1.68	75	63.56	63.56	63.56
Edie BOYER	76 U94	1.83	81	59.36	55.94	55.94
Laura DeSNOO	22 D96	1.79	102	59.84	52.76	52.76
Pam DUKES	36 D96	1.83	88	61.14	60.54	60.54
Dawn DUMBLE	51 D96	1.73	84	60.88	60.24	60.24
Allison FRANKE	07 D96	1.77	75	51.68	51.68	50.38
Carla GARRETT	34 D96	1.75	106	60.54	58.92	58.92
Ingrid HANTHO	48 U94	1.78	86	55.12	50.08	50.08
Nada KAWAR	41 D96	1.87	94	56.06	56.06	56.06
Julie KOEBCKE	32 N94	1.68	71	52.48	51.22	51.22
Kristin KUEHL	46 U94	1.83	91	60.16	57.36	57.36
Rachelle NOBLE	05 D96	1.69	78	59.20	59.20	59.20
Suzy POWELL	35 D96	1.80	77	59.88	59.88	59.88
Alana PRESTON	55 U94	1.68	69	54.84	53.92	53.92
Connie PRICE-SMITH	60 U94	1.91	95	64.82	59.46	59.46
Melisa WEIS	61 U94	1.75	79	55.86	51.72	51.72
Mean		1.78	84	58.25	56.28	56.16
S.D.		±0.07	±10	±3.63	±3.87	±4.00

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open
(**) by the end of the meet in which the athlete was analyzed

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., they are produced by 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).

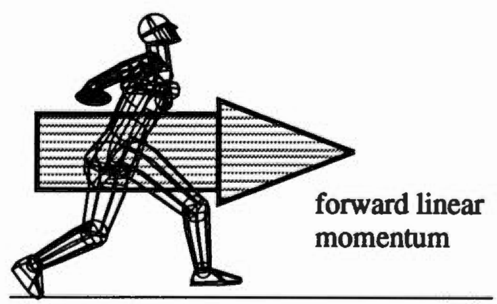


Figure 1

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.

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.

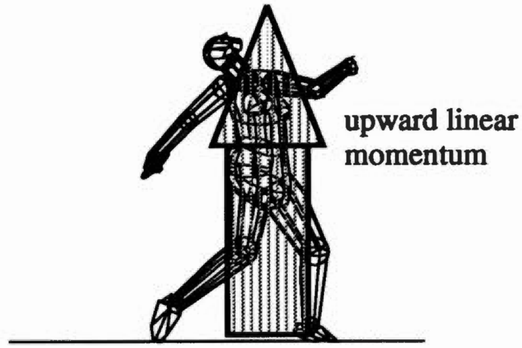


Figure 2

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

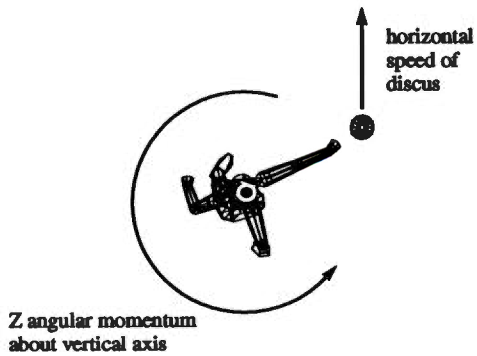


Figure 3

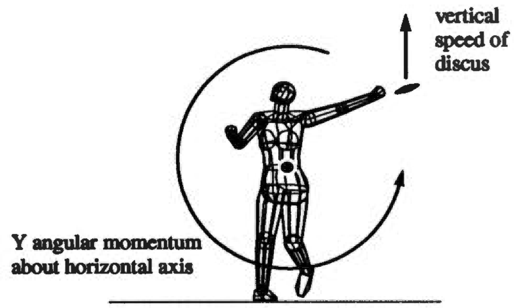


Figure 4

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 8% of the *vertical* speed of the discus at release, while the Y angular momentum contributed the remaining 92%. 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 from 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 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

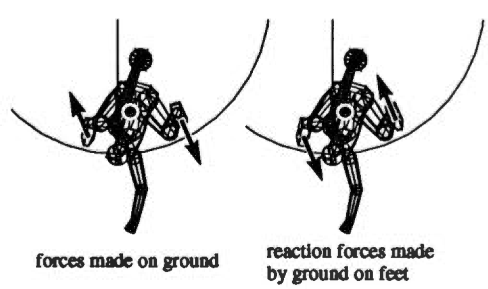


Figure 5

the present project (and of a similar project with male discus throwers —Dapena & Anderst, 1997), 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.)

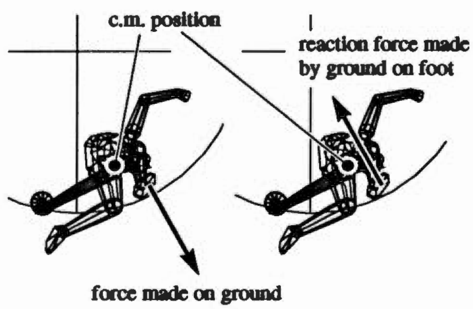


Figure 6

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.

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 (and of the parallel study on the men's discus —Dapena & Anderst, 1997); in our preliminary work (Dapena, 1993a, 1993b, 1994a, 1994b) this increase

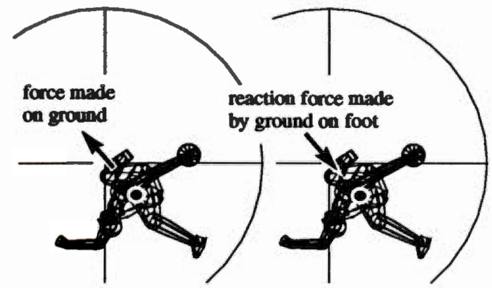


Figure 7

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.

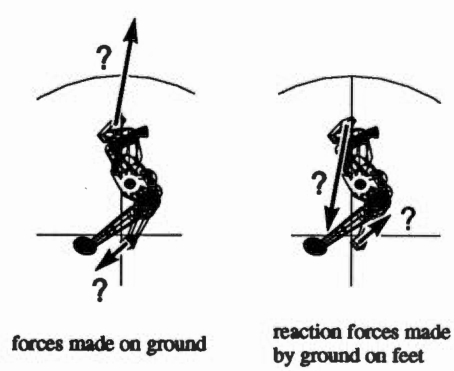


Figure 8

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.

Figure 9

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).

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. It simultaneously produced some slowing down of the counterclockwise rotation of the thrower's body, although this effect was smaller than in the men, due to the small weight of the women's discus.

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

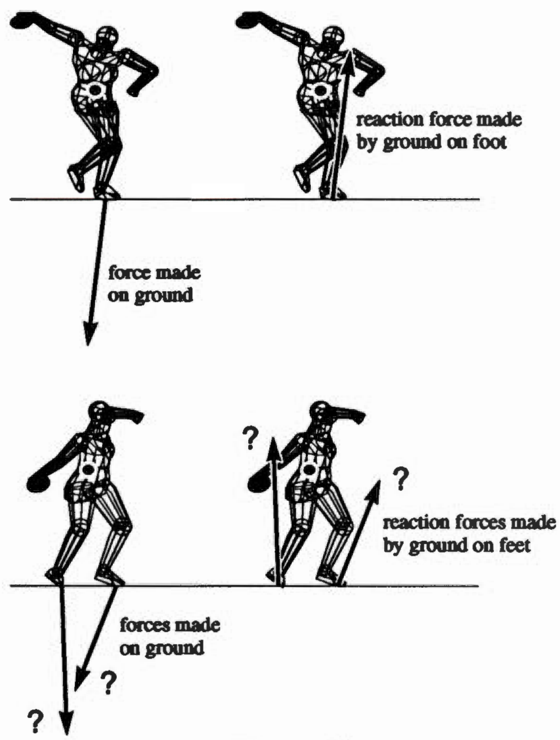


Figure 10

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 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 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.

On the average, the Y angular momentum of the system did not change much during the second half of the delivery phase. 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 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

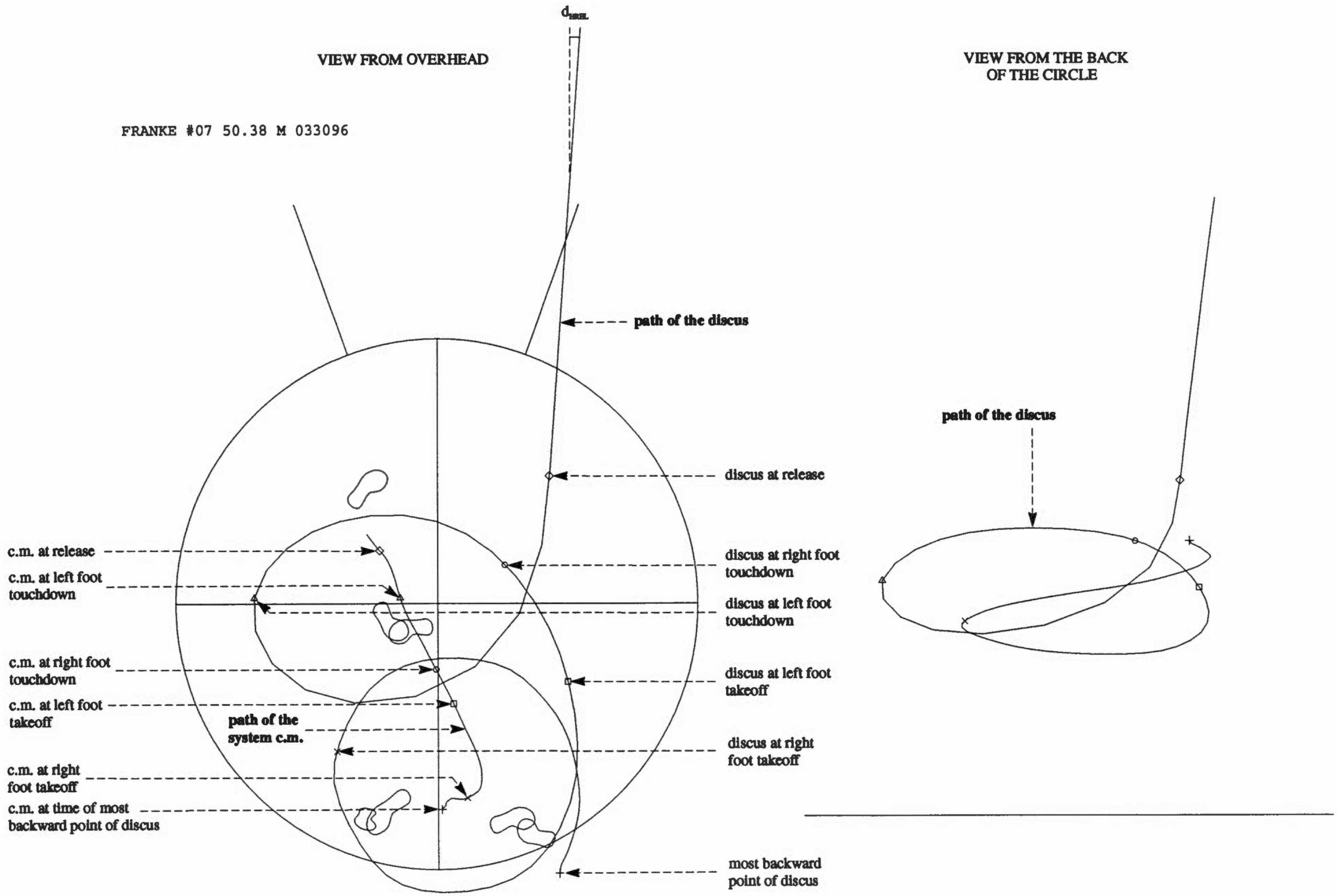

VIEW FROM OVERHEAD
FRANKE #07 50.38 M 033096
path of the discus
discus at release
c.m. at release
c.m. at left foot touchdown
discus at right foot touchdown
discus at left foot touchdown
c.m. at right foot touchdown
c.m. at left foot takeoff
discus at left foot takeoff
path of the system c.m.
discus at right foot takeoff
c.m. at right foot takeoff
c.m. at time of most backward point of discus
most backward point of discus
VIEW FROM THE BACK OF THE CIRCLE
path of the discus

Figure 11

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.

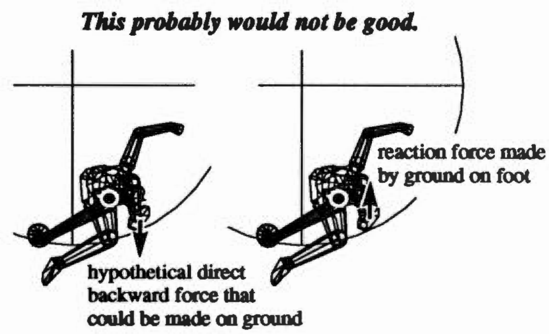


Figure 12

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 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

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_{HSSR}); horizontal speed and direction of motion of the system c.m. at left foot landing (v_{HLTO} 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_{HSSR} (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)
Apiafi	13 D96	2.5	-19	-0.5	2.0	-20	-0.8	1.2	-55	1.1	-41	2	-43	0.8
Barnes-Mil.	37 D96	2.4	-27	-0.2	2.2	-24	-1.3	0.9	-23	1.0	-6	17	-22	0.9
Boyer	76 U94	2.5	-23	-0.8	1.7	-18	-0.8	1.0	-15	1.1	-4	8	-11	1.1
DeSnoo	22 D96	2.1	-24	0.0	2.2	-16	-1.0	1.1	-20	1.4	-23	-1	-22	1.3
Dukes	36 D96	2.3	-28	-0.7	1.7	-12	-0.7	1.0	-6	1.0	-10	1	-10	1.0
Dumble	51 D96	2.4	-15	-0.4	2.0	-20	-0.3	1.7	-24	1.6	-22	-9	-13	1.5
Franke	07 D96	2.1	-27	-0.4	1.7	-18	-0.5	1.2	-41	1.2	-34	4	-38	1.0
Garrett	34 D96	2.0	-27	0.3	2.3	-12	-1.0	1.3	-17	1.4	-15	14	-28	1.3
Hantho	48 U94	2.5	-25	-0.9	1.6	-34	-1.0	0.6	-29	0.7	-28	4	-32	0.6
Kawar	41 D96	2.2	-7	-0.7	1.5	-11	0.0	1.5	-28	1.3	-28	9	-36	1.1
Koebcke	32 N94	2.0	-26	0.3	2.3	-27	-1.2	1.2	-38	1.5	-30	5	-35	1.2
Kuehl	46 U94	2.7	-12	-0.9	1.8	-12	-0.7	1.1	-17	1.0	-4	4	-8	1.0
Noble	05 D96	2.7	-23	-0.4	2.3	-15	-1.0	1.3	-13	1.3	-11	-6	-5	1.3
Powell	35 D96	2.4	-17	-0.2	2.3	-6	-0.6	1.7	-14	1.8	-8	8	-16	1.7
Preston	55 U94	3.1	-3	-1.1	1.9	-11	-1.1	0.9	7	0.9	9	18	-9	0.9
Price-Smith	60 U94	2.4	-14	-0.5	1.9	-11	-1.0	0.9	-15	1.1	-17	11	-27	0.9
Weiss	61 U94	2.8	-16	-0.5	2.3	-10	-1.2	1.1	-5	1.6	-3	13	-16	1.6
Mean		2.4	-20	-0.4	2.0	-16	-0.8	1.2	-21	1.2	-16	6	-22	1.1
S.D.		±0.3	±7	±0.4	±0.3	±7	±0.3	±0.3	±14	±0.3	±13	±7	±12	±0.3

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

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 ± 0.3 m/s. The direction of motion was oblique forward and toward the left (a_{LTO} = -20 ± 7°). (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_{HSSR} = -0.4 ± 0.4 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 ± 0.3 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} = -16 ± 7°). During the double-support delivery phase there was a greater loss of horizontal speed (Δv_{HDLV} = -0.8 ± 0.3 m/s). By the time of release, the system c.m. was traveling with a horizontal speed v_{HREL} = 1.2 ± 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} = -21 ± 14°).

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} = 1.2 ± 0.3 m/s). (By coincidence, this had the same mean value and standard deviation 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 = -16 ± 13°). 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} = 6 ± 7°). The difference between the two angles (c_Q = -22 ± 12°) 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 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} = 1.1 ± 0.3 m/s, only 0.1 m/s smaller than the value of v_{HQ} (1.2 ± 0.3 m/s). This was because the average divergence angle c_Q was small (-22 ± 12°). Since the average horizontal speed of the discus at release was 18.7 m/s (see below), the 0.1 m/s loss due to the divergence of the

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} = 1.2 m/s; horizontal speed of discus at release v_{HD} = 18.7 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) and wind tunnel data on the women's discus taken from Ganslen (personal communication to James Hay, April 14, 1986).

c_Q (°)	Δv_{HCON} (m/s)	ΔD_c (m)
0	0.00	0.0
-10	-0.02	-0.1
-20	-0.07	-0.2/-0.4
-30	-0.16	-0.5/-1.0
-40	-0.28	-0.9/-1.7
-50	-0.43	-1.4/-2.5

system and discus paths was (0.1/18.7=) 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 0.3 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 and using wind tunnel data on the women's discus taken from Ganslen (personal communication to James Hay, April 14, 1986) 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 0.3 m and 0.5 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.

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} = 54.7 ± 2.2% 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} = 56.3 ± 2.5%), and markedly higher at the instant that the discus was released (h_{REL} = 58.7 ± 3.0%). These numbers seem to make good sense.

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 86.8 ± 7.0% of standing height in the grounded-release throwers, and at 89.3 ± 5.0% of standing height in the airborne-release throwers. (These data are not shown in the tables.) Considering the 1.78 m average standing height of the throwers in our sample, 2.5% (i.e., 89.3%-86.8%) of standing height represented a difference of 0.04 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 0.04 m at release would only produce a trivial difference in the distance of the throw, about 0.06 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} = 1.5 ± 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} = 1.2 ± 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} = 1.0 ± 0.2 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, it would

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} (m/s)	v_{ZTO} (m/s)	v_{ZREL} (m/s)	v_{ZCON} (m/s)	h_{LTD} (m)	h_{LTD} (%)	h_{TO} (m)	h_{TO} (%)	h_{REL} (m)	h_{REL} (%)	
Apiafi	13 D96	-0.3	1.4	1.1	1.2	0.87	47.0	0.98	53.0	1.02	55.0	
Barnes-Mil.	37 D96	-0.3	1.9	1.7	1.5	0.79	47.0	0.92	55.0	0.96	57.0	
Boyer	76 U94	0.1	1.6	1.0	1.4	0.93	50.5	1.07	58.5	1.16	63.0	
DeSnoo	22 D96	0.2	—	1.1	0.8	0.83	46.5	—	—	0.93	51.5	
Dukes	36 D96	0.2	—	1.1	1.1	0.90	49.0	—	—	1.04	57.0	
Dumble	51 D96	0.2	—	1.1	1.2	0.85	49.0	—	—	1.02	59.0	
Franke	07 D96	0.0	1.2	1.2	1.1	0.85	48.0	0.98	55.5	0.99	55.5	
Garrett	34 D96	-0.1	—	0.9	0.8	0.88	50.0	—	—	0.94	53.5	
Hantho	48 U94	0.3	—	0.6	0.8	0.86	48.0	—	—	0.97	54.5	
Kawar	41 D96	0.4	0.9	0.9	1.0	0.95	51.0	1.10	59.0	1.10	59.0	
Koebcke	32 N94	-0.3	—	1.1	0.9	0.84	50.0	—	—	0.91	54.0	
Kuehl	46 U94	-0.2	1.5	0.8	1.3	0.90	49.0	1.08	59.0	1.17	64.0	
Noble	05 D96	0.0	1.9	1.5	1.7	0.76	45.0	0.92	54.5	0.99	58.5	
Powell	35 D96	-0.1	—	0.9	0.7	0.90	50.0	—	—	0.96	53.5	
Preston	55 U94	0.0	1.5	1.0	1.2	0.79	47.0	0.89	53.0	0.95	56.5	
Price-Smith	60 U94	-0.4	1.7	1.6	1.4	0.99	51.5	1.14	59.5	1.14	60.0	
Weiss	61 U94	0.1	—	1.2	1.0	0.83	47.5	—	—	0.95	54.5	
Mean		0.0	—	1.1	1.1	0.87	48.6	—	—	1.01	56.8	(ALL THROWS)
S.D.		±0.2	—	±0.3	±0.3	±0.06	±1.7	—	—	±0.08	±3.3	
Mean		-0.1	1.5	1.2	1.3	0.87	48.4	1.01	56.3	1.05	58.7	(AIRBORNE
S.D.		±0.2	±0.3	±0.3	±0.2	±0.07	±2.1	±0.09	±2.5	±0.08	±3.0	RELEASE)
Mean		0.1	—	1.0	0.9	0.86	48.8	—	—	0.96	54.7	(GROUNDED
S.D.		±0.2	—	±0.2	±0.2	±0.03	±1.2	—	—	±0.04	±2.2	RELEASE)

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

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} = 1.3 ± 0.2 m/s; v_{ZREL} = 1.2 ± 0.3 m/s), while in the grounded-release throws it was smaller than the vertical speed of the system at release (v_{ZCON} = 0.9 ± 0.3 m/s; v_{ZREL} = 1.0 ± 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 ($v_{ZCON} = 1.3 \pm 0.2$ m/s for the airborne-release throwers; $v_{ZCON} = 0.9 \pm 0.2$ m/s for the grounded-release throwers). Due to the small number of subjects in the two subgroups of throwers, 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., 1.3 m/s - 0.9 m/s) make in the distance of a throw? The average vertical speed of the discus at release was 13.0 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 (0.4/13.0=) 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 1.8 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 0.9 m and 1.6 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. The two processes are linked. A statistical analysis of the data in Tables 2 and 4 showed that, to a certain extent, 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}). In the parallel study on men's discus throwing (Dapena & Anderst, 1997), the linkage was stronger: We found that the male throwers could 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. In the women, we found the same kind of relationship, although not so clear-cut as in the men.

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 generally 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 tend to 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 tend to 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 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

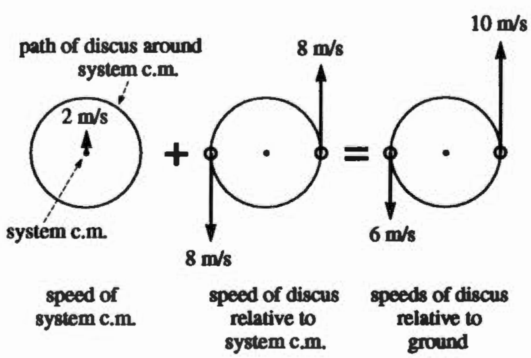


Figure 13

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 near the time when 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

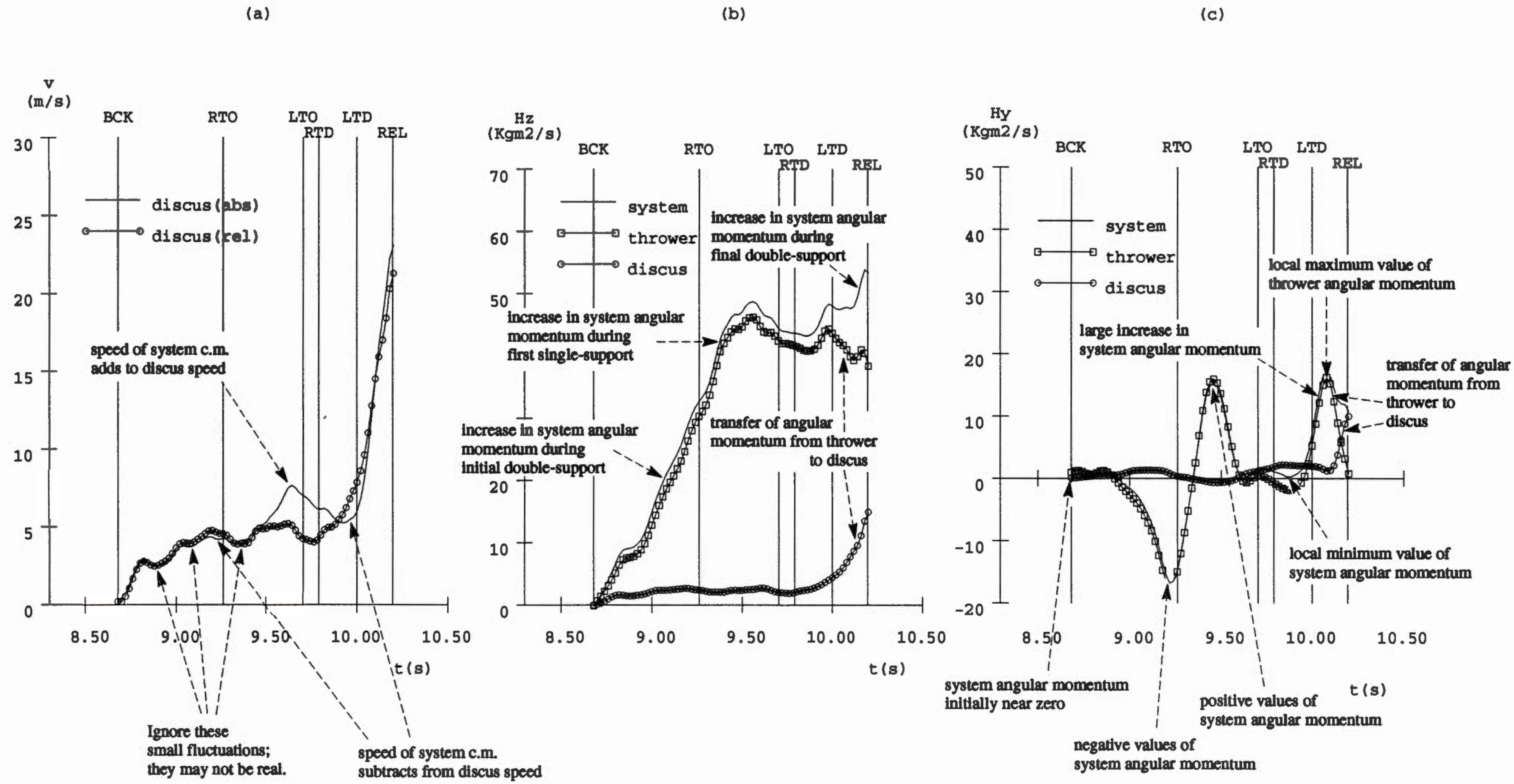

(a)
(b)
(c)
v
(m/s)
BCK
RTO
LTO
RTD
LTD
REL
30
25
20
15
10
5
0
discus(abs)
discus(rel)
speed of system c.m.
adds to discus speed
8.50
9.00
9.50
10.00
10.50
t(s)
Ignore these
small fluctuations;
they may not be real.
speed of system c.m.
subtracts from discus speed
Hz
(Kgm2/s)
70
60
50
20
10
0
system
thrower
discus
increase in system angular
momentum during
final double-support
increase in system angular
momentum during
first single-support
increase in system angular
momentum during
initial double-support
transfer of angular
momentum from thrower
to discus
Hy
(Kgm2/s)
40
-10
-20
local maximum value of
thrower angular momentum
large increase in
system angular momentum
transfer of angular
momentum from
thrower to
discus
local minimum value of
system angular momentum
system angular momentum
initially near zero
positive values of
system angular momentum
negative values of
system angular momentum

Figure 14

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. 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; 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 right foot takeoff (RTO), followed by small increases and decreases (which may be real or not!), and a final increase which started (very roughly) around the instant of landing of the ***right*** foot. This pattern was similar in most of the throwers, and it indicates that they 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 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

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
Apiafi	13 D96	0.3	39.4	42.6	42.6	41.5	54.6	1	136	146	146	143	188	1	72	78	78	76	100
Barnes-Mil.	37 D96	1.6	35.3	42.7	42.7	40.2	50.0	7	167	202	202	190	236	3	71	85	85	80	100
Boyer	76 U94	0.8	35.8	44.5	44.5	46.1	50.4	3	132	164	164	170	186	2	71	88	88	91	100
DeSnoo	22 D96	-0.3	38.9	45.1	45.1	44.6	54.1	-1	119	138	138	136	166	-1	72	83	83	82	100
Dukes	36 D96	0.9	33.7	45.0	45.0	53.6	57.4	3	114	153	153	182	195	2	59	78	78	93	100
Dumble	51 D96	-0.7	43.3	50.1	50.1	45.4	48.4	-3	172	199	199	181	193	-1	90	104	104	94	100
Franke	07 D96	-0.2	34.2	38.0	38.0	36.2	45.6	-1	146	162	162	154	194	0	75	83	83	79	100
Garrett	34 D96	-0.4	34.9	43.8	43.8	53.0	50.2	-1	108	135	135	163	155	-1	70	87	87	105	100
Hantho	48 U94	3.2	37.6	47.1	47.1	42.7	46.1	12	138	173	173	157	169	7	81	102	102	93	100
Kawar	41 D96	2.9	50.2	51.3	51.3	45.2	52.6	9	153	156	156	137	160	6	95	98	98	86	100
Koebcke	32 N94	-1.6	27.2	34.0	34.0	33.9	38.8	-8	136	170	170	169	193	-4	70	88	88	87	100
Kuehl	46 U94	1.4	46.1	50.4	50.4	49.3	53.7	5	151	165	165	162	176	3	86	94	94	92	100
Noble	05 D96	-0.2	32.7	43.9	43.9	48.1	53.3	-1	147	197	197	216	239	0	61	82	82	90	100
Powell	35 D96	0.2	30.8	36.3	36.3	39.9	45.7	1	124	145	145	160	183	0	68	79	79	87	100
Preston	55 U94	1.1	34.8	43.6	43.6	38.7	42.5	6	178	224	224	199	218	3	82	103	103	91	100
Price-Smith	60 U94	1.4	36.4	48.2	48.2	47.7	57.5	4	105	139	139	138	166	2	63	84	84	83	100
Weiss	61 U94	-0.1	37.1	43.3	43.3	39.5	45.3	0	153	179	179	163	187	0	82	96	96	87	100
Mean		0.6	37.0	44.1	44.1	43.9	49.8	2	140	167	167	166	188	1	75	89	89	88	100
S.D.		±1.2	±5.4	±4.6	±4.6	±5.4	±5.1	±5	±21	±25	±25	±22	±23	±3	±10	±9	±9	±7	±0

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

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

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 ($Kg \cdot m^2/s$), 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_{ZT} (non-normalized) ($Kg \cdot m^2/s$)						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
Apiafi	13 D96	0.0	35.5	39.1	39.9	36.8	40.6	0	122	134	137	127	139	0	65	72	73	67	74
Barnes-Mil.	37 D96	1.5	31.3	39.9	40.2	34.9	35.5	7	148	188	190	165	168	3	63	80	80	70	71
Boyer	76 U94	0.8	32.9	40.3	40.4	41.8	35.4	3	121	149	149	154	130	2	65	80	80	83	70
DeSnoo	22 D96	-0.3	36.7	42.8	42.9	40.1	40.8	-1	112	131	131	123	125	-1	68	79	79	74	75
Dukes	36 D96	0.7	31.8	42.5	42.3	49.0	41.9	2	108	144	144	166	142	1	56	74	74	85	73
Dumble	51 D96	-0.8	39.7	46.7	47.1	40.5	34.9	-3	158	186	188	161	139	-2	82	96	97	84	72
Franke	07 D96	-0.2	30.8	35.1	34.8	30.0	32.1	-1	131	149	148	128	137	0	67	77	76	66	70
Garrett	34 D96	-0.4	31.8	41.5	41.6	47.5	36.7	-1	98	128	128	146	113	-1	63	83	83	95	73
Hantho	48 U94	3.1	34.8	45.2	44.9	38.5	31.9	11	128	166	165	141	117	7	76	98	97	83	69
Kawar	41 D96	2.9	46.3	48.5	48.3	38.9	38.2	9	141	148	147	118	116	6	88	92	92	74	73
Koebcke	32 N94	-1.5	24.6	31.0	30.9	28.0	26.8	-8	123	155	154	140	134	-4	63	80	80	72	69
Kuehl	46 U94	1.6	42.9	47.5	47.3	44.6	36.0	5	141	156	155	146	118	3	80	88	88	83	67
Noble	05 D96	-0.1	30.3	41.9	41.9	43.7	38.4	-1	136	188	188	196	172	0	57	79	79	82	72
Powell	35 D96	0.1	28.2	33.7	33.7	34.7	31.3	0	113	135	135	139	126	0	62	74	74	76	69
Preston	55 U94	0.9	32.1	40.7	40.6	34.9	28.3	4	165	209	208	179	145	2	76	96	96	82	67
Price-Smith	60 U94	1.5	34.4	46.0	45.9	43.1	40.0	4	99	133	132	124	116	3	60	80	80	75	70
Weiss	61 U94	0.0	35.1	40.9	40.7	34.2	33.5	0	145	169	168	141	139	0	78	90	90	76	74
Mean		0.6	34.1	41.4	41.4	38.9	35.4	2	129	157	157	147	134	1	69	83	83	78	71
S.D.		±1.2	±5.1	±4.7	±4.7	±5.6	±4.2	±5	±19	±23	±23	±21	±17	±3	±9	±8	±8	±7	±2

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

of the system already had 75 ± 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 89 ± 9% 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. 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 ± 9%. 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 88 ± 7% of the release value. During the double-support delivery there was usually an increase in the Z angular momentum of the system (12 ± 7%) to reach the full value of 100% at release. These results confirmed our previous finding

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), 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 ($s^{-1}\cdot10^{-3}$), and as a percent of the Z angular momentum of th 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) ($s^{-1}\cdot10^{-3}$)						H_{zD} (percent of H_{zSREL}) (%)					
		BCK	RTO	LTO	RTD	LTD	REL	BCK	RTO	LTO	RTD	LTD	REL	BCK	RTO	LTO	RTD	LTD	REL
Apiafi	13 D96	0.3	4.0	3.5	2.7	4.7	14.0	1	14	12	9	16	48	1	7	6	5	9	26
Barnes-Mil.	37 D96	0.1	4.0	2.9	2.6	5.3	14.5	0	19	13	12	25	68	0	8	6	5	11	29
Boyer	76 U94	0.0	3.0	4.1	4.1	4.3	15.0	0	11	15	15	16	55	0	6	8	8	9	30
DeSnoo	22 D96	-0.1	2.1	2.3	2.1	4.5	13.3	0	7	7	7	14	41	0	4	4	4	8	25
Dukes	36 D96	0.2	1.9	2.5	2.7	4.6	15.5	1	6	9	9	16	52	0	3	4	5	8	27
Dumble	51 D96	0.2	3.6	3.4	2.9	4.9	13.5	1	15	14	12	20	54	0	8	7	6	10	28
Franke	07 D96	0.0	3.4	2.9	3.2	6.2	13.5	0	15	13	14	26	57	0	8	6	7	14	30
Garrett	34 D96	0.0	3.2	2.4	2.2	5.4	13.5	0	10	7	7	17	42	0	6	5	4	11	27
Hantho	48 U94	0.1	2.7	1.9	2.3	4.2	14.3	0	10	7	8	15	52	0	6	4	5	9	31
Kawar	41 D96	0.0	3.9	2.8	3.0	6.2	14.4	0	12	8	9	19	44	0	7	5	6	12	27
Koebcke	32 N94	0.0	2.6	3.0	3.1	5.9	12.0	0	13	15	15	29	60	0	7	8	8	15	31
Kuehl	46 U94	-0.1	3.2	2.9	3.1	4.7	17.6	0	11	10	10	16	58	0	6	5	6	9	33
Noble	05 D96	0.0	2.4	2.0	2.0	4.4	14.9	0	11	9	9	20	67	0	4	4	4	8	28
Powell	35 D96	0.1	2.6	2.6	2.5	5.2	14.3	0	11	10	10	21	58	0	6	6	6	11	31
Preston	55 U94	0.2	2.7	3.0	3.0	3.8	14.2	1	14	15	16	20	73	1	6	7	7	9	33
Price-Smith	60 U94	-0.1	2.0	2.3	2.3	4.6	17.5	0	6	7	7	13	50	0	3	4	4	8	30
Weiss	61 U94	-0.1	2.0	2.4	2.6	5.2	11.8	0	8	10	11	22	49	0	4	5	6	12	26
Mean		0.0	2.9	2.8	2.7	4.9	14.3	0	11	11	11	19	55	0	6	6	6	10	29
S.D.		±0.1	±0.7	±0.5	±0.5	±0.7	±1.5	±0	±3	±3	±3	±4	±9	±0	±2	±1	±1	±2	±2

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

that most of the Z angular momentum of the system (89 ± 9% 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 (12 ± 7%) was usually generated during the double-support delivery in the front of the circle.

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 6% of the total Z angular momentum that the system had at that time was in the discus; the rest (about 94%) 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 41.4 Kg·m²/s to 35.4 Kg·m²/s, a difference of 6.0 Kg·m²/s —see Table 6) was smaller than the gain experienced by the discus (from 2.7 Kg·m²/s to 14.3 Kg·m²/s, a difference of 11.6 Kg·m²/s —see Table 7). The reason for this was that the forces received from the ground through the feet during 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

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) RS	LTD	DS	REL	H_{YS} (normalized) ($s^{-1}\cdot10^{-3}$) RS	LTD	DS	REL	H_{YS} (percent of H_{YSREL}) (%) RS	LTD	DS	REL
Apiafi	13 D96	-1.6	5.7	25.4	19.6	-6	19	87	67	-8	29	130	100
Barnes-Mil.	37 D96	-5.2	10.0	—	19.0	-25	47	—	90	-27	53	—	100
Boyer	76 U94	-1.8	12.4	27.7	28.3	-7	46	102	104	-7	44	98	100
DeSnoo	22 D96	-12.2	14.4	23.5	16.5	-37	44	72	50	-74	87	142	100
Dukes	36 D96	-3.3	11.9	32.8	37.7	-11	40	111	128	-9	31	87	100
Dumble	51 D96	4.5	20.6	26.7	34.7	18	82	106	138	13	59	77	100
Franke	07 D96	-1.8	9.0	12.8	14.7	-8	38	55	63	-12	61	87	100
Garrett	34 D96	-4.7	14.5	18.1	25.9	-14	45	56	80	-18	56	70	100
Hantho	48 U94	-6.7	15.9	25.7	27.7	-25	58	94	102	-24	57	93	100
Kawar	41 D96	3.7	13.6	21.1	23.4	11	41	64	71	16	58	90	100
Koebcke	32 N94	0.3	14.6	14.4	13.1	1	73	72	65	2	111	110	100
Kuehl	46 U94	-8.8	-1.5	24.7	23.4	-29	-5	81	77	-38	-6	106	100
Noble	05 D96	0.2	7.2	17.4	11.1	1	32	78	50	2	65	158	100
Powell	35 D96	2.0	17.1	20.0	27.7	8	69	80	111	7	62	72	100
Preston	55 U94	-1.6	7.6	14.4	14.2	-8	39	74	73	-11	54	101	100
Price-Smith	60 U94	-6.1	-6.1	25.0	18.9	-17	-17	72	54	-32	-32	133	100
Weiss	61 U94	2.5	12.9	16.5	25.9	10	53	68	107	10	50	64	100
Mean		-2.4	10.6	21.6	22.5	-8	41	80	84	-12	49	101	100
S.D.		±4.4	±6.5	±5.5	±7.3	±15	±24	±16	±26	±22	±31	±26	±0

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

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 8% 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 92% 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

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 ($Kg\cdot m^2/s$), 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_{YT} (non-normalized) ($Kg\cdot m^2/s$)				H_{YT} (normalized) ($s^{-1}\cdot 10^{-3}$)				H_{YT} (percent of H_{YSREL}) (%)			
		RS	LTD	DS	REL	RS	LTD	DS	REL	RS	LTD	DS	REL
Apiafi	13 D96	-3.5	3.6	24.0	9.6	-12	13	83	33	-18	19	122	49
Barnes-Mil.	37 D96	-7.8	6.5	—	11.6	-37	31	—	55	-41	34	—	61
Boyer	76 U94	-4.7	10.0	26.5	19.8	-17	37	98	73	-17	35	94	70
DeSnoo	22 D96	-14.3	11.8	22.4	7.9	-44	36	69	24	-87	72	136	48
Dukes	36 D96	-6.8	8.0	27.6	26.6	-23	27	94	90	-18	21	73	71
Dumble	51 D96	-1.5	15.8	24.3	24.8	-6	63	97	99	-4	46	70	72
Franke	07 D96	-5.0	5.8	12.4	7.7	-21	24	53	33	-34	39	84	52
Garrett	34 D96	-6.4	11.6	16.3	18.7	-20	36	50	58	-25	45	63	72
Hantho	48 U94	-8.4	13.7	23.8	18.8	-31	50	87	69	-30	49	86	68
Kawar	41 D96	0.0	10.9	20.9	16.7	0	33	64	51	0	46	89	71
Koebcke	32 N94	-2.8	12.0	12.2	5.9	-14	60	61	30	-22	91	93	45
Kuehl	46 U94	-11.4	-3.9	23.3	14.0	-37	-13	76	46	-49	-17	99	60
Noble	05 D96	-1.9	5.3	16.2	1.4	-8	24	73	6	-17	48	147	13
Powell	35 D96	-1.2	11.9	18.5	18.6	-5	48	74	74	-4	43	67	67
Preston	55 U94	-3.6	5.5	12.1	5.2	-19	28	62	27	-26	38	85	37
Price-Smith	60 U94	-8.8	-8.8	24.8	11.7	-25	-25	72	34	-47	-47	132	62
Weiss	61 U94	-1.3	9.4	14.0	18.3	-5	39	58	76	-5	36	54	71
Mean		-5.3	7.6	20.0	14.0	-19	30	73	52	-26	35	93	58
S.D.		±3.8	±6.1	±5.2	±6.9	±12	±22	±15	±25	±21	±30	±27	±16

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

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

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 ($s^{-1}\cdot10^{-3}$), 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_{YD} (non-normalized) (Kg· m²/s)				H_{YD} (normalized) ($s^{-1}\cdot10^{-3}$)				H_{YD} (percent of H_{YSREL}) (%)			
		RS	LTD	DS	REL	RS	LTD	DS	REL	RS	LTD	DS	REL
Apiafi	13 D96	1.8	2.0	1.4	10.0	6	7	5	34	9	10	7	51
Barnes-Mil.	37 D96	2.6	3.5	—	7.4	12	17	—	35	14	19	—	39
Boyer	76 U94	2.8	2.4	1.2	8.4	11	9	5	31	10	8	4	30
DeSnoo	22 D96	2.2	2.6	1.0	8.6	7	8	3	26	13	16	6	52
Dukes	36 D96	3.4	3.8	5.2	11.1	12	13	18	38	9	10	14	29
Dumble	51 D96	6.0	4.8	2.4	9.9	24	19	10	39	17	14	7	28
Franke	07 D96	3.2	3.3	0.4	7.0	13	14	2	30	21	22	3	48
Garrett	34 D96	1.8	2.9	1.8	7.2	5	9	5	22	7	11	7	28
Hantho	48 U94	1.8	2.2	2.0	8.9	6	8	7	33	6	8	7	32
Kawar	41 D96	3.7	2.8	0.2	6.7	11	8	1	21	16	12	1	29
Koebcke	32 N94	3.1	2.6	2.2	7.2	15	13	11	36	24	20	17	55
Kuehl	46 U94	2.6	2.4	1.5	9.3	8	8	5	31	11	10	6	40
Noble	05 D96	2.1	1.9	1.2	9.7	9	9	6	43	19	17	11	87
Powell	35 D96	3.2	5.2	1.5	9.1	13	21	6	36	12	19	6	33
Preston	55 U94	2.1	2.2	2.3	9.0	11	11	12	46	15	15	16	63
Price-Smith	60 U94	2.8	2.8	0.2	7.2	8	8	1	21	15	15	1	38
Weiss	61 U94	3.8	3.5	2.5	7.6	16	14	10	31	15	13	10	29
Mean		2.9	3.0	1.7	8.5	11	12	7	33	14	14	8	42
S.D.		±1.0	±0.9	±1.2	±1.2	±4	±4	±4	±7	±5	±4	±5	±16

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

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 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. 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 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.

