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A Kinematic Model of the Human Spine and Torso

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Disciplines

Computer Engineering

Comments

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Abstract

In order to advance current human figure motion models, a more realistic model of the body must include a flexible torso and spine. The spinal column is a series of interdependent joints with three degrees of rotational freedom. A study of anatomical architecture supports the model's principal ideas, and indicates the parameters for spinal movement. By defining a database of spine attributes (obtained from medical data), and a small set of input parameters, inverse kinematic control of the spine may be achieved.

1 Introduction

Human figure models have been studied in computer graphics almost since the introduction of the medium [1]. Through the last dozen years or so, the structure, flexibility, and fidelity of human models has increased dramatically: from the wire-frame stick figure, through simple polyhedral models, to curved surfaces, and even finite element models (e.g. [2, 3, 4, 5]). Computer graphics modelers have tried to

maximize detail and realism while maintaining a reasonable overall display cost. The same issue pertains to control: improving motion realism requires a great number of degrees of freedom in the body linkage, and such redundancy strains effective and intuitively useful control methods. We can either simplify control by simplying the model, thereby risking unrealistic movements; or complicate control with a complex model and hope the resulting motions appear more natural. The recent history of computer animation of human figures is focused on the quest to move the technology from the former situation towards the latter while simultaneously forcing the control complexity into algorithms rather than skilled manual manipulation.

This point of view motivates our efforts in human figure modeling and animation, as well as those of several other groups. In particular, notable algorithms for greater animation power have addressed kinematics [6], dynamics [7, 8, 9], inverse kinematics [10, 11, 12, 13], available torque [14], global optimization [15, 16], locomotion [10, 17], deformation [18, 5, 19] and gestural and directional control [20, 21]. Throughout this range of studies, however, the human models themselves tended to be rather simplified versions of real human flexibility. In the early 1980's we warned that increased realism in the models would demand ever more accurate and complicated motion control; now that the control regimes are improving, it is time to return to the human models and ask if we must re-evaluate their structure to take advantage of algorithmic improvements. When we considered this question, we determined that a more accurate model of the human spine and torso would be essential to further realism in human motion.

Although many models have appeared to have a flexible torso, they have been computer constructions of the surface shape manipulated by skilled animators [22]. We needed a torso that was suitable for animation, but also satisfied our research project requirements for anthropometric scalability [23, 24]. Thus a single model of fixed proportions could not be acceptable when vast differences among human body types would potentially need to be modeled. A similar type of flexible figure is found in snakes [25, 26], but the anthropometry issues do not arise. Miller's animation approach is dynamics-based; humans do not need to locomote with their torsos and so a kinematics model was deemed adequate. On the other hand, Zeltzer and Stredney's "George" skeleton model had a detailed vertebral column, but it was not articulated nor was it bent during kinematic animation [6]. Limited neck vertebral motion in the saggital plane was simulated by Willmert [27].

The default polyhedral figures used in *Jack* (the software system developed at the University of Pennsylvania for human figure modeling and manipulation [28]) lacked much detail in the human torsos. The graphically displayed bodies appeared to be impersonating robots with stiff backs, bending only from the waist. A five-segment torso was created a year ago with more possiblities of articulation. But the back was modeled without any curves, contrary to what exists in actual human anatomy. If the spine were realistically modeled, then the torso, a vessel connected and totally dependent on the spine, could then be viewed and manipulated interactively. So one of us (Monheit) undertook the development of a far more satisfactory and highly flexible vertebral model of the spine and its associated torso shape.

The conceptual model of the spinal column is derived from medical data and heuristics related to human kinesiology. The spine is a collection of vertebrae connected by ligaments, small muscles, vertebral joints (called processes), and intervertebral discs [29]. Nature has designed the spine for [30, 31]:

1. support of the body's weight

2. stability of the torso

3. flexibility of motion

4. protection of the spinal cord.

The spine moves as a series of vertebrae connected by dependent joints [32], meaning that it is impossible to isolate movement of one vertebral joint from the surrounding vertebrae. Muscle groups of the head, neck, abdomen and back initiate the movement of the spine, and the interconnecting ligaments allow the movement of neighboring vertebrae [29, 33].

The following sections describe both the model and the representation of the model within *Jack*.

Motion of the Spine

The model of the spinal motion is based on:

- The anatomy of the physical vertebrae and discs.

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- The range of movement of each vertebra.

- The effect of the surrounding ligaments and muscles.

2.1 Anatomy of the vertebrae and disc

The spinal column consists of 33 vertebrae organized into 5 regions [29]:

- Cervical

- Thoracic

- Lumbar

- Sacral

- Coccyx

The vertebrae are labeled by medical convention: C1 - C7, T1 - T12, L1 - L5, and S1 - S5. The regions listed above are in vertical descending order. Which regions should be considered part of the torso? The cervical spine lies within the neck. Also, the sacrum and coccyx contain vertebrae that are fixed through fusion [30]. So, the mobile part of the torso includes the 12 thoracic and 5 lumbar vertebrae. Therefore 17 vertebrae and 18 joints of movement are included in the torso model.