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-LSS}), time (t_{LSS}) and average right leg radius (r_{RL-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. ($H_{LA-DSLSS}$), time (t_{DSLSS}), and average left arm radius ($r_{LA-DSLSS}$) 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 ($Kg·m^2·10^{-3}$/ $Kg·m^2$)	H_{RL-LSS} ($s^{-1}·10^{-3}$)	t_{LSS} (s)	r_{RL-LSS} (m)	r_{RL-LSS} (%)	LAA ($Kg·m^2·10^{-3}$/ $Kg·m^2$)	$H_{LA-DSLSS}$ ($s^{-1}·10^{-3}$)	t_{DSLSS} (s)	$r_{LA-DSLSS}$ (m)	$r_{LA-DSLSS}$ (%)	RLLAA ($Kg·m^2·10^{-3}$/ $Kg·m^2$)
Apiafi	13 D96	25.7	55	0.47	0.242	13.1	28.0	29	0.97	0.528	28.5	53.6
Barnes-Mil.	37 D96	29.8	72	0.42	0.228	13.6	28.2	33	0.86	0.494	29.4	58.0
Boyer	76 U94	25.1	55	0.45	0.225	12.3	26.9	27	1.00	0.547	29.9	52.0
DeSnoo	22 D96	23.7	54	0.44	0.244	13.6	28.7	23	1.26	0.523	29.2	52.4
Dukes	36 D96	31.2	68	0.46	0.286	15.6	25.2	20	1.28	0.546	29.8	56.4
Dumble	51 D96	24.6	72	0.34	0.235	13.6	29.8	32	0.92	0.481	27.8	54.3
Franke	07 D96	24.4	59	0.41	0.205	11.6	32.8	29	1.14	0.516	29.2	57.2
Garrett	34 D96	15.8	39	0.40	0.195	11.2	23.6	23	1.01	0.439	25.1	39.3
Hantho	48 U94	36.9	71	0.52	0.293	16.5	33.5	28	1.21	0.553	31.1	70.4
Kawar	41 D96	27.9	71	0.39	0.283	15.1	26.6	33	0.80	0.545	29.1	54.5
Koebcke	32 N94	34.7	73	0.48	0.245	14.6	24.1	21	1.15	0.431	25.7	58.8
Kuehl	46 U94	22.4	62	0.36	0.232	12.7	29.7	25	1.21	0.502	27.4	52.1
Noble	05 D96	36.4	82	0.44	0.268	15.8	33.8	33	1.02	0.517	30.6	70.2
Powell	35 D96	26.7	58	0.46	0.227	12.6	26.5	28	0.96	0.547	30.4	53.3
Preston	55 U94	35.8	92	0.39	0.281	16.7	42.2	34	1.23	0.506	30.1	77.9
Price-Smith	60 U94	32.9	60	0.55	0.276	14.5	28.8	25	1.13	0.563	29.5	61.7
Weiss	61 U94	31.1	69	0.45	0.245	14.0	33.7	32	1.06	0.534	30.5	64.7
Mean		28.5	65	0.44	0.248	13.9	29.5	28	1.07	0.516	29.0	58.0
S.D.		±5.6	±12	±0.05	±0.028	±1.6	±4.4	±4	±0.14	±0.037	±1.6	±8.7

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

[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 contribution of the left arm action in the back of the circle to the rotation of the system (LAA = 29.5 ± 4.4 · 10^{-3} $Kg·m^2/Kg·m^2$) was similar to the contribution of the action of the right leg (RLA = 28.5 ± 5.6 · 10^{-3} $Kg·m^2/Kg·m^2$).

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 less than half the size of the corresponding value for the right leg

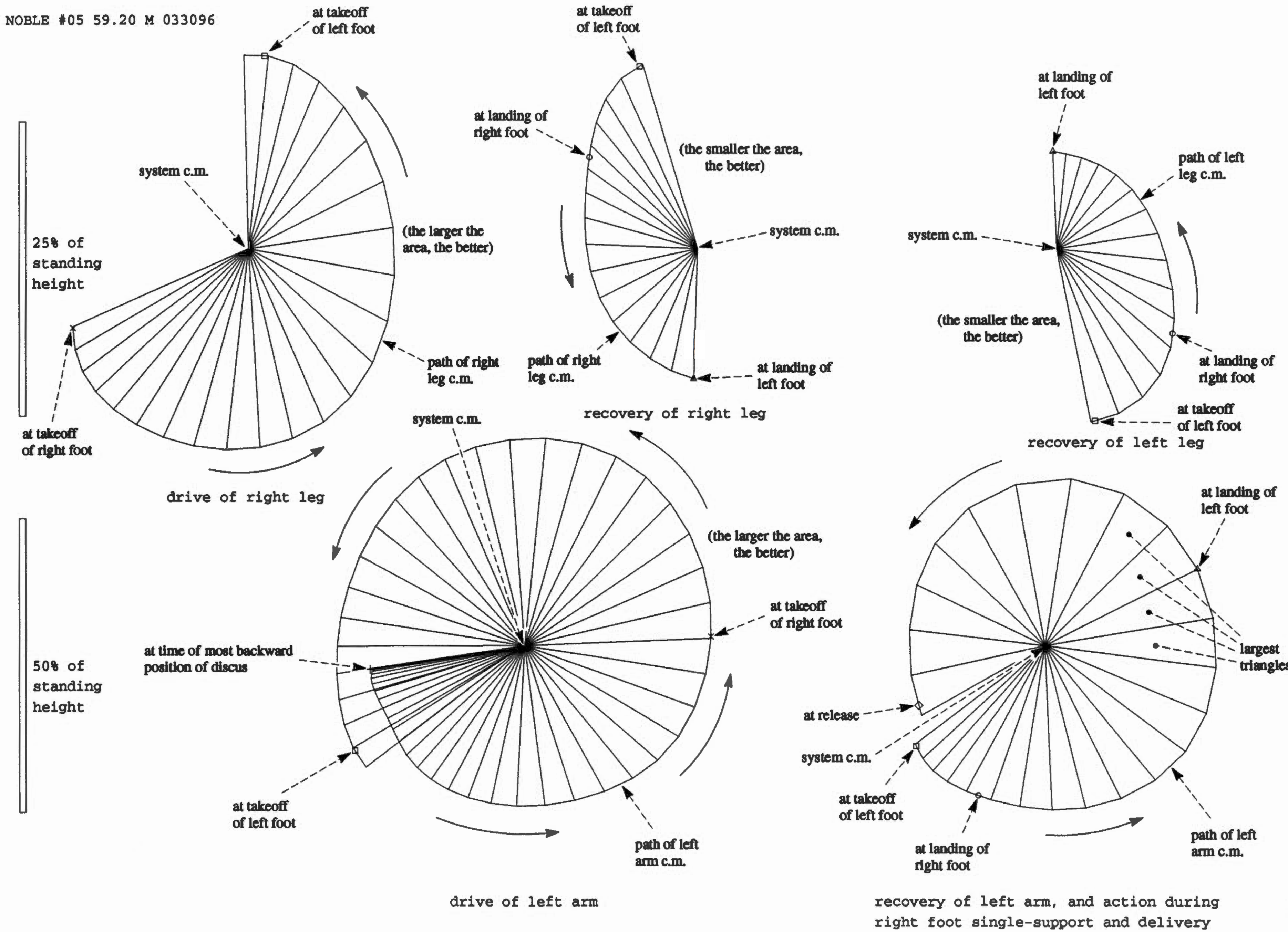

NOBLE #05 59.20 M 033096
25% of standing height
50% of standing height
at takeoff of left foot
system c.m.
(the larger the area, the better)
path of right leg c.m.
at takeoff of right foot
drive of right leg
at takeoff of left foot
at landing of right foot
(the smaller the area, the better)
system c.m.
path of right leg c.m.
at landing of left foot
recovery of right leg
at landing of left foot
path of left leg c.m.
system c.m.
(the smaller the area, the better)
at landing of right foot
at takeoff of left foot
recovery of left leg
system c.m.
(the larger the area, the better)
at takeoff of right foot
at time of most backward position of discus
at takeoff of left foot
path of left arm c.m.
drive of left arm
at landing of left foot
largest triangles
at release
system c.m.
at takeoff of left foot
at landing of right foot
path of left arm c.m.
recovery of left arm, and action during right foot single-support and delivery

Figure 15

($H_{LA\text{-}DSLSS} = 28 \pm 4 \cdot 10^{-3}\ s^{-1}$ for the left arm; $H_{RL\text{-}LSS} = 65 \pm 12 \cdot 10^{-3}\ s^{-1}$ for the right leg), but the swing of the left arm lasted more than twice as long as the swing of the right leg ($t_{DSLSS} = 1.07 \pm 0.14$ s for the left arm; $t_{LSS} = 0.44 \pm 0.05$ s for the right leg). So the longer duration of its swing is what allowed the left arm to make about the same contribution to the rotation of the system as 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 ($H_{LA\text{-}DSLSS}$ 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 $r_{LA\text{-}DSLSS}$). 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

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 th 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)	(%)
Apiafi	13 D96	0.186	10.0	0.164	8.9	0.175	9.5	26	0.497	26.9
Barnes-Mil.	37 D96	0.240	14.3	0.170	10.1	0.205	12.2	34	0.336	20.0
Boyer	76 U94	0.171	9.3	0.163	8.9	0.167	9.1	34	0.385	21.0
DeSnoo	22 D96	0.209	11.7	0.164	9.2	0.186	10.4	17	0.398	22.2
Dukes	36 D96	0.182	10.0	0.166	9.0	0.174	9.5	30	0.467	25.5
Dumble	51 D96	0.147	8.5	0.145	8.4	0.146	8.4	41	0.458	26.5
Franke	07 D96	0.166	9.4	0.141	8.0	0.154	8.7	26	0.429	24.2
Garrett	34 D96	0.198	11.3	0.177	10.1	0.187	10.7	29	0.312	17.8
Hantho	48 U94	0.194	10.9	0.146	8.2	0.170	9.5	33	0.451	25.3
Kawar	41 D96	0.150	8.0	0.135	7.2	0.142	7.6	37	0.420	22.5
Koebcke	32 N94	0.179	10.6	0.158	9.4	0.168	10.0	24	0.390	23.2
Kuehl	46 U94	0.158	8.6	0.153	8.3	0.155	8.5	24	0.420	23.0
Noble	05 D96	0.194	11.5	0.176	10.4	0.185	11.0	44	0.481	28.5
Powell	35 D96	0.181	10.0	0.172	9.6	0.176	9.8	28	0.448	24.9
Preston	55 U94	0.176	10.5	0.163	9.7	0.170	10.1	44	0.419	24.9
Price-Smith	60 U94	0.182	9.5	0.172	9.0	0.177	9.3	33	0.446	23.3
Weiss	61 U94	0.184	10.5	0.157	9.0	0.170	9.7	28	0.410	23.5
Mean		0.182	10.3	0.160	9.0	0.171	9.6	31	0.422	23.7
S.D.		±0.022	±1.4	±0.012	±0.8	±0.015	±1.1	±7	±0.047	±2.5

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

possible. Table 12 shows the average value of each of these distances ($r_{RL-NSRSS}$ and $r_{LL-NSRSS}$ for the right and left legs, respectively) as well as the mean value for the two legs ($r_{LAVG-NSRSS}$) during the non-support 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 ($H_{LA\text{-}NS} = 31 \pm 7\ s^{-1} \cdot 10^{-3}$). For an individual thrower, the lower this value, the better.

If the value of $H_{LA\text{-}NS}$ 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 ($r_{LA\text{-}NS}$). 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. After reaching maximum size, the areas of the triangles decreased again. In some throwers, 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, indicated by the progressive *narrowing* of the triangles. In other throwers (such as the one shown in Figure 15), 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

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 ($H_{LA-RSSDEL}$) 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 ($Kg{\cdot}m^2{\cdot}10^{-3}$/ $Kg{\cdot}m^2$)	$H_{LA-RSSDEL}$ ($s^{-1}{\cdot}10^{-3}$)	t_{RSSDEL} (s)	H_{MAX} ($s^{-1}{\cdot}10^{-3}$)	H_{REL}	ΔH
Apiafi	13 D96	16.5	39	0.42	63	27	-36
Barnes-Mil.	37 D96	15.5	43	0.36	57	20	-37
Boyer	76 U94	20.6	45	0.46	64	31	-33
DeSnoo	22 D96	10.9	22	0.49	42	15	-27
Dukes	36 D96	16.7	41	0.41	59	41	-18
Dumble	51 D96	16.9	45	0.38	59	21	-37
Franke	07 D96	9.0	24	0.37	32	18	-14
Garrett	34 D96	13.4	34	0.39	56	15	-41
Hantho	48 U94	16.3	35	0.46	44	28	-16
Kawar	41 D96	14.5	38	0.38	50	19	-31
Koebcke	32 N94	10.0	31	0.32	42	22	-19
Kuehl	46 U94	16.7	40	0.42	62	26	-36
Noble	05 D96	21.1	52	0.40	68	30	-38
Powell	35 D96	12.7	28	0.45	48	11	-37
Preston	55 U94	20.6	49	0.42	61	31	-30
Price-Smith	60 U94	12.2	32	0.38	37	15	-23
Weiss	61 U94	14.3	34	0.41	52	33	-19
Mean		15.2	37	0.41	53	24	-29
S.D.		±3.5	±8	±0.04	±10	±8	±9

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open 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 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.

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 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.

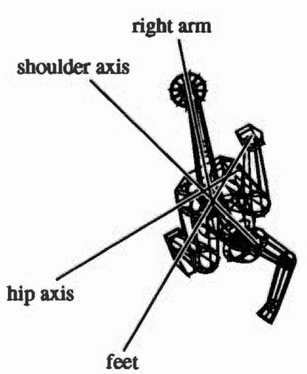


Figure 16

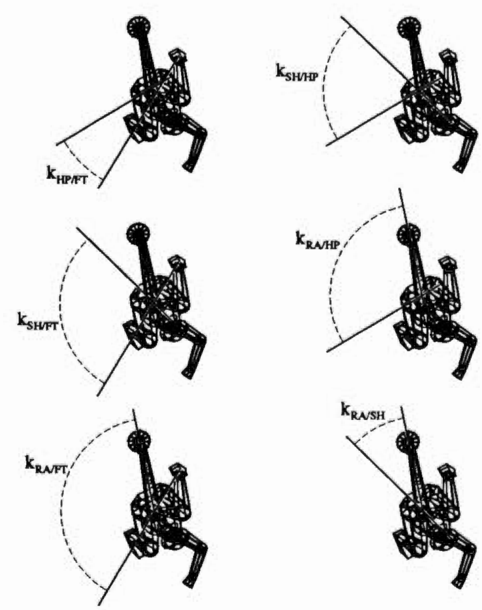


Figure 17

KOEBCKE #32 51.22 M 050694

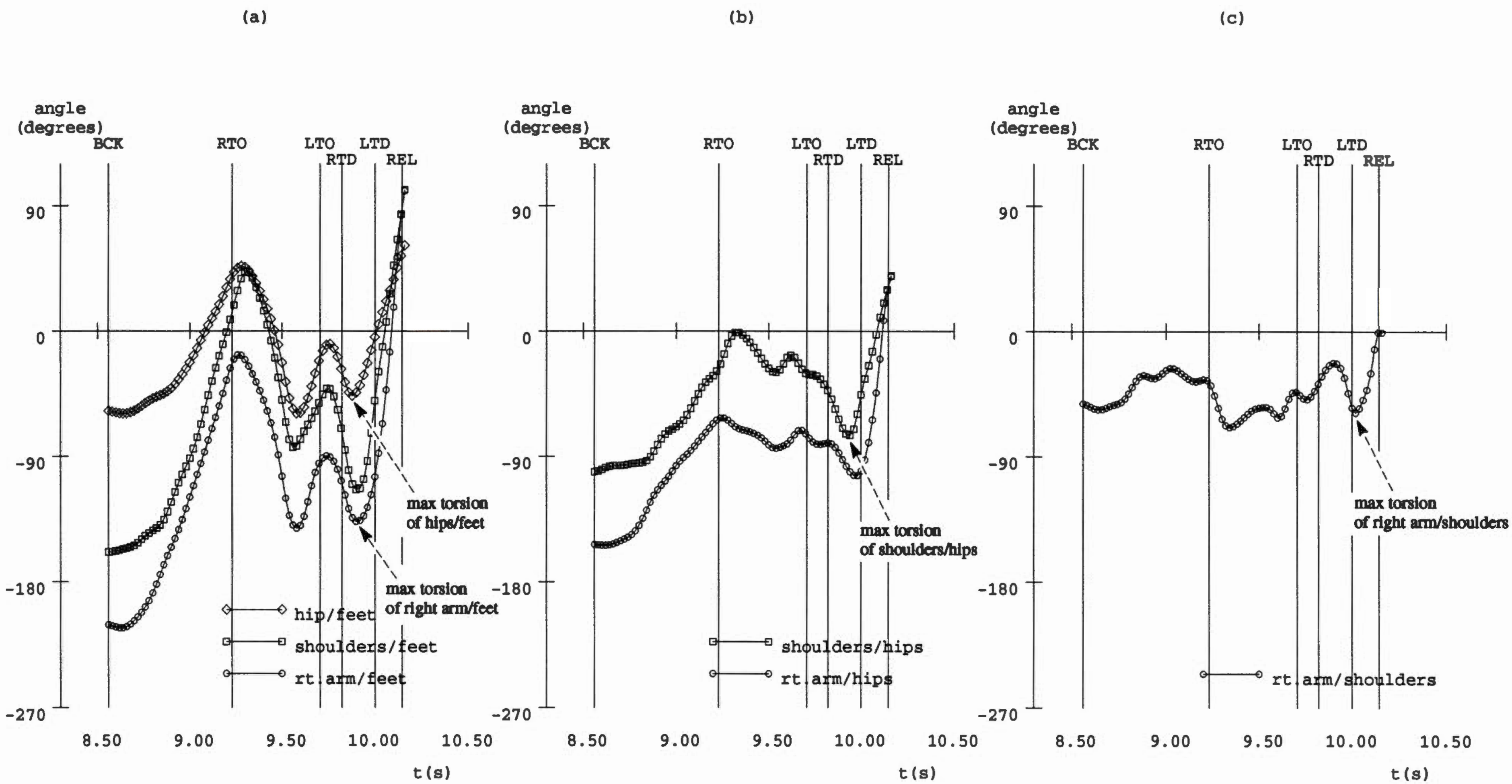


Figure 18

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)
Apiafi	13 D96	-39	-102	-117	-75	-91	-55	10.00	9.88	9.92	9.88	9.90	10.12
Barnes-Mil.	37 D96	-24	-109	-172	-87	-150	-70	9.98	9.94	9.92	9.94	9.92	9.88
Boyer	76 U94	-53	-143	-142	-91	-106	-67	9.92	9.94	9.92	9.94	10.08	10.10
DeSnoo	22 D96	-29	-124	-137	-98	-113	-52	9.84	9.88	9.90	9.90	9.92	10.06
Dukes	36 D96	-45	-136	-140	-94	-99	-31	9.92	9.90	9.94	9.88	9.98	10.02
Dumble	51 D96	-68	-140	-156	-72	-95	-29	9.92	9.92	9.94	9.94	10.00	10.10
Franke	07 D96	-54	-106	-143	-57	-95	-44	9.86	9.90	9.92	9.92	9.92	9.98
Garrett	34 D96	-18	-107	-135	-89	-118	-41	9.90	9.90	9.92	9.92	9.92	10.06
Hantho	48 U94	-71	-117	-159	-66	-112	-63	9.88	9.84	9.92	9.80	10.00	9.92
Kawar	41 D96	-62	-97	-147	-37	-96	-70	9.90	9.90	9.94	9.86	9.98	9.98
Koebcke	32 N94	-47	-114	-137	-75	-104	-58	9.88	9.90	9.90	9.94	9.98	10.02
Kuehl	46 U94	-58	-121	-153	-66	-110	-64	9.90	9.92	9.96	9.96	10.10	10.12
Noble	05 D96	-48	-98	-126	-53	-85	-40	9.90	9.92	9.94	9.94	9.96	10.08
Powell	35 D96	-31	-99	-137	-69	-107	-59	9.90	9.88	9.90	9.88	9.92	10.06
Preston	55 U94	-62	-112	-135	-51	-98	-71	9.94	9.94	9.96	9.92	10.06	10.08
Price-Smith	60 U94	-37	-72	-125	-35	-89	-67	9.90	9.94	9.98	9.94	10.00	10.02
Weiss	61 U94	-51	-115	-131	-65	-83	-36	9.94	9.94	9.94	9.92	9.90	10.08
Mean		-47	-112	-141	-69	-103	-54	9.91	9.91	9.93	9.91	9.97	10.04
S.D.		±15	±17	±13	±18	±15	±14	±0.04	±0.03	±0.02	±0.04	±0.06	±0.07

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

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 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 largest 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 average, maximum torsion of the hips relative to the feet ($k_{HP/FT}$ = -47 ± 15°) and maximum torsion of the shoulders relative to the hips ($k_{SH/HP}$ = -69 ± 18°) were reached at the same time (t = 9.91 ± 0.04 s); in half of the throwers, maximum torsion of the hips relative to the feet was reached slightly earlier; in the other half, maximum torsion of the shoulders relative to the hips was reached slightly earlier. In almost all the throwers (15 out of 16), the maximum torsion of the right arm relative to the shoulders ($k_{RA/SH}$ = -54 ± 14° at t = 10.04 ± 0.07 s) occurred after the maximum torsions of the hips relative to the feet and of the shoulders relative to the hips.

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					
		$k_{HP/FT}$ (°)	$k_{SH/FT}$ (°)	$k_{RA/FT}$ (°)	$k_{SH/HP}$ (°)	$k_{RA/HP}$ (°)	$k_{RA/SH}$ (°)	$k_{HP/FT}$ (°)	$k_{SH/FT}$ (°)	$k_{RA/FT}$ (°)	$k_{SH/HP}$ (°)	$k_{RA/HP}$ (°)	$k_{RA/SH}$ (°)
Apiafi	13 D96	-26	-88	-117	-62	-91	-29	97	114	108	16	11	-6
Barnes-Mil.	37 D96	-22	-107	-172	-85	-150	-64	72	88	86	16	14	-2
Boyer	76 U94	-53	-141	-142	-89	-89	0	76	59	65	-17	-10	6
DeSnoo	22 D96	-25	-123	-137	-98	-112	-14	64	87	102	23	38	14
Dukes	36 D96	-43	-129	-140	-85	-97	-12	88	66	80	-21	-7	14
Dumble	51 D96	-67	-139	-156	-72	-89	-17	94	75	89	-19	-6	14
Franke	07 D96	-48	-104	-143	-57	-95	-38	91	88	86	-3	-5	-2
Garrett	34 D96	-17	-106	-135	-89	-118	-29	44	87	107	43	63	20
Hantho	48 U94	-65	-95	-159	-30	-94	-63	71	62	62	-9	-9	0
Kawar	41 D96	-55	-84	-147	-29	-92	-63	84	76	67	-8	-16	-9
Koebcke	32 N94	-44	-114	-137	-70	-92	-23	56	88	87	32	32	-1
Kuehl	46 U94	-48	-115	-153	-66	-105	-38	73	91	85	18	12	-6
Noble	05 D96	-44	-97	-126	-53	-82	-30	87	92	107	5	20	15
Powell	35 D96	-31	-99	-137	-69	-106	-37	82	91	92	9	10	1
Preston	55 U94	-61	-109	-135	-49	-75	-26	93	81	67	-12	-26	-14
Price-Smith	60 U94	-37	-65	-125	-28	-88	-59	57	87	101	30	44	14
Weiss	61 U94	-51	-115	-131	-64	-80	-17	72	70	79	-2	8	9
Mean		-43	-108	-141	-64	-97	-33	77	82	86	6	10	4
S.D.		±15	±19	±13	±21	±17	±19	±15	±13	±15	±19	±23	±10

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

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 ($k_{RA/FT}$ = -141 ± 13° at t = 9.93 ± 0.02 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 ± 0.02 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} = 22.8 ± 0.9 m/s) and the initial direction of motion of the discus relative to the horizontal plane (d_{VREL} = 35 ± 2°). It also shows the breakdown of the resultant speed into horizontal speed (v_{HD} = 18.7 ± 1.0 m/s) and vertical speed (v_{ZD} = 13.0 ± 0.8 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 its upper side (rather than its underside) 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 followed by the path of the discus exposes the *under*side of the discus 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 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

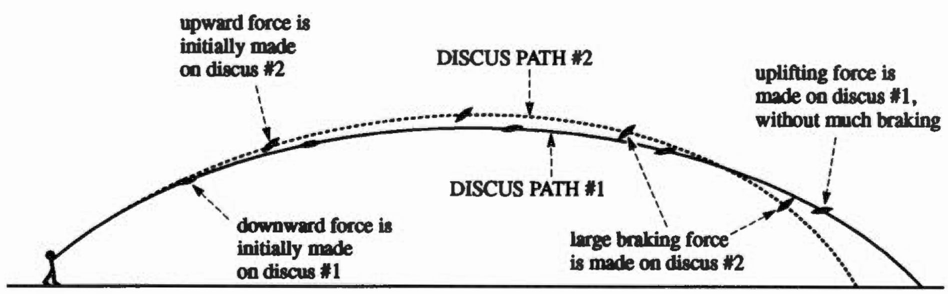


Figure 19

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)	
Apiafi	13 D96	22.0	38	17.4	13.4	1.67	90.5	49.44	53.60	4.16	
Barnes-Mil.	37 D96	23.1	35	19.0	13.1	1.40	83.5	52.60	63.56	10.96	
Boyer	76 U94	23.6	34	19.5	13.3	1.77	97.0	55.03	55.94	0.91	
DeSnoo	22 D96	21.6	36	17.5	12.8	1.43	79.5	47.15	52.76	5.61	
Dukes	36 D96	23.1	37	18.4	14.1	1.78	97.0	54.68	60.54	5.86	
Dumble	51 D96	23.2	36	18.8	13.6	1.60	92.5	54.11	60.24	6.13	
Franke	07 D96	21.7	32	18.4	11.5	1.58	89.0	44.97	50.38	5.41	
Garrett	34 D96	23.0	32	19.4	12.4	1.39	79.5	50.73	58.92	8.19	
Hantho	48 U94	22.1	36	18.0	12.9	1.58	89.0	48.81	50.08	1.27	
Kawar	41 D96	22.5	31	19.3	11.6	1.79	96.0	48.17	56.06	7.89	
Koebcke	32 N94	21.4	34	17.7	11.9	1.28	76.0	44.35	51.22	6.87	
Kuehl	46 U94	23.9	31	20.4	12.4	1.58	86.5	53.85	57.36	3.51	
Noble	05 D96	23.1	35	19.0	13.3	1.40	83.0	53.29	59.20	5.91	
Powell	35 D96	23.2	35	19.1	13.2	1.60	89.0	53.59	59.88	6.29	
Preston	55 U94	23.0	39	17.9	14.4	1.43	85.0	53.81	53.92	0.11	
Price-Smith	60 U94	24.9	33	21.0	13.4	1.79	93.5	59.77	59.46	-0.31	
Weiss	61 U94	21.7	39	16.9	13.6	1.60	91.5	48.42	51.72	3.30	
Mean		22.8	35	18.7	13.0	1.57	88.1	51.34	56.17	4.83	(ALL THROWS)
S.D.		±0.9	±2	±1.0	±0.8	±0.15	±6.1	±3.93	±3.99	±2.98	
Mean		23.2	35	19.0	13.3	1.62	90.4	53.28	54.75	1.46	(1994 USATF
S.D.		±1.1	±3	±1.5	±0.6	±0.12	±4.1	±3.86	±3.22	±1.47	CHAMPIONSHIPS)
Mean		22.6	35	18.6	12.9	1.56	88.0	50.87	57.51	6.64	(1996 UC SAN
S.D.		±0.6	±2	±0.7	±0.8	±0.15	±6.0	±3.15	±3.93	±1.81	DIEGO OPEN)

(*) N94 = 1994 National Inv.; U94 = 1994 USATF Championships; D96 = 1996 UCSD Open

angle (d_{VREL}) and discus tilt in three different wind conditions (10 m/s tailwind, no wind, and 10 m/s headwind) for the men's discus throw. We repeated Frohlich's computer simulations, but using wind tunnel data for the *women's* discus taken from Ganslen (personal communication to James Hay, April 14, 1986), and a release speed of 22.8 m/s. The optimum combinations of angles were as follows: for a 10 m/s tailwind, release angle = 49° and tilt angle = 49°; for zero wind, release angle = 31° and tilt angle = 21°; for a 10 m/s headwind, release angle = 19° and tilt angle = 16° (Dapena, unpublished results). If these computer simulations of the discus flight are valid, the 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.

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 suggests that a deviation of only 4° from the optimum angle of tilt when throwing the women's discus into a 10 m/s headwind can produce a loss of 5-8 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 = 51.34 ± 3.93 m). A comparison of this theoretical vacuum distance with the actual distance of the throw (D = 56.17 ± 3.99 m) shows that the aerodynamic forces exerted by the air on the discus during its flight produced an average improvement of 4.83 ± 2.98 m (ΔD) in the distance of the throws. Estimates of the distance gained or lost by women discus throwers through aerodynamic forces (ΔD) have only been reported previously in one publication. In a 3D analysis of throws pooled from two women'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 = 4.05 ± 3.15 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 reduce 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.]

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 = 54.75 ± 3.22 m) was only slightly longer than the distance predicted for a vacuum (D_V = 53.28 ± 3.86 m); the effect of the aerodynamic forces was ΔD = 1.46 ± 1.47 m. The small value of ΔD suggests that there was a tailwind during this competition.

As pointed out in the men's report (Dapena & Anderst, 1997), the wind conditions at the 1996 UC San Diego Open were quite different. A strong headwind was evident in San Diego. The average distance of the throws (D = 57.51 ± 3.93 m) was much longer than the predicted distance in a vacuum (D_V = 50.87 ± 3.15 m); the effect of the aerodynamic forces was ΔD = 6.64 ± 1.81 m. Also, five of the 10 athletes analyzed in the San Diego competition broke their personal records during the meet, and three more were within one meter of their personal records; these excellent results also point to favorable wind conditions.

[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 shooting 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 differences in the wind's influence on the distance of the throws (i.e., to differences in the ΔD values of different throws). However, it is also necessary to keep in mind, as pointed out earlier, that a deviation of only 4° from the optimum angle of tilt when throwing into a 10 m/s headwind can produce a loss of 5-8 meters in a 60-meter throw. This makes it very possible that the variability in the value of ΔD between athletes was 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

Lacy BARNES-MILEHAM

Trial 37 was Barnes-Mileham's personal record, 63.56 m, thrown at the 1996 UC San Diego Open.

The graph that shows the overhead view of the footprints and the c.m. path shows that Barnes-Mileham started at the back of the circle with her right foot near the theoretical line that bisects the circle into right and left halves, and her left foot in a position that was about 45° more counterclockwise (when viewed from the center of the circle). Therefore, she was positioned in a more counterclockwise initial orientation than most other throwers. Then she shifted the system c.m. very well toward her left foot. However, due to the initial position of this foot the subsequent drive across the circle was slightly more diagonal than in most other throwers (a_{LTO} = -27°; a_{LTD} = -24°). Then, after she planted the left foot on the ground in the front of the circle, the path of the system c.m. curved toward the right. Barnes-Mileham may have achieved this by pulling hard on the ground with the right foot toward the left of the circle during the delivery phase. As a result, during the last quarter-turn of the discus the direction of motion of the system c.m. was almost directly forward (a_Q = -6°). This was very good, and although the horizontal direction of travel of the discus at release was farther toward the right than in most other throwers (d_{HREL} = 17°), the divergence angle between the directions of motion of the system and of the discus was still reasonably small (c_Q = -22°). Therefore, the rather marked diagonal direction of travel of Barnes-Mileham's c.m. across the circle in the middle part of the throw ultimately did not pose a significant problem.

The horizontal speed of the system c.m. at the instant of takeoff of the left foot from the back of the circle was average (v_{HLTO} = 2.4 m/s). Then, Barnes-Mileham managed not to slow down much during the right foot support (Δv_{HSSR} = -0.2 m/s), and therefore at the time that she planted the left foot on the ground at the front of the circle the horizontal speed of the system was somewhat faster than average (v_{HLTD} = 2.2 m/s). During the double-support delivery, she made a large forward and downward force on the ground. The backward horizontal reaction force reduced the horizontal speed of the system c.m. to an amount which was somewhat smaller than average (v_{HQ} = 1.0 m/s). Since the divergence angle between the directions of motion of the system and of the discus was only moderate (c_Q = -22°), the contribution of the horizontal speed of the system to the horizontal speed of the discus was not much smaller than average (v_{HCON} = 0.9 m/s).

As previously mentioned, during the double-support delivery Barnes-Mileham pushed very hard forward and downward against the ground (and also somewhat toward the left). When a discus thrower pushes hard forward on the ground during the delivery phase, there is generally also a tendency to push hard *downward*, and Barnes-Mileham was no exception. Although the large horizontal forward push made the system c.m. lose a fairly large amount of forward speed (as we saw before), the large downward component of the push also made the system gain a very large amount of vertical speed, which made a large contribution to the vertical speed of the discus (v_{ZCON} = 1.5 m/s).

The combination of the contributions which we have just seen to the speed of the discus by the horizontal and vertical translations of the system c.m. (v_{HCON} = 0.9 m/s, and v_{ZCON} = 1.5 m/s, respectively) was excellent.

The swinging actions of the right leg and of the left arm at the back of the circle, as well as their combined value were very close to average (RLA = $29.8 \cdot 10^{-3}$ Kg·m²/Kg·m²; LAA = $28.2 \cdot 10^{-3}$ Kg·m²/Kg·m²; RLLAA = $58.0 \cdot 10^{-3}$ Kg·m²/Kg·m²).

At the instant of landing of the left foot in the front of the circle, the system had 80% of the Z angular momentum (counterclockwise rotation in a view from overhead) that it would eventually reach at release. This was a smaller fraction of the final value than in other throwers. It indicates that Barnes-Mileham was relatively better at generating Z angular momentum in the front of the circle than in the back of the circle. However, we think that her generation of angular momentum at the back of the circle was probably adequate.

The Z angular momentum of the system serves two main purposes in discus throwing: First, it rotates the thrower into the appropriate position for the start of the final delivery; then, the angular momentum becomes available for transfer from the body into the discus during the final delivery, and therefore contributes to the acceleration of the discus. For the final transfer to the discus, what counts is the non-normalized value of the angular momentum, but for the rotation that gets the thrower into position, what counts is the normalized angular momentum. The system's non-normalized Z angular momentum at the takeoff of the left foot in the middle of the throw was slightly smaller than average (H_{ZS} = 42.7 Kg· m²/s). To a great extent, this was due to the fact that Barnes-Mileham was one of the shortest and lightest throwers in the sample; the *normalized* Z angular momentum of the system, which is adjusted for the thrower's height and weight, was very large (H_{ZS} = 202· 10^{-3} s^{-1}). Barnes-Mileham's large amount of normalized Z angular momentum allowed her to rotate counterclockwise very fast in the middle part of the throw, in spite of the fact that the recovery actions of her legs and left arm did not help much, as we will see next.

After the left foot took off from the ground, Barnes-Mileham hept her legs very far from the longitudinal axis ($r_{LAVG-NSRSS}$ = 12.2% of standing height); the right leg was particularly far from the axis ($r_{RL-NSRSS}$ = 14.3% of standing height). Therefore, the legs did not help to speed up the counterclockwise rotation of the lower body in the middle of the throw. Barnes-Mileham also left a somewhat large amount of counterclockwise angular momentum in her left arm during the non-support phase in the middle of the throw (H_{LA-NS} = 34 · 10^{-3} s^{-1}); although she kept the left arm rather close to the body (r_{LA-NS} = 20.0% of standing height), she allowed it to continue rotating counterclockwise too fast during the non-support phase. Therefore, the left arm did not make available (i.e., did not transfer) much of its own angular momentum to the rest of the system, and thus it also did not contribute much to the counterclockwise rotation of the lower body in the middle part of the throw. Inefficient recovery actions such as the ones just described would normally make the system rotate too slowly, particularly the lower body. However, they did not pose a problem for Barnes-Mileham, for two reasons. First of all, she had a large amount of normalized Z angular momentum at the instant of takeoff of the left foot, as we saw previously, and this allowed her to rotate fast in spite of her spread-out body configuration. Also, by the end of the single-support phase on the left foot she had rotated her lower body to a position that was well ahead of her upper body (in the torsion angle graphs, see the torsion angle of the right arm relative to the feet), and then she maintained this markedly wound-up body configuration until the single-support on the right foot. Therefore, she did not need to speed up very much the rotation of the lower body relative to the upper body in the non-support and single-support on the right foot, because the lower body was already far ahead. For these reasons, in spite of the apparently questionable recovery actions of her legs and of her left arm, Barnes-Mileham was able to attain a good (in fact, an outstanding) position before the final acceleration of the discus, as we will see next.

Barnes-Mileham reached an extremely wound-up position in the single-support phase over the right foot ($k_{RA/FT}$ = -172°). This was very good, because the subsequent unwinding helped her to transfer angular momentum from the body to the discus (and probably also helped her to get more angular momentum from the ground). The advantage of Barnes-Mileham with respect to the average thrower at the instant of maximum torsion of the system resided in part in the angle of the shoulders relative to the hips (Barnes-Mileham $k_{SH/HP}$ = -85°; average = -64°), and in part in the angle of the right arm relative to the shoulders (Barnes-Mileham $k_{RA/SH}$ = -64°; average = -33°). These extreme torsion angles more than compensated for the weak torsion of her hips relative to her feet (Barnes-Mileham $k_{HP/FT}$ = -22°; average = -43°).

The second propulsive swing of the left arm (LAA2 = 15.5 · 10^{-3} Kg·m²/Kg·m²) was average, which implies that it only made an average contribution to the generation of angular momentum for the system in the front of the circle. However, the maximum angular momentum that this arm reached (H_{MAX} = 57·10^{-3} s^{-1}) was slightly larger than average, and the amount of angular momentum that it still had at release was slightly smaller than average (H_{REL} = 20· 10^{-3} s^{-1}). The combination of these two factors amounted to a large loss of angular momentum by the left arm in the late part of the delivery phase (ΔH = -37 · 10^{-3} s^{-1}), and the transfer of that angular momentum from the arm to the rest of the system, possibly to the discus. This was good.

As pointed out earlier, Barnes-Milehan generated a large additional amount of Z angular momentum during the double-support delivery phase. This was achieved through the interactions of her feet with the ground, and was probably facilitated by the unwinding of the thrower-plus-discus system. She also transfered a good amount of the Z angular momentum of the system to the discus (29% of the total), which was definitely facilitated also by the unwinding of the system. This enabled Barnes-Mileham to give a good amount of horizontal speed to the discus (v_{HD} = 19.0 m/s).

At release, in the view from the back of the circle the counterclockwise angular momentum of the thrower-plus-discus system (H_{YS} = 19.0 Kg · m²/s) was somewhat smaller than average, and the fraction of it that was transfered to the discus (39% of the total) was near average. Therefore, the Y angular momentum of the discus at release was somewhat small (H_{YD} = 7.4 Kg · m²/s). However, the contribution of the vertical speed of the system c.m. to the vertical speed of the discus was very good, as we saw before (v_{ZCON} = 1.5 m/s). Possibly because of this, the vertical speed of the discus at release was reasonably good (v_{ZD} = 13.1 m/s).

The resultant speed that Barnes-Mileham gave to the discus (v_{RD} = 23.1 m/s) was good. However, Table 16 shows that the top six throwers at the San Diego meet all achieved practically the same resultant speed at release. Still, Barnes-Mileham's throw reached a much longer distance than those of the other throwers. This was due to her excellent use of aerodynamic forces (ΔD = 10.96 m), which gave her a 3-5 meter advantage with respect to the other top-six placers at the San Diego meet.

Summary

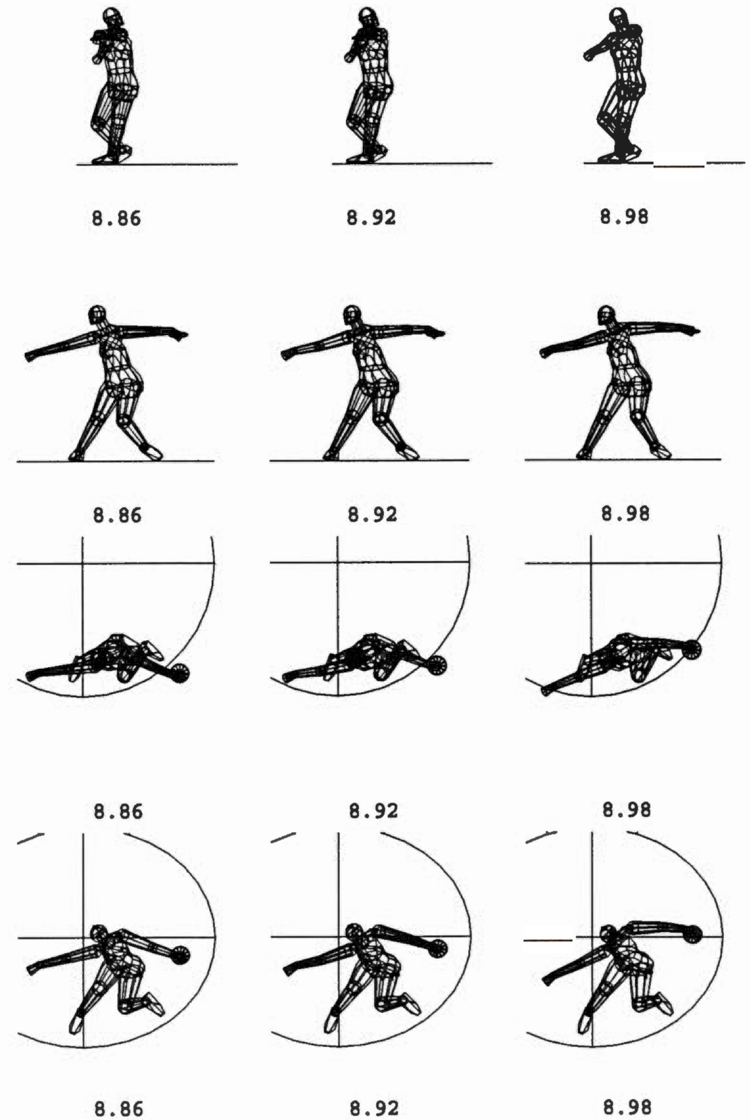
The direction of the horizontal translation of the system c.m. was somewhat too diagonal in the middle part of the throw, but this was corrected in the delivery phase. She exerted large forward and downward forces on the ground during the delivery phase. The contribution of the horizontal speed of the 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 much larger than average. Therefore, this part of her technique was overall very good. The combined swinging actions of the right leg and left arm in the back of the circle were of average quality. She was able to generate a rather large increase in the Z angular momentum of the system during the delivery phase, which suggests that she may not have generated as much of it as she could have in the back of the circle, but this probably was not a problem. She did generate enough angular momentum at the back of the circle to achieve a good position at the start of the delivery phase, in spite of little help from the recovery actions of the legs and left arm in the middle of the throw. The left arm did not slow down very much during the non-support phase in the middle of the throw, and this limited the range of motion that it had available for its second propulsive swing in the front of the circle. She was still able to swing it hard, and then to slow it down well during the final part of the throw. She produced a very large torsion angle between the right arm and the feet. Then, she unwound well, and gave a good amount of speed to the discus. However, her most important advantage over other throwers was her excellent use of aerodynamic forces.

Recommendations

Barnes-Mileham's technique was somewhat unusual in some respects, such as her starting position at the back of the circle, which was more counterclockwise than in most other throwers, and her very spread-out body configuration in the middle of the throw. But we don't see that these peculiarities led to any glaring problems. (In fact, it is possible that the very spread-out body configuration that she adopted in the middle of the throw may have been an advantage which prevented her large amount of normalized Z angular momentum from producingan excessive amount of counterclockwise rotation in the middle of the throw and an excessively "in-the-bucket" position at the front of the circle.) The various aspects of Barnes-Mileham's technique seem to be coherent with each other, and therefore we will not recommend any major changes.

The main change that we propose for Barnes-Mileham is a minor one. During the non-support phase in the middle of the throw, she should slow down the left arm, and even rotate it clockwise, wrapping it somewhat across her chest, before accelerating it very strongly counterclockwise after the right foot lands, and then slowing it down very much again before the release of the discus. In trial 37, she already was doing the acceleration and the final slowing down very well. However, the counterclockwise range of motion available for this action of the left arm was somewhat limited in trial 37 because by the time that the right foot landed, the left arm had drifted into a position that was too counterclockwise. A more backward (i.e., more clockwise) position of the left arm at the instant of landing of the right foot would make available a longer counterclockwise range of motion for the left arm in the final part of the throw, which in turn would enable Barnes-Mileham to obtain still more angular momentum from the ground, and would also put into the left arm more angular momentum which could then be transmitted to the discus as the left arm is slowed down before release.