Each vertebra is uniquely sized and shaped, but all vertebrae contain a columnar body and an arch. The body is relatively large and cylindrical, supporting most of the weight of the entire spine. The vertebral bodies increase gradually in size from the cervical to the lumbar region [30].

The arch supports seven processes: four articular, two transverse, and one spinous [30]. The processes are bony protrusions on the vertebra that aid and limit the vertebral motion. The transverse and spinous processes serve as levers for both muscles and ligaments [29]. The articular processes provide a joint facet for the joint between successive vertebral arches. These processes, due to their geometry, cause the vertebrae to rotate with 3 degrees of freedom. Ligaments and small muscles span successive vertebral processes. They give the spinal column its stability. Because of this strong interconnectivity, spinal movement is modeled as interdependent movement of neighboring joints.

Vertebrae are each separated by intervertebral discs. The disc has 3 parts [32]:

- **nucleus pulposus** - the sphere in the center, consisting of 85% water

- **annulus fibrosus** - the fibers running as concentric cylinders around the nucleus

- **cartilaginous plates** - a thin wall separating the disc from the vertebral body.

The disc changes shape as the neighboring vertebrae bend. But, since the nucleus is 85% water, there is very little compression. The disc can bulge out spherically, as force is applied to the columnar body above or below. Therefore, overall the disc does not function as a spring, but as a deformable cylindrical separation between vertebrae, supporting the theory that the vertebrae do not slide, but rotate around an axis [32].

2.2 Range of movement of each vertebra

Vertebral movement is limited by the relative size of the disks, the attached ligaments, and the shape and slant of the processes and facet joints. Statistics for joint limits between each sucessive vertebra have been recorded and compiled [32]. Also, the spine has a natural shape at rest position. The initial joint position of each vertebra is input to the model.

The range of movement of each region of the spine is different. For instance, the optimum movement of the lumbar region is flexion or extension. The thoracic area easily moves laterally, while flexion/extension in the sagittal plane is limited. The cervical area is very flexible for both axial twisting and lateral bending. The joint limits for each region affect how much that joint is able to participate in any given movement. The posture of the torso is a result of the specialization of the spinal regions [34].

2.3 Effect of the surrounding ligaments and muscles

The vertebrae are interconnected by a complex web of ligaments and muscles. If the force initiated by a muscle group is applied at one joint, the joint moves and the neighboring joints also move to a lesser degree. Some joints farther away might not be affected by the initiator joint's movement.

It is possible to deactivate joints that are not initiating the movement. This action is achieved by simultaneous contractions of extensor and flexor muscles around the spinal column [34]. Depending on the force of these resisting muscles, the joints on or near the joint closest to the resistor will move less than they would if the resisting force had not been applied. The final position of the spine is a function of the initiator force, the resisting muscle, and the amount of resistance.

3 Input Parameters

The spine is modeled as a black box with an initial state, input parameters, and an output state. To initiate movement of the spine, several input parameters are introduced. These parameters are:

joint range FROM and TO: Within the total number of joints in the spine, any non-empty contiguous subset of vertebral joints may be specified by two joint indices. These joints indicate which part of the spine is active in movement. For example, the user specifies movement in the range between T5 and T10. All other joints are frozen in the movement.

initiator joint: The joint where movement begins, usually the joint with greatest motion.

resistor joint: The joint that resists the movement. This may be equated to a muscle that contracts and tries to keep part of the spine immobile.

resistance: The amount of resistance provided by the resistor joint.

spine target position: This is a 3D vector describing the target position after rotation around the x, y, and z axis. The target position is the sum of all joint position vectors in the spine after movement succeeds.

zero interpolation: A value of "yes" indicates that movement is interpolated through the joint rest position. A value of "no" indicates that only the joint limits are used to interpolate movement.

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4 Spine target position

The joint between each vertebra has three degrees of rotation. The spine will move toward the target position by rotating around the three possible axes [32]:

ROTATION OF THE SPINE		
flexion/extension	Forward and backward bending	Rotation around the x axis
axial rotation	Twisting	Rotation around the y axis
lateral bending	Side bending	Rotation around the z axis

The position of the flexion rotational axis for each vertebral joint has been measured from cadavers, and is not equidistant to the two adjacent vertebrae, but is closer to the bottom vertebra [32]. The origin of the axis of movement determines how the vertebrae move. When the torso is modeled on the spine, the axis also directly determines how the torso changes shape.

Elongation and compression are absent from the model. The hydrophilic intervertebral disc, when submitted to prolonged compression induces a slight decrease in height due to fluid leakage. Conversely, after a long period of rest or zero-gravity, the spine elongates by maximum filling of the nucleus pulposus (at the center of the disc) [32]. Dehydration during a day's activity can result in a loss of height of 2 cm in an adult person. In any short duration of movement the disc is essentially incompressible, and therefore elongation is imperceptible [35].

Shearing or sliding (translational movements) of the vertebrae would lead to variation in the intervertebral separation. This would not be allowed by the mechanics of the intervertebral disc [32]. Therefore, the assumption is made that for normal activities the three degrees of rotational movement are the only ones possible for each vertebral joint.

5 Spine database

Any human figure can have a wide variety of torso shapes. Also, each person has a different degree of flexibility and range of movement. In order to model the position and shape changes of an individual's spine, a database has been designed

for creating a unique set of features for the spine and torso. Medical data is the source of the database elements of an average person [32].

Database elements:

- Size of vertebra - x,y,z dimension.

- Intervertebral disc size - separation between vertebrae.

- Joint limits - 3 rotations, 2 limits per rotation.

- Joint rest position - The initial joint position of the spine.

6 Application of the motion model

Consider a stationary spine and its attributes. Each vertebra has a current position defined by the joint position between each vertebra for each of the three degrees of rotation. Also defined in the spinal database are joint rest positions and 6 joint limits for every joint. If each attribute is summed up for all joints, then 3D vectors are defined for current position, joint rest position, and two joint limits for the global spine. The target position – the 3D vector sum of final joint positions – is supplied as an input parameter. Movement towards the target position is either bending or unbending, meaning either towards the joint limits or towards the spine's rest position. Motion is defined as an interpolation between the current position and either the spine's position of maximum limit, or the spine's rest position.

Three rotations are calculated independently and then merged into one. For example, a 3D orientation vector (e.g. bend forward 45 degrees, twist 20 degrees left, and side bend 15 degrees right) can be accomplished in one function with 3 loop iterations. It is assumed for the model that the maximum vertebral joint limit in one dimension will not affect the joint limits of another dimension.

The spine's rest position is included in the model, because it is a position of highest comfort and stability. If the spine is unbending in one dimension of movement, it will move towards that position of highest comfort in that rotational dimension. What determines how much each vertebra bends as the spine moves? First, consider one dimensional rotation, then apply the principles to the 3D model. Within one dimension there are several factors:

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- The current position.

- The target position.

- Direction of movement: Unbending or bending.

- The position of the vertebra.

- The initiator joint.

- The resistor joint.

- The amount of resistance.

- Is this joint frozen, or is it participating?

- Is the position calculated past the joint limit? If so, set the position to the joint limit.

6.1 Participation of the spine

A participation vector is derived from the spine's current position, target position, and maximum position. This global participation represents a 3D vector of the ratio of spine movement to the maximum range of movement. Participation is used to calculate the joint weights.

The following formulas are defined in each of three degrees of freedom:

let

$Target$ = spine target position
$Current$ = spine current position
Max = spine sum of joint limits
$Rest$ = spine sum of joint rest positions
P = participation

then if spine is bending

$$P = \frac{Target - Current}{Max - Current}$$

else if spine is unbending

$$P = \frac{Target - Current}{Rest - Current}.$$

6.2   Calculation of joint weights

The joint positions of the entire spine must sum up to the target position. To determine how much the joint participates, a set of weights is calculated for each joint. The participation weight is a function of the joint number, the initiator joint, and global participation derived above. Also, a resistance weight is based on the resistor joint, degree of resistance, and global participation. To calculate the weight for a given joint:

let

i = joint number
j = joint position
$limit$ = the joint limit
$rest$ = the joint's rest position
w = weight
p = participation weight
r = resistance weight

then if spine is bending

$$w_i = p_i \cdot r_i \cdot (limit_i - j_i)$$

else if spine is unbending

$$w_i = p_i \cdot r_i \cdot (rest_i - j_i).$$

The range of weights is from 0 to 1. A weight of 1 specifies that the movement will go 100% of the differential between the current position and either the joint limit (for bending) or the joint rest position (for unbending). A weight of 0 means that the joint will move 0% of the differential (none at all). The weights are a function of the input parameters and global participation.

6.3 Resistance

To understand resistance, divide the spine into two regions split at the resistor joint. The region of higher activity contains the initiator. Label these regions, active and resistive. The effect of resistance is that joints in the resistive region will resist participating in the movement specified by the parameter degree of resistance. Also, joints inbetween the initiator and resistor will have less activity depending on the degree of resistance.

Resistance does not freeze any of the joints. Even at 100% resistance, the active region will move until all joints reach their joint limits. Then, if there is no other way to satisfy the target position, the resistive region then begins to participate.