BARNES-MILEHAM #37 63.56 M 033096



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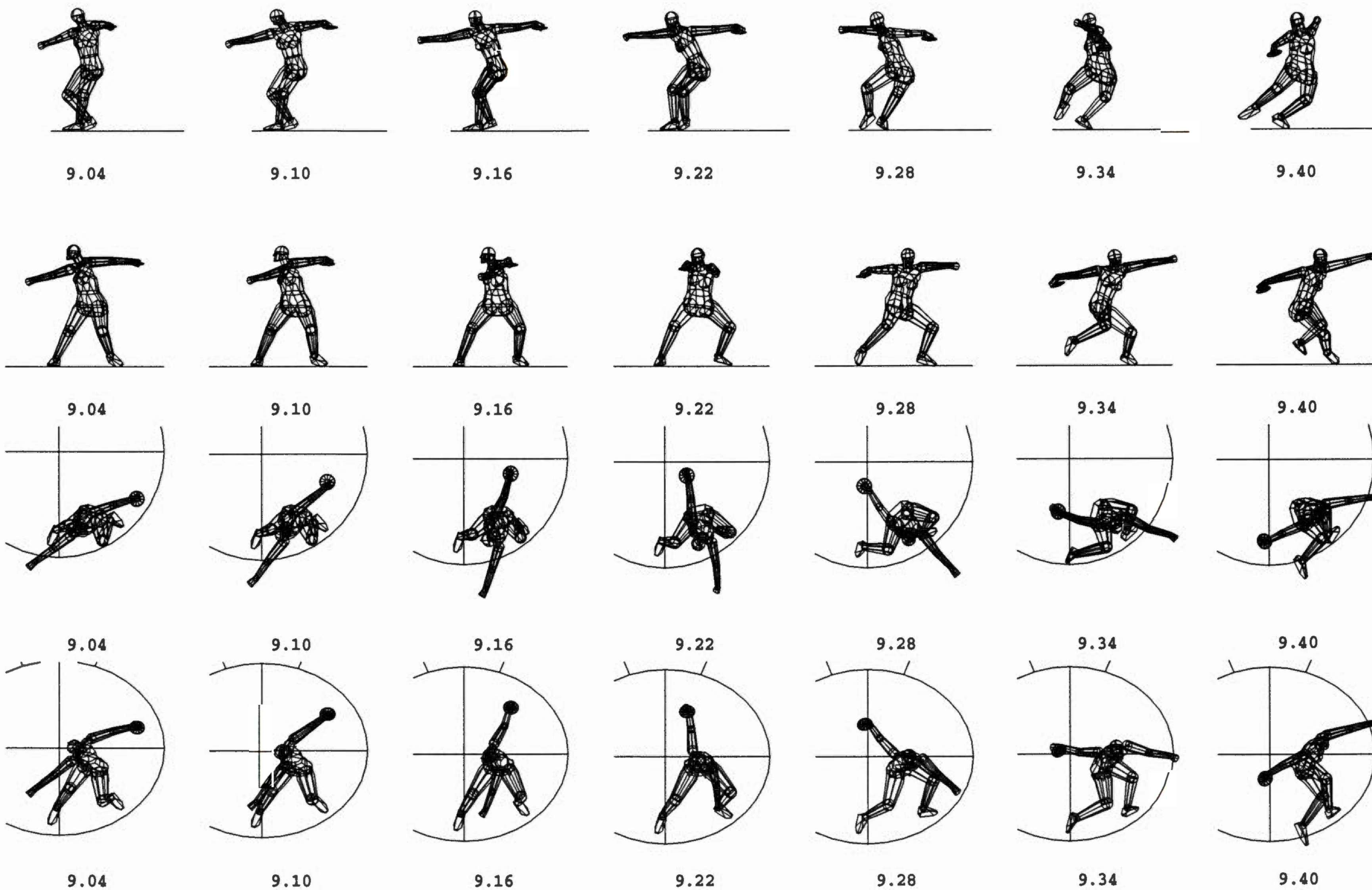

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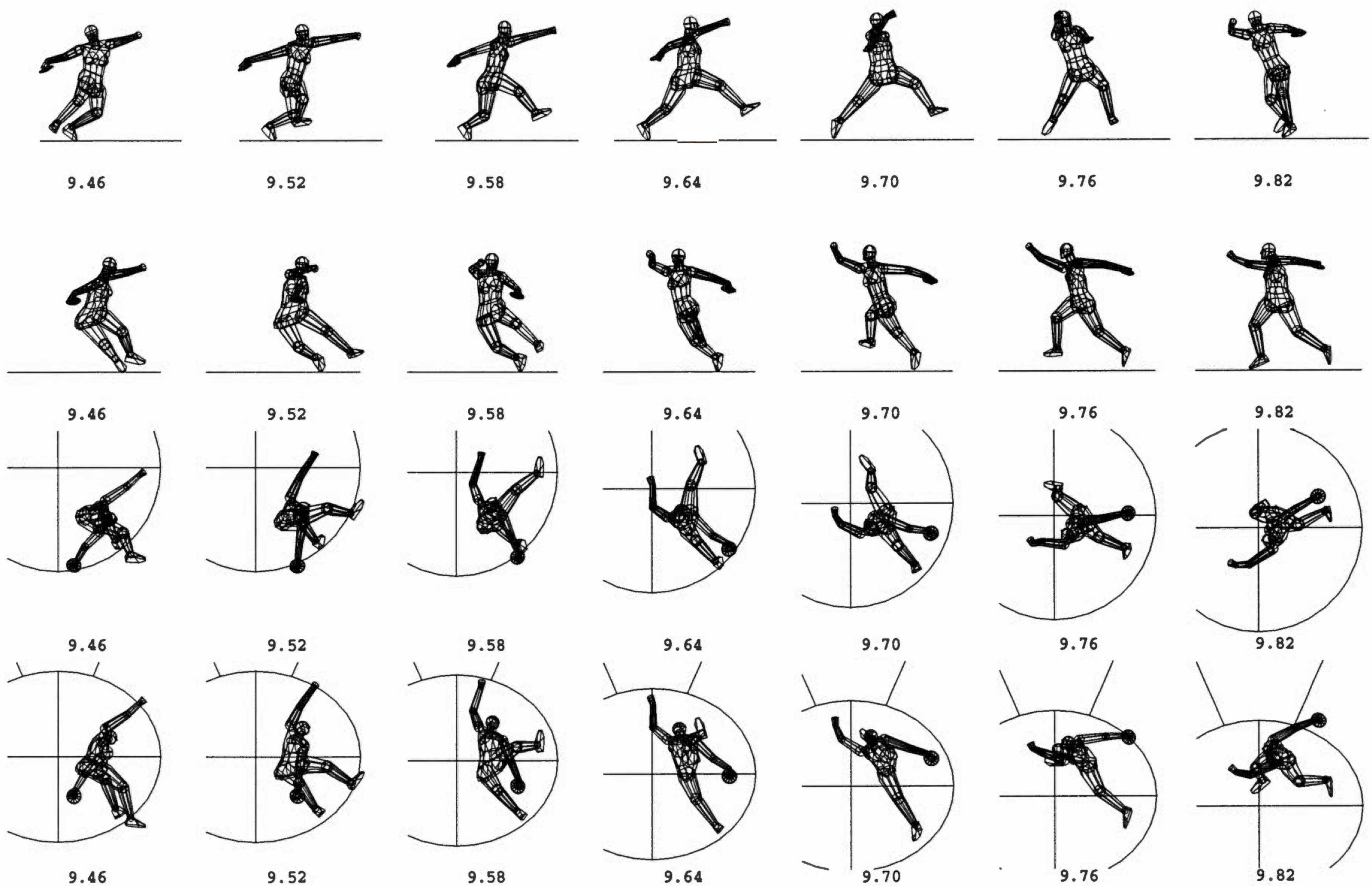

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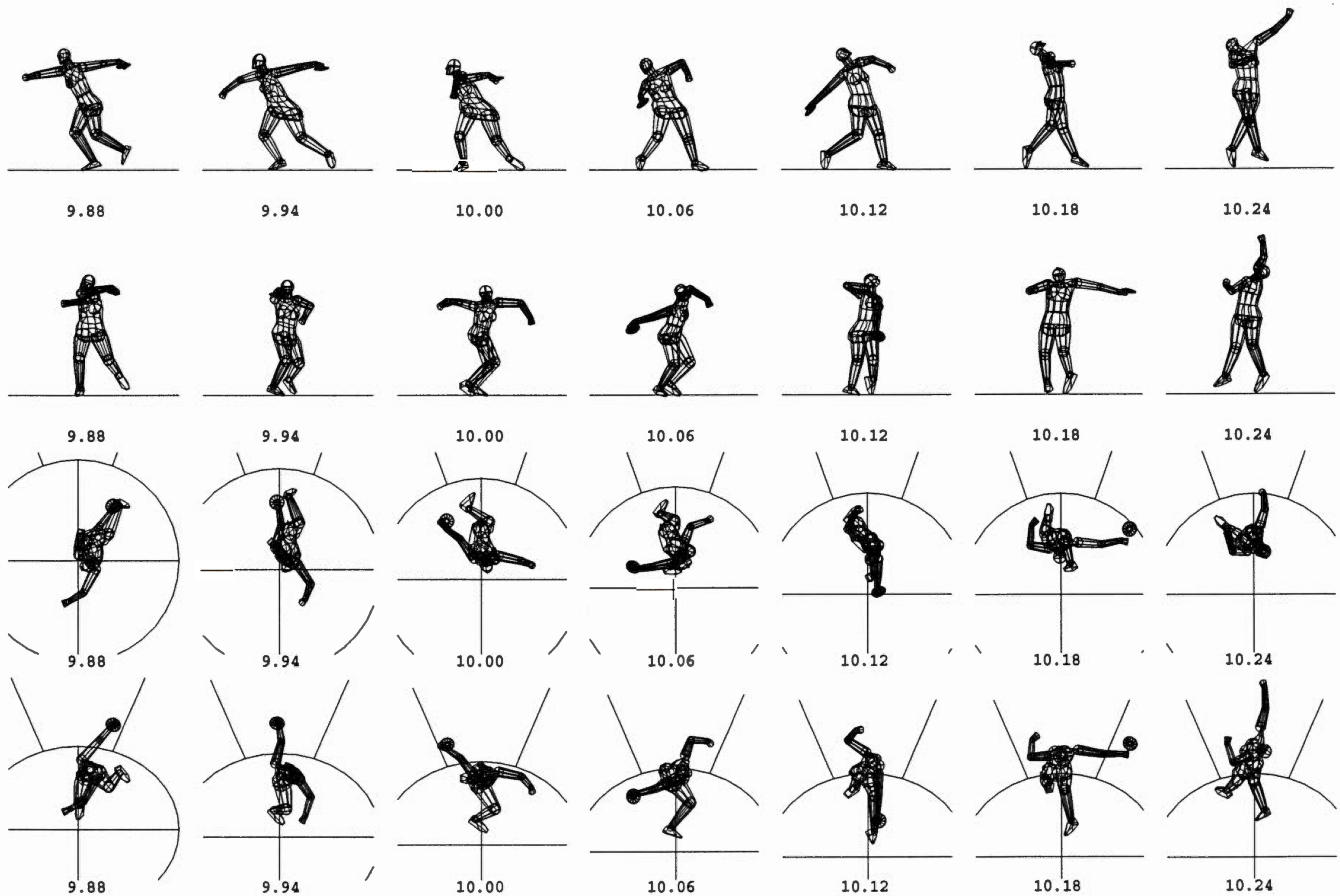

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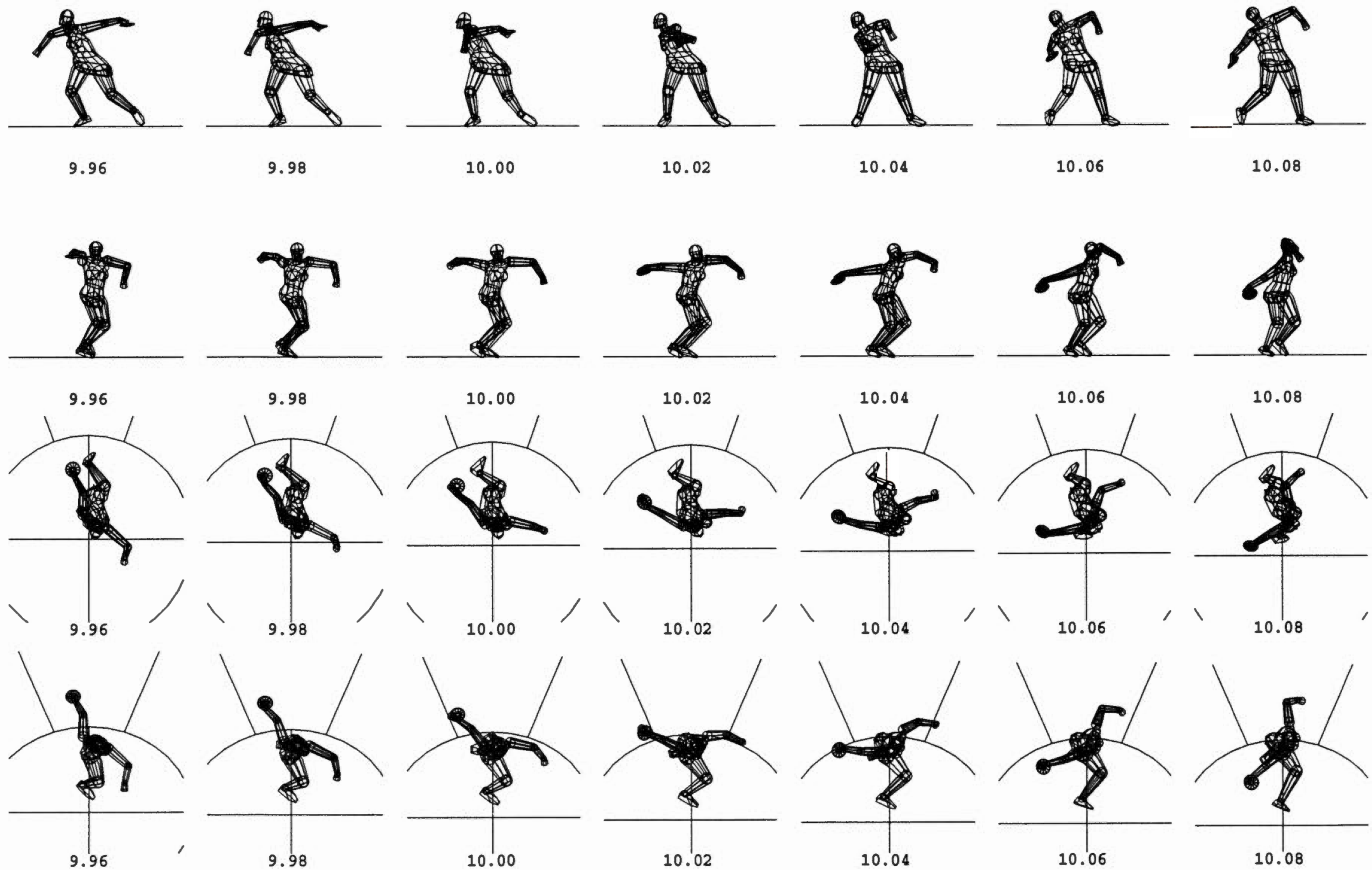

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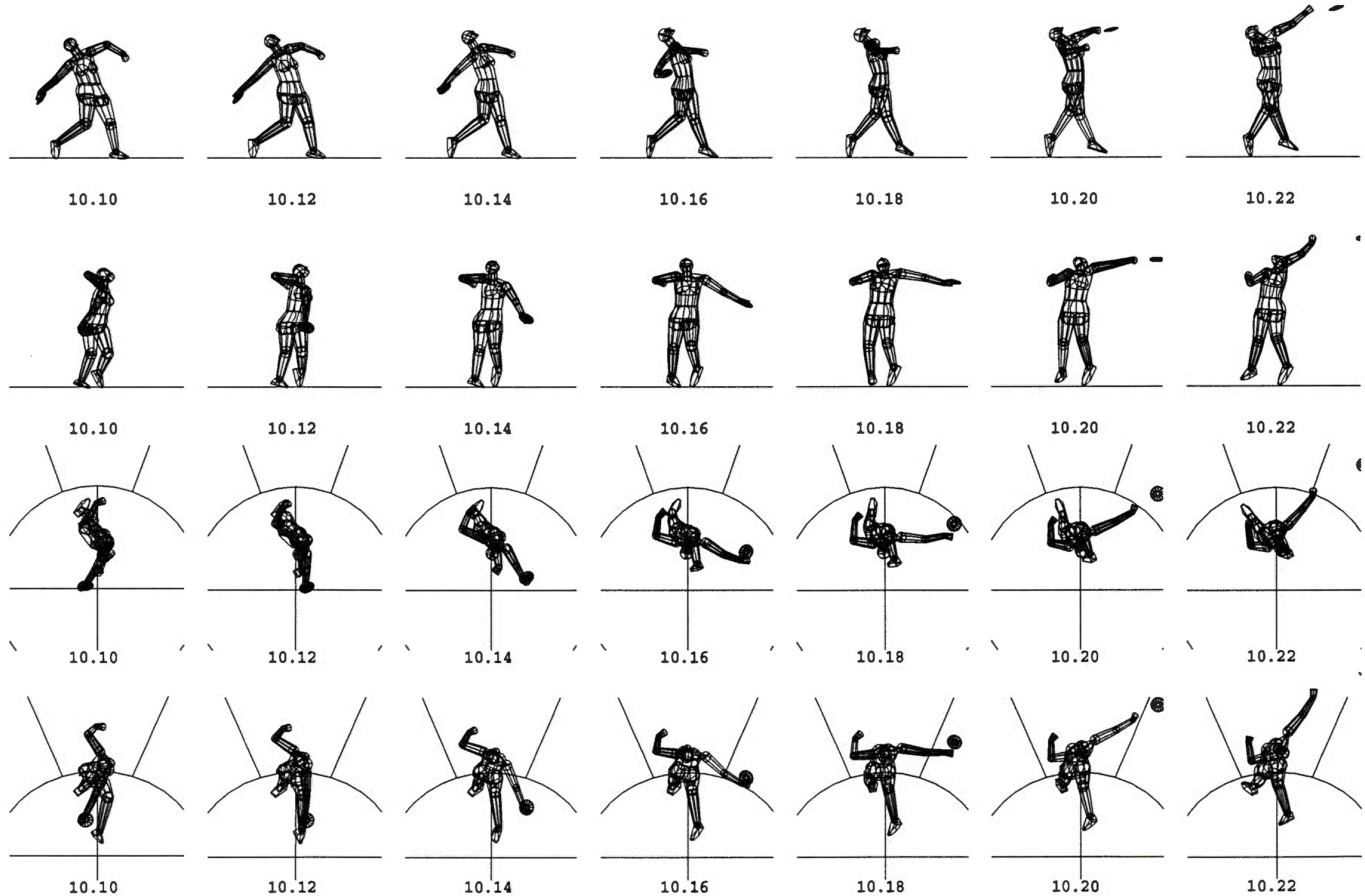

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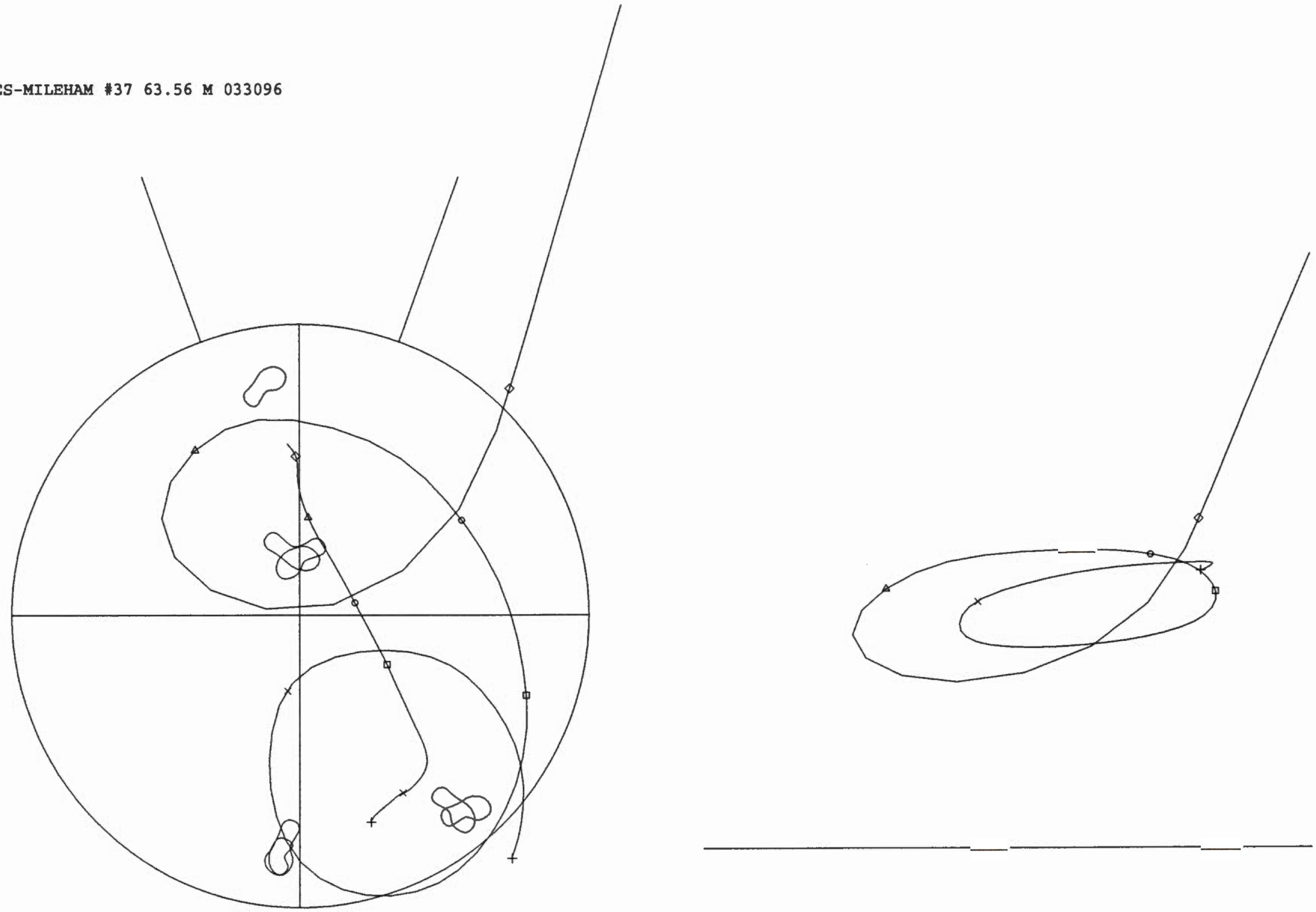

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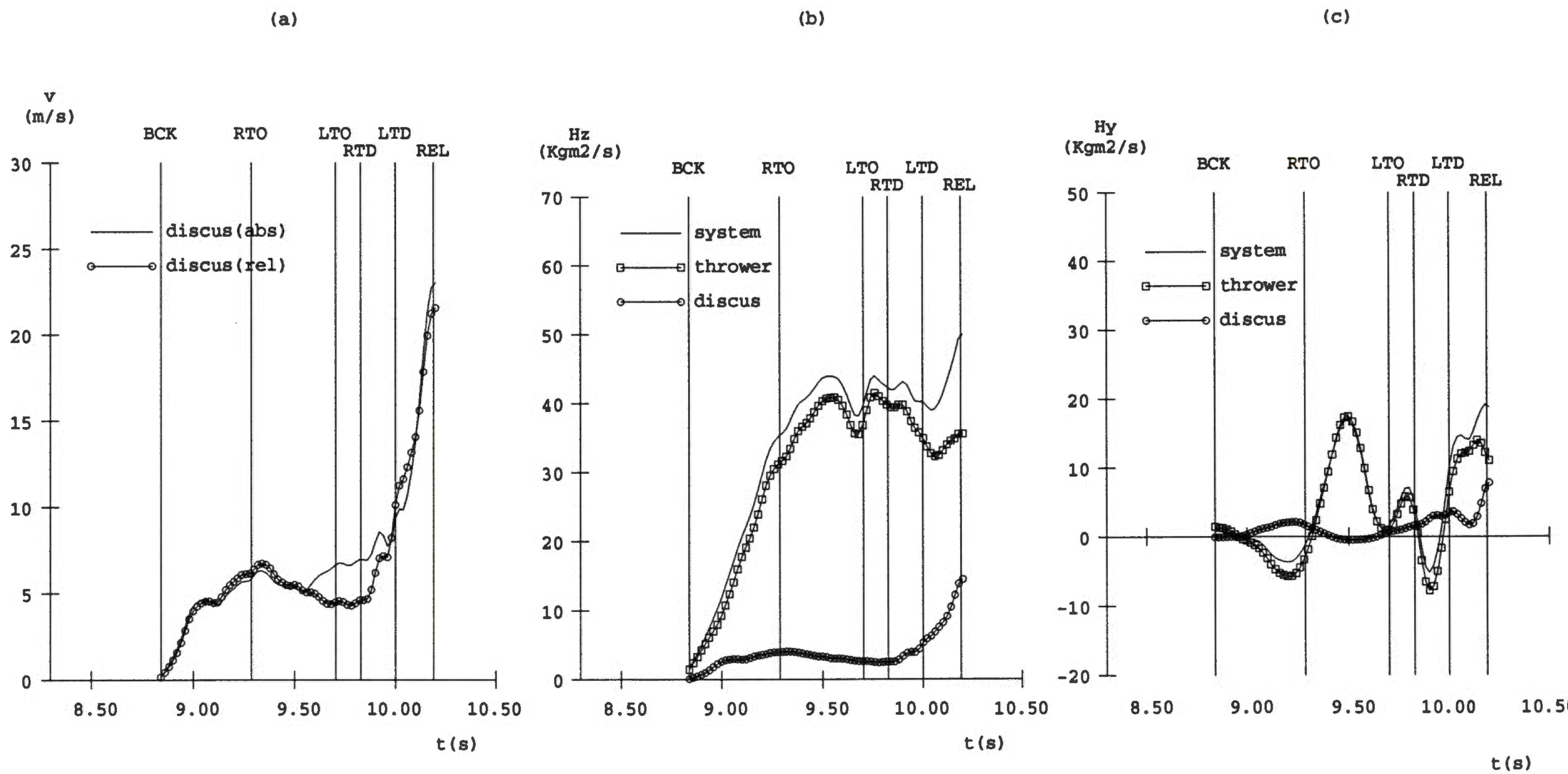

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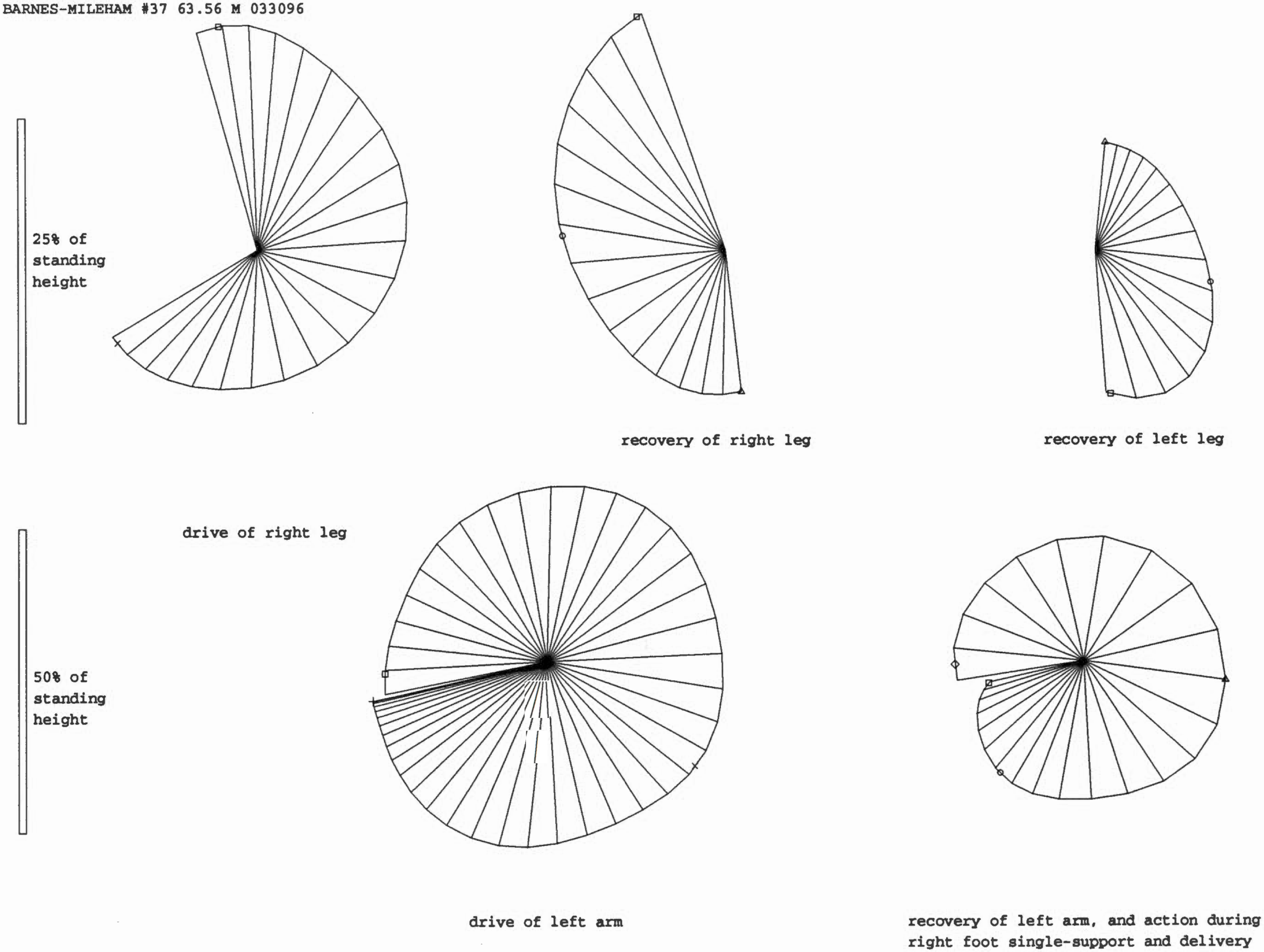

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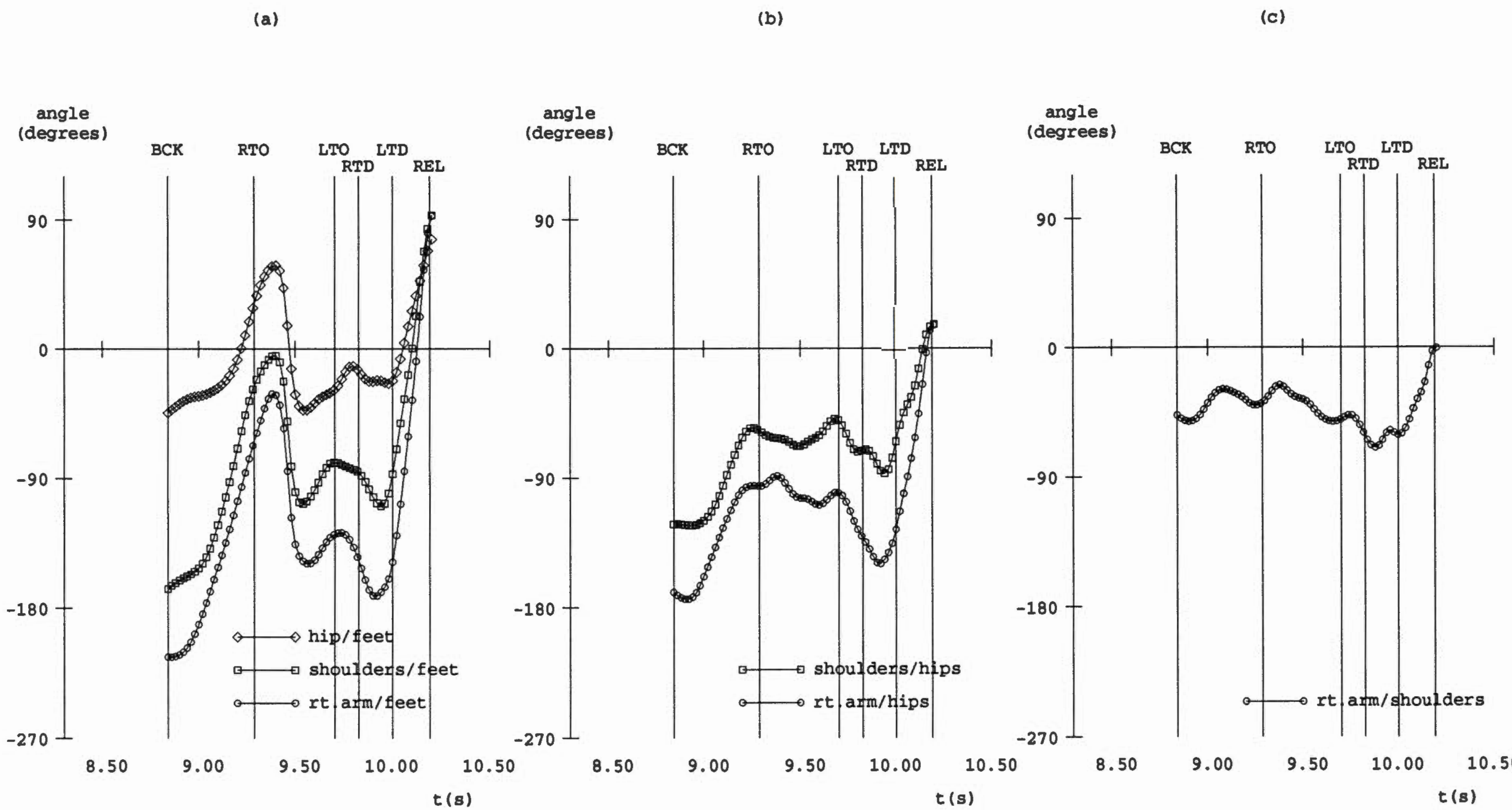


Pam DUKES

Trial 36 was Dukes' best throw at the 1996 UC San Diego Open, 60.54 m.

Dukes started the throw with her feet positioned rather far from the back edge of the circle. (See the graph that shows the overhead view of the footprints and the c.m. path.) She used a left-heel-pivot technique, and we believe that this caused some problems. The need to keep the left heel on the ground and the tip of the left foot up in the air during the preliminary backswing limited how far clockwise Dukes could rotate her hips and shoulders, and therefore also how far clockwise she could rotate the left arm, the right arm and the discus. This limited the range of motion available for the subsequent counterclockwise rotation.

Dukes shifted the system c.m. toward her left foot. Then, she drove with the left leg against the ground, and traveled across the throwing circle in a direction that was not too deviated from directly forward (a_{LTO} = -28°; a_{LTD} = -12°; a_Q = -10°). The horizontal direction of travel of the discus at release was almost perfectly forward in trial 36 (d_{HREL} := 1°). Because of this, the divergence angle between the directions of motion of the system and of the discus was small (c_Q = -10°). (NOTE: The apparent inconsistency in the data (-10 -1 ≠ -10) was due to the rounding off of the values of a_Q, d_{HREL} and c_Q.)

The horizontal speed of the system c.m. at the instant of takeoff of the left foot was somewhat small (v_{HLTO} = 2.3 m/s). Then, while Dukes was in the air her body tilted very much toward the back of the circle. (See the side view in the sequence of images, between t = 9.64 s and t = 9.76 s.) Possibly due to this backward lean, Dukes lost a large amount of horizontal speed during the single-support on the right foot (t = 9.76/10.00 s), and by the time that she planted the left foot on the ground the horizontal speed of the system c.m. was clearly slower than average (v_{HLTD} = 1.7 m/s). Then, Dukes made only a moderate forward and downward force on the ground during the double-support delivery. The backward horizontal ground reaction force produced only a moderate reduction in the horizontal speed of the system c.m. Therefore, during the last quarter-turn of the discus the horizontal speed of the system c.m. (v_{HQ} = 1.0 m/s) was still smaller than the average, but closer to it. Because of the small size of the divergence angle between the directions of motion of the system and of the discus in throw 36 (c_Q =-10°), the contribution of the horizontal speed of the system to the horizontal speed of the discus (v_{HCON} = 1.0 m/s) was very close to the average, although still slightly smaller.

As previously mentioned, during the double-support delivery Dukes pushed moderately forward and downward against the ground. The downward component of the push made the system gain a moderate amount of vertical speed, which made a moderate contribution to the vertical speed of the discus (v_{ZCON} = 1.1 m/s).

The combination of the contributions which we have just seen to the speed of the discus by the horizontal and vertical translations of the system c.m. (v_{HCON} = 1.0 m/s, and v_{ZCON} = 1.1 m/s, respectively) was close to average.

The swinging action of the right leg at the back of the circle was good (RLA = 31.2 $\cdot 10^{-3}$ Kg·m²/Kg·m²). However, the swinging action of the left arm was weak (LAA = 25.2 $\cdot 10^{-3}$ Kg·m²/Kg·m²). The weak action of the left arm may have been due to an insufficiently clockwise position of that arm at the end of the preliminary backswing. The sequence of images (overhead view) suggests that the left arm rotated strongly counterclockwise (t = 8.44/9.40 s), but then approached the end of its anatomical range of motion at the shoulder, and had to slow down almost to a stop before the takeoff of the left foot (t = 9.40/9.64 s). This suggests that the problem might be corrected if the left arm starts from a more clockwise initial position. However, that may be difficult to achieve if Dukes continues using the heel-pivot technique. The combination of the strong action of the right leg with the weak action of the left arm was somewhat weaker than average (RLLAA = 56.4 $\cdot 10^{-3}$ Kg·m²/Kg·m²).

At the instant of landing of the left foot in the front of the circle, the system already had a large amount (93%) of the Z angular momentum (counterclockwise rotation in a view from overhead) that it would eventually reach at release. This suggests that Dukes' generation of angular momentum in the back of the circle was at least reasonably good.

The recovery actions of the legs were close to average. The average radius of the legs ($r_{LAVG-NSRSS}$ = 9.5% of standing height) shows that Dukes brought both legs reasonably close together below her body. This helped the legs to rotate reasonably fast, and therefore contributed to produce a reasonably well wound-up body configuration prior to the final effort of the throw. The recovery of Dukes' left arm was also reasonably good ($H_{LA\text{-}NS} = 30 \cdot 10^{-3}$ s^{-1}, which was not too large).

The second propulsive swing of the left arm ($LAA2 = 16.7 \cdot 10^{-3}$ $Kg \cdot m^2/Kg \cdot m^2$) was reasonably good. The maximum angular momentum that the left arm reached ($H_{MAX} = 59 \cdot 10^{-3}$ s^{-1}) was slightly larger than average, and therefore not bad. However, much of this angular momentum was still in the left arm at the instant of release ($H_{REL} = 41 \cdot 10^{-3}$ s^{-1}): There was little loss of angular momentum by the left arm in the late part of the delivery phase ($\Delta H = -18 \cdot 10^{-3}$ s^{-1}), and this implies that there was not much transfer of angular momentum from the left arm to the rest of the system in the late part of the delivery phase. Therefore the actions of the left arm were not very helpful for increasing the speed of the discus

Dukes reached a moderately wound-up position in the single-support phase over the right foot ($k_{RA/FT} = -140°$). At the instant of maximum torsion of the system, the torsion of the shoulders relative to the hips was larger in Dukes than in the average thrower (Dukes $k_{SH/HP} = -85°$; average = -64), while the torsion of the right arm relative to the shoulders was smaller in Dukes than in the average thrower (Dukes $k_{RA/SH} = -12°$; average = -33°).

Dukes transfered a reasonably good amount of the Z angular momentum of the system to the discus (27% of the total). It enabled her to give a moderate amount of horizontal speed to the discus ($v_{HD} = 18.4$ m/s).

At release, in the view from the back of the circle the counterclockwise angular momentum of the thrower-plus-discus system was very large ($H_{YS} = 37.7$ $Kg \cdot m^2/s$). Only 29% of it was transfered to the discus, but in absolute terms this gave the discus a very large amount of Y angular momentum at release ($H_{YD} = 11.1$ $Kg \cdot m^2/s$), which in turn contributed to give a very large vertical speed to the discus at release ($v_{ZD} = 14.1$ m/s).

The resultant speed of the discus was good ($v_{RD} = 23.1$ m/s), similar to the speeds achieved by the other top throwers at the San Diego meet. Dukes made reasonably effective use of aerodynamic forces ($\Delta D = 5.86$ m). In this respect, she was similar to most of the other top throwers at the San Diego meet, but not nearly as effective as Barnes-Mileham.

Summary

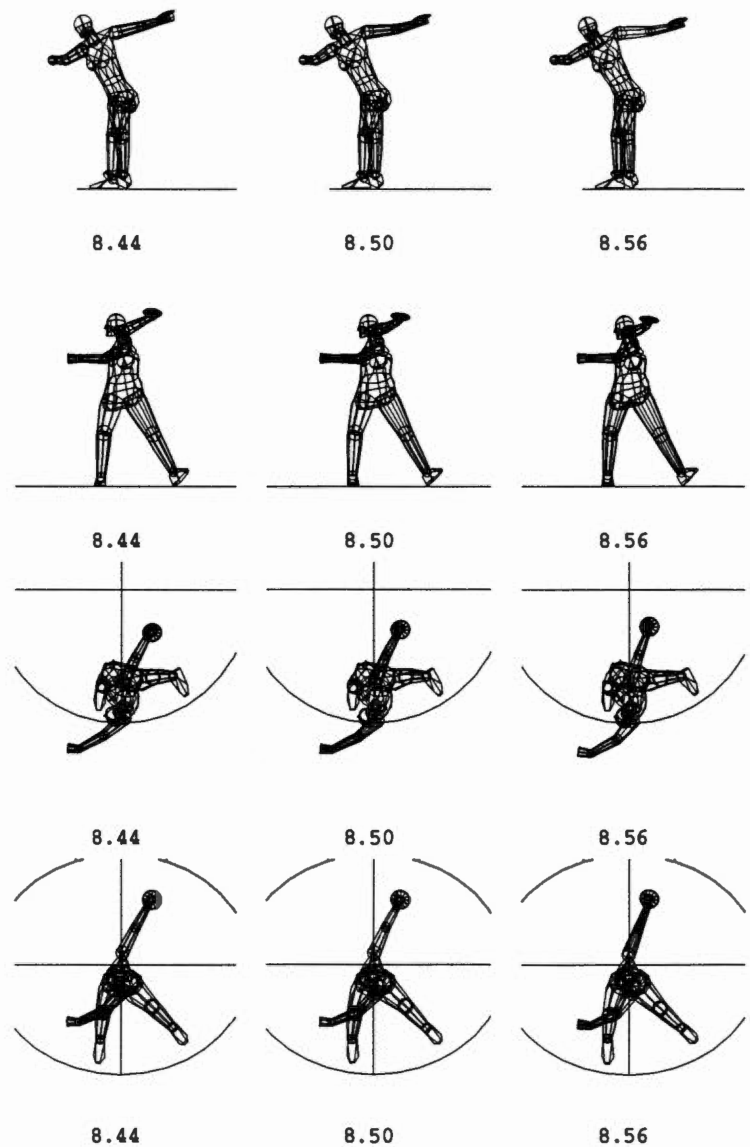
Dukes used a left-heel-pivot technique. The direction of the horizontal translation of the system c.m. across the throwing circle was not too diagonal. Her horizontal speed was slowed down considerably during the single support on the right foot. After release, the discus traveled almost directly forward. The divergence angle was small. During the delivery phase, Dukes exerted on the ground moderate horizontal and vertical forces. The contributions of the horizontal and vertical speeds of the system to the speed of the discus were average. The swinging action of the right leg in the back of the circle was good, but the swinging action of the left arm was weak. The generation of Z angular momentum at the back of the circle seemed to be reasonably good. The recovery actions of the legs and of the left arm after the takeoff of the left foot from the ground were reasonably good. Dukes made a strong swing with the left arm in the front of the circle, but then she did not slow it down enough prior to release. She produced a moderate torsion angle between the right arm and the feet. The transfer of Z and Y angular momentum from the body to the discus was good. She was able to give a moderate vertical speed and a very large vertical speed to the discus.

Recommendations

We think that Dukes' left-heel-pivot technique may have been the cause of some of the problems in her technique. For instance, the preliminary clockwise rotation of the body in the back of the circle was restricted by Dukes' left-heel-pivot technique, and this probably led to the weak counterclockwise swing of the left arm in the back of the circle. However, we are not going to advise Dukes to change her left-heel-pivot technique, because we feel that this would constitute a drastic change in her technique which might have unpredictable consequences.

Dukes should start the throw with her feet closer to the back edge of the circle, in order to have more horizontal space available for her subsequent motions. Then, she should drive harder with her left leg. This will allow her to have a larger horizontal speed by the time that the left foot leaves the ground. Thus, even if she loses a large amount of horizontal speed in the single-support on the right foot, she will still have a larger leftover horizontal speed available for the delivery phase. Then, during the delivery phase she should push harder forward and downward against the ground. The larger vertical force will produce a larger vertical speed of the system c.m. The backward reaction to the larger horizontal force exerted on the ground will produce a larger reduction in the horizontal speed of the system c.m., but if Dukes has a larger initial horizontal speed as a result of her stronger push from the back of the circle, she may still end up with the same or more horizontal speed than in the original throw. Larger horizontal and vertical speeds of the system c.m. in the last quarter-turn will increase the horizontal and vertical speeds of the discus at release, and therefore the distance of the throw.