6.4 Calculation of joint positions

If the desired movement is from the current position to one of two maximally bent positions, then the weights calculated should be 1.0 for each joint participating. The algorithm interpolates correctly to either maximally bent position. It also interpolates correctly to the position of highest comfort. To calculate the position of each joint after movement succeeds:

let

j = joint position
j^* = new joint position
$Target$ = spine target position
$Current$ = spine current position

$M = Target - Current =$ incremental movement of the spine

then

$$j_i^* = j_i + \frac{Mw_i}{\sum w_i}.$$

Prove $\sum j_i^* = Target$:

$$\sum j_i^* = \sum(j_i + \frac{Mw_i}{\sum w_i}$$
$$= \sum j_i + \sum \frac{Mw_i}{\sum w_i}$$
$$= Current + M\frac{\sum w_i}{\sum w_i}$$
$$= Current + M$$
$$= Target.$$

6.5 *Bendspine* function

Given inputs:

- Initiator joint

- Rotational movement vector

- Resistor joint

- Resistance

and a database of joint positions and joint limits, the *bendspine* function outputs the new position of each vertebra after movement takes place.

6.6 *Movespine* function

This function is the driver for spinal movement. It captures the joint limits and positions and, after prompting for input parameters, calls *bendspine*. Upon returning the new joint positions, *Jack* sets the joint angles and redraws the window.

6.7 Design for a new torso

First, a torso was created using 17 segments corresponding with 18 vertebral joints. Each segment is (arbitrarily) a hexagonal slice, with sites (points of attachment) located at the posterior side of the torso. These sites correspond to the spinal vertebral joints. This torso serves as an approximation of the anatomy in order to display movement efficiently.

Next, more detailed human models based on biostereometrically scanned real (and hence anatomically-correct) subjects[1] were converted to bodies with 17 contoured slices replacing the original one segment torso. These slices were designed to overlap one another, preventing gaps from showing up as the torso bends. Each slice was then tiled and tested in the *movespine* and *bendspine* functions. The final result is a realistic torso that moves according to the kinematic properties of the spine.

Examples

The following examples show a range of postures and motion sequences involving a bendable torso and spine. The acid test of the model is real-time and video animation. We are continuing our efforts in the direction of realistic human performance.

Figures 1 - 6: These human models are based on the 95th percentile height male of a sample of biostereometrically-scanned real subjects. The torsos are displayed in the Jack software system and bent using the interactive functions *movespine* and *bendspine*. The target state (x,y,z) indicates the sum of joint positions in three degrees of freedom for the 18-joint spine.

Figures 7 - 12: Setting the zero interpolation flag to "no", the spine is rolled forward and backward around its local x-axis. Note the figure-eight path drawn by the site at the top of the head. Three other vertebral joints are traced through the space while rolling the spine.

Figures 13-14: While tracing three vertebral joints, the spine is circled by

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[1]The original subject data was supplied by Kathleen Robinette of the Armstrong Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base.

varying all three degrees of freedom in coordination. The knees and ankles bend as the spine moves backwards.

Figure 15: As the body breathes, there is an extension of the upper torso while flexion of the lower torso. The pattern reverses on exhalation. On a 5.0 second breath cycle, the green outline indicates positions at 0.0 sec, red at 1.6 sec, and yellow at 4.0 sec.

8 Future work

The *movespine* function will be used to generate a vocabulary of torso gestures, postures, and choreography. Several new torsos will be designed and incorporated into *Jack*. Body linkages will include a flexible neck with seven cervical vertebrae. The model and software *can* discriminate each cervical joint without any coding changes. In fact, any number of vertebral joints may be input to the system. Motion involving interactive reach [13] will be redefined to include the spine model. Joint limits of one rotational degree of freedom should be affected by position within other degrees of freedom. In addition, the model should be enhanced to indicate the interdependence of lateral inclination and axial rotation due to the obliquity of the posterior articular facets [32]. Overall, the model of movement should not be oversimplified. The experiments so far, however, have justified the effort put into the model and appear to have added considerably to realistic human figure animation.

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Figure 1.

$(flexion, axial, lateral) = (-52 \deg, 58 \deg, -7 \deg)$

Figures 1-6. Contoured bodies are bent to a target state vector (flexion, axial, lateral).