Dukes should also change the actions of her left arm. In the back of the circle, her left arm did not swing actively enough; in the front of the circle, it made a good swing, but then it did not slow down enough before the release of the discus. To improve the actions of her left arm, in the back of the circle Dukes should *rotate her left arm to a more clockwise position before starting the counterclockwise rotation*. (This would be facilitated by a left-toe-pivot technique as opposed to her current left-heel-pivot technique, but she may be able to improve even using the left-heel-pivot technique.) Then, during the remainder of the double-support phase and during the single-support on the left foot she needs to throw the left arm hard in the counterclockwise direction. This will help her to generate more Z angular momentum in the back of the circle. By starting from a more clockwise initial position, Dukes should be able to throw the left arm hard counterclockwise in the back of the circle without having to slow it down early for lack of sufficient range of motion at the shoulder joint. During the non-support phase, Dukes should slow down the left arm as she did in trial 36. Then, after the right foot lands in the middle of the circle, she should again throw the left arm very hard in the counterclockwise direction, at least as well as she did in trial 36. Finally, *she should slow down the left arm very much before release.*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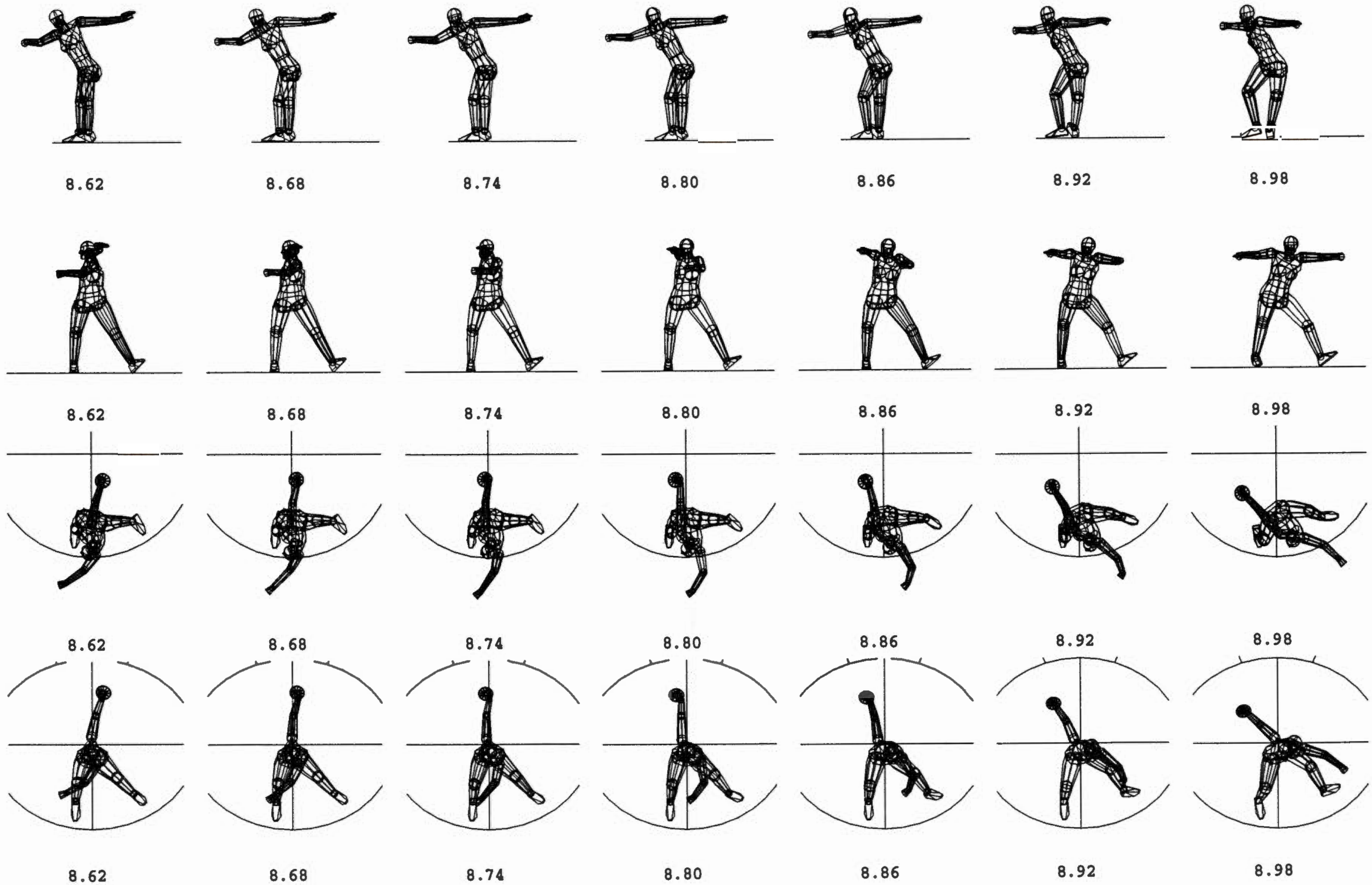

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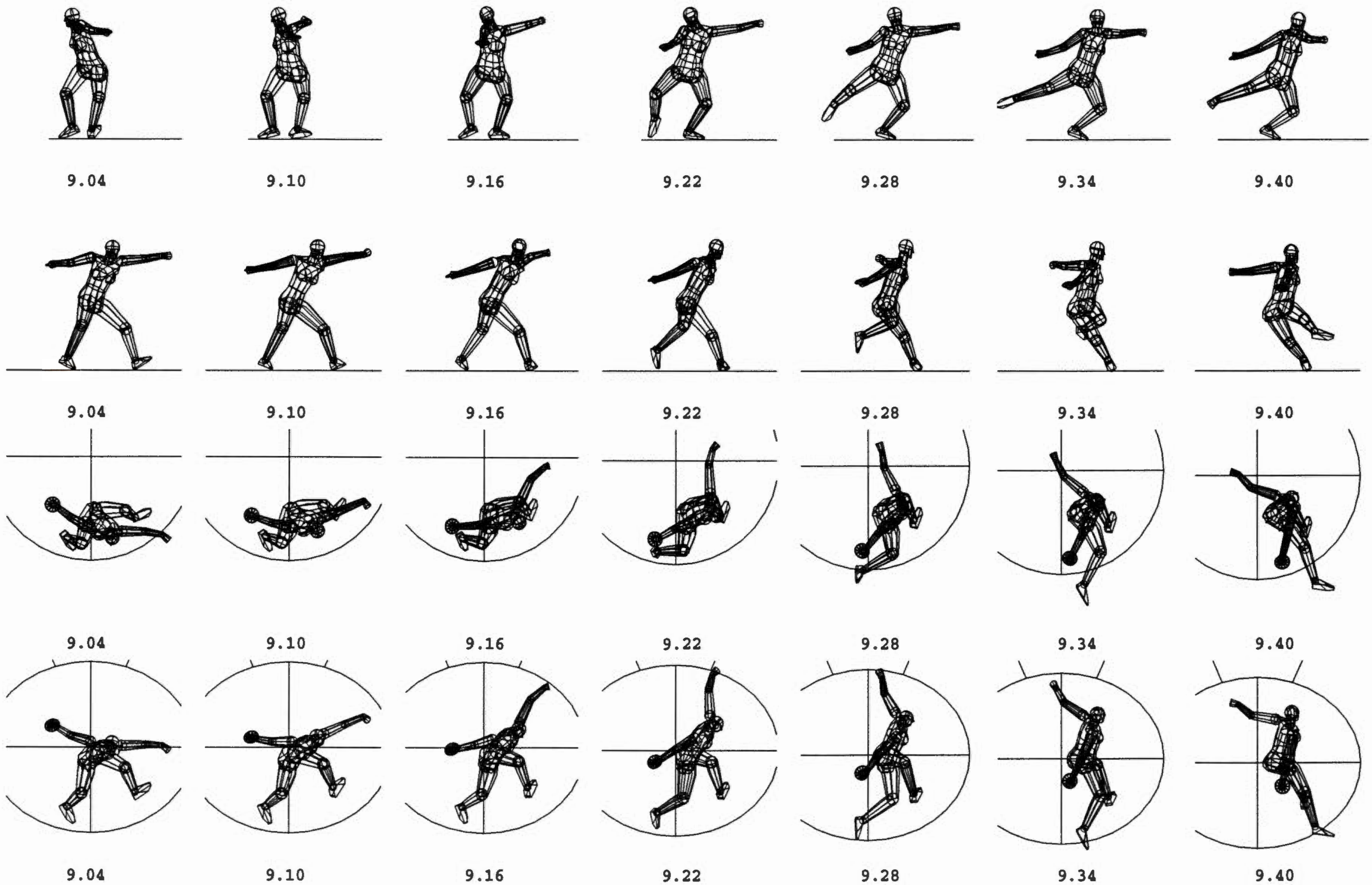

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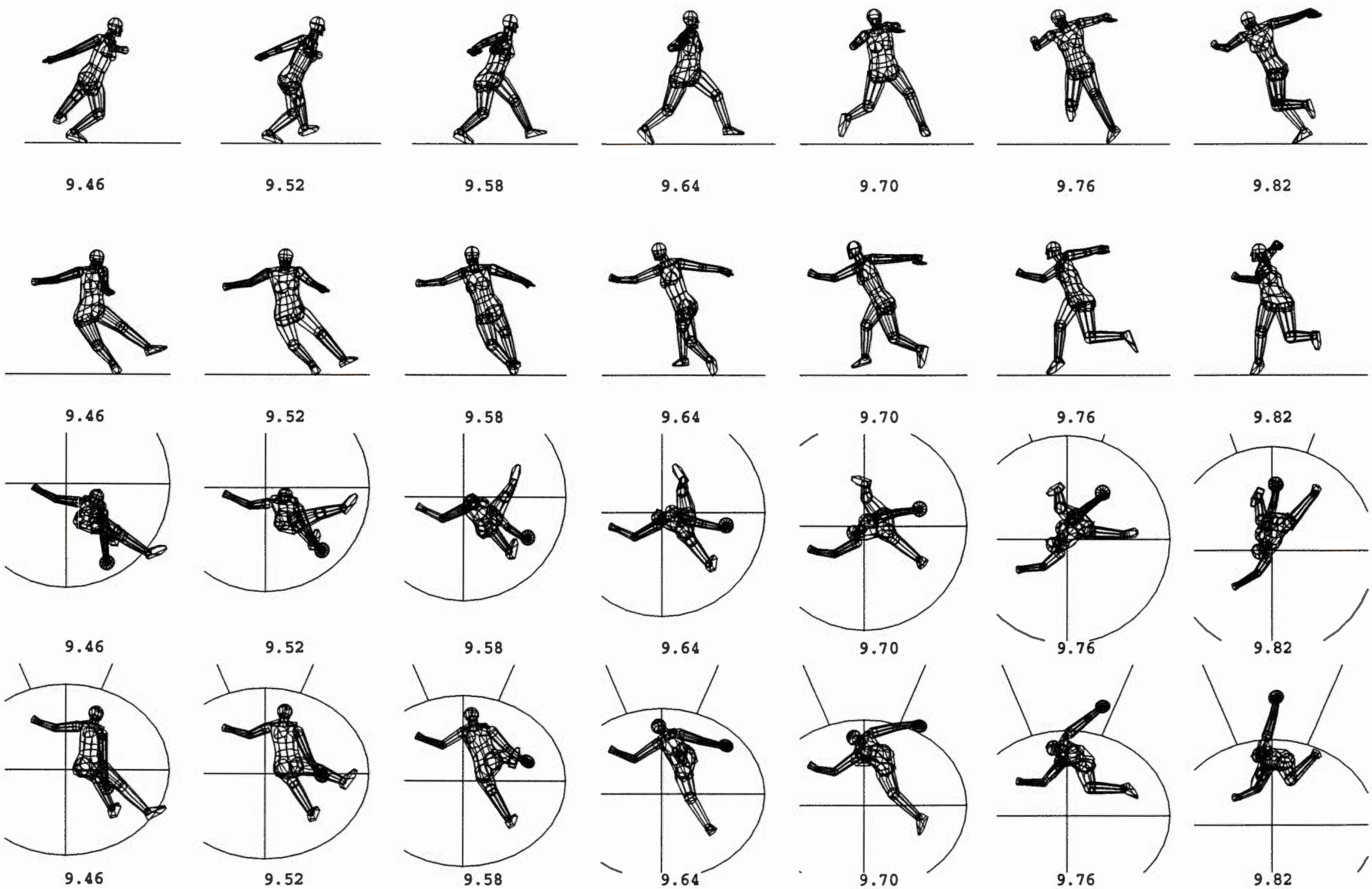

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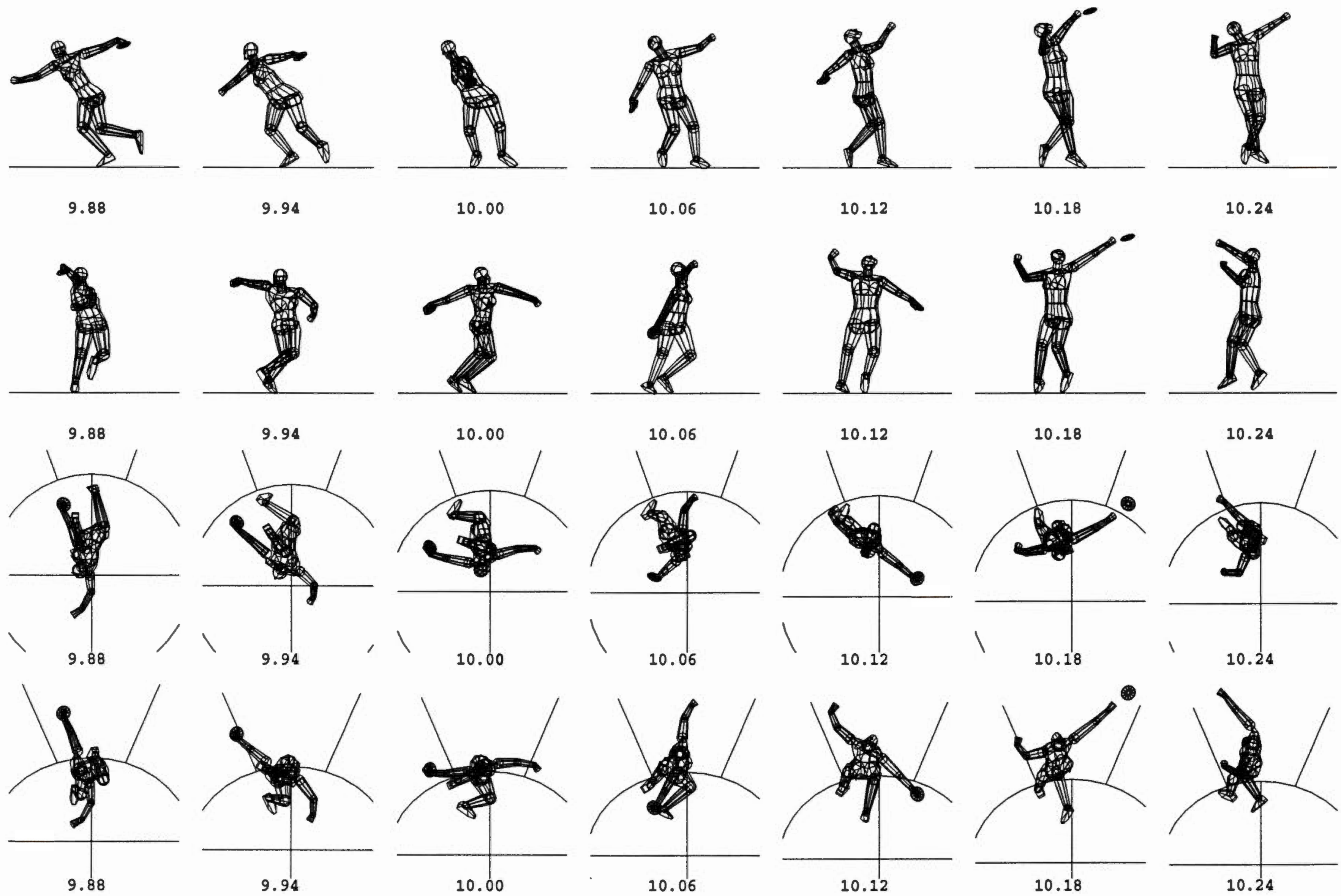

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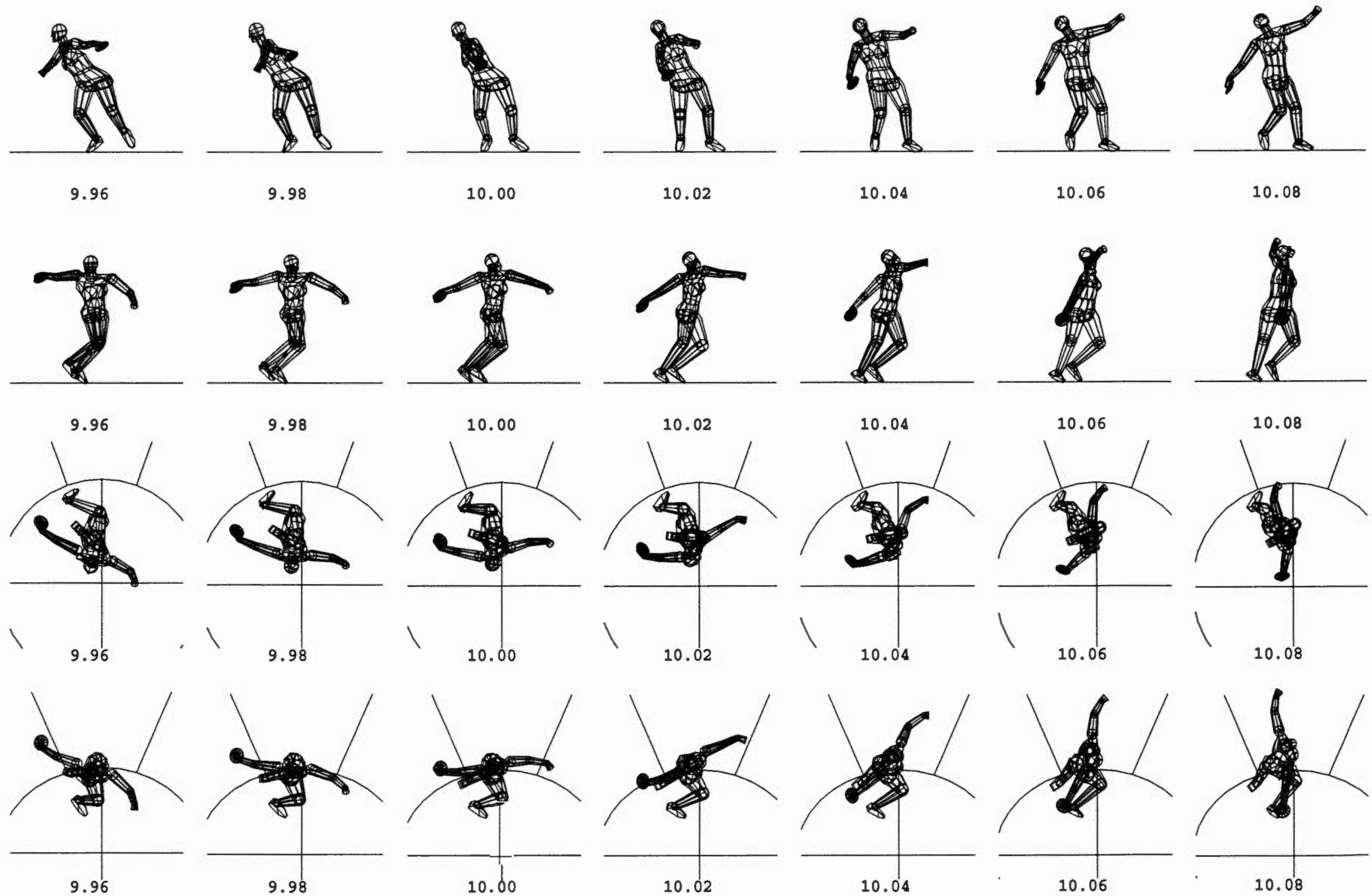

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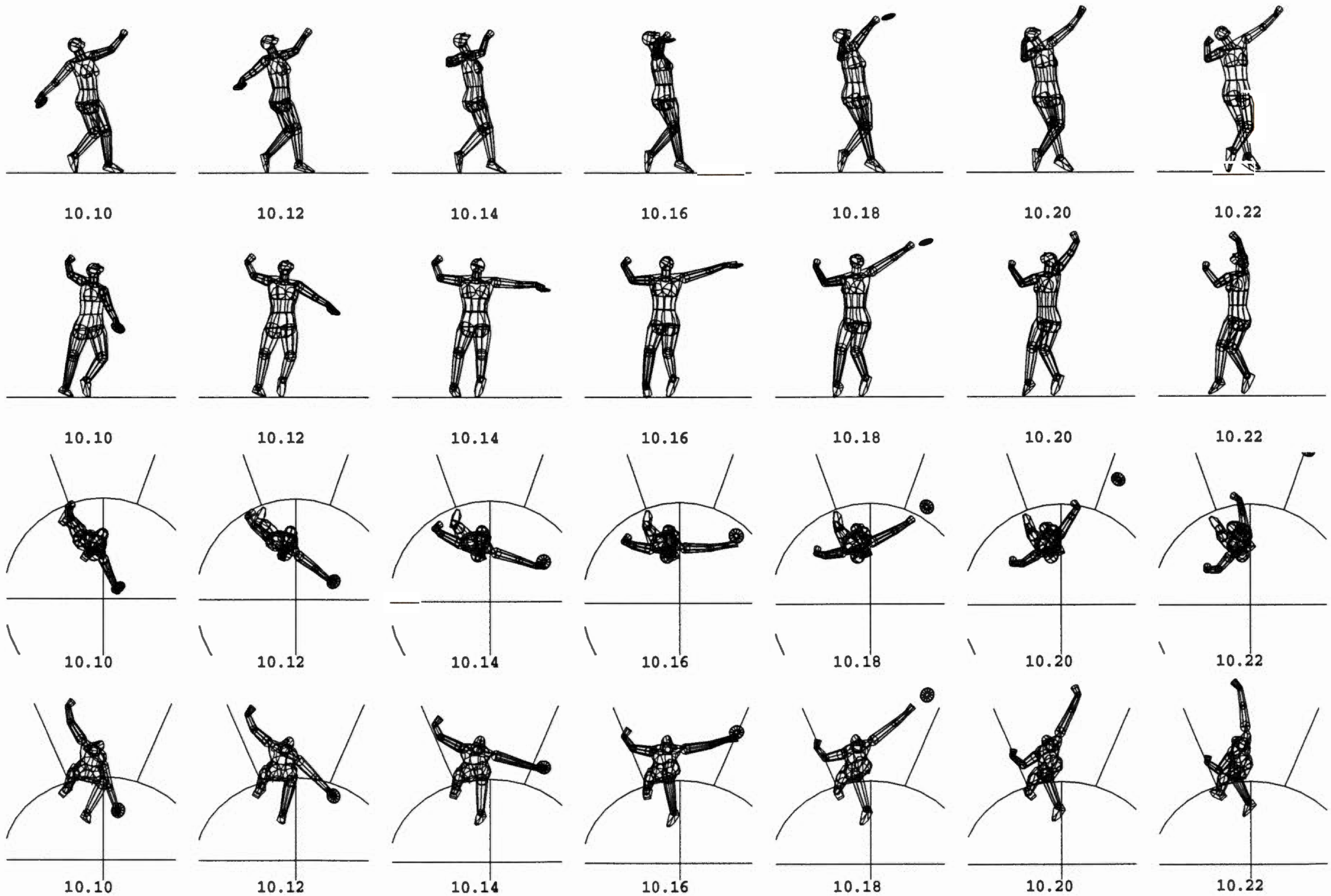

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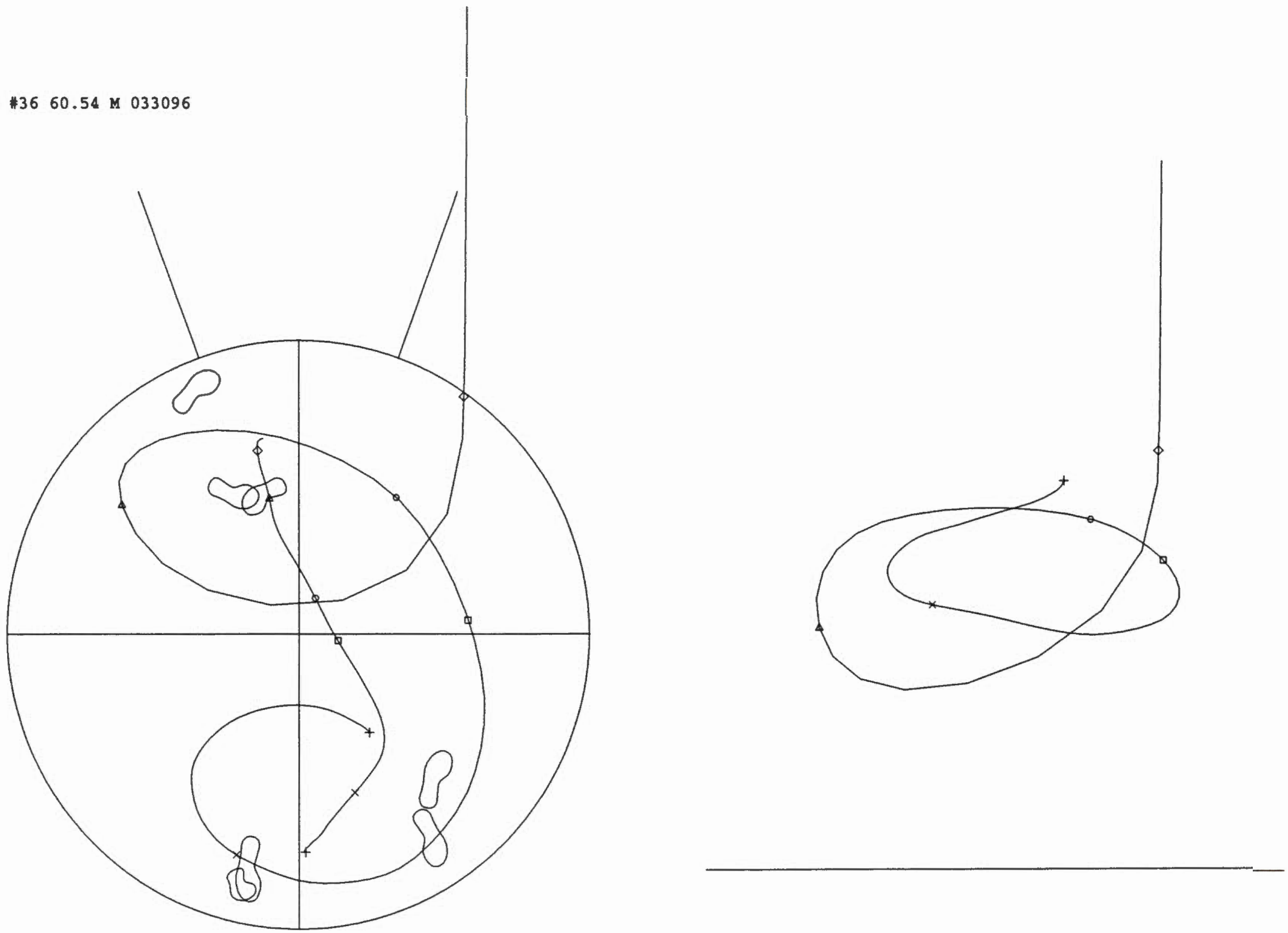

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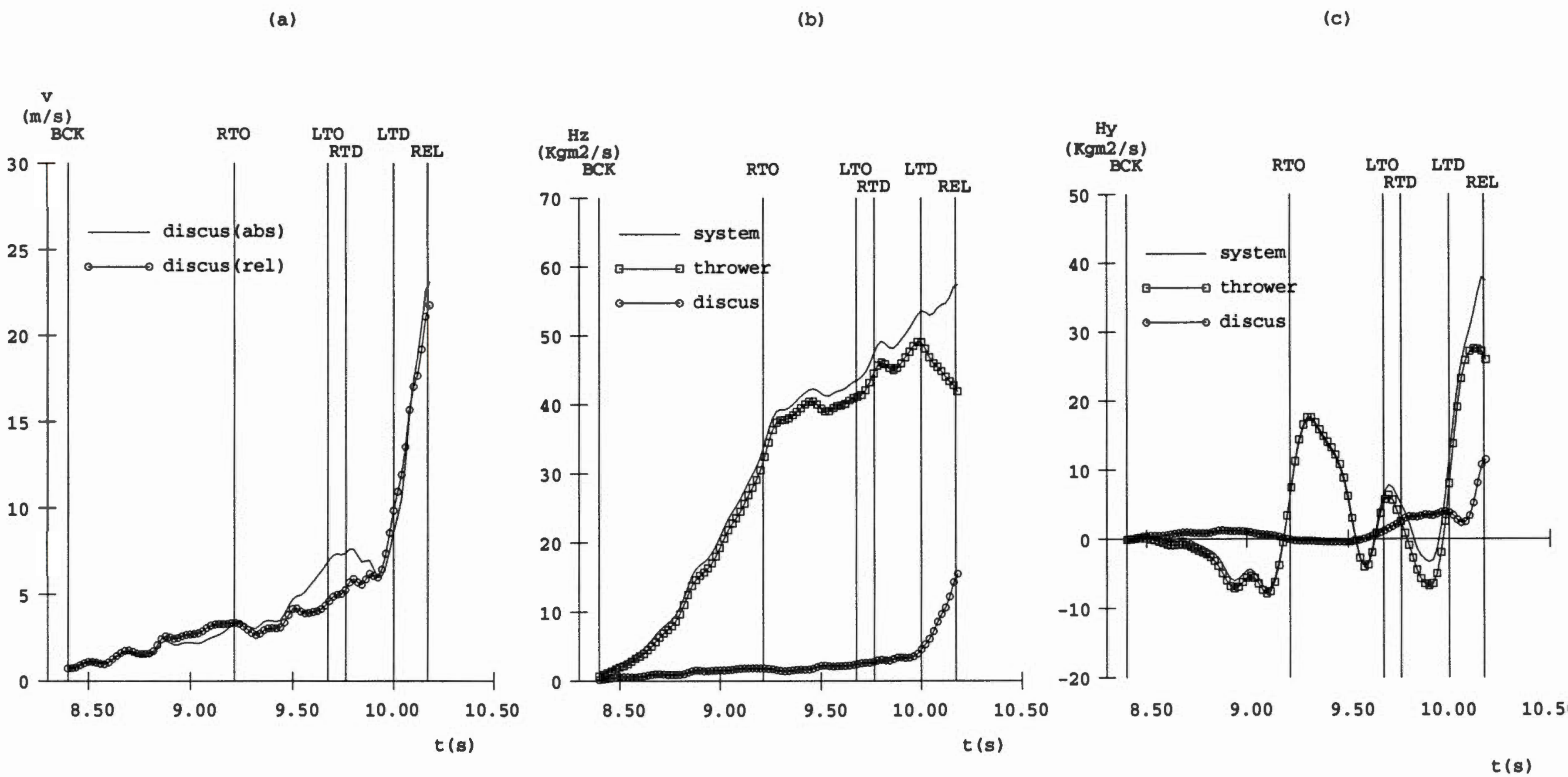

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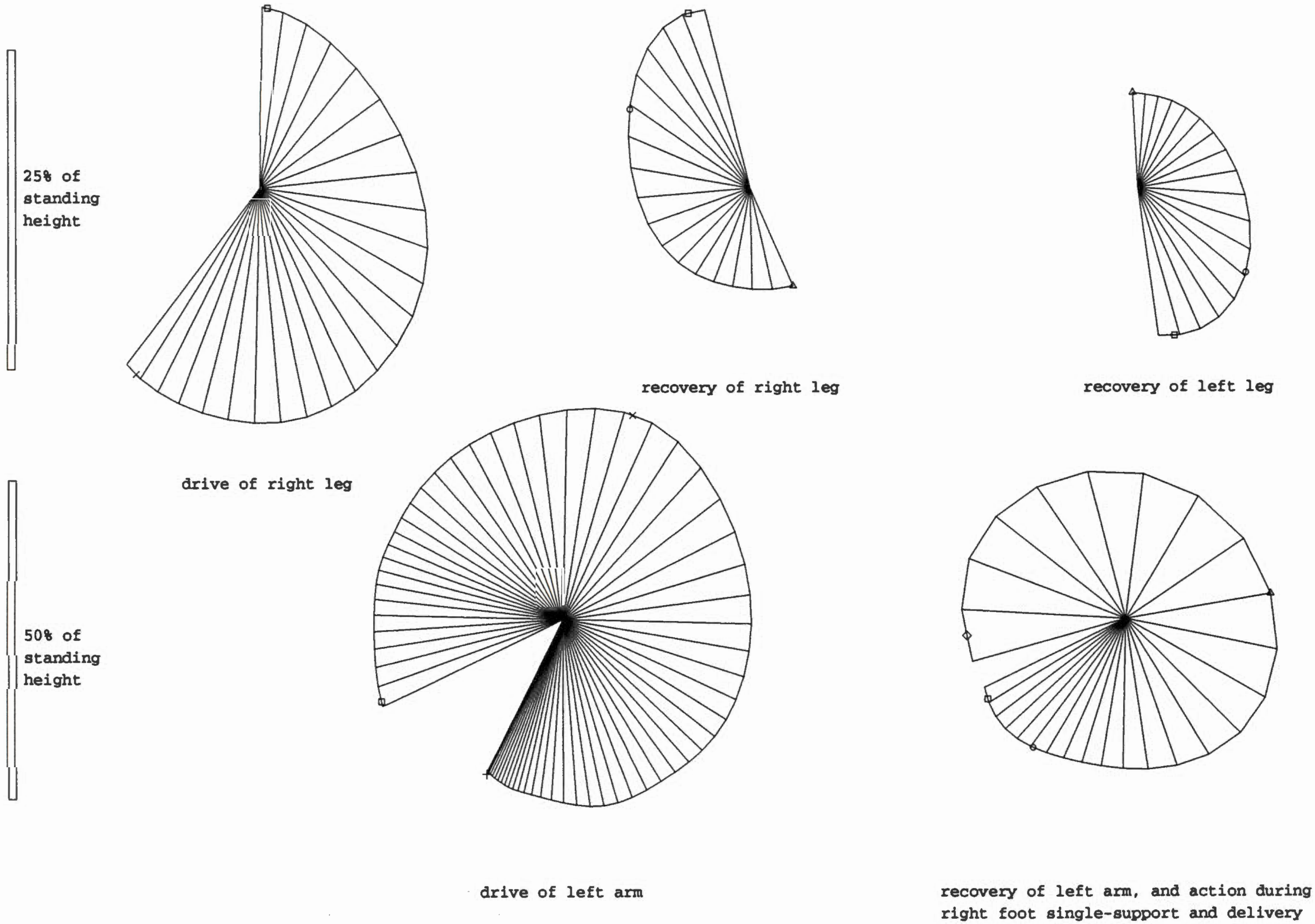

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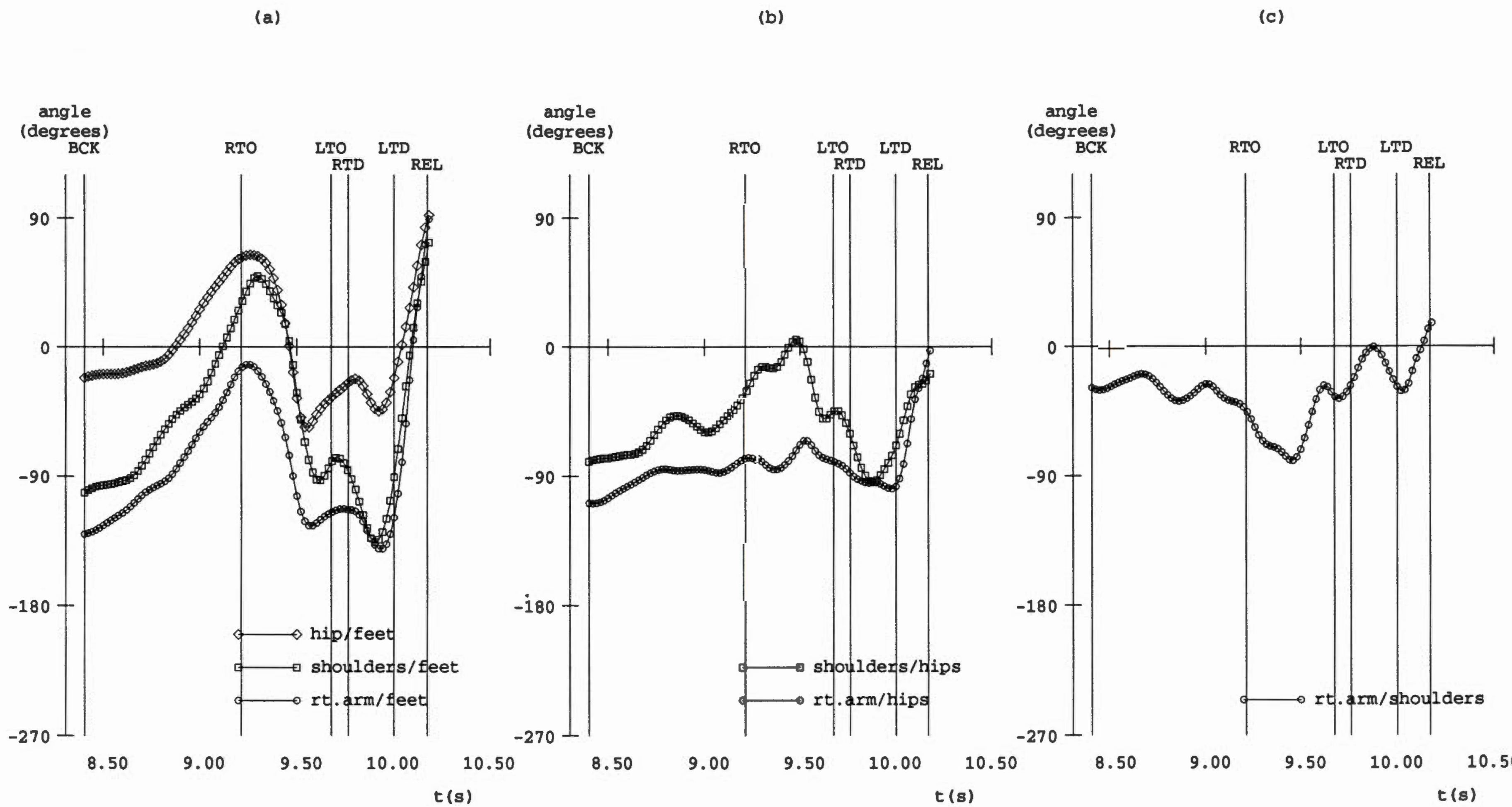


Dawn DUMBLE

Trial 51 was Dumble's best throw at the 1996 UC San Diego Open, 60.24 m.

At the back of the circle, Dumble shifted the system c.m. toward her left foot. Then, she drove with the left leg against the ground, and traveled across the throwing circle in a direction that was not too deviated from directly forward (a_{LTO} = -15°; a_{LTD} = -20°). During the last quarter-turn of the discus the direction of motion of the system c.m. (a_Q = -22°) was somewhat more diagonal than in the average thrower. However, the horizontal direction of travel of the discus at release was slightly toward the left in trial 51 (d_{HREL} = -9°), while in most throwers it was toward the right. Because of this, the divergence angle between the directions of motion of the system and of the discus was small (c_Q = -13°).

The horizontal speed of the system c.m. across the throwing circle was average (v_{HLTO} = 2.4 m/s; v_{HLTD} = 2.0 m/s). However, the forward horizontal force that Dumble made on the ground during the double-support delivery was small, and therefore during the last quarter-turn of the discus the leftover horizontal speed of the system (v_{HQ} = 1.6 m/s) was much larger in Dumble's trial 51 than in most other throwers of the sample. Together with the small divergence angle between the horizontal directions of motion of the discus and of the system c.m. (c_Q = -13°), this made a very large contribution to the horizontal speed of the discus (v_{HCON} = 1.5 m/s).

Although Dumble did not push very hard on the ground in the forward horizontal direction during the delivery, she managed to push reasonably hard in the vertical direction. In other words, her push against the ground during the delivery phase was mainly downward, and only slightly forward. The ground reaction to the vertical force gave the system a good vertical speed which contributed to increase the vertical speed of the discus (v_{ZCON} = 1.2 m/s).

Overall, the combination of the contributions to the speed of the discus by the horizontal and vertical translations of the system c.m. (v_{HCON} = 1.5 m/s, and v_{ZCON} = 1.2 m/s, respectively) was excellent.

The swinging action of the left arm at the back of the circle was average (LAA = 29.8 · 10^{-3} Kg·m²/Kg·m²), while the swinging action of the right leg, as well as the combination of the swinging actions of the left arm and of the right leg, were somewhat weaker than average (RLA = 24.6 · 10^{-3} Kg·m²/Kg·m²; RLLAA = 54.3 · 10^{-3} Kg·m²/Kg·m²).

At the instant of landing of the left foot in the front of the circle, the system already had a large amount (94%) of the Z angular momentum (counterclockwise rotation in a view from overhead) that it would eventually reach at release. This suggests that Dumble's generation of angular momentum in the back of the circle was good.

The recovery actions of the legs were excellent. The small average radius of the legs ($r_{LAVG\text{-}NSRSS}$ = 8.4% of standing height) shows that Dumble brought both legs very close together below her body. This helped her legs to rotate faster, and therefore contributed to produce a well wound-up body configuration prior to the final effort of the throw.

The recovery of Dumble's left arm was not so good ($H_{LA\text{-}NS}$ = 41 · 10^{-3} s⁻¹, which was too large). In part, this was because the arm was kept too far out during the non-support phase ($r_{LA\text{-}NS}$ = 26.5% of standing height), and in part because the arm did not slow down its rotation enough. Keeping the left arm too far out during the non-support phase slowed down the overall rotation of the thrower-plus-discus system. However, this did not seem to be an important problem for Dumble, because she still managed to rotate her body enough in the counterclockwise direction to reach a good position at the start of the delivery phase. (This may have been due to the compact configuration of the body about the longitudinal axis produced by the excellent positions of the legs.) What may have posed a problem was the insufficient slowing down of the rotation of the left arm during the non-support phase: It made the left arm travel too far counterclockwise during the non-support phase, and thus limited the range of motion available for its second propulsive swing. The second propulsive swing of the left arm (LAA2 = 16.9 · 10^{-3} Kg·m²/Kg·m²) was still reasonably good, but it would have been still better if a longer range of motion had been available for the arm. The maximum angular momentum that the left arm reached (H_{MAX} = 59· 10^{-3} s⁻¹) was slightly larger than average, and the amount of angular momentum that it still had at release was slightly smaller than average (H_{REL} = 21 · 10^{-3} s⁻¹). The combination of these two factors implied a large loss of angular momentum by the left arm in the late part of the delivery phase (ΔH = -37 · 10^{-3} s⁻¹), and the transfer of that angular momentum from the arm to the rest of the system, possibly to the discus. This was good, but it might have been still better if a longer range of motion had been available for the left arm in this whole process.

Dumble reached a markedly wound-up position in the single-support phase over the right foot ($k_{RA/FT}$ = -156°). This was very good, because the subsequent unwinding helped her to transfer angular momentum from the body to the discus (and probably also helped her to get a little bit more more angular momentum from the ground). The main advantage of Dumble with respect to the average thrower at the instant of maximum torsion of the system was in the torsion of the hips relative to the feet (Dumble $k_{HP/FT}$ = -67°; average = -43°).

Dumble transfered a good amount of the Z angular momentum of the system to the discus (28% of the total). This was facilitated by the unwinding of the thrower-plus-discus system, and it enabled Dumble to give a good amount of horizontal speed to the discus (v_{HD} = 18.8 m/s).

At release, in the view from the back of the circle the counterclockwise angular momentum of the thrower-plus-discus system was very large (H_{YS} = 34.7 Kg· m²/s), but only 28% of it was transfered to the discus. Still, in absolute terms the discus had a good amount of Y angular momentum at release (H_{YD} = 9.9 Kg· m²/s). This gave the discus a very good vertical speed at release (v_{ZD} = 13.6 m/s).

The resultant speed of the discus was good (v_{RD} = 23.2 m/s), similar to the speeds achieved by the other top throwers at the San Diego meet. Dumble made reasonably effective use of aerodynamic forces (ΔD = 6.13 m). In this respect, she was similar to most of the other top throwers at the San Diego meet, but not nearly as effective as Barnes-Mileham.

Summary

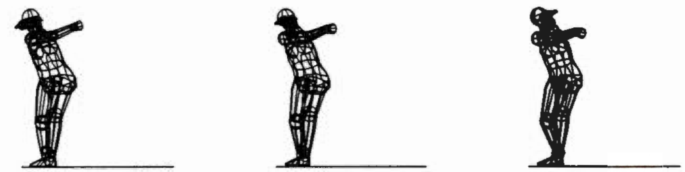
The direction of the horizontal translation of the system c.m. was not too diagonal. After release, the discus traveled slightly toward the left, and this limited the divergence angle to a small value. During the delivery phase, Dumble exerted on the ground a small horizontal force and a large vertical force. The contribution of the horizontal speed of the system to the horizontal speed of the discus was much larger than average, while the contribution of the vertical speed of the system to the vertical speed of the discus was near average. Therefore, this part of her technique was overall very good. The swinging action of the right leg in the back of the circle was somewhat weak. The generation of Z angular momentum at the back of the circle was good. The recovery actions of the legs after the takeoff of the left foot from the ground were very good. The left arm did not slow down very much during the non-support phase in the middle of the throw, and this limited the range of motion that it had available for its second propulsive swing in the front of the circle. Dumble was still able to swing the left arm hard in the front of the circle, and then slow it down very well prior to release. She produced a very large torsion angle between the right arm and the feet. Then, she unwound well, and gave a good amount of speed to the discus. The transfer of Z and Y angular momentum from the body to the discus was good.

Recommendations

We did not find any glaring problems in Dumble's technique. The main change that we propose for her is a minor one. During the non-support phase in the middle of the throw, she should slow down the left arm, and even rotate it clockwise, wrapping it somewhat across her chest, before accelerating it very strongly counterclockwise after the right foot lands, and then slowing it down very much again before the release of the discus. In trial 51, she already was doing the acceleration and the final slowing down very well. However, the counterclockwise range of motion available for this action of the left arm was somewhat limited in trial 51 because by the time that the right foot landed, the left arm had drifted into a position that was too counterclockwise. A more backward (i.e., more clockwise) position of the left arm at the instant of landing of the right foot would make available a longer counterclockwise range of motion for the left arm in the final part of the throw, which in turn would enable Dumble to obtain still more angular momentum from the ground, and would also put into the left arm more angular momentum which could then be transmitted to the discus when the left arm is slowed down before release.

It may also be advantageous to swing the right leg a little bit wider in the back of the circle. This may help Dumble to generate more angular momentum.

DUMBLE #51 60.24 M 033096



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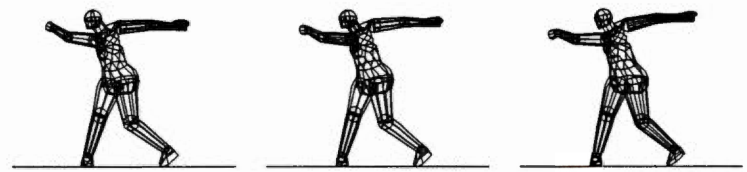

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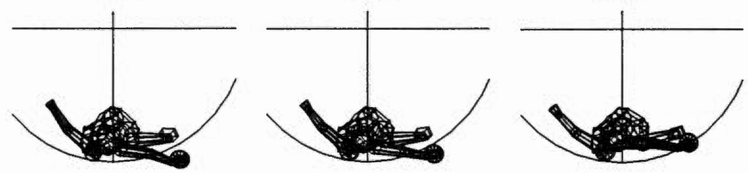

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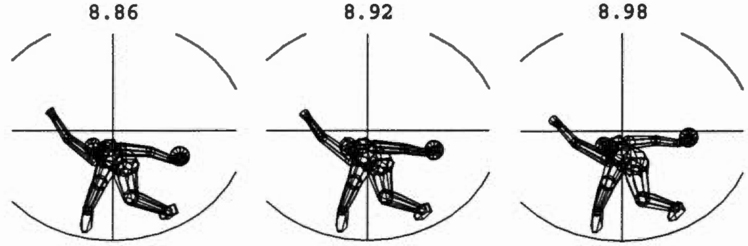

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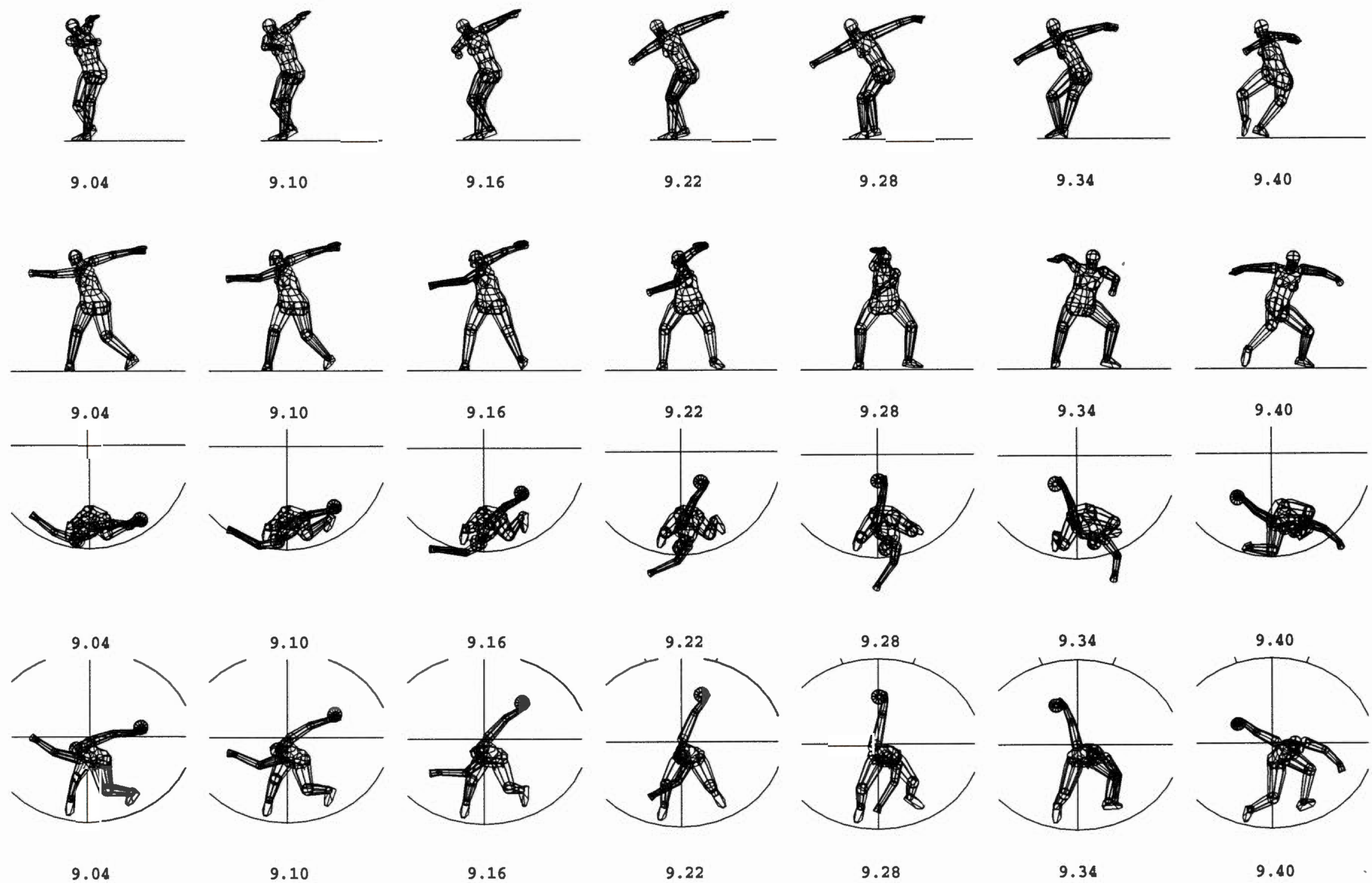

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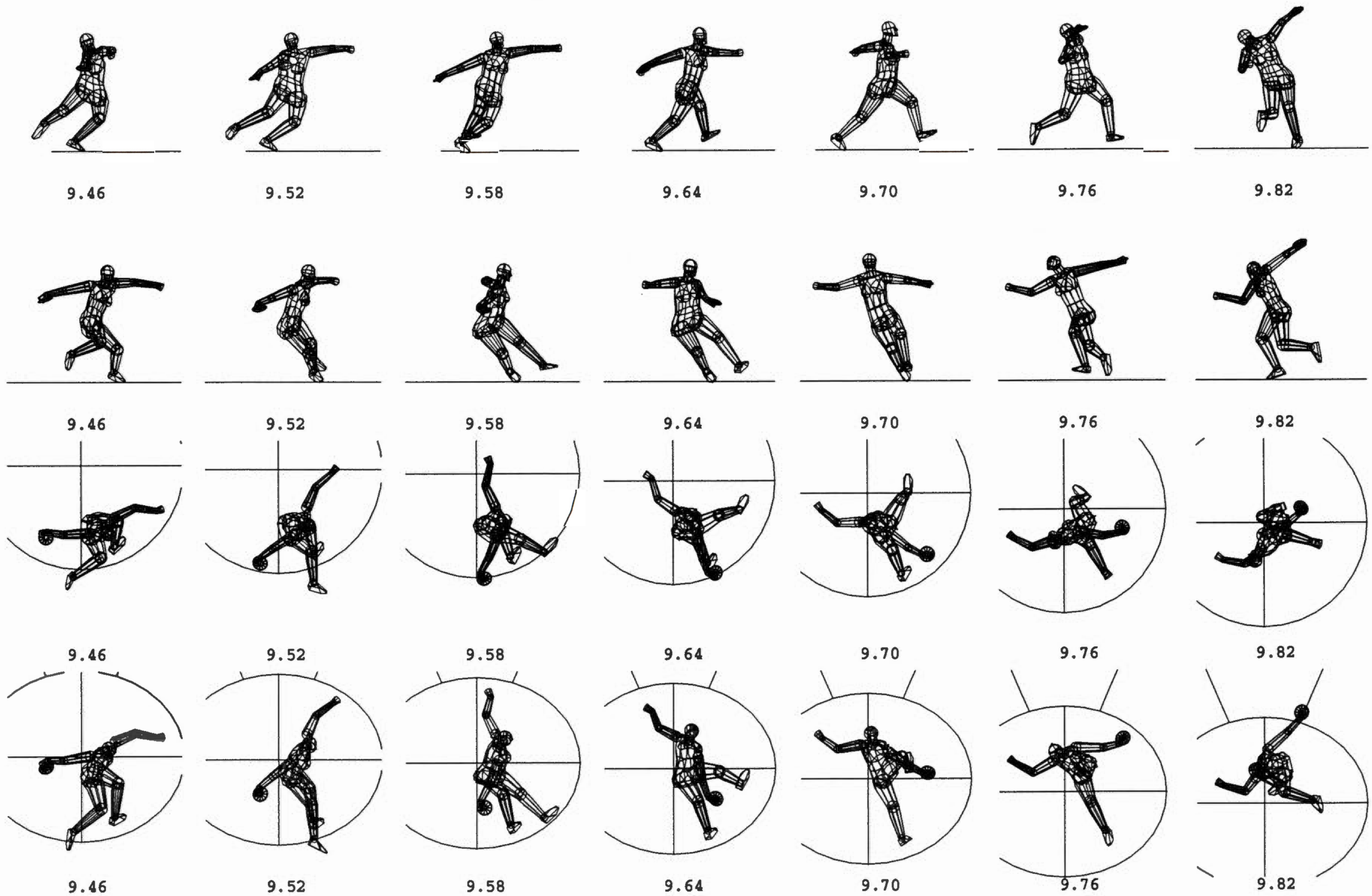

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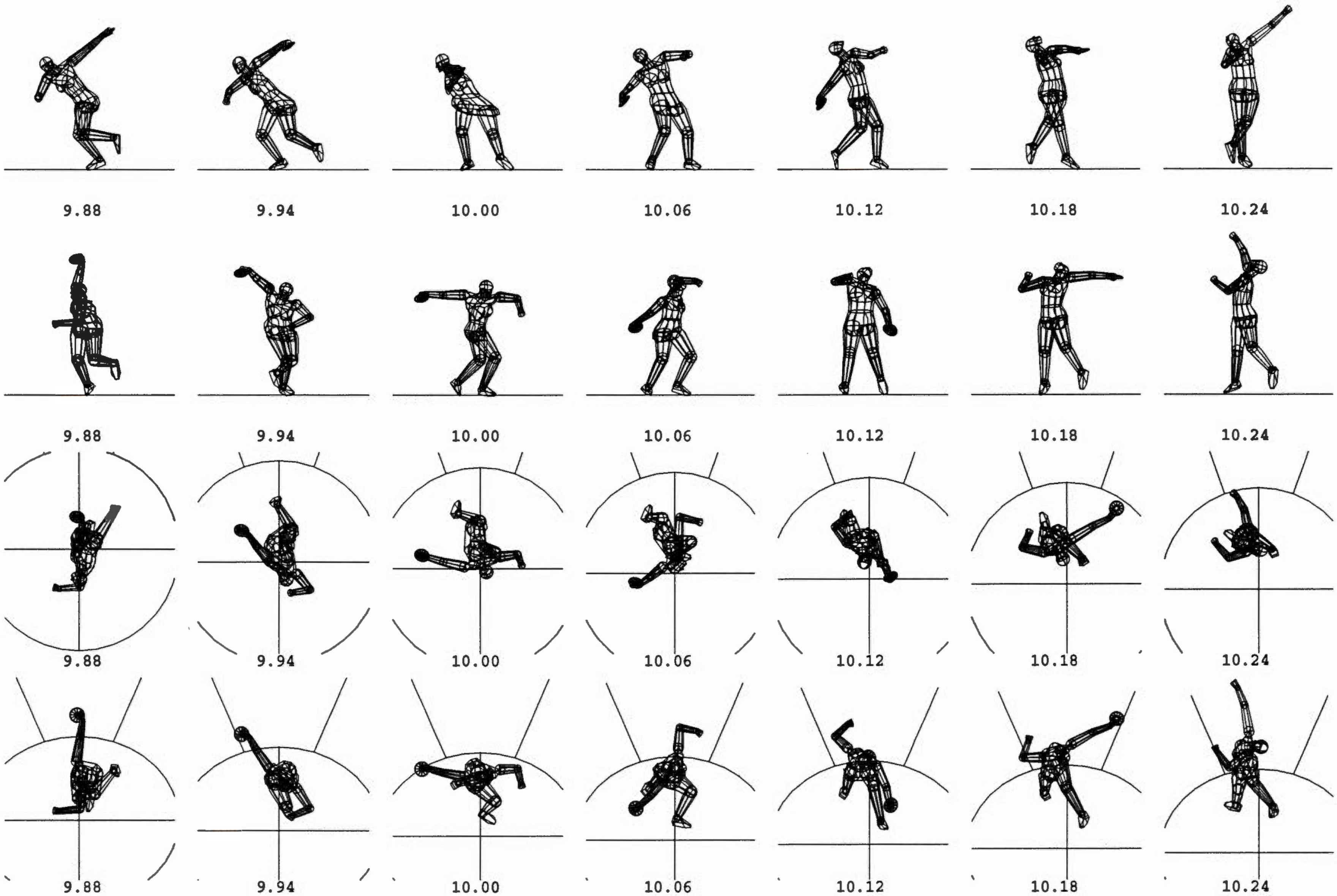

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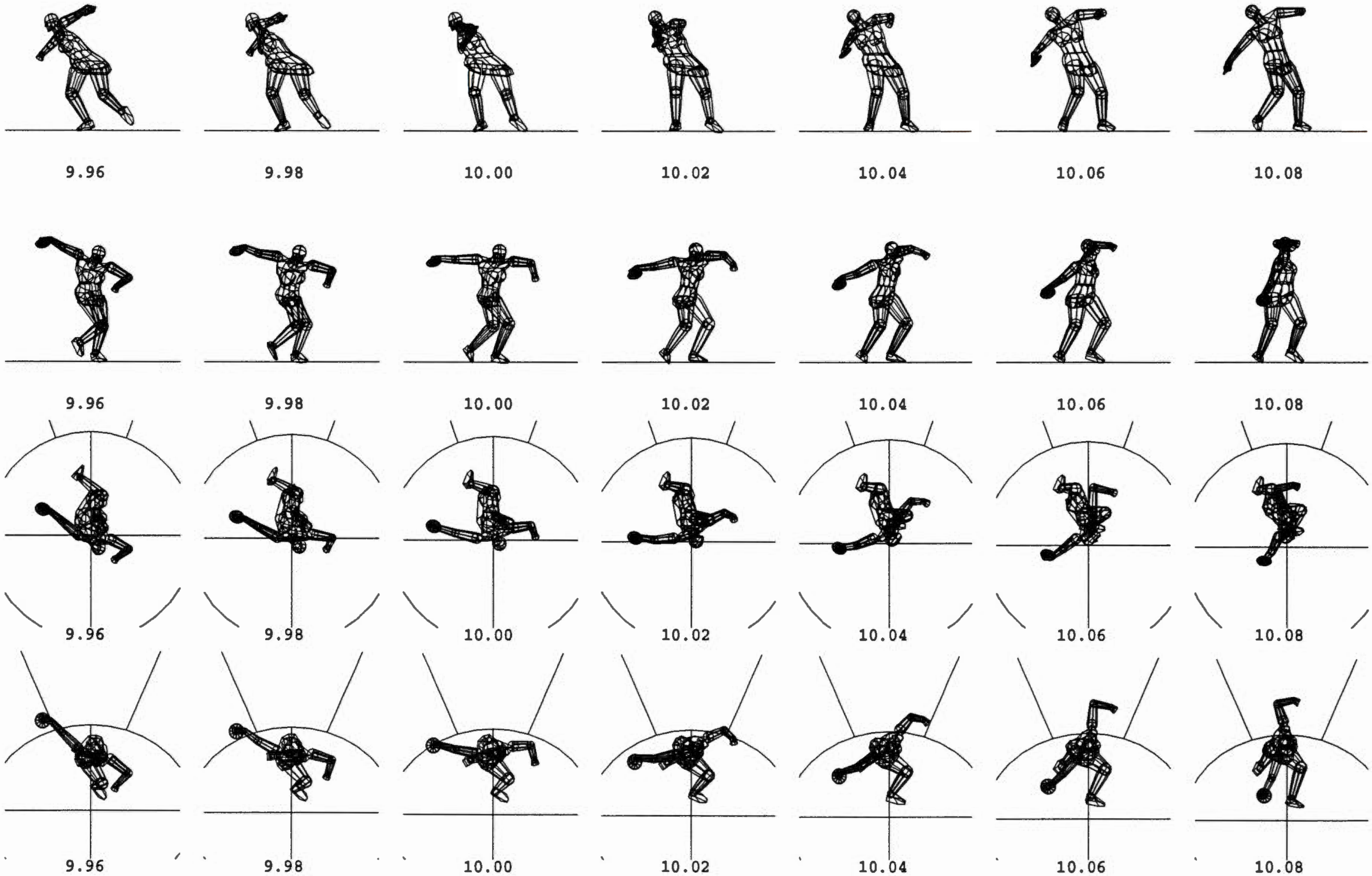

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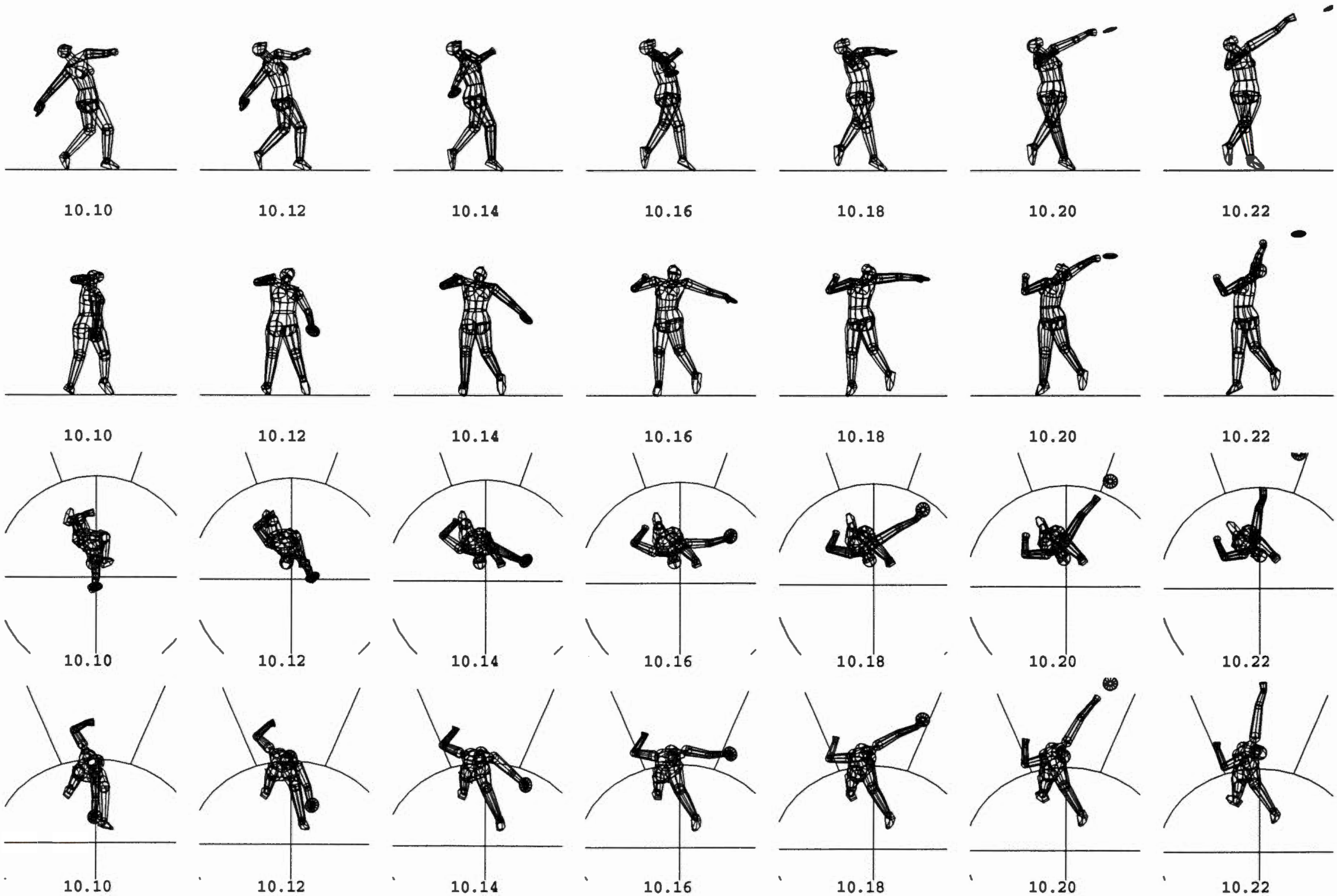

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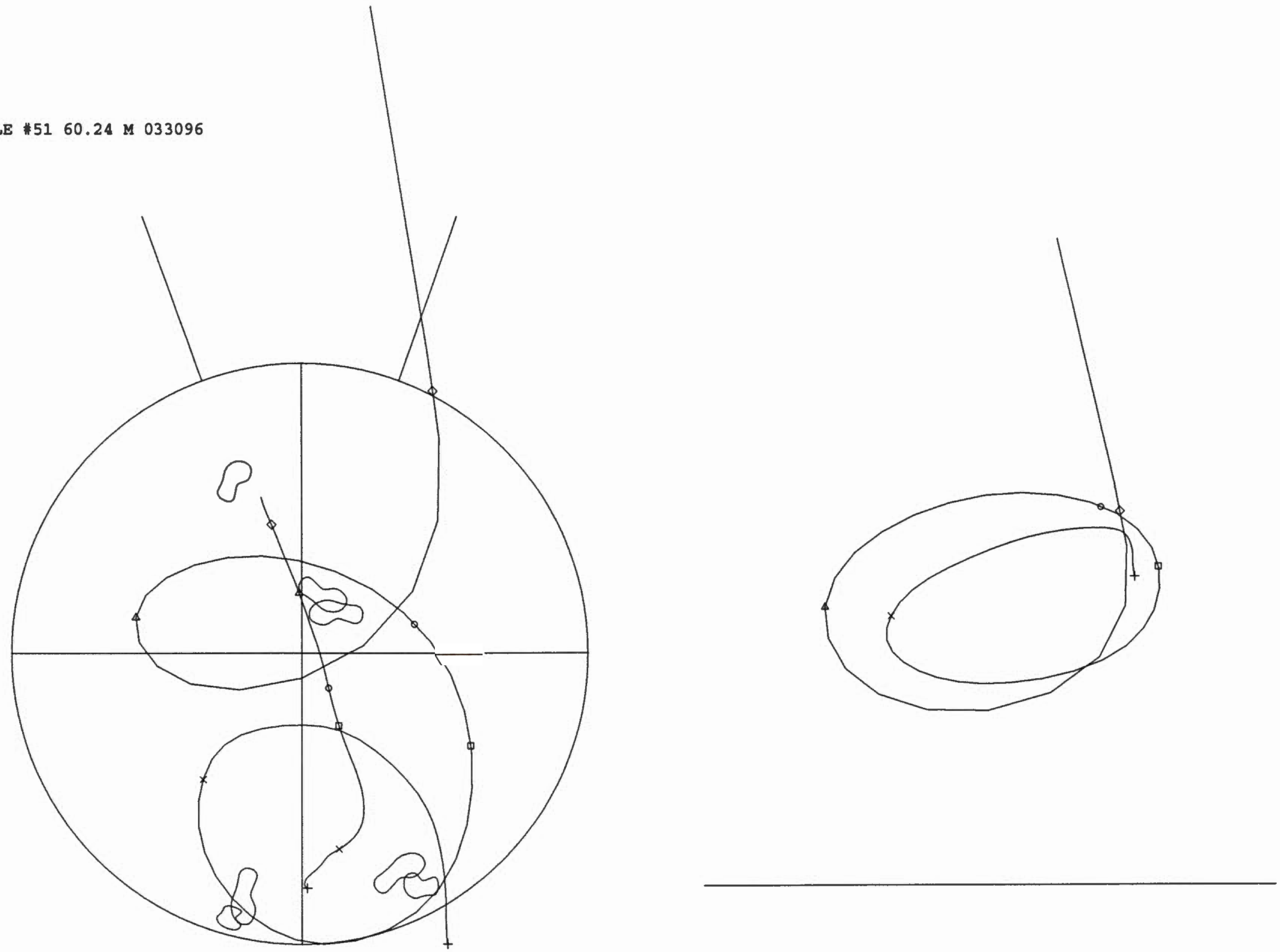

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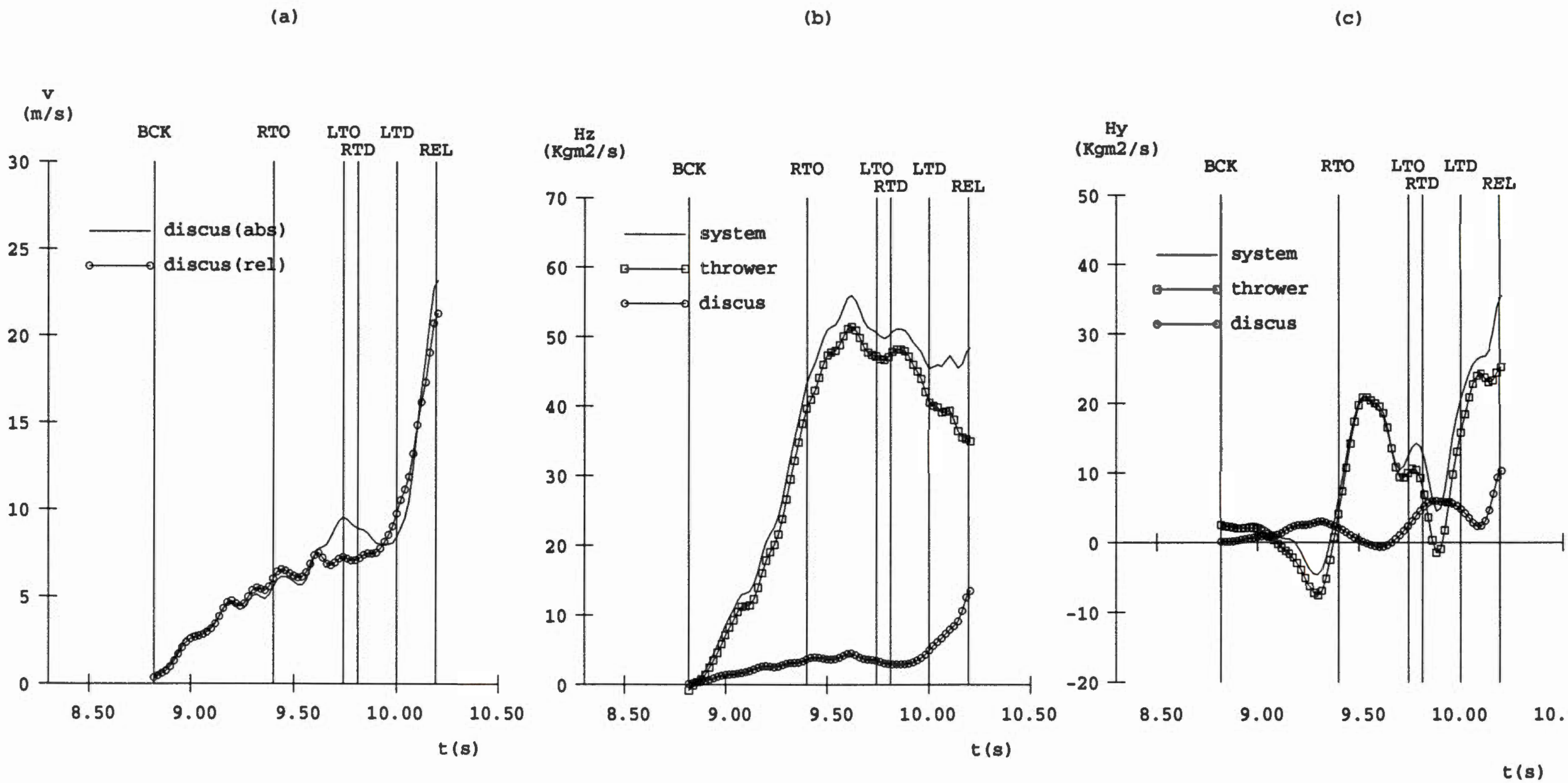
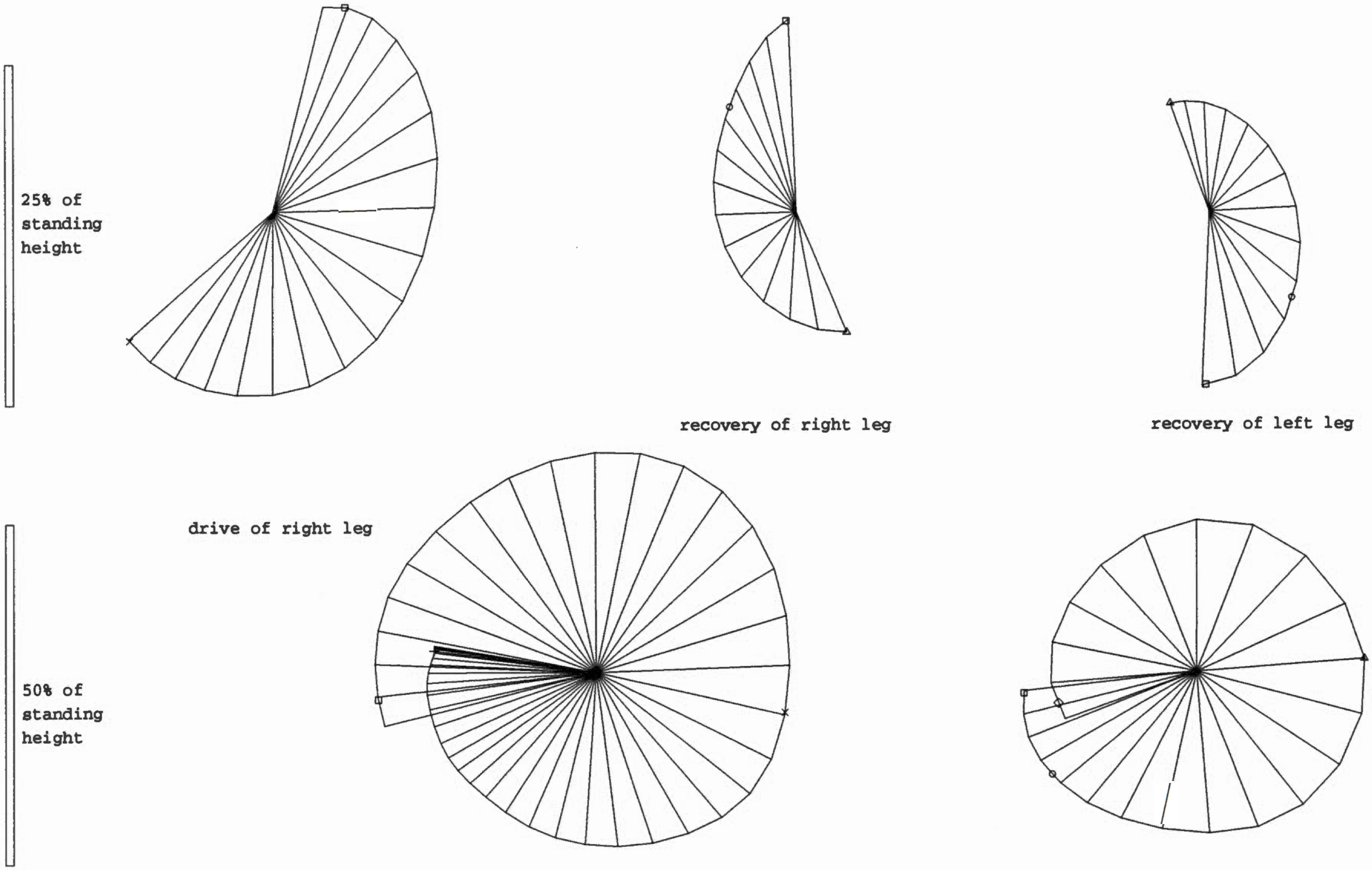
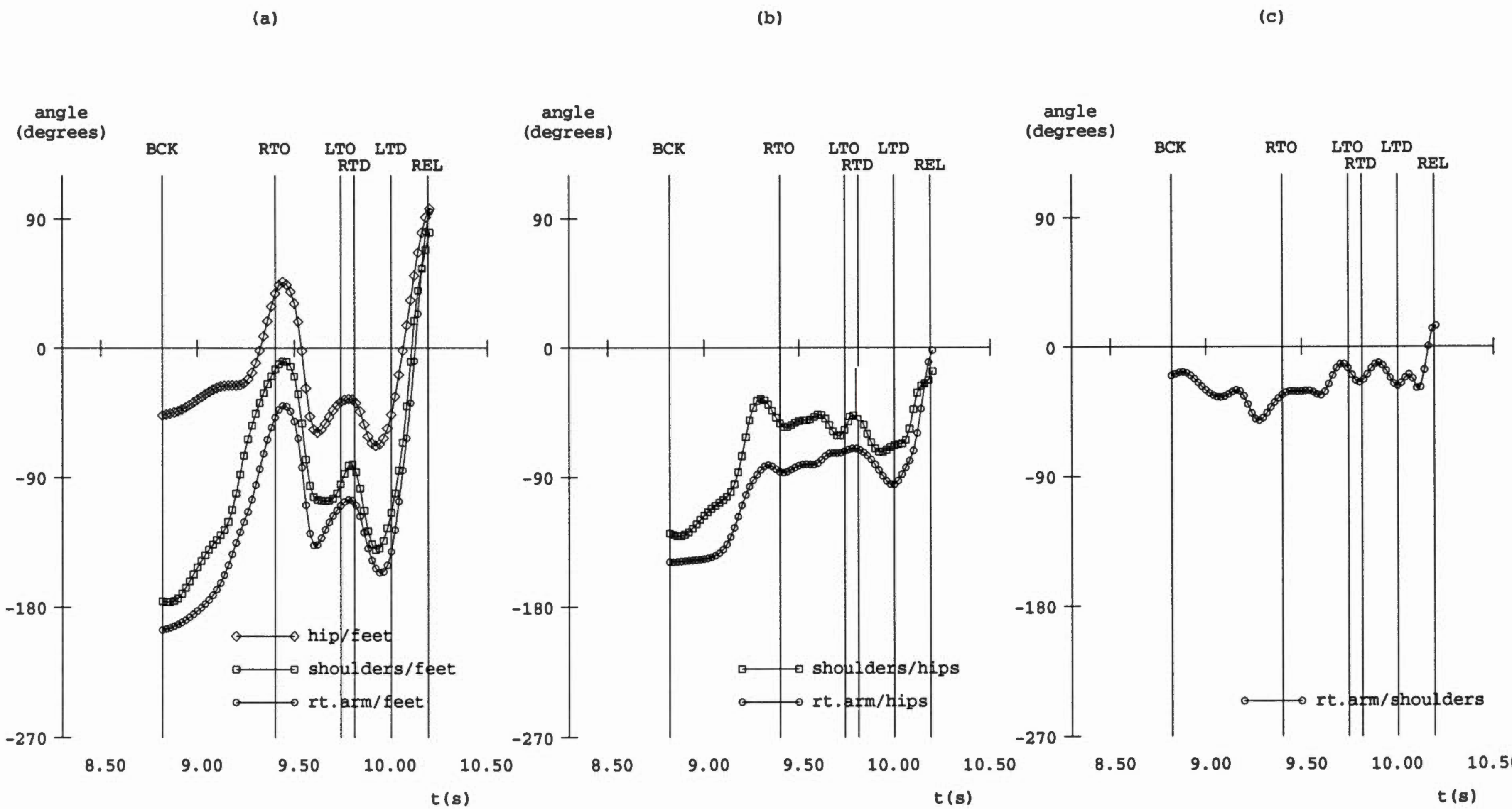




drive of left arm

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

DUMBLE #51 60.24 M 033096



Carla GARRETT

Trial 34 was Garrett's best throw at the 1996 UC San Diego Open, 58.92 m.

At the back of the circle, Garrett shifted the system c.m. toward her left foot. Then, she drove with the left leg against the ground, and traveled across the throwing circle in a direction that was not too deviated from directly forward (a_{LTO} = -27°; a_{LTD} = -12°). During the last quarter-turn of the discus, the direction of motion of the system c.m. (a_Q = -15°) was similar to that of the average thrower, and reasonably good. However, the horizontal direction of travel of the discus at release was markedly toward the right in trial 34 (d_{HREL} = 14°). This made the divergence angle between the directions of motion of the system and of the discus be somewhat too large (c_Q = -28°).

The horizontal speed of the system c.m. at the instant of takeoff of the left foot was small (v_{HLTO} = 2.0 m/s). Then, during the single support, Garrett made a strong drive with the right foot, and actually increased the horizontal speed of the system c.m. By the time that she planted the left foot on the ground, the horizontal speed of the system c.m. had been increased to a good amount (v_{HLTD} = 2.3 m/s). Then, Garrett made a rather large forward horizontal force on the ground during the double-support delivery. The backward horizontal ground reaction force reduced the horizontal speed of the system c.m., but during the last quarter-turn of the discus the horizontal speed of the system c.m. (v_{HQ} = 1.4 m/s) was still clearly larger than average. The divergence between the directions of motion of the system and of the discus in throw 34 (c_Q =-28°) reduced the contribution of the horizontal speed of the system to the horizontal speed of the discus (v_{HCON} = 1.3 m/s), but this value was still clearly larger than average.

Although Garrett pushed hard on the ground in the forward horizontal direction during the delivery, she did not push very hard in the vertical direction. In other words, her push against the ground during the delivery phase was mainly forward, and only slightly downward. This was the worst possible combination. The ground reaction to her weak vertical force gave the system a small vertical speed which only made a small contribution to the vertical speed of the discus (v_{ZCON} = 0.8 m/s).

Overall, the combination of the contributions to the speed of the discus by the horizontal and vertical translations of the system c.m. (v_{HCON} = 1.3 m/s, and v_{ZCON} = 0.8 m/s, respectively) was not particularly good.

The swinging action of the left arm at the back of the circle was very weak (LAA = 23.6 $\cdot 10^{-3}$ Kg $\cdot$ m²/ Kg $\cdot$ m²), and the swinging action of the right leg was extremely weak (RLA = 15.8 $\cdot 10^{-3}$ Kg $\cdot$ m²/Kg $\cdot$ m²). Therefore, the combination of the two was also very weak (RLLAA = 39.3 $\cdot 10^{-3}$ Kg $\cdot$ m²/Kg $\cdot$ m²). The main problem was that Garrett kept the left arm and the right leg too close to her body during the swings. She was still able to generate a reasonably large amount of Z angular momentum in the back of the circle. However, the fact that it was generated with very poor swinging actions of the left arm and of the right leg makes us think that she probably could have generated a larger amount of Z angular momentum in the back of the circle if she had used wider swinging actions of the left arm and of the right leg.

After the left foot took off from the ground, Garrett kept her legs somewhat too far apart ($r_{LAVG-NSRSS}$ = 10.7% of standing height). This slowed down the speed of rotation of the legs, and probably contributed to the somewhat small amount of wind-up torsion between Garrett's upper and lower body in the single-support on the right foot. (See below.) The recovery of Garrett's left arm was reasonably good (H_{LA-NS} = 29 $\cdot 10^{-3}$ s^{-1}, which was not too large).

The maximum angular momentum that the left arm reached in the second swing (H_{MAX} = 56 $\cdot 10^{-3}$ s^{-1}) was slightly larger than average, and the amount of angular momentum that it still had at release was very small (H_{REL} = 15 $\cdot 10^{-3}$ s^{-1}). The combination of these two factors implied a very large loss of angular momentum by the left arm in the late part of the delivery phase (ΔH = -41 $\cdot 10^{-3}$ s^{-1}), and the transfer of that angular momentum from the arm to the rest of the system, possibly to the discus. This was good.

Garrett reached a moderately wound-up position in the single-support phase over the right foot ($k_{RA/FT}$ = -135°). At the instant of maximum torsion of the system, the torsion of the shoulders relative to the hips was larger in Garrett than in the average thrower (Garrett $k_{SH/HP}$ = -89°; average = -64), while the torsion of the hips relative to the feet was smaller in Garrett than in the average thrower (Garrett $k_{HP/FT}$ = -17°; average = -43°).

Garrett transfered a good amount of the Z angular momentum of the system to the discus (27%

of the total). This gave the discus a very good amount of horizontal speed (v_{HD} = 19.4 m/s).

At release, in the view from the back of the circle the counterclockwise angular momentum of the thrower-plus-discus system was reasonably large (H_{YS} = 25.9 Kg· m²/s), but only 28% of it was transfered to the discus. In absolute terms, the Y angular momentum that was transfered to the discus was somewhat small (H_{YD} = 7.2 Kg· m²/s). Together with the small contribution by the vertical speed of the system c.m. (v_{ZCON} = 0.8 m/s), this gave the discus a somewhat small vertical speed at release (v_{ZD} = 12.4 m/s).

The resultant speed of the discus was good (v_{RD} = 23.0 m/s), similar to the speeds achieved by the other top throwers at the San Diego meet. Garrett made very effective use of aerodynamic forces (ΔD = 8.19 m). In this respect, she was better than most of the other top throwers at the San Diego meet, although not as effective as Barnes-Mileham.