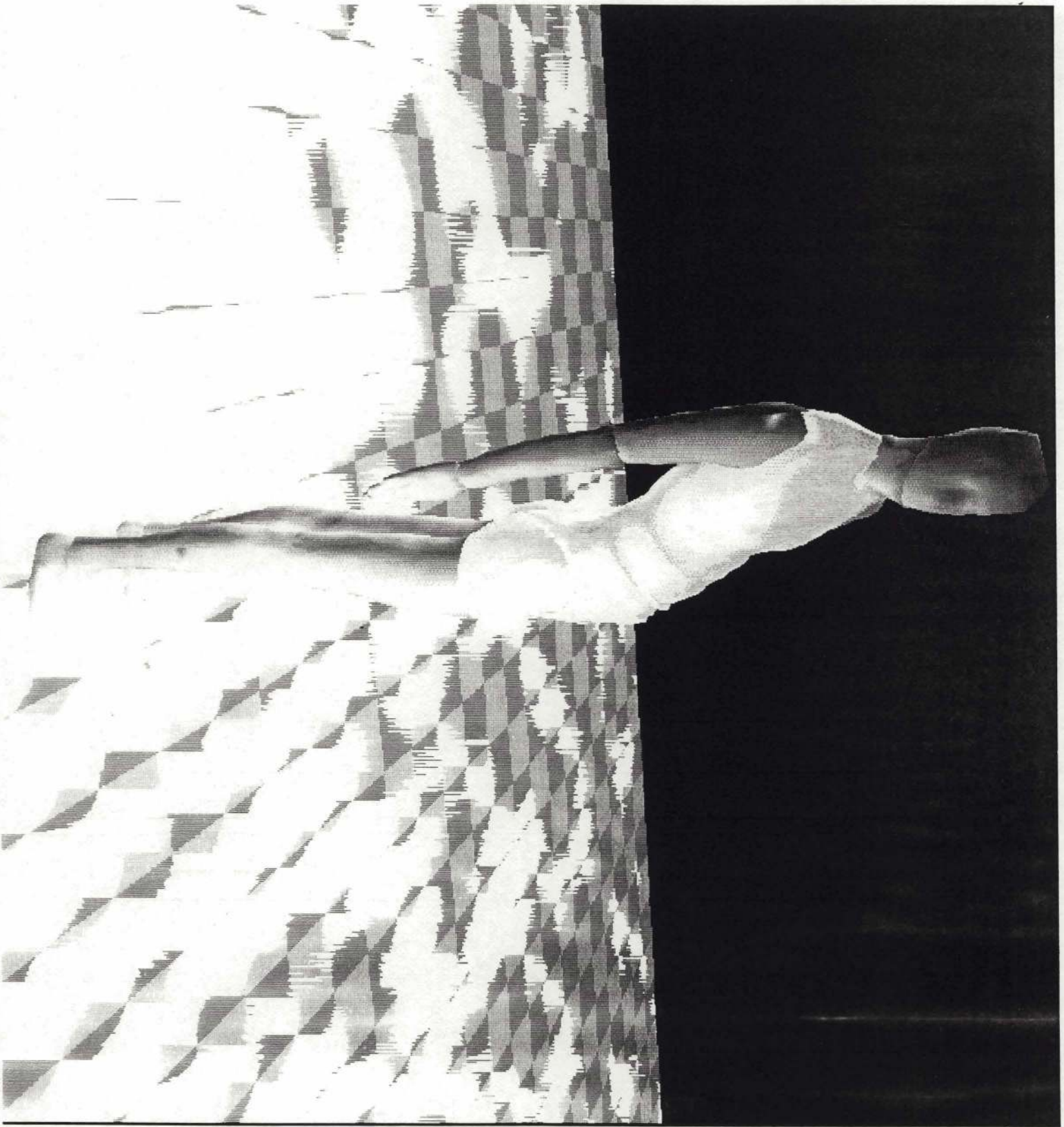Figure 2.

(flexion, axial, lateral) $= (-1 \deg, -60 \deg, -6 \deg)$

Figure 3.