Summary

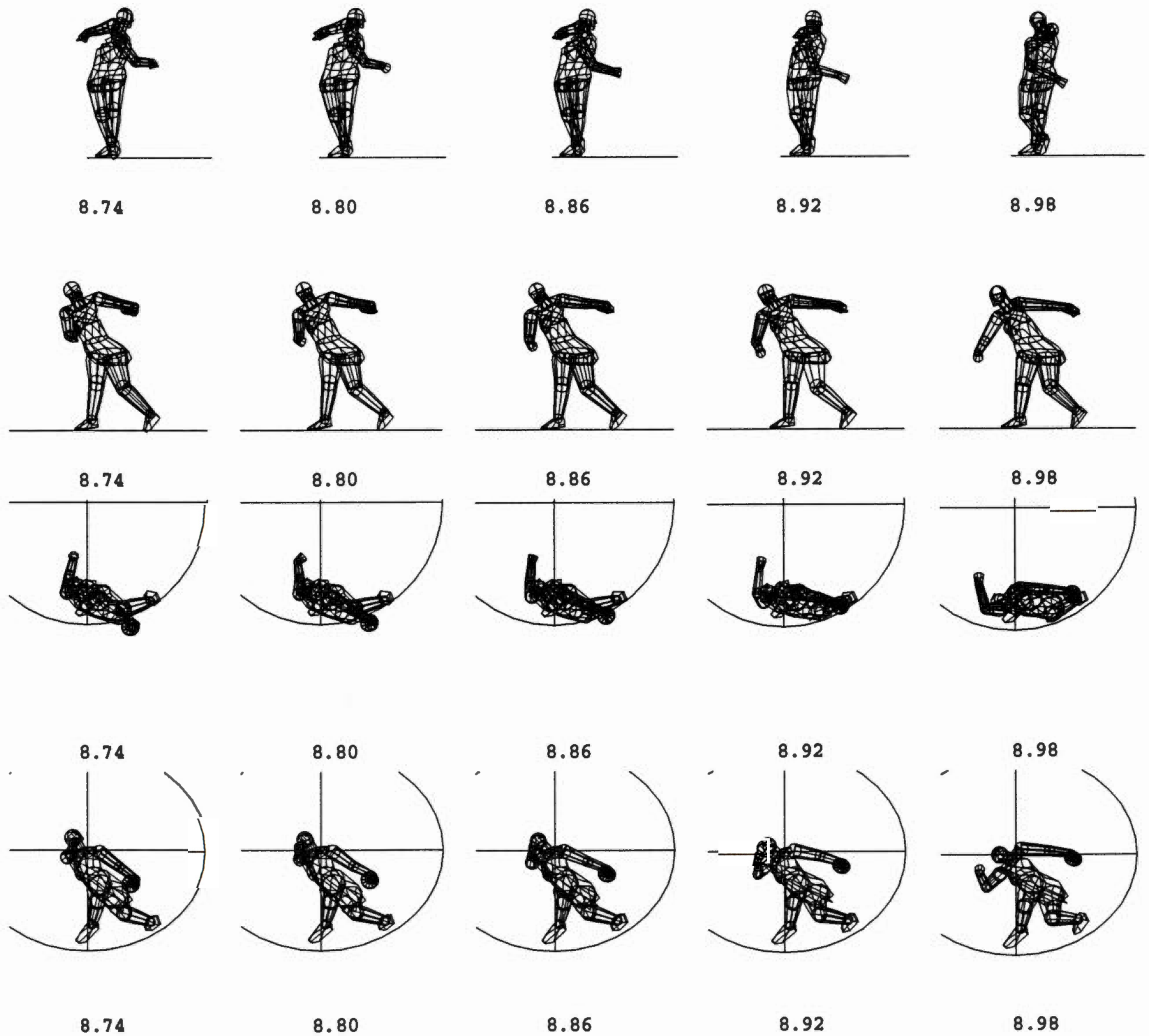
The direction of the horizontal translation of the system c.m. across the throwing circle was not too diagonal. However, the discus traveled too far toward the right after release, and this increased the divergence angle to a value that was somewhat too large. Garrett's initial horizontal speed at the takeoff of the left foot from the back of the circle was small, but she increased it to a good value through a strong drive of the right leg in the middle of the circle. During the delivery phase, Garrett exerted on the ground a rather large horizontal force and a small vertical force. The contribution of the horizontal speed of the system to the horizontal speed of the discus was somewhat larger than average, while the contribution of the vertical speed of the system to the vertical speed of the discus was small. This part of her technique was not particularly good. The swinging actions of the right leg and of the left arm in the back of the circle were very weak. Although Garrett generated a reasonably large amount of Z angular momentum at the back of the circle, she probably could have generated more if she had used wider motions of her left arm and right leg. The recovery actions of the legs after the takeoff of the left foot from the ground were slightly worse than average, while the recovery action of the left arm was reasonably good. In the front of the circle, Garrett made a strong swing of her left arm, and then slowed it down very well prior to release. She produced a moderate torsion angle between the right arm and the feet. The transfer of angular momentum from the body to the discus was overall good; the transfer of the Z angular momnentum was better than the transfer of the Y angular momentum. Garrett made good use of aerodynamic forces.

Recommendations

In the back of the circle, Garrett should swing her left arm and right leg farther from her body. The arm should be less flexed at the elbow, and the right foot should "flare out" much more than in trial 34. This will allow her to get more Z angular momentum from the ground. (NOTE: It is important that she bring the right leg back below the body after the left foot takes off from the ground.) A larger amount of angular momentum in the system will later facilitate the transfer of a larger amount of angular momentum to the discus. The result will be a larger horizontal speed of the discus, and a longer throw.

During the delivery phase, Garrett should extend her legs very actively against the ground. This will increase the vertical speed of the system c.m., and therefore the contribution of the vertical motion of the system to the vertical speed of the discus.

GARRETT #34 58.92 M 033096



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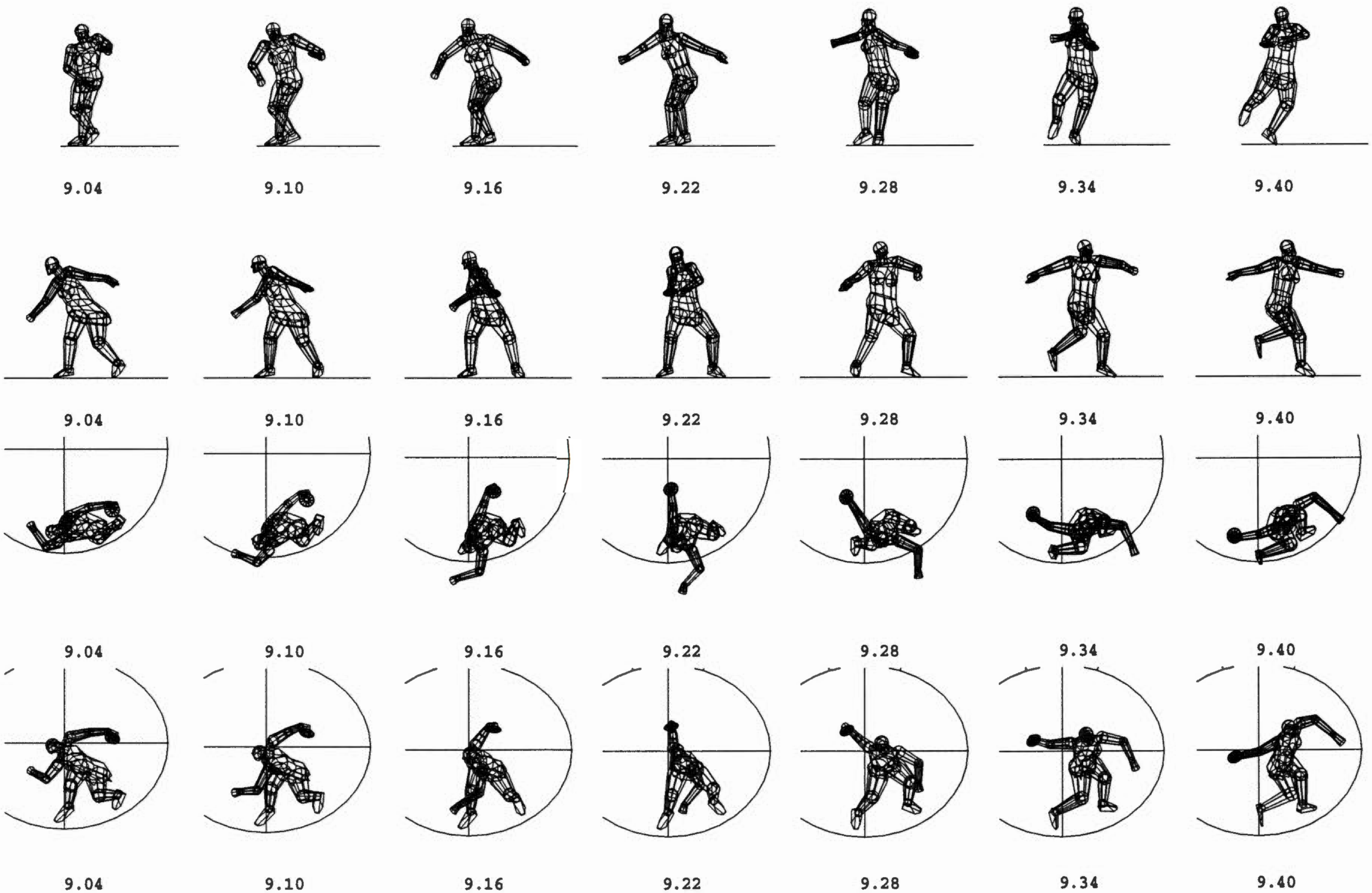

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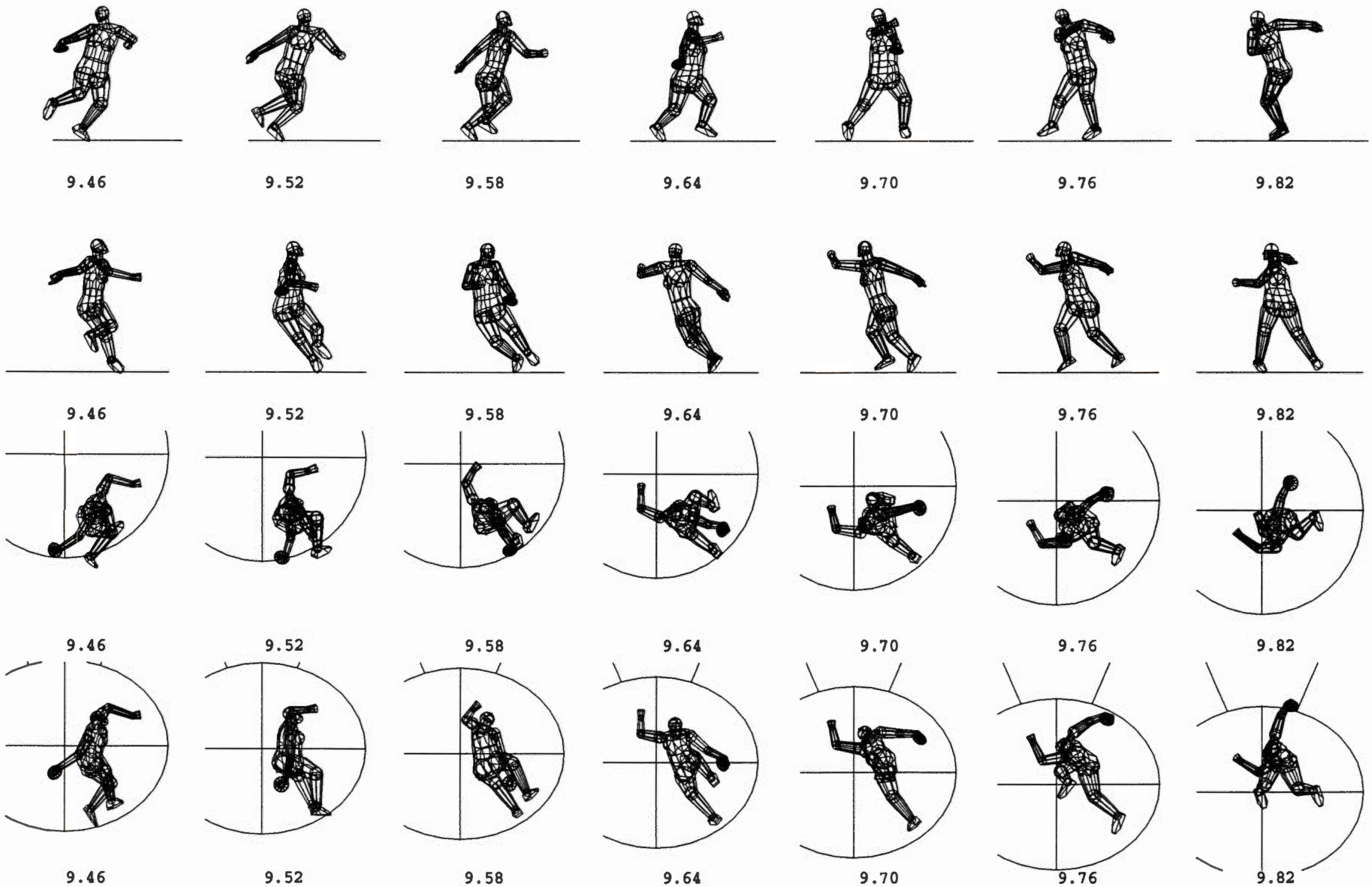

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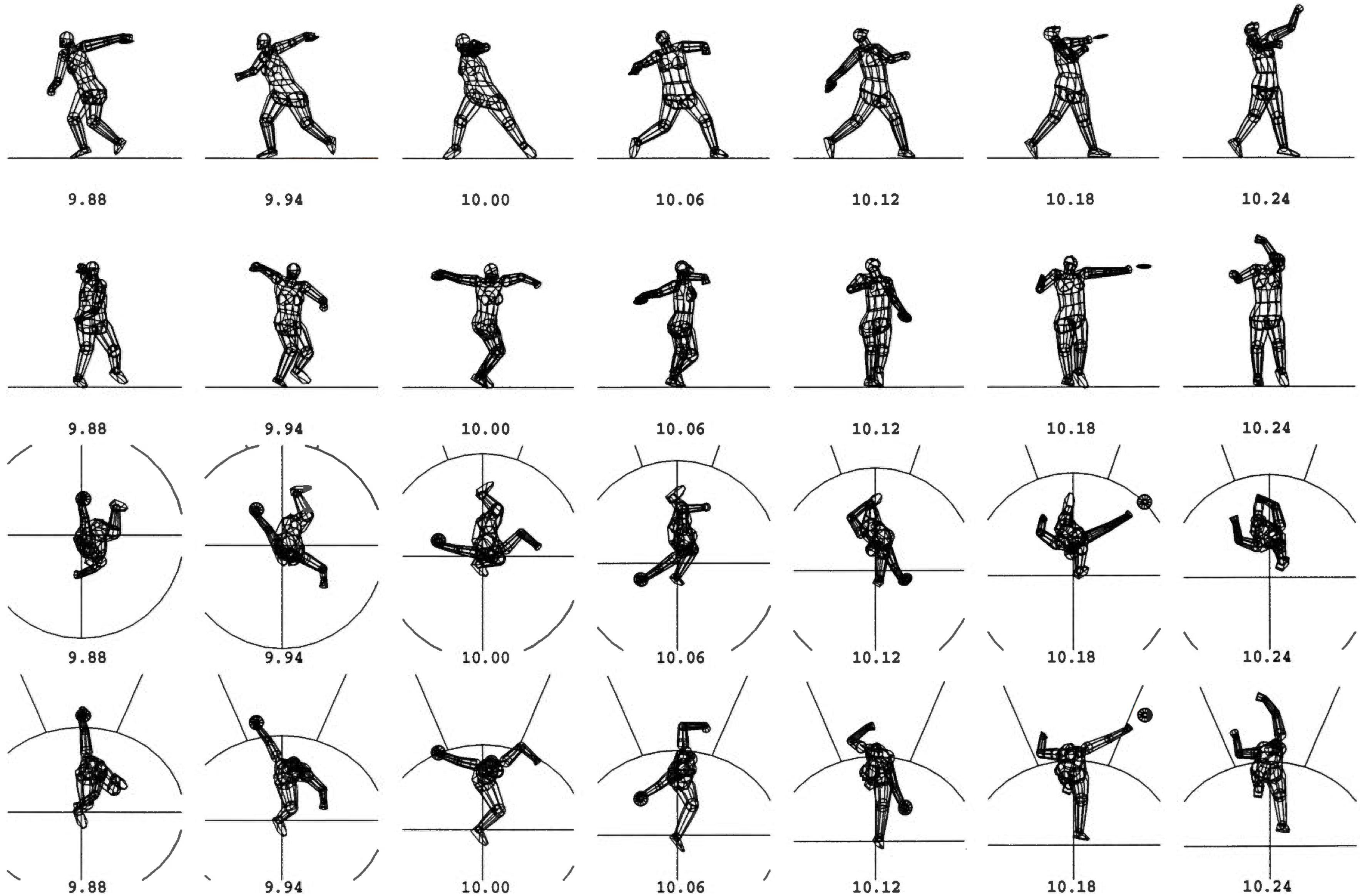

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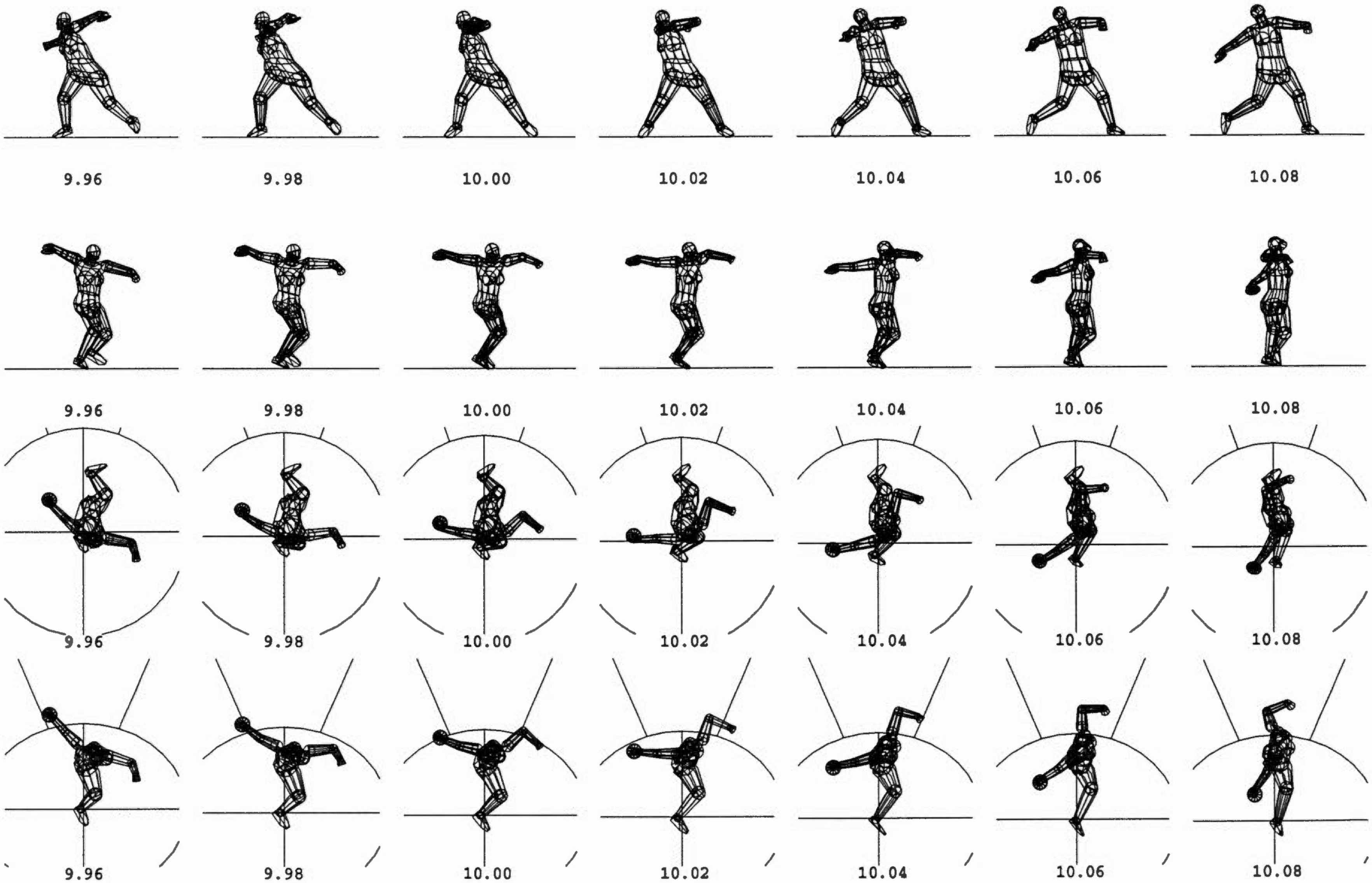

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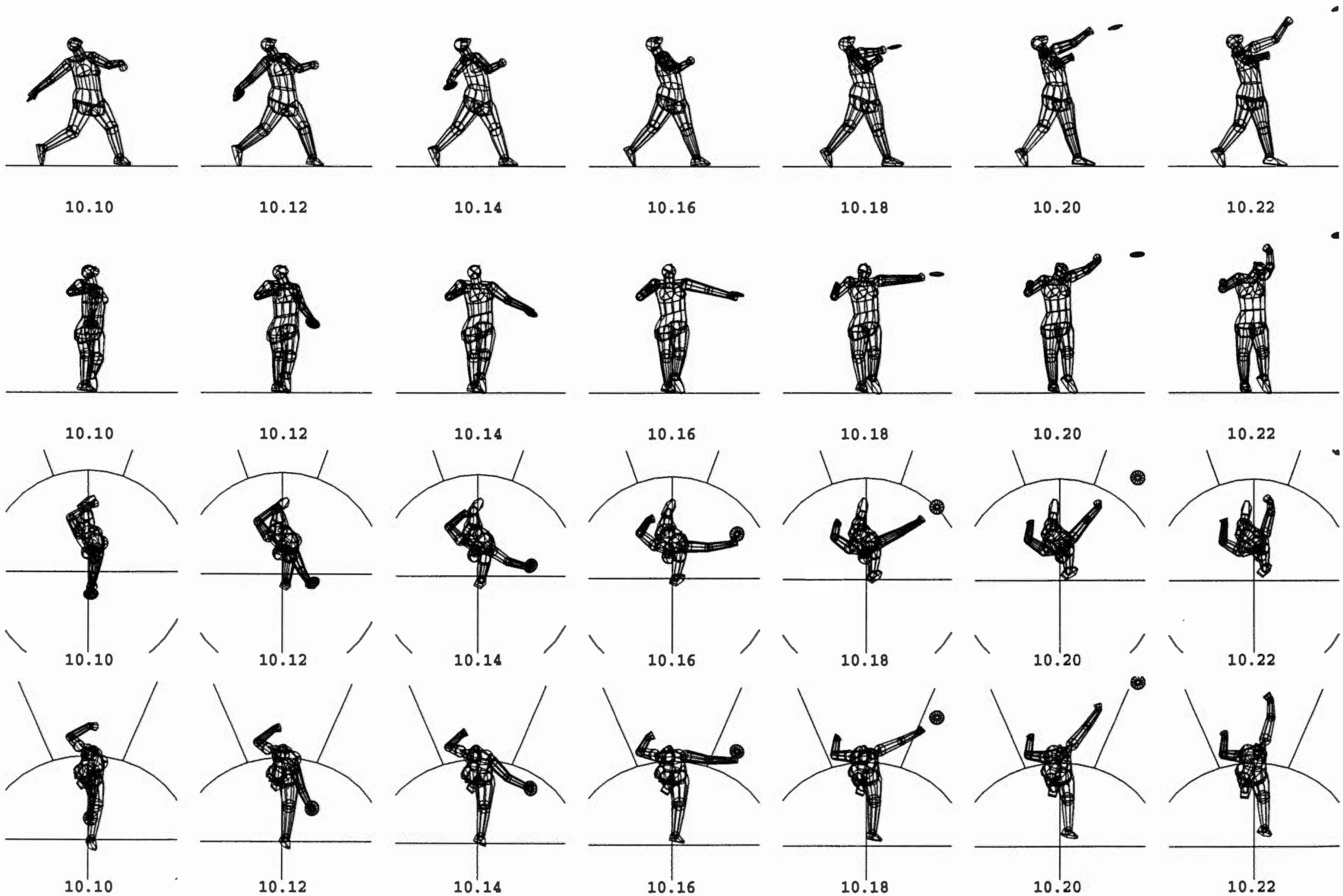

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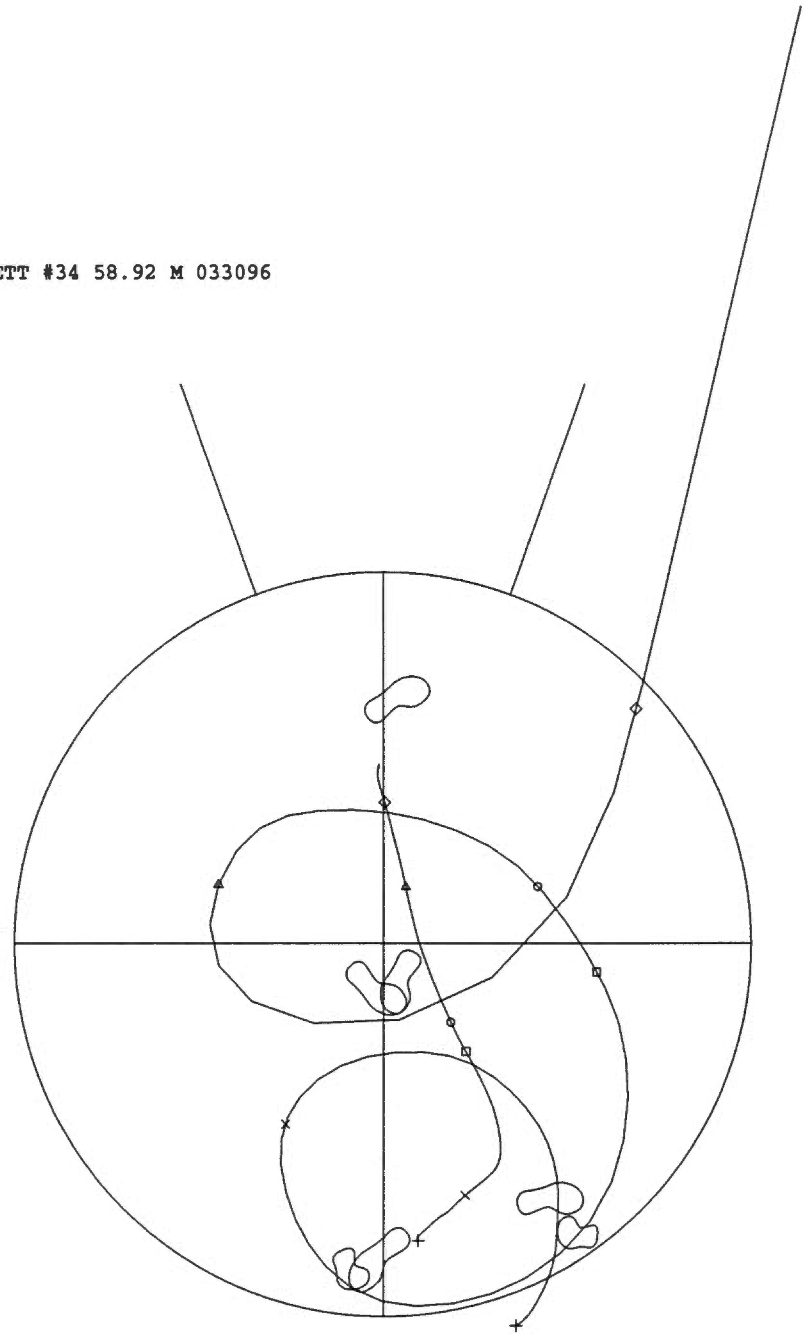

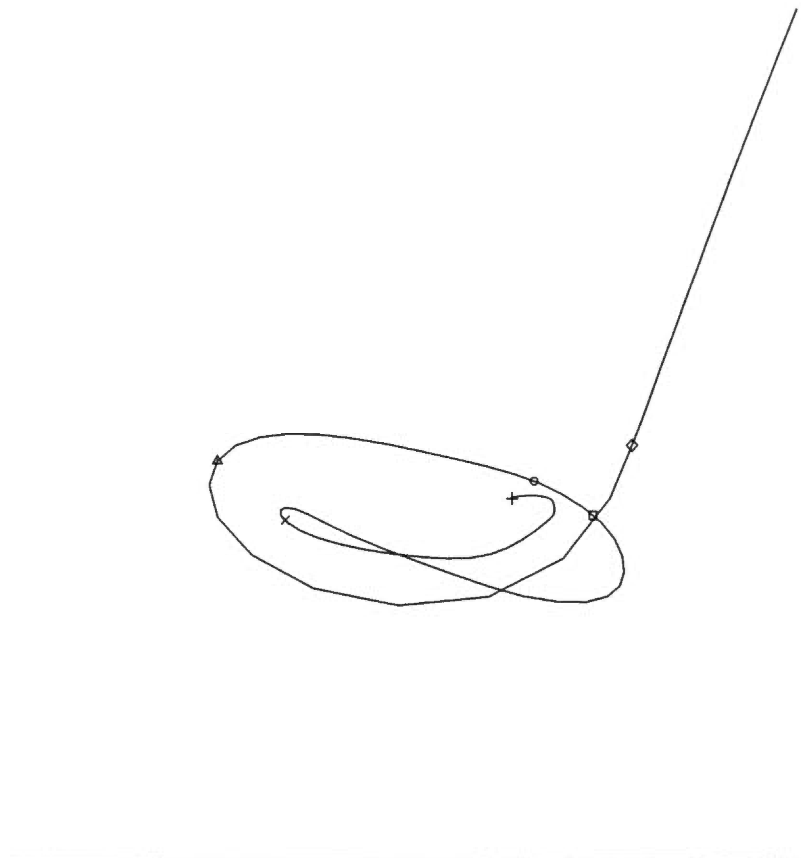

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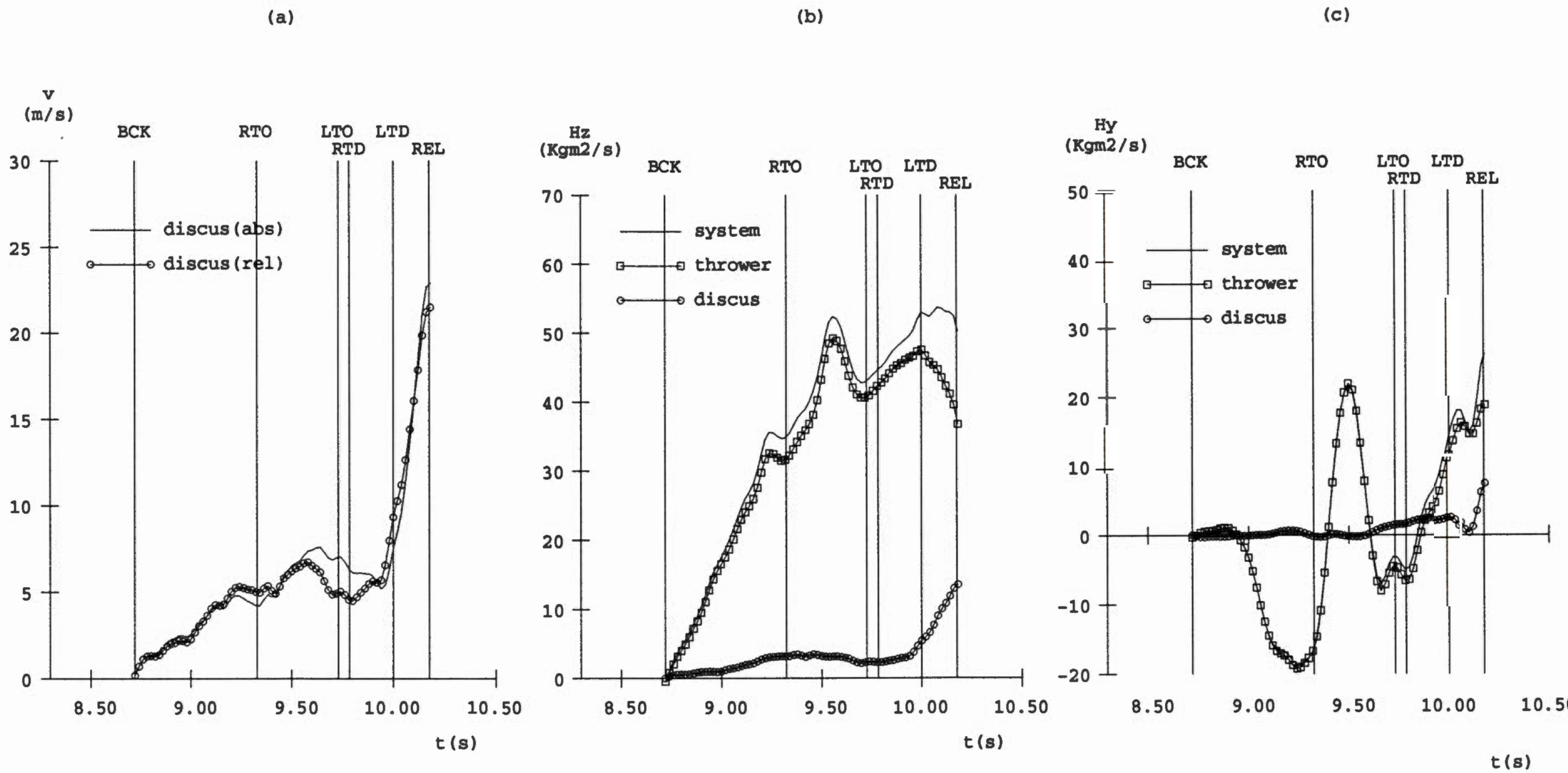

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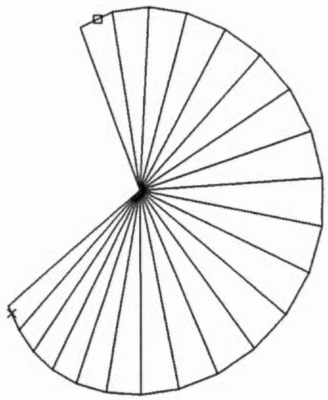
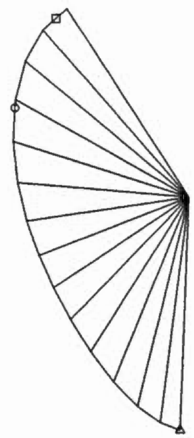
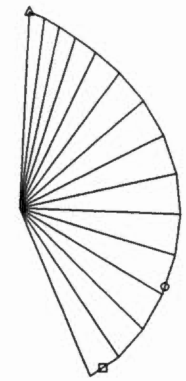
25% of
standing
height



drive of right leg

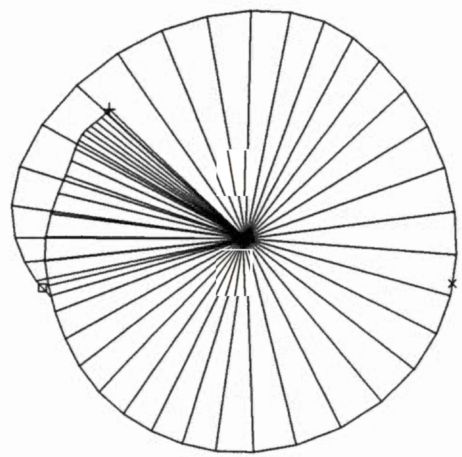


recovery of right leg

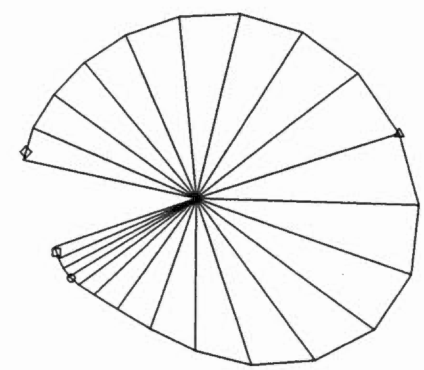


recovery of left leg

50% of
standing
height

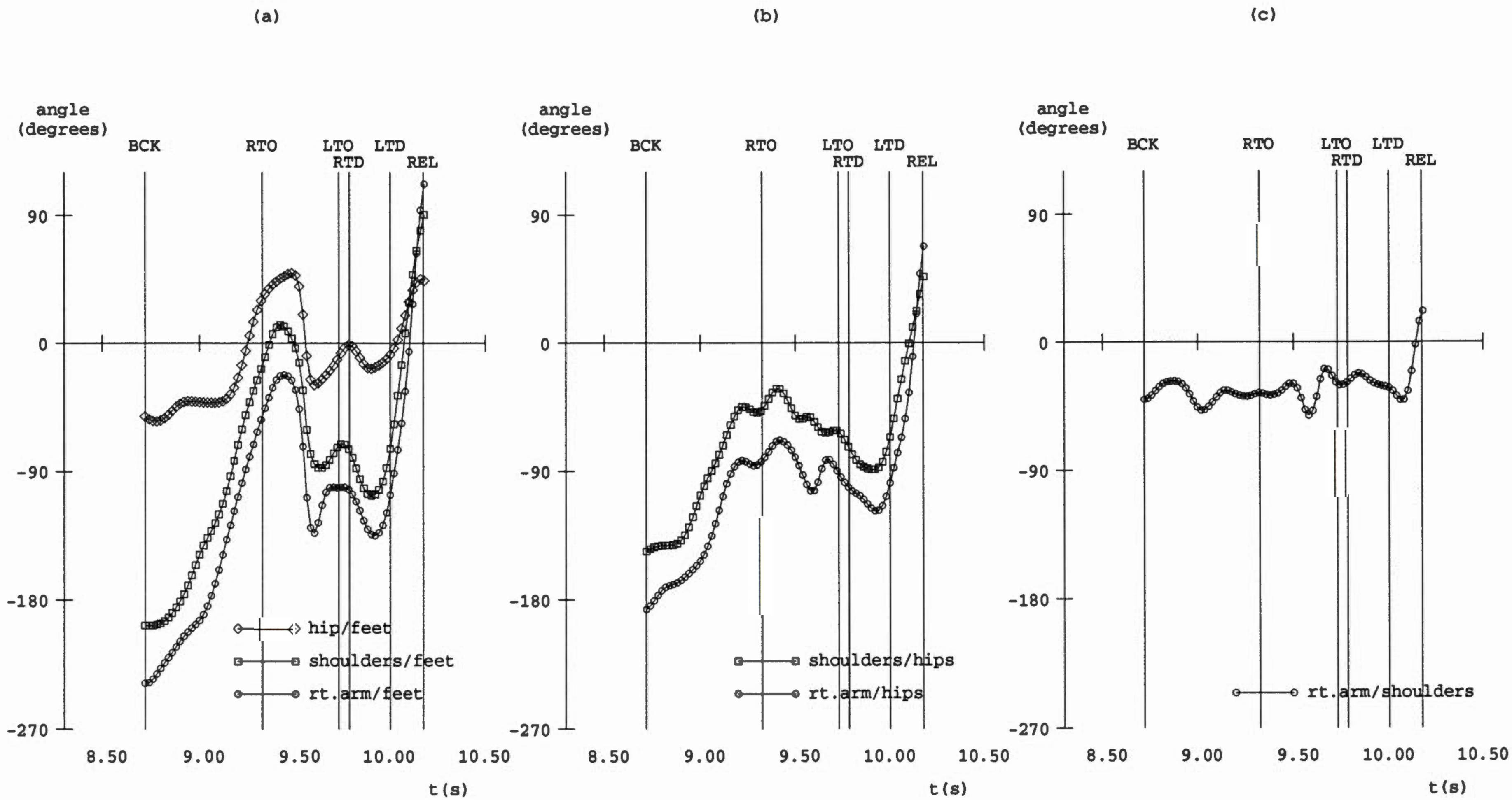


drive of left arm



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

GARRETT #34 58.92 M 033096



Rachelle NOBLE

Trial 05 was Noble's personal record, 59.20 m, thrown at the 1996 UC San Diego Open.

At the back of the circle, Noble shifted the system c.m. toward her left foot. Then, she drove with the left leg against the ground, and traveled across the throwing circle in a direction that was not too deviated from directly forward (a_{LTO} = -23°; a_{LTD} = -15°). During the last quarter-turn of the discus, the c.m. was traveling only slightly toward the left (a_Q = -11°). The horizontal direction of travel of the discus at release was also slightly toward the left in trial 05 (d_{HREL} = -6°), while in most other throwers it was toward the right. Because of this, the divergence angle between the directions of motion of the system and of the discus was very small (c_Q = -5°).

The horizontal speed of the system c.m. across the throwing circle was very large (v_{HLTO} = 2.7 m/s; v_{HLTD} = 2.3 m/s). Then, Noble made a large forward and downward force on the ground during the double-support delivery. The backward horizontal reaction force reduced considerably the horizontal speed of the system c.m. However, due to Noble's large initial horizontal speed, during the last quarter-turn of the discus the horizontal speed of the system c.m. was still larger than average (v_{HQ} = 1.3 m/s). Since the divergence angle between the directions of motion of the system and of the discus was very small (c_Q = -5°), the contribution of the horizontal speed of the system to the horizontal speed of the discus was clearly larger than average (v_{HCON} = 1.3 m/s).

As previously mentioned, during the double-support delivery Noble pushed very hard forward and downward against the ground. When a discus thrower pushes hard forward on the ground during the delivery phase, there is generally also a tendency to push hard *downward*, and Noble was no exception. Although the large horizontal forward push made the system c.m. lose a fairly large amount of forward speed (as we saw before), the large downward component of the push also made the system *gain* a large amount of vertical speed, which made a very large contribution to the vertical speed of the discus (v_{ZCON} = 1.7 m/s).

The combination of the contributions which we have just seen to the speed of the discus by the horizontal and vertical translations of the system c.m. (v_{HCON} = 1.3 m/s, and v_{ZCON} = 1.7 m/s, respectively) was excellent.

The swinging actions of the right leg and of the left arm at the back of the circle were excellent (RLA = 36.4 · 10^{-3} Kg· m²/Kg· m²; LAA = 33.8 · 10^{-3} Kg· m²/Kg· m²), and of course, so was their sum (RLLAA = 70.2 · 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 (90%) of the Z angular momentum (counterclockwise rotation in a view from overhead) that it would eventually reach at release. All this suggests that Noble's generation of Z angular momentum in the back of the circle was very good.

After the left foot took off from the ground, Noble kept her legs too far apart ($r_{LAVG-NSRSS}$ = 11.0% of standing height). This slowed down the speed of rotation of the legs, and probably contributed to the small amount of wind-up torsion between Noble's upper and lower body in the single-support on the right foot. (See below.) This may have had a detrimental effect on her performance.

Noble left a very large amount of counterclockwise angular momentum in her left arm during the non-support phase in the middle of the throw (H_{LA-NS} = 44 · 10^{-3} s^{-1}). In part, this was due to the fact that she kept the left arm too far from the body (r_{LA-NS} = 28.5% of standing height), and in part to the fact that she allowed the left arm to continue rotating counterclockwise too fast during the non-support phase. As a result, the left arm did not make available (i.e., did not transfer) much of its own angular momentum to the rest of the system, and thus it also did not contribute much to the counterclockwise rotation of the lower body in the middle part of the throw.

The insufficient slowing down of the rotation of the left arm during the non-support phase also made the left arm travel too far counterclockwise during the non-support phase, and thus limited the range of motion available for its second propulsive swing. However, the second propulsive swing of the left arm (LAA2 = 21.1 · 10^{-3} Kg·m²/Kg· m²) was still very good (in fact, excellent), probably due to the fact that Noble kept the arm almost completely straight during the swing. The maximum angular momentum that the left arm reached (H_{MAX} = 68 · 10^{-3} s^{-1}) was very large, and then Noble reduced it very much (ΔH = -38 · 10^{-3} s^{-1}) prior to the release of the discus. The angular momentum lost by the arm was transfered to the rest of the system, possibly to the discus. This was all done very well.

A weakness of Noble's technique was the maximum torsion that she achieved in the front of the circle, which was too small ($k_{RA/FT}$ = -126°), clearly smaller than average (-141°). The main disadvantage that Noble had with respect to the average thrower in the sample at the instant of maximum torsion of the system was the smaller torsion of her shoulders relative to her hips (Noble $k_{SH/HP}$ = -53°; average = -64°). The origin of this problem was the large separation of the legs during the non-support phase, and possibly also the insufficient slowing down of the counterclockwise rotation of the left arm during the same period.

In spite of her rather small amount of maximum torsion, Noble transfered a good amount of the Z angular momentum of the system to the discus (28% of the total). This enabled her to give a good amount of horizontal speed to the discus (v_{HD} = 19.0 m/s).

At this point, we need to consider the question of Noble's lean. In the view from the back, Noble was leaning markedly toward the right at the instant of release. (See the sequence of images at t = 10.18/ 10.20 s.) This shifted the right shoulder toward the right, and in the view from overhead took the discus farther from the system c.m. For a given amount of Z angular momentum of the discus, the longer 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 ***slower*** 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. However, we still want to give a warning about this problem to the throwers who tilt very much toward the right at the instant of release, such as Noble.) By tilting her body toward the right near the instant of release, Noble lengthened the distance between the c.m. and the discus (in effect, she lengthened the radius of motion of the discus), and thus decreased the horizontal speed of the discus in relation to what it might have been if she had kept a shorter radius.

At release, in the view from the back of the circle the counterclockwise angular momentum of the thrower-plus-discus system was very small (H_{YS} = 11.1 Kg·m²/s). (The small size of this angular momentum during the late stages of the delivery is what made Noble have a greater lean toward the right at release than most other throwers.) Fortunately, most of this Y angular momentum (87% of it) was transfered to the discus, and therefore in absolute terms the discus had a very good amount of Y angular momentum at release (H_{YD} = 9.7 Kg·m²/s). This gave the discus a reasonably good vertical speed at release (v_{ZD} = 13.3 m/s).

We saw before that Noble's lean toward the right at release affected the horizontal speed of the discus. We will see now that it also affected the vertical speed of the discus. The shift of the right shoulder toward the right 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 vertical speed of the discus. By tilting her body toward the right near the instant of release, Noble produced a long distance between the system c.m. and the discus (in effect, she lengthened the radius of motion of the discus in the view from the back), and thus decreased the vertical speed of the discus.

The resultant speed of the discus was good (v_{RD} = 23.1 m/s), similar to the speeds achieved by the other top throwers at the San Diego meet. Noble made reasonably effective use of aerodynamic forces (ΔD = 5.91 m). In this respect, she was similar to most of the other top throwers at the San Diego meet, but not nearly as effective as Barnes-Mileham.

Summary

The direction of the horizontal translation of the system c.m. was not too diagonal. After release, the discus traveled slightly toward the left, and this limited the divergence angle to a very small value. Noble traveled horizontally very fast across the circle. Then, in the front of the circle she exerted on the ground very large forward and downward forces. This resulted in a reasonably large contribution of the horizontal speed of the system to the horizontal speed of the discus and a very large contribution of the vertical speed of the system to the vertical speed of the discus. The swinging actions of the left arm and right leg in the back of the circle were very strong, and the generation of Z angular momentum in the back of the circle was good. She kept the legs too far apart after the takeoff of the left foot from the ground, and this may have led to the small amount of torsion between the right arm and the feet in the single-support over the right foot. The left arm did not slow down very much during the non-support phase in the middle of the throw, and this limited the range of motion that it had available for its second propulsive swing in the front of the circle. However, Noble was still able to swing the left arm very hard in the front of the circle, and she then slowed it down very well prior to release. Noble transfered a good amount of Z angular momentum from her body to the discus. She had very little Y angular momentum, but she was able to transfer most of it to the discus. Her marked tilt toward the right at release may have limited the horizontal and vertical speeds of the discus.

Recommendations

Noble's technique was overall very good. We believe that the main problem in it may be her excessive tilt toward the right at release. If she kept the body more vertical during the delivery, we think that she would probably be able to produce a greater increase in the speed of the discus.

Another possible problem is Noble's small amount of torsion during the single-support on the right foot. To correct this problem, Noble should bring her feet closer together after the left foot takes off from the ground. She should also momentarily slow down the counterclockwise rotation of the left arm while she is in the air in the middle of the throw. She should also use her trunk musculature to make her hips rotate markedly ahead of her shoulders. These actions will produce a more wound-up configuration of the system in the single-support on the right foot, and they will help Noble to make a greater transfer of angular momentum from the body to the discus as the system unwinds. (NOTE: She should not forget to accelerate the left arm counterclockwise again after the right foot lands, and then to decelerate it before release.)

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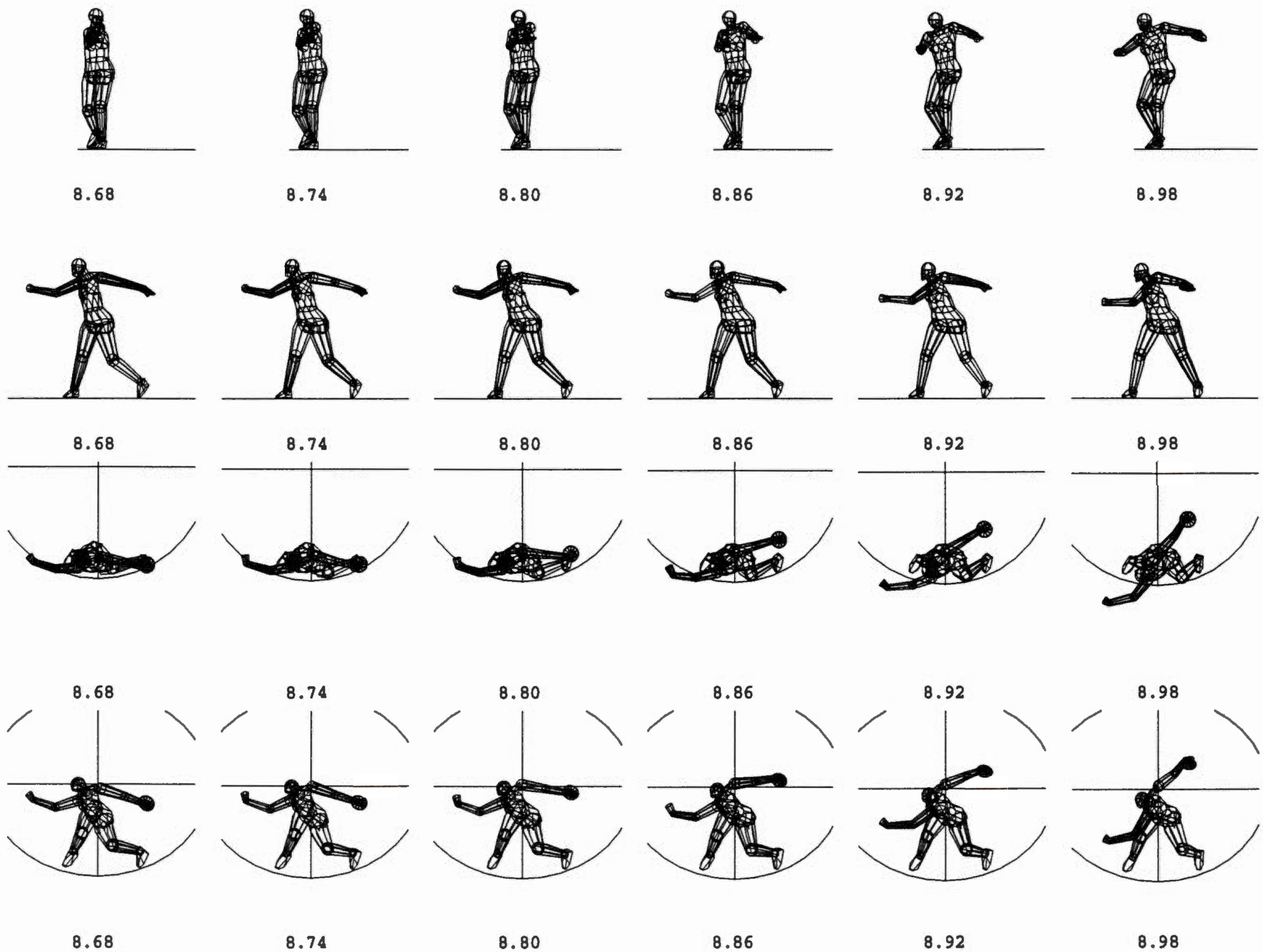

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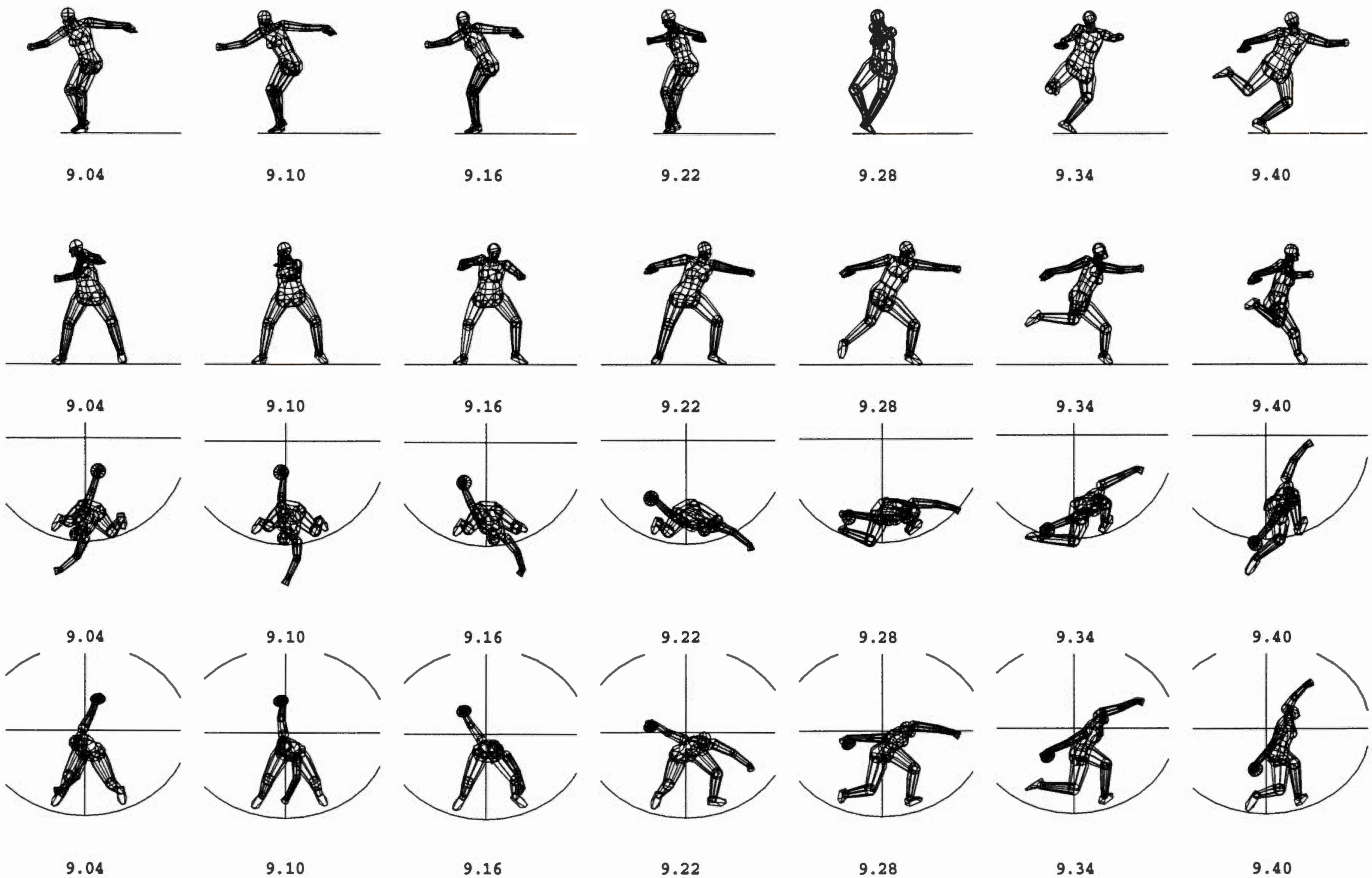

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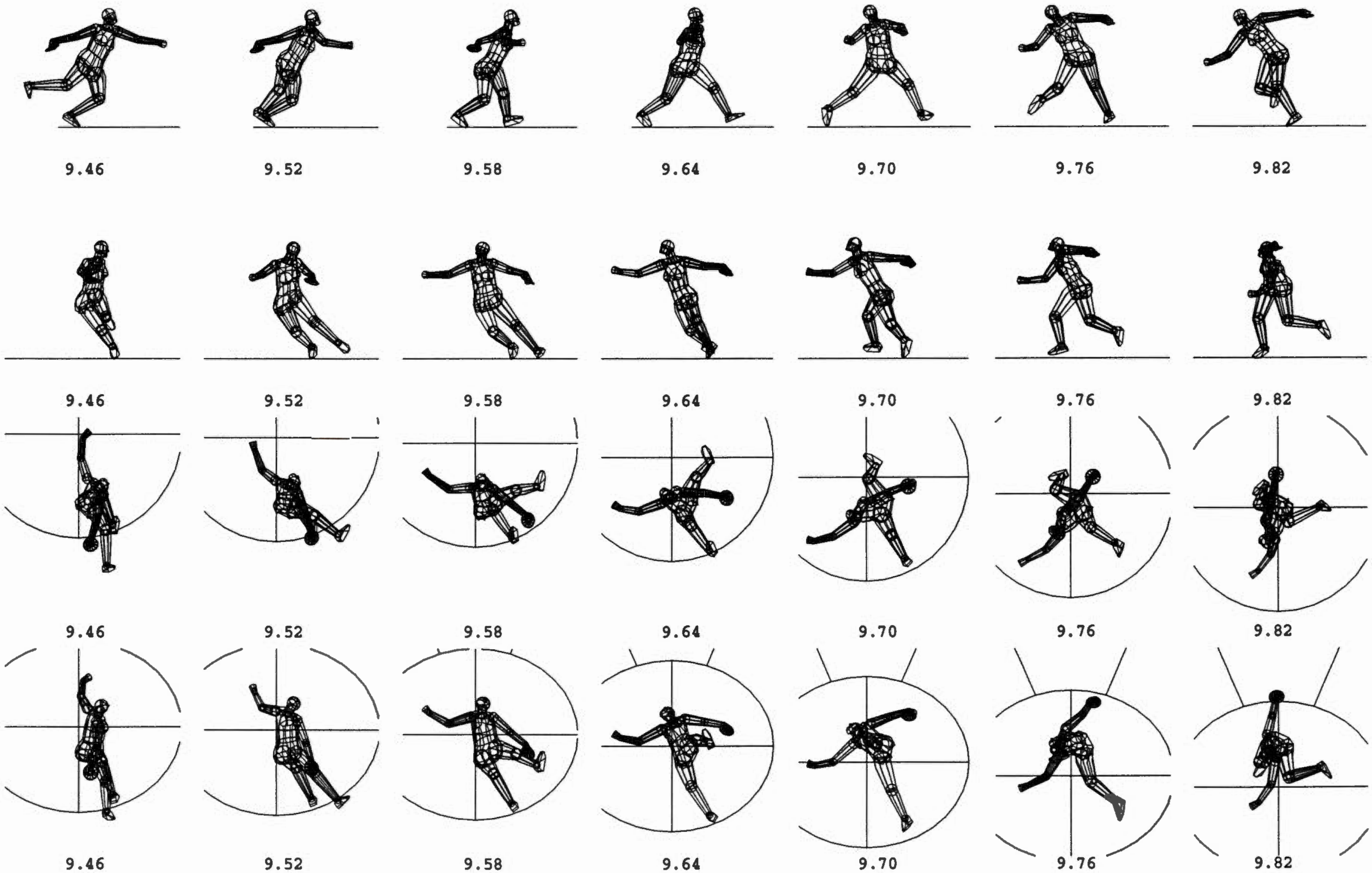

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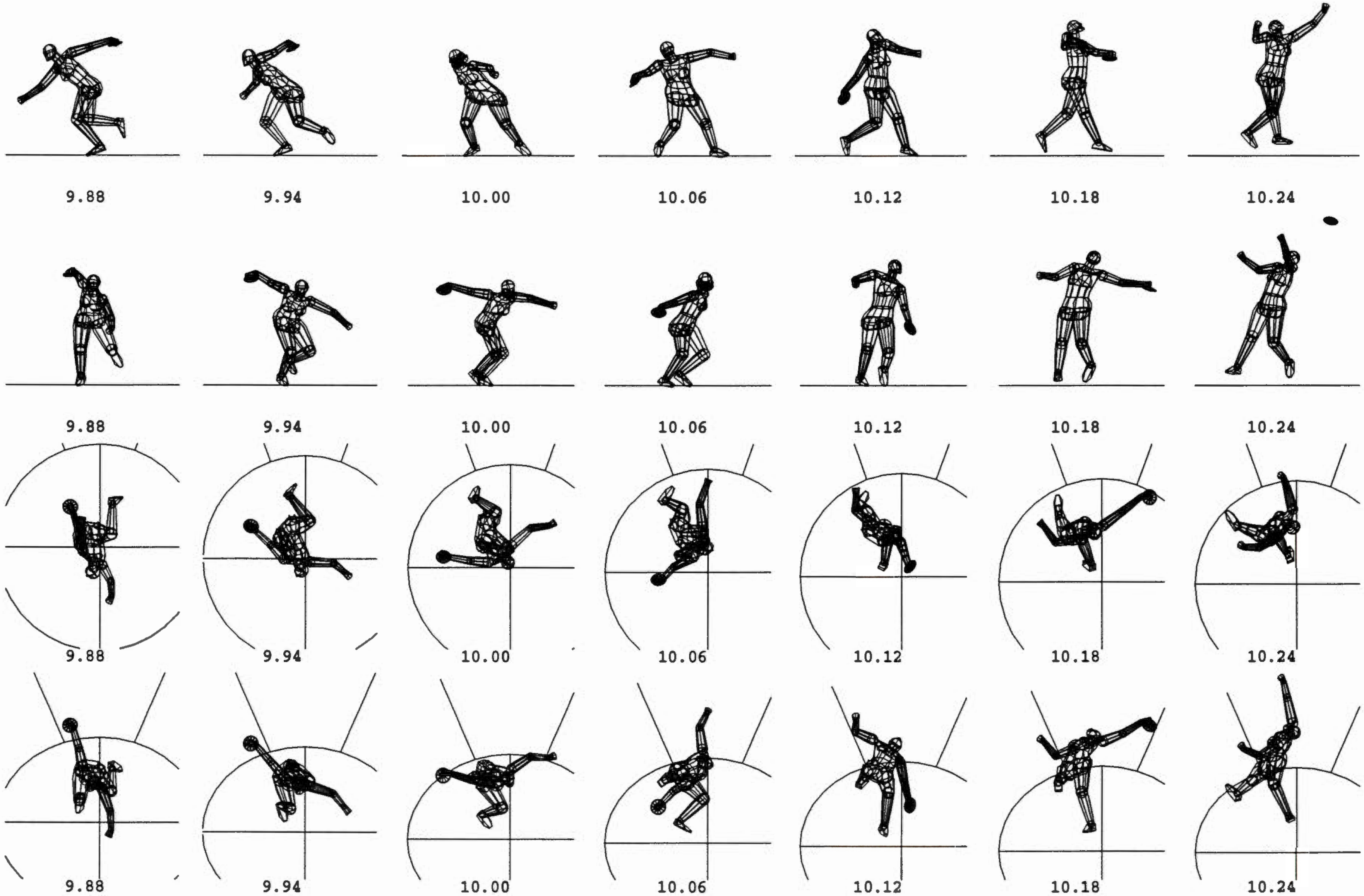

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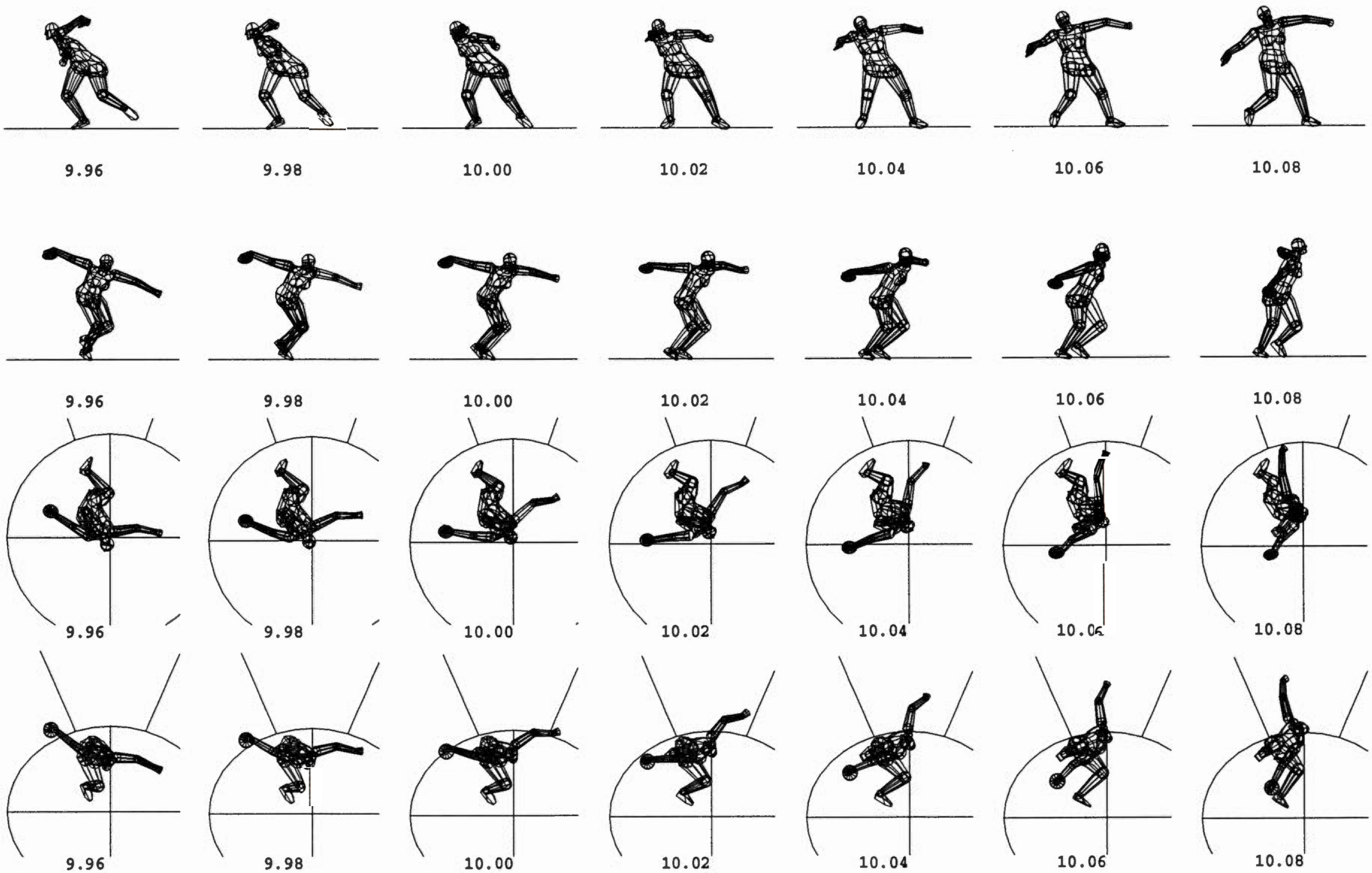

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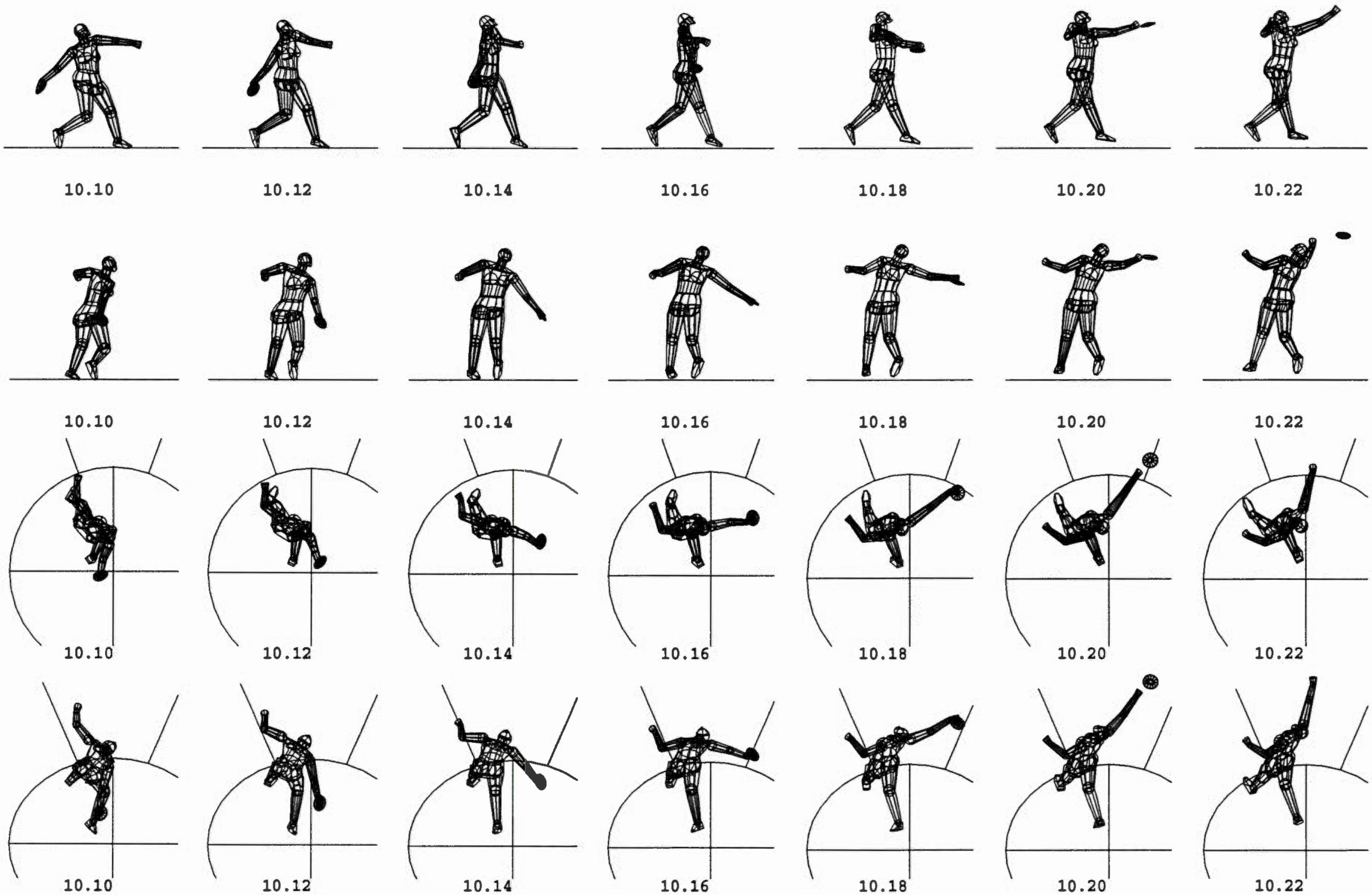

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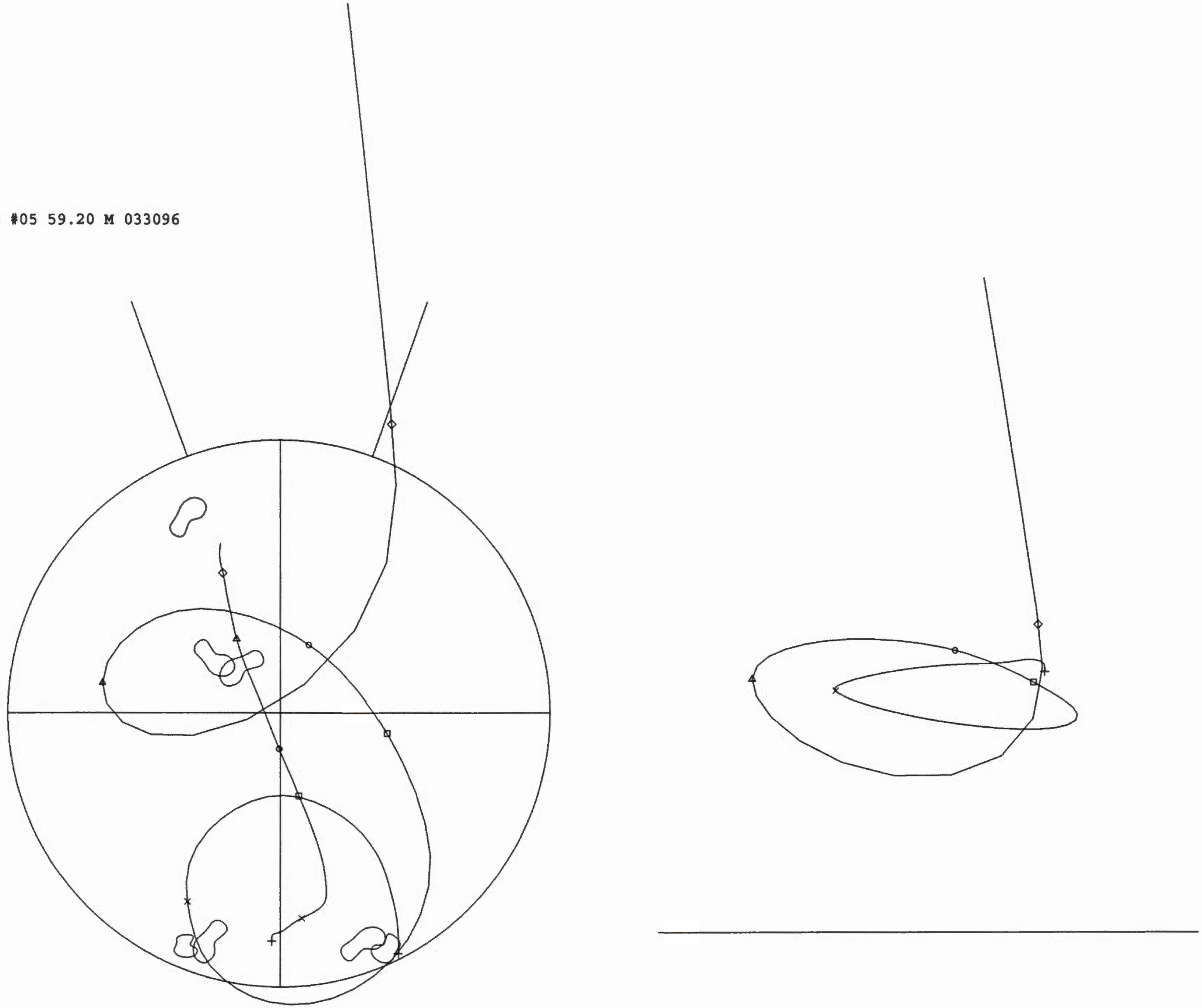

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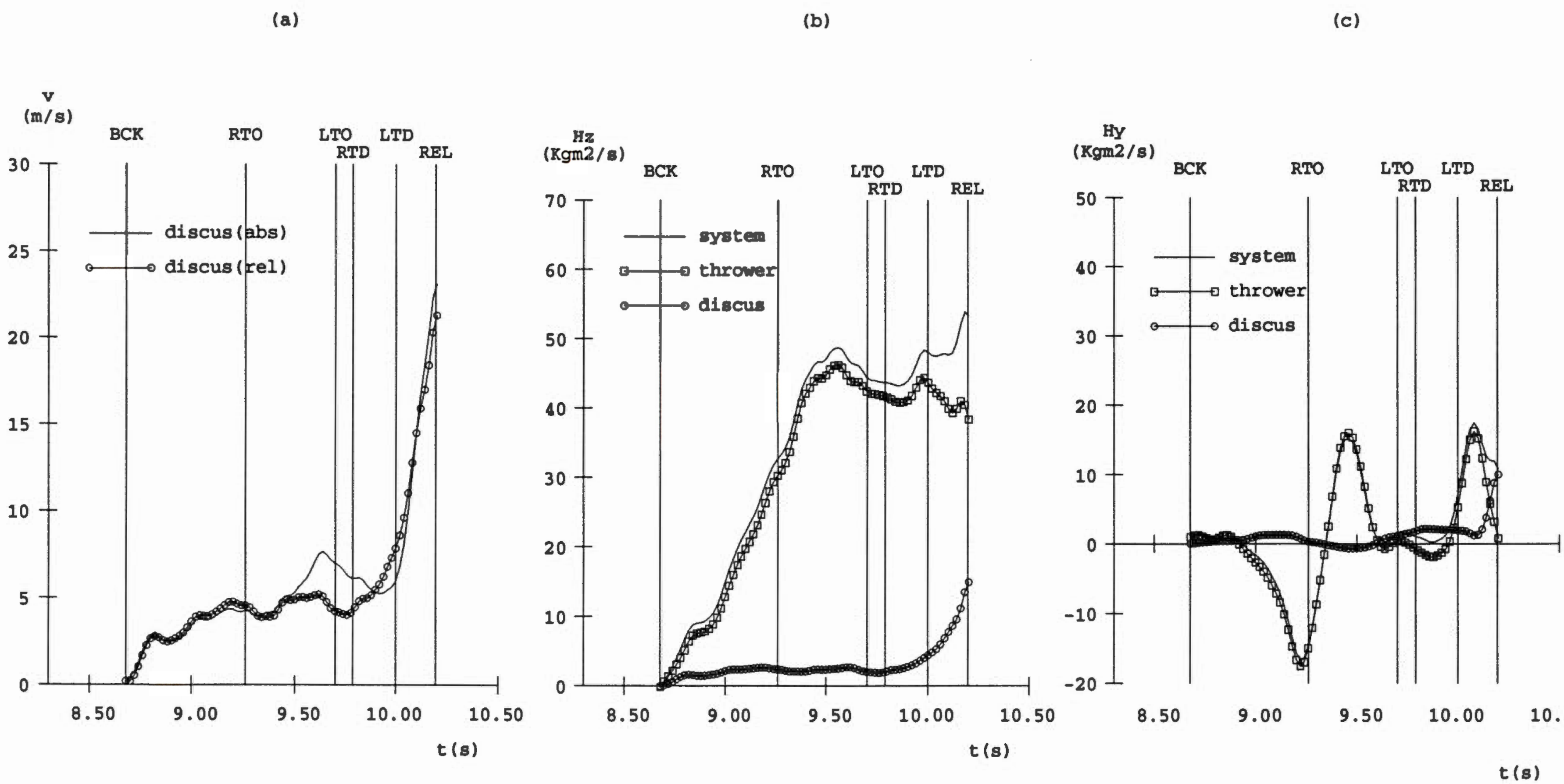

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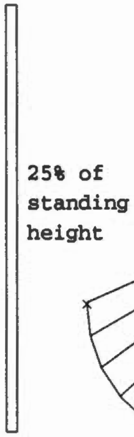
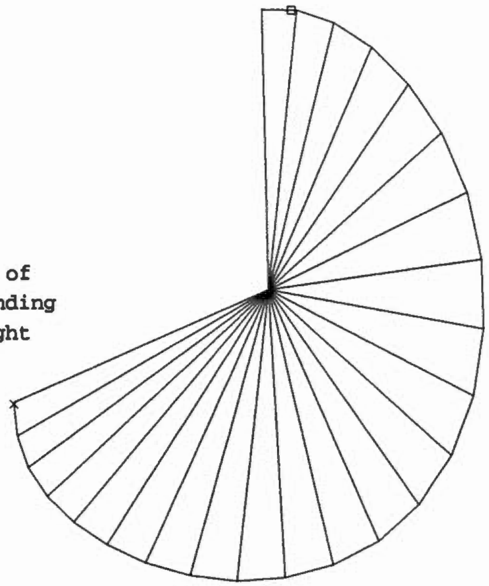
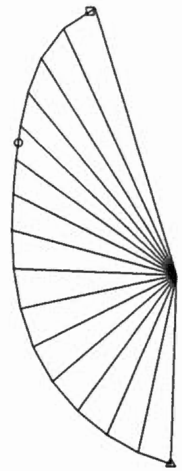
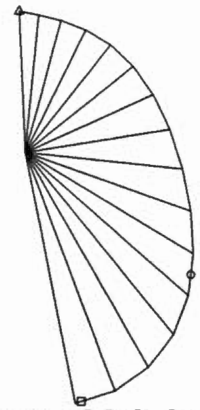




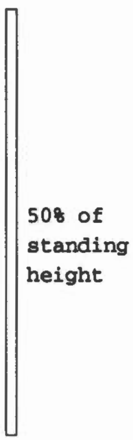
drive of right leg

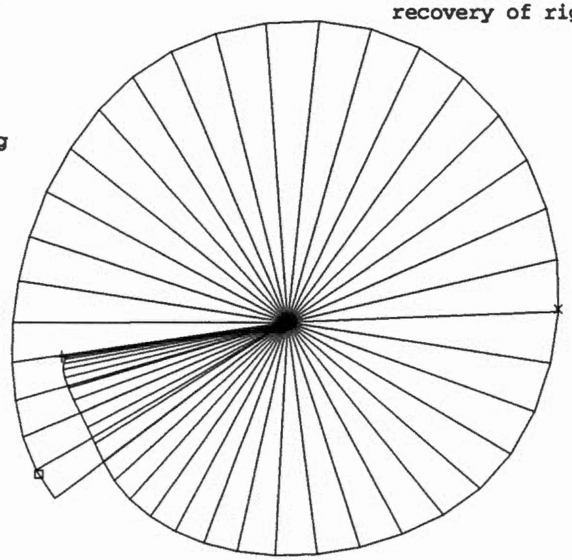


recovery of right leg

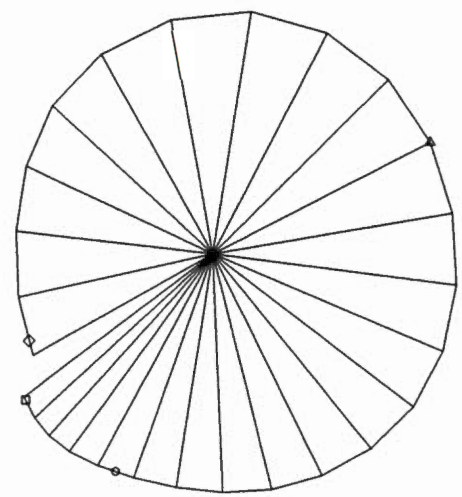


recovery of left leg





drive of left arm



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

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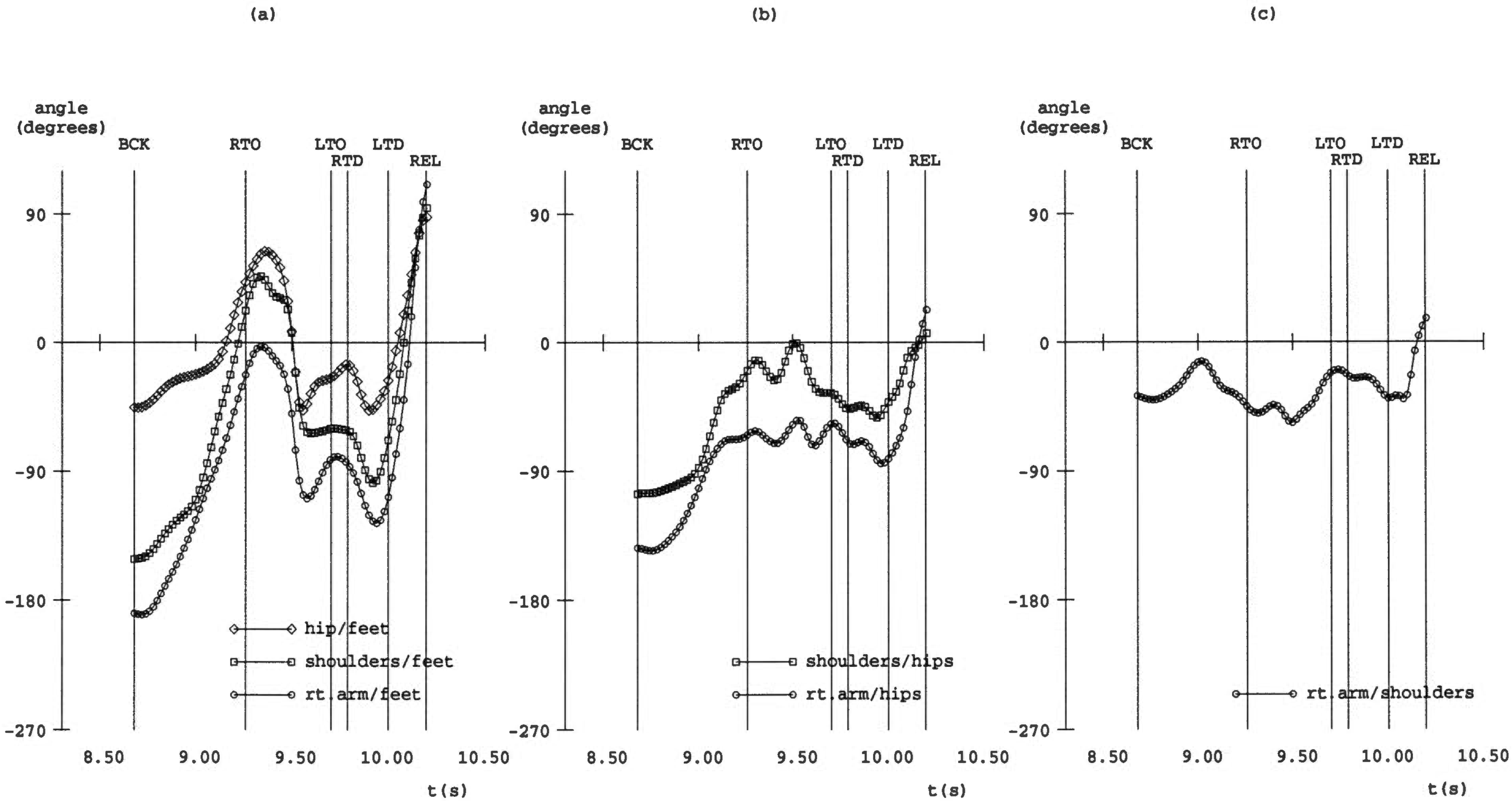

Suzy POWELL

Trial 35 was Powell's personal record, 59.88 m, thrown at the 1996 UC San Diego Open.

At the back of the circle, Powell shifted the c.m. of the thrower-plus-discus system toward her left foot. Then, she drove with the left leg against the ground, and traveled across the throwing circle in a direction that was not too deviated from directly forward (a_{LTO} = -17°). After the right foot landed in the middle of the circle, it pushed toward the left of the circle (as viewed from the back of the circle). The reaction force exerted by the ground on the foot pointed toward the right. This ground reaction force made the path of the system c.m. curve slightly toward the right (see the graph that shows the overhead view of the footprints and the c.m. path), and by the time that Powell planted the left foot on the ground the system c.m. was traveling almost directly forward (a_{LTD} = -6°). After that, the horizontal direction of motion of the system c.m. did not change much; during the last quarter-turn of the discus the c.m. was traveling slightly toward the left (a_Q = -8°). The horizontal direction of travel of the discus at release was slightly toward the right (d_{HREL} = 8°), and therefore the divergence angle between the directions of motion of the system and of the discus was small (c_Q = -16°). This was good.

The horizontal speed of the system c.m. at the instant of takeoff of the left foot from the back of the circle was average (v_{HLTO} = 2.4 m/s). However, Powell did not lose much of it as she passed over the right foot support. Therefore, at the instant when the left foot landed in the front of the circle the horizontal speed of the c.m. was much faster than in the average thrower (v_{HLTD} = 2.3 m/s). The forward horizontal force that Powell made on the ground during the subsequent double-support delivery phase was small, and because of this the leftover horizontal speed of the system during the last quarter-turn of the discus (v_{HQ} = 1.8 m/s) was larger in Powell's trial 35 than in any other analyzed throw. Together with the rather small divergence angle between the horizontal directions of motion of the discus and of the system c.m. (c_Q = -16°), this made a very large contribution to the horizontal speed of the discus (v_{HCON} = 1.7 m/s).

As pointed out in the previous paragraph, Powell did not push on the ground very hard in the forward horizontal direction during the double-support delivery. She also did not push on the ground very hard downward in the vertical direction. This is very frequent in discus throwing: The athletes who don't push very hard horizontally forward (and therefore conserve much of the horizontal speed of the system) also generally don't push very hard vertically downward (and therefore don't get much vertical speed). Powell's push against the ground during the delivery phase was small, both in the horizontal and vertical directions. Consequently, the system did not obtain much vertical speed; the contribution of the vertical speed of the system c.m. to the vertical speed of the discus was small: v_{ZCON} = 0.7 m/s.

It is not easy to judge the overall advantage or disadvantage of the combination of a very large contribution to the speed of the discus by the horizontal translation of the system c.m. (v_{HCON} = 1.7m/s) and a small contribution to the speed of the discus by the vertical translation of the system c.m. (v_{ZCON} = 0.7m/s). In other words, we don't know if Powell would have been better off or worse off with a combination of, say, v_{HCON} = 1.1 m/s; v_{ZCON} = 1.1m/s.

We are not completely sure why the force that Powell made on the ground during the double-support delivery was small, but we have two theories: (1) Perhaps she found it physically difficult to make on the ground a large force in the vertical direction while simultaneously making only a small force in the horizontal direction, although we know that other athletes have achieved such a combination (e.g., Dumble, Kawar). (2) The second possibility is that Powell may have limited her vertical speed on purpose. Her large horizontal speed helped to add horizontal speed to the discus, but it also put Powell in great danger of fouling. To avoid fouling, after releasing the discus she needed to make with her feet forward horizontal forces on the ground, to stop her own forward motion before stepping over the edge of the circle. If she had also generated a large vertical speed, after release her feet probably would have been off the ground or barely in contact with the ground. This would have made it more difficult for Powell to stop the forward motion before fouling. At this point, we are not sure which theory is the right one.

The swinging action of the right leg at the back of the circle was average (RLA = 26.7 $\cdot 10^{-3}$ Kg$\cdot$m^2/Kg$\cdot$m^2), while the swinging action of the left arm, as well as the combination of the swinging actions of the left arm and of the right leg, were somewhat weaker than average (LAA = 26.5 $\cdot 10^{-3}$ Kg$\cdot$m^2/Kg$\cdot$m^2; RLLAA = 53.3 $\cdot 10^{-3}$ Kg$\cdot$m^2/Kg$\cdot$m^2). The action of the left arm could have been stronger if it had started from a more clockwise initial position at the back of the circle.