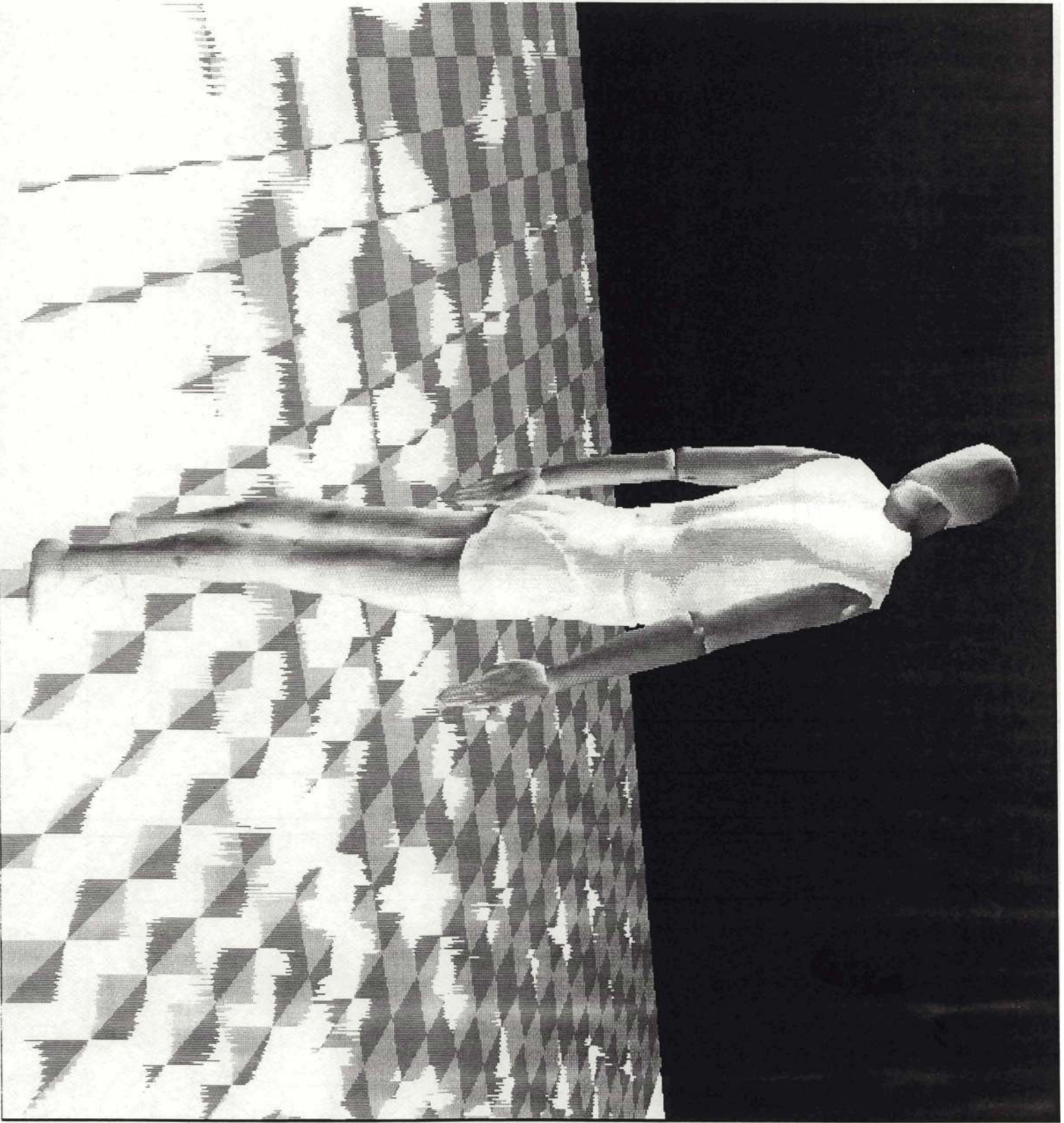*(flexion, axial, lateral)* = (3 deg, –12 deg, 23 deg)

Figure 4.

$(flexion, axial, lateral) = (-10\,deg, 108\,deg, -45\,deg)$

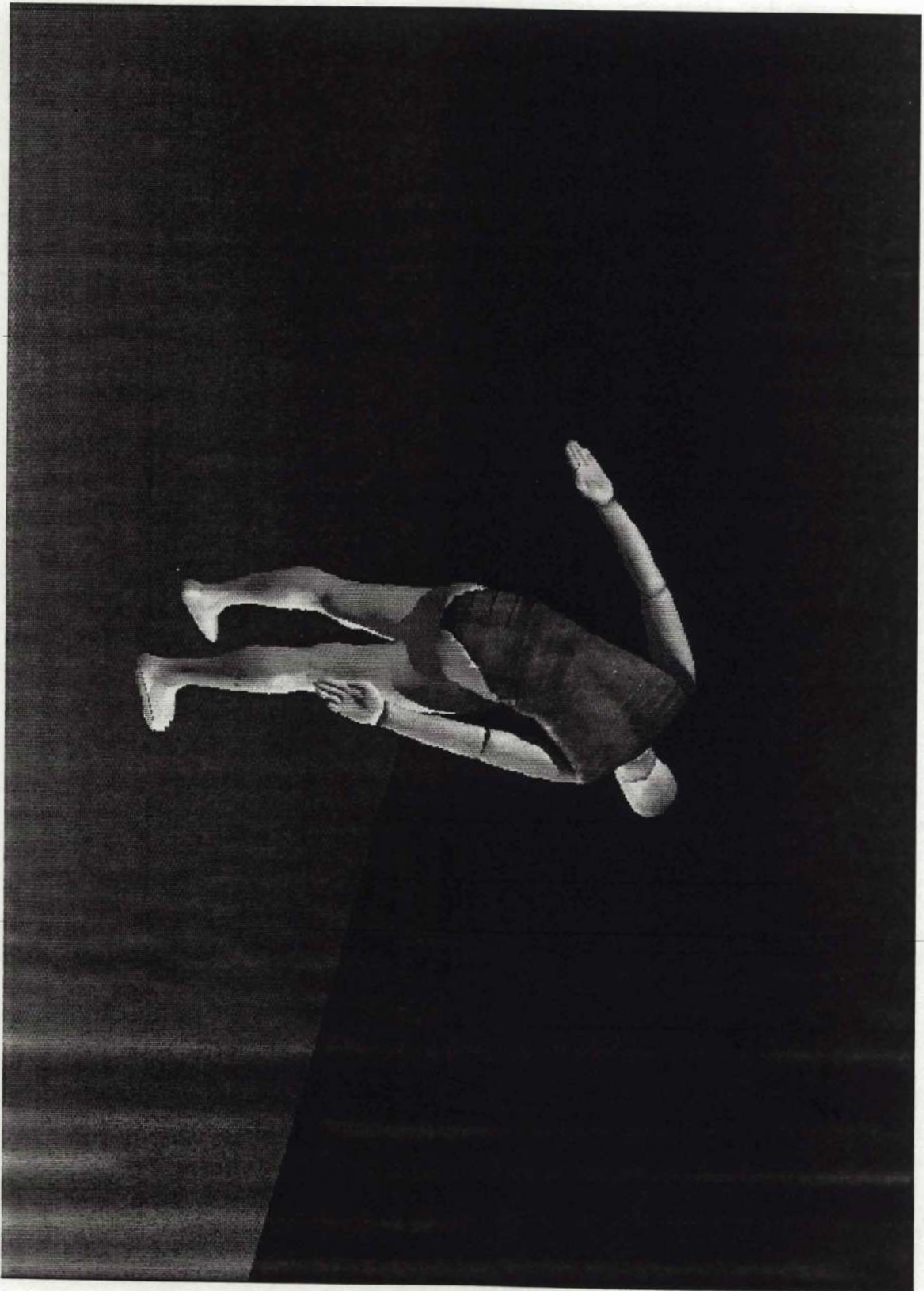Figure 5.

$(flexion, axial, lateral) = (18\,deg, 108\,deg, -68\,deg)$

Figure 6. $(flexion, axial, lateral) = (-33\,\mathrm{deg}, 39\,\mathrm{deg}, 6\,\mathrm{deg})$

Figures 7-12. Wireframe polygonal body with visible spine moves through a rolling sequence. Zero interpolation flag is set to "no".
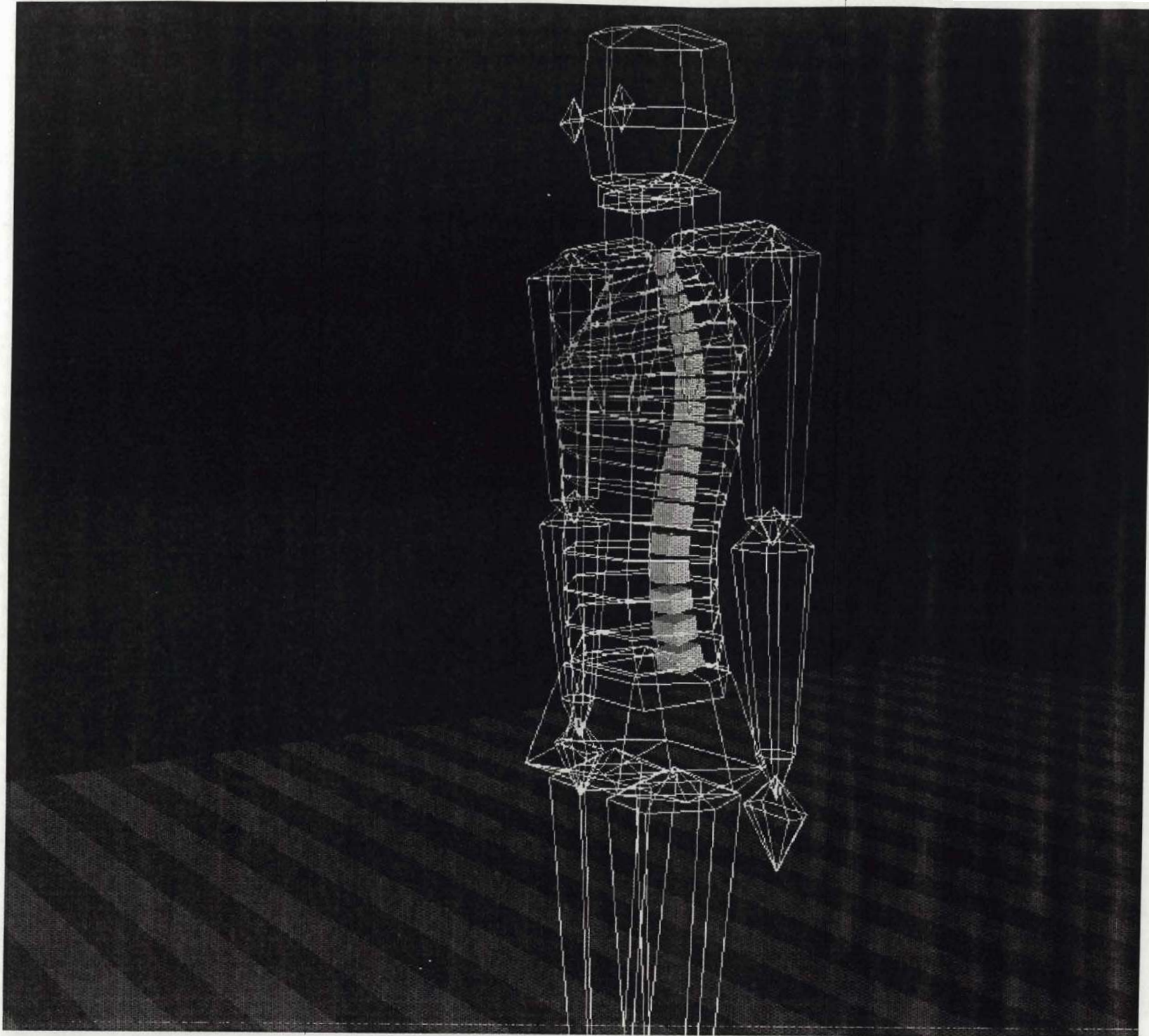
Figure 7