At the instant of landing of the left foot in the front of the circle, the system already 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. This suggests that Powell's generation of angular momentum in the back of the circle was reasonably good.

The recovery actions of the legs were of average quality. The moderate average radius of the legs ($r_{LAVG-NSRSS}$ = 9.8% of standing height) shows that Powell brought both legs reasonably close together below her body. The recovery of Powell's left arm was also reasonably good ($H_{LA-NS} = 28 \cdot 10^{3}\ s^{-1}$, which was somewhat smaller than average); Powell slowed down the left arm well during the non-support phase.

The second propulsive swing of the left arm was weak ($LAA2 = 12.7 \cdot 10^{3}$ Kg$\cdot$m²/Kg$\cdot$m²). This probably limited the amount of additional angular momentum that Powell was able to get from the ground in the late stages of the throw. The maximum angular momentum that the left arm reached ($H_{MAX} = 48 \cdot 10^{3}\ s^{-1}$) was rather small, but the amount of angular momentum that the left arm still had at release was *very* small ($H_{REL} = 11 \cdot 10^{-3}\ s^{-1}$). The combination of these two factors implied a large loss of angular momentum by the left arm in the late part of the delivery phase ($\Delta H = -37 \cdot 10^{3}\ s^{-1}$), and the transfer of that angular momentum from the arm to the rest of the system, possibly to the discus. This was good. However, Powell could have contributed even more to the speed of the discus if the value of LAA2 had been larger. The origin of the problem was that she kept the left arm too flexed at the elbow during this second swing.

Powell reached a reasonably wound-up position in the single-support phase over the right foot ($k_{RA/FT} = -137°$). Even though her maximum degree of torsion was only moderate, when Powell unwound out of that position she transfered a very large amount of the Z angular momentum of the system to the discus (31% of the total). In this process, Powell gave a very good amount of horizontal speed to the discus (v_{HD} = 19.1 m/s).

At release, in the view from the back of the circle the counterclockwise angular momentum of the thrower-plus-discus system was very large (H_{YS} = 27.7 Kg$\cdot$m²/s), but in comparison with other throwers only a rather small fraction of it (33%) was transfered to the discus. Still, in absolute terms a reasonably good amount of Y angular momentum had been transmitted to the discus by the time of release (H_{YD} = 9.1 Kg$\cdot$m²/s). This gave the discus a reasonably good vertical speed at release (v_{ZD} = 13.2 m/s).

The resultant speed of the discus at release was good (v_{RD} = 23.2 m/s), similar to the speeds achieved by the other top throwers at the San Diego meet. Powell made reasonably effective use of aerodynamic forces (ΔD = 6.29 m). In this respect, she was similar to most of the other top throwers at the San Diego meet, but not nearly as effective as Barnes-Mileham.

Summary

The direction of the horizontal translation of the system c.m. was not too diagonal, and the divergence angle between the horizontal paths of the discus and of the system c.m. was small. Powell lost very little horizontal speed in the single-support on the right foot. The horizontal and vertical forces that she exerted on the ground during the delivery phase were small. As a result, she ended up with a large contribution of the horizontal speed of the system to the horizontal speed of the discus and a small contribution of the vertical speed of the system to the vertical speed of the discus. The swinging action of the left arm in the back of the circle was somewhat weak. The generation of Z angular momentum at the back of the circle seemed to be good. The recovery actions of the legs after the takeoff of the left foot from the ground were of moderate quality; the recovery action of the left arm was better. Powell did not swing her left arm very strongly in the front of the circle, but she slowed it down very well prior to release. She produced a moderately large torsion angle between the right arm and the feet. Then, she unwound very well, transfered a large amount of Z angular momentum to the discus, and thus contributed to increase its horizontal speed. She also transfered a good amount of Y angular momentum from the body to the discus, and thus contributed to increase its vertical speed.

Recommendations

There are two areas in which we feel that Powell may be able to improve her technique, and therefore her results: the generation of more vertical speed for the system c.m. during the delivery phase, and the generation of more Z angular momentum.

In her workout throws, we advise Powell to do some experimentation with the forces that she makes on the ground during the delivery phase: (a) She should try to exert a larger vertical force against the ground, while keeping the horizontal force about the same as in her current throws. To do this, she should probably think of pushing very hard *vertically* on the ground during the delivery phase. This should produce longer throws, but it could also lead to more fouls. (b) Another experiment that she should try is to push hard downward *and forward* against the ground during the delivery phase. This combination of larger vertical *and* horizontal forces should not increase the tendency to foul, but it will tend to increase the vertical speed of the discus while decreasing its horizontal speed. The distance of the throw may end up being the same, or longer, or shorter than in the original throw —there is no way to find out other than to experiment with it.

Powell has shown that she is very good at transfering Z angular momentum from the body to the discus. However, if this transfer leaves the body with too little angular momentum, her capacity to keep transmitting angular momentum to the discus becomes impaired. (Please read the middle paragraph in the left column of p. 23.) To prevent an excessive reduction in the angular momentum of the body of the thrower when angular momentum is transfered to the discus, the athlete needs to gain more angular momentum from the ground, and this is what Powell needs to focus on. She can get more angular momentum from the ground in various parts of the throw: In the back of the circle, she needs to rotate her left arm to a more clockwise position before starting the counterclockwise rotation. Then, during the remainder of the double-support phase and during the single-support on the left foot she needs to throw the arm harder in the counterclockwise direction than she did in trial 35. This will help her to generate more Z angular momentum in the back of the circle. During the non-support phase, she should slow down the left arm as she did in trial 35. Then, after the right foot lands in the middle of the circle, she should again throw the left arm very hard in the counterclockwise direction, *making sure that it is kept straight at the elbow.* This will help Powell to generate more Z angular momentum in the late stages of the throw. Finally, she should slow down the left arm a second time before release, as she already did very well in trial 35.

It is also *possible* that Powell might benefit from a slight change of emphasis in her conditioning program. As we have seen before, Powell is very good at transfering angular momentum from her body to the discus. Conversely, in relation to this excellent capacity to *transfer* angular momentum, her capacity to *obtain from the ground* angular momentum for the thrower-plus-discus system is relatively weaker. The main muscles involved in the transfer of angular momentum from the thrower to the discus are the muscles of the mid-trunk and of the shoulder. Those same muscles are also necessary for obtaining angular momentum from the ground. But for this, in addition, the muscles of the legs also need to brought into play. The fact that Powell excels at transfering angular momentum to the discus, and is relatively weaker in obtaining angular momentum from the ground implies that, in relation to most other throwers, she uses her mid-trunk and shoulder muscles more, and her leg muscles less. One possibility is that this may a simple question of choice in her technique: She may have chosen to follow that pattern of motion. But another possibility is that, in relation to other throwers, her mid-trunk and shoulder muscles may be relatively stronger than her leg muscles. We don't know if this is the case or not, but her coach surely knows. If this is not the case, then it is purely a technique question, and Powell needs to try to increase her Z angular momentum through the technique changes proposed in the previous paragraph. HOwever, if her leg muscles are indeed relatively weak in comparison to her mid-trunk and shoulder muscles, then she should make in her training a particular emphasis on the strengthening of her legs. That would be a pre-requisite for the improvement of her ability to obtain angular momentum from the ground.

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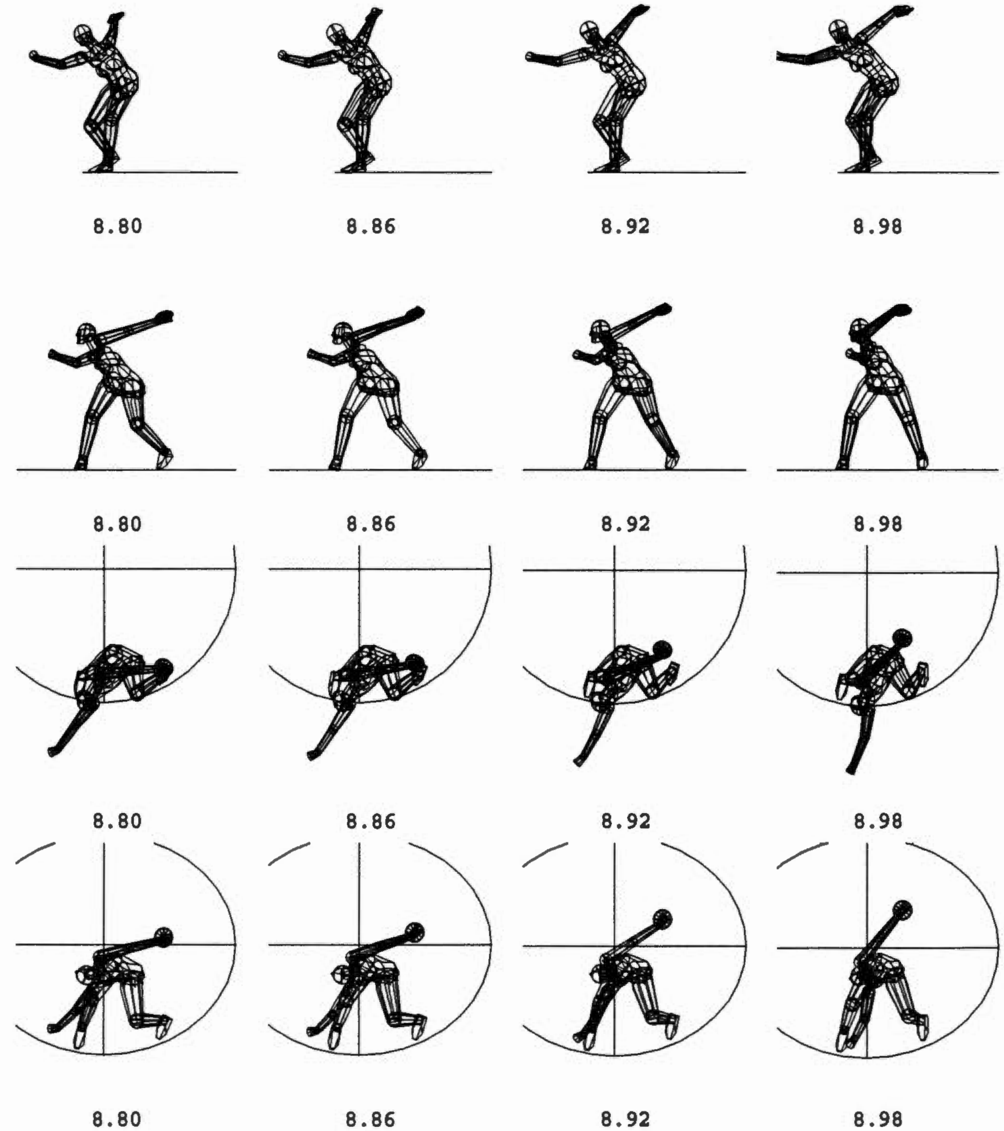

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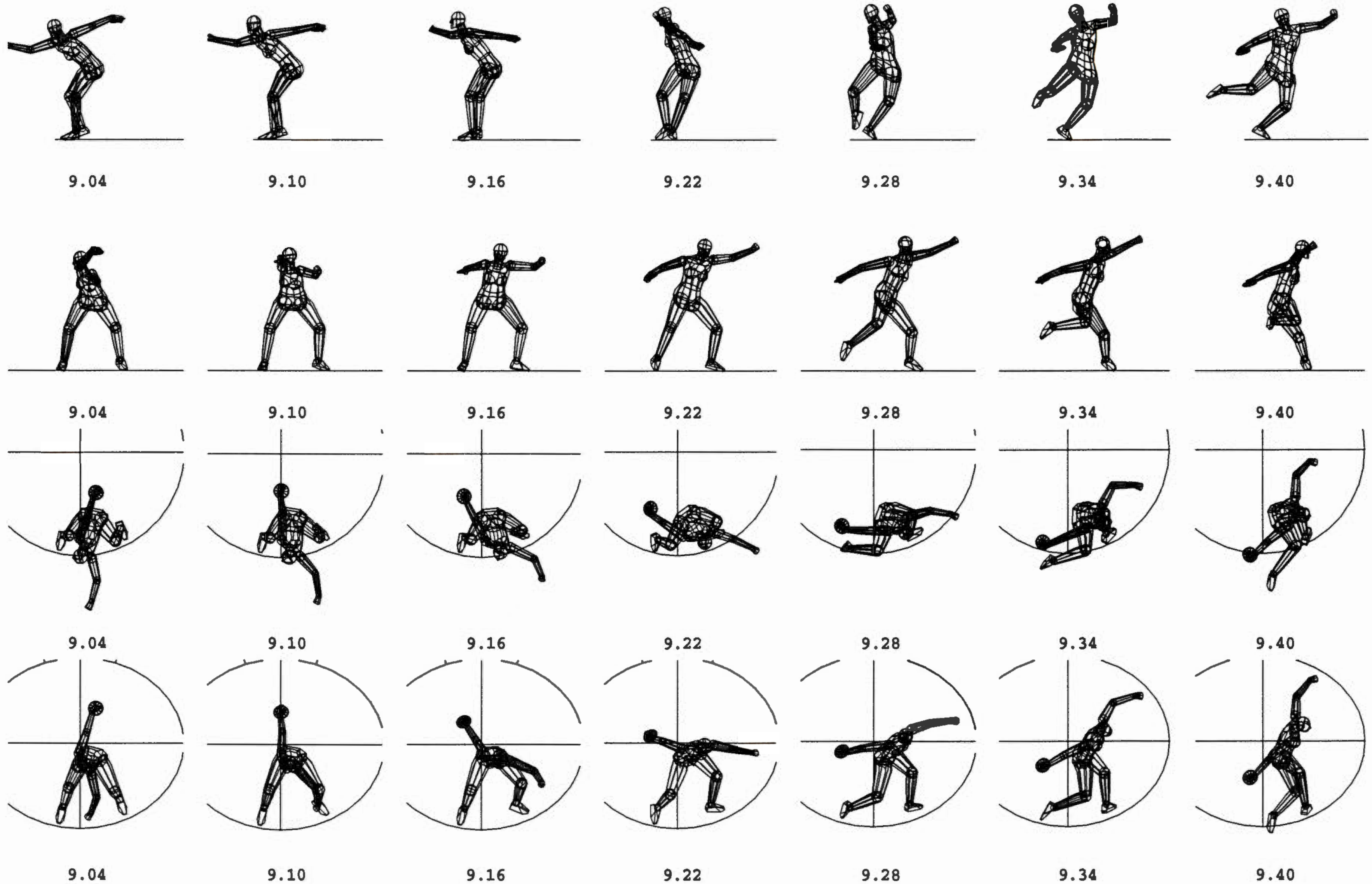

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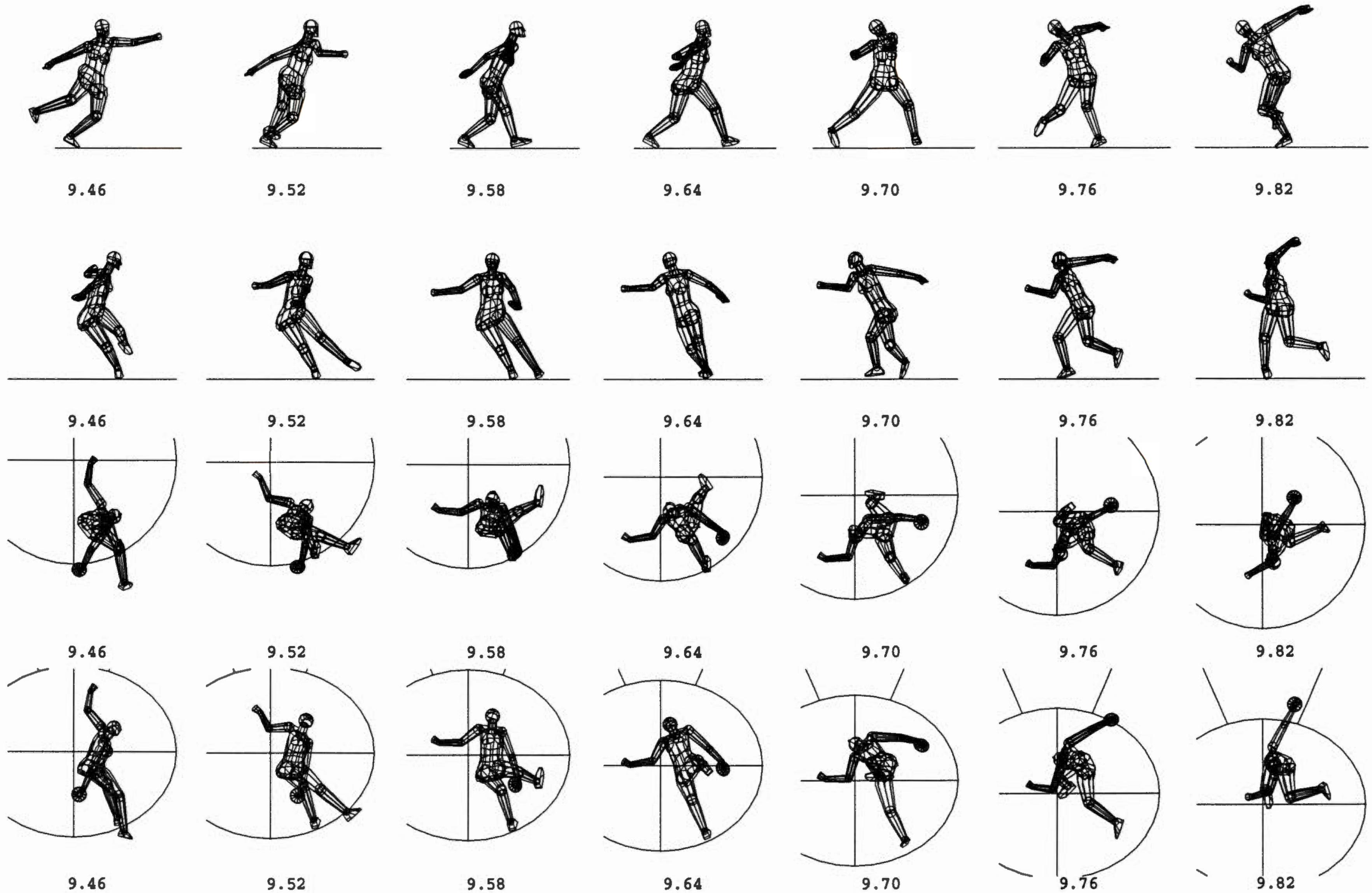

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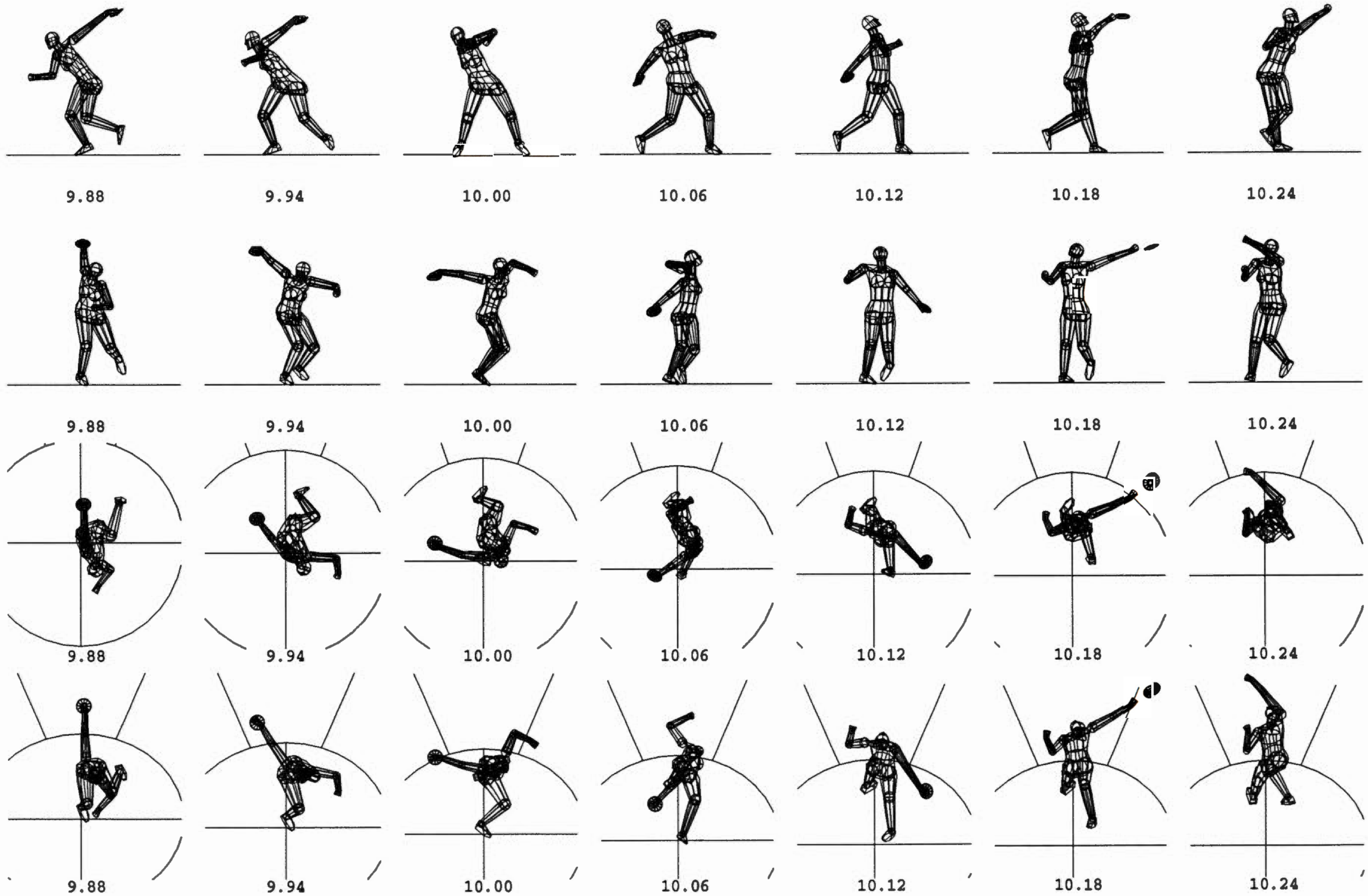

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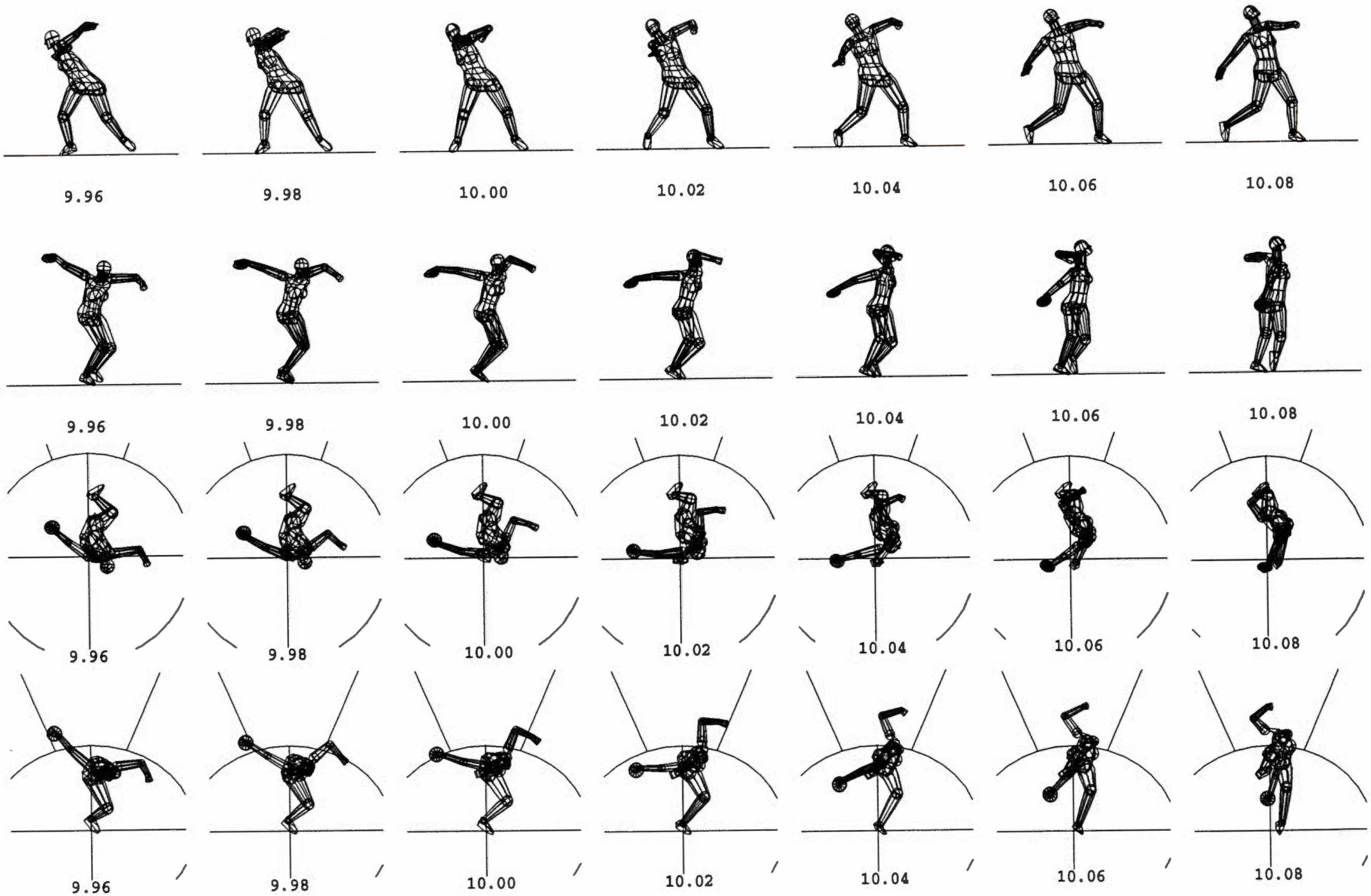

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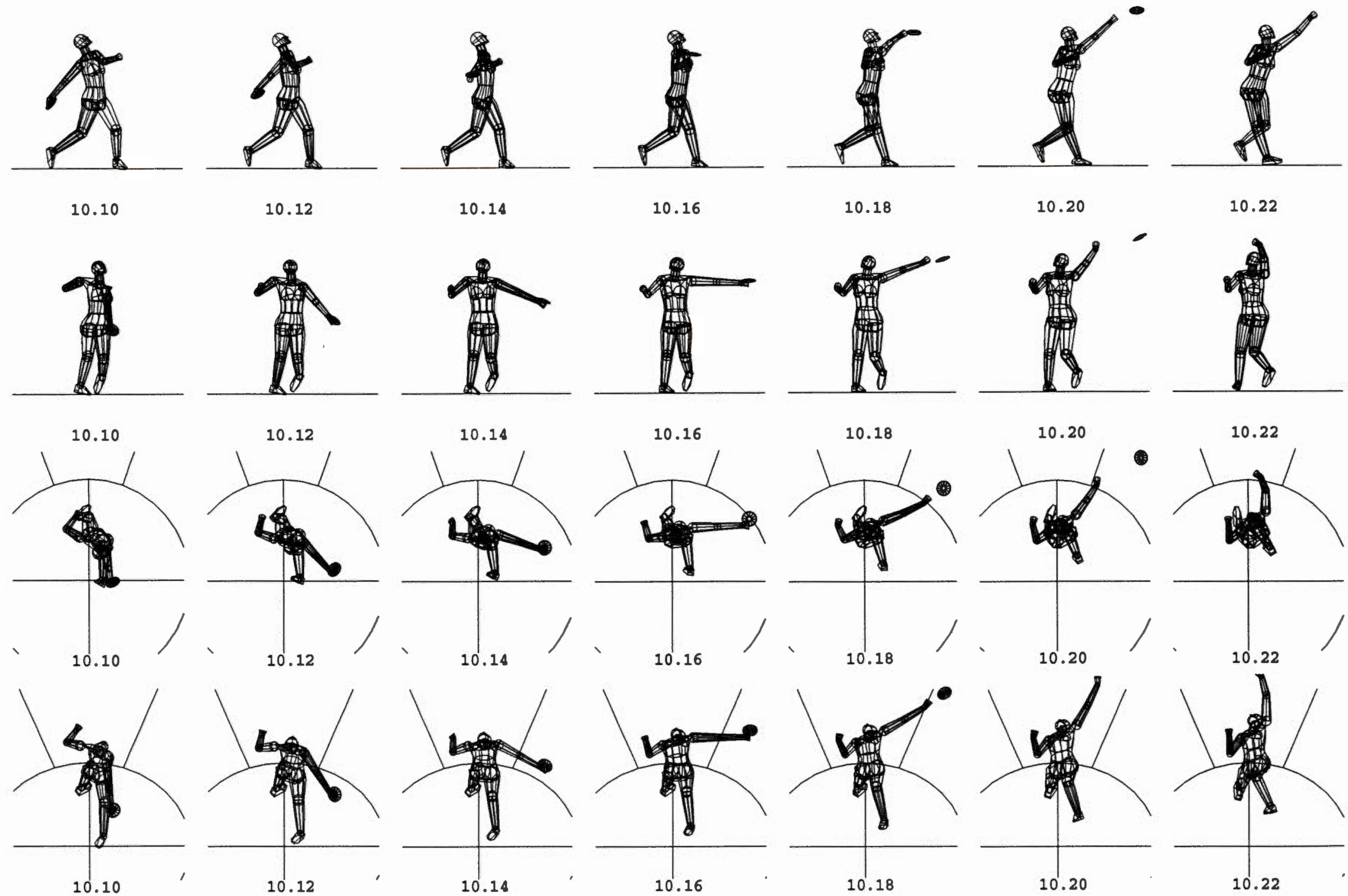

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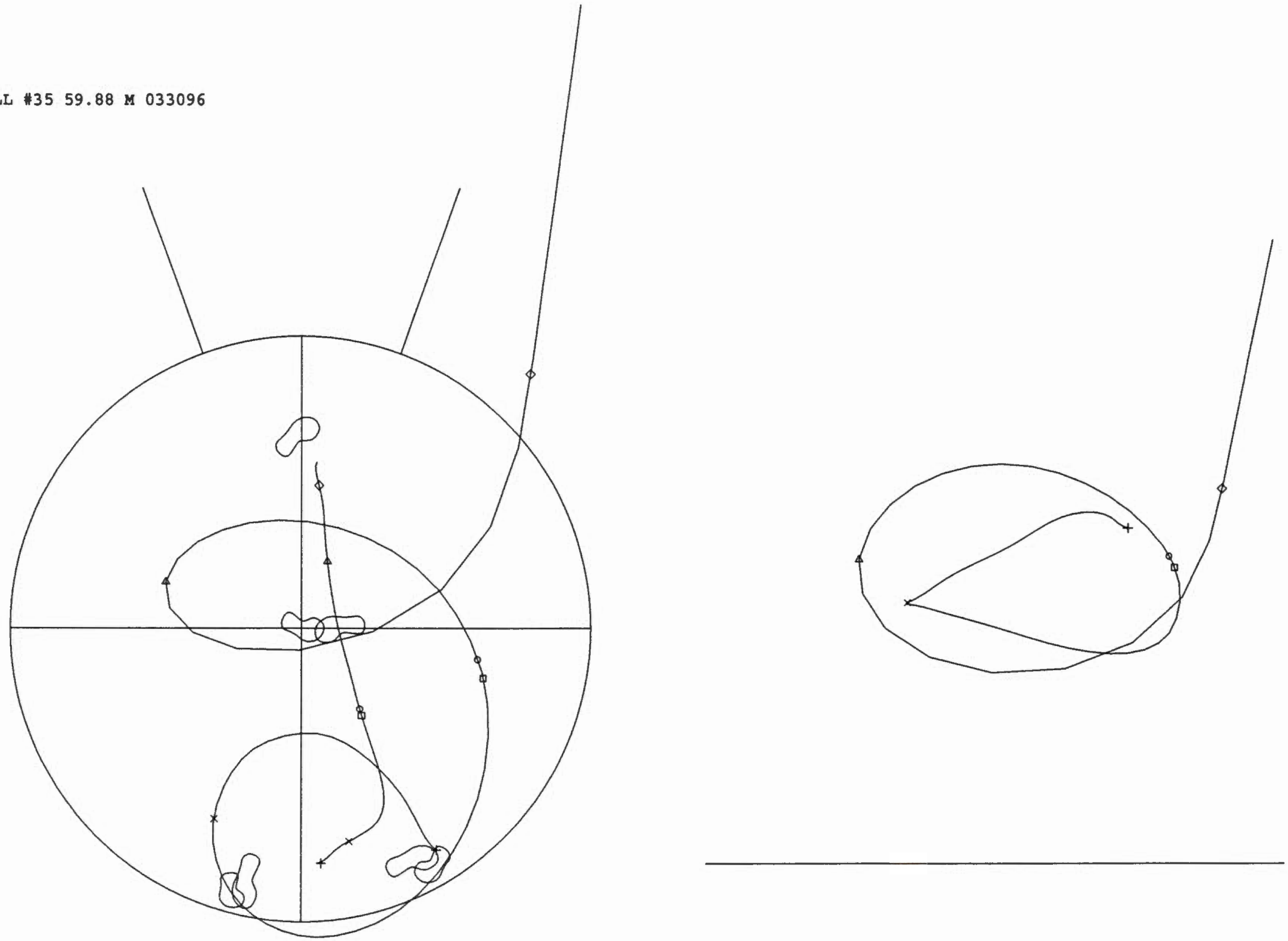

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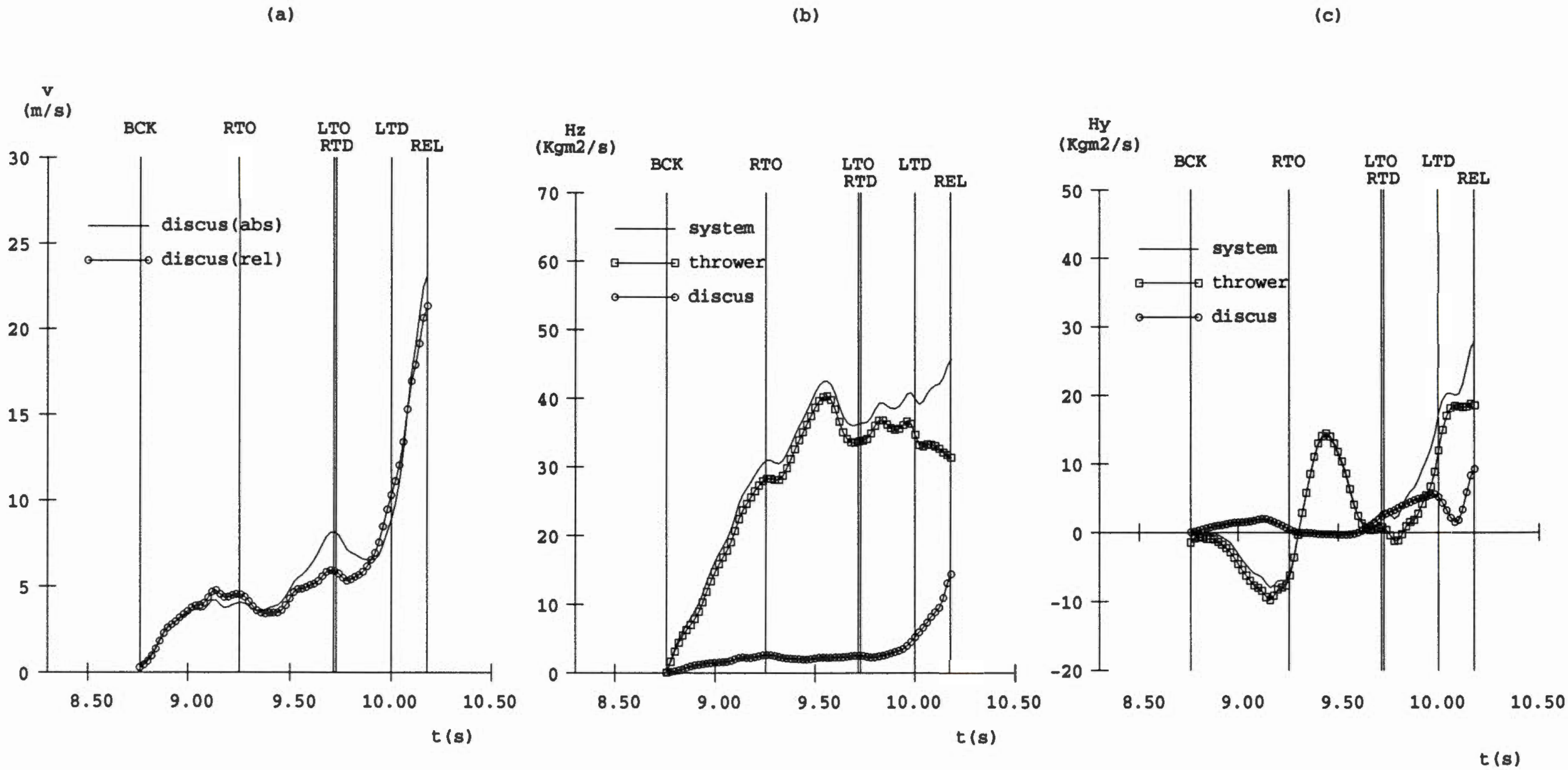

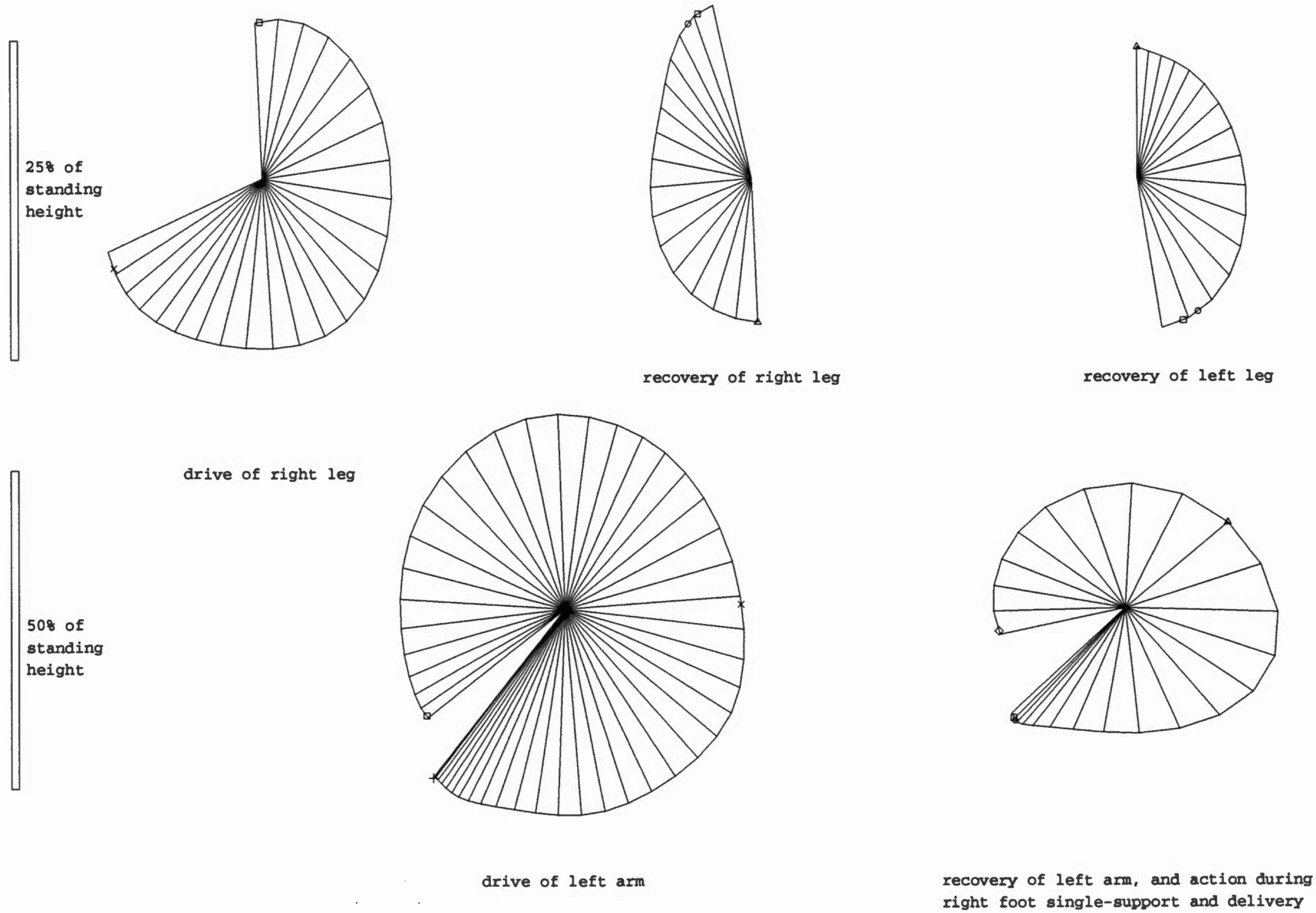
25% of
standing
height
recovery of right leg
recovery of left leg
drive of right leg
50% of
standing
height
drive of left arm
recovery of left arm, and action during
right foot single-support and delivery

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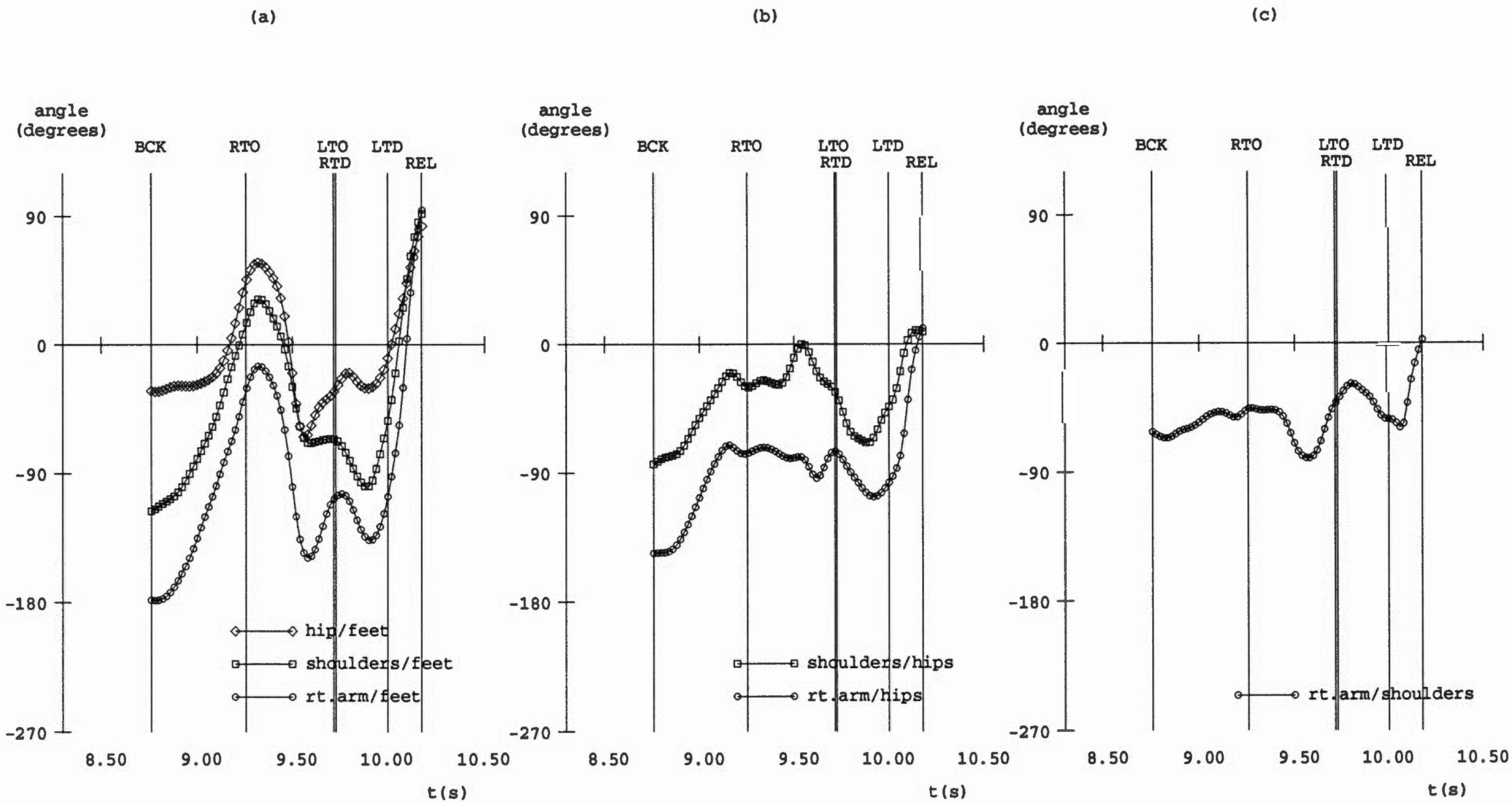

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