Figure 8
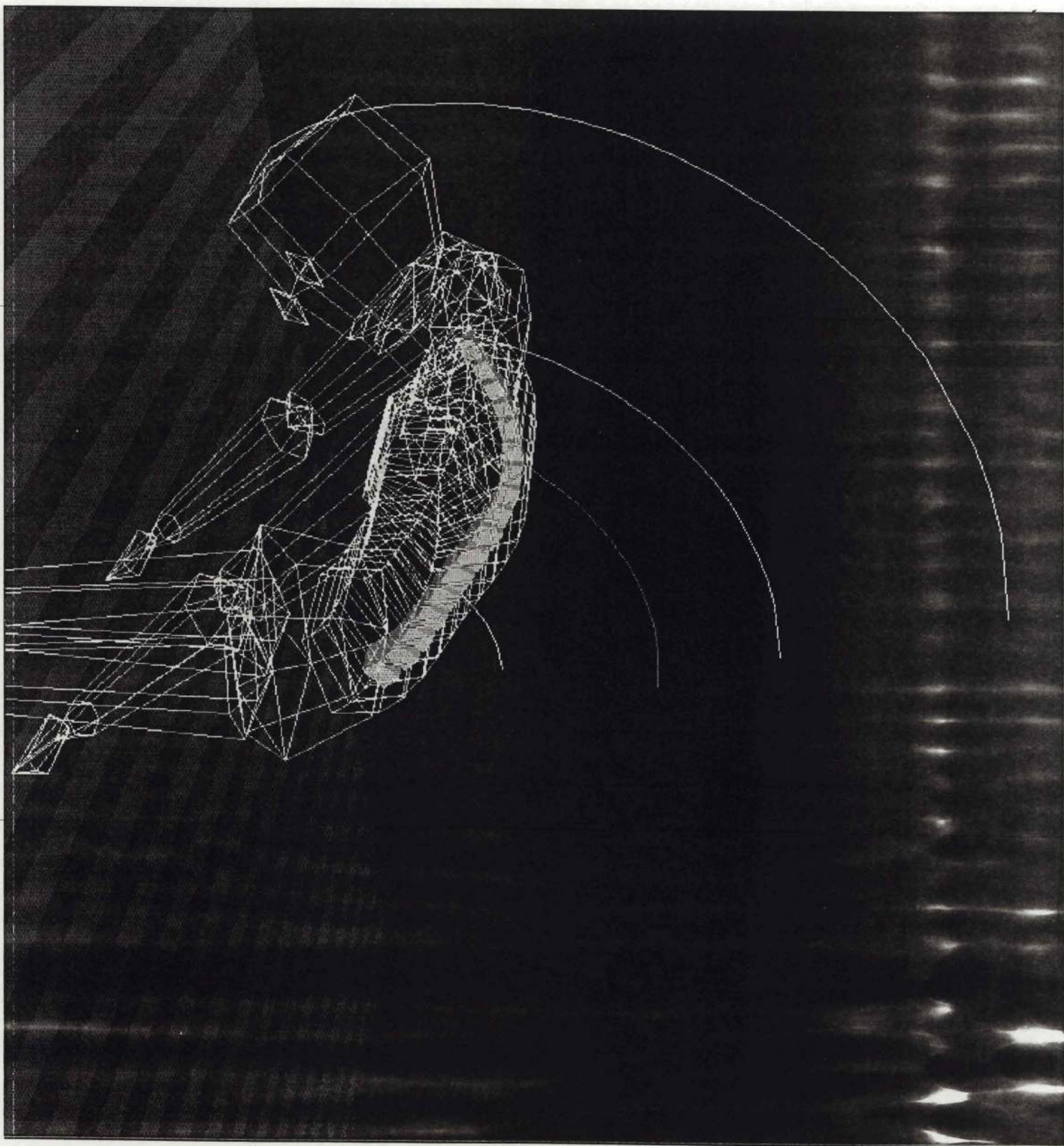
Figure 9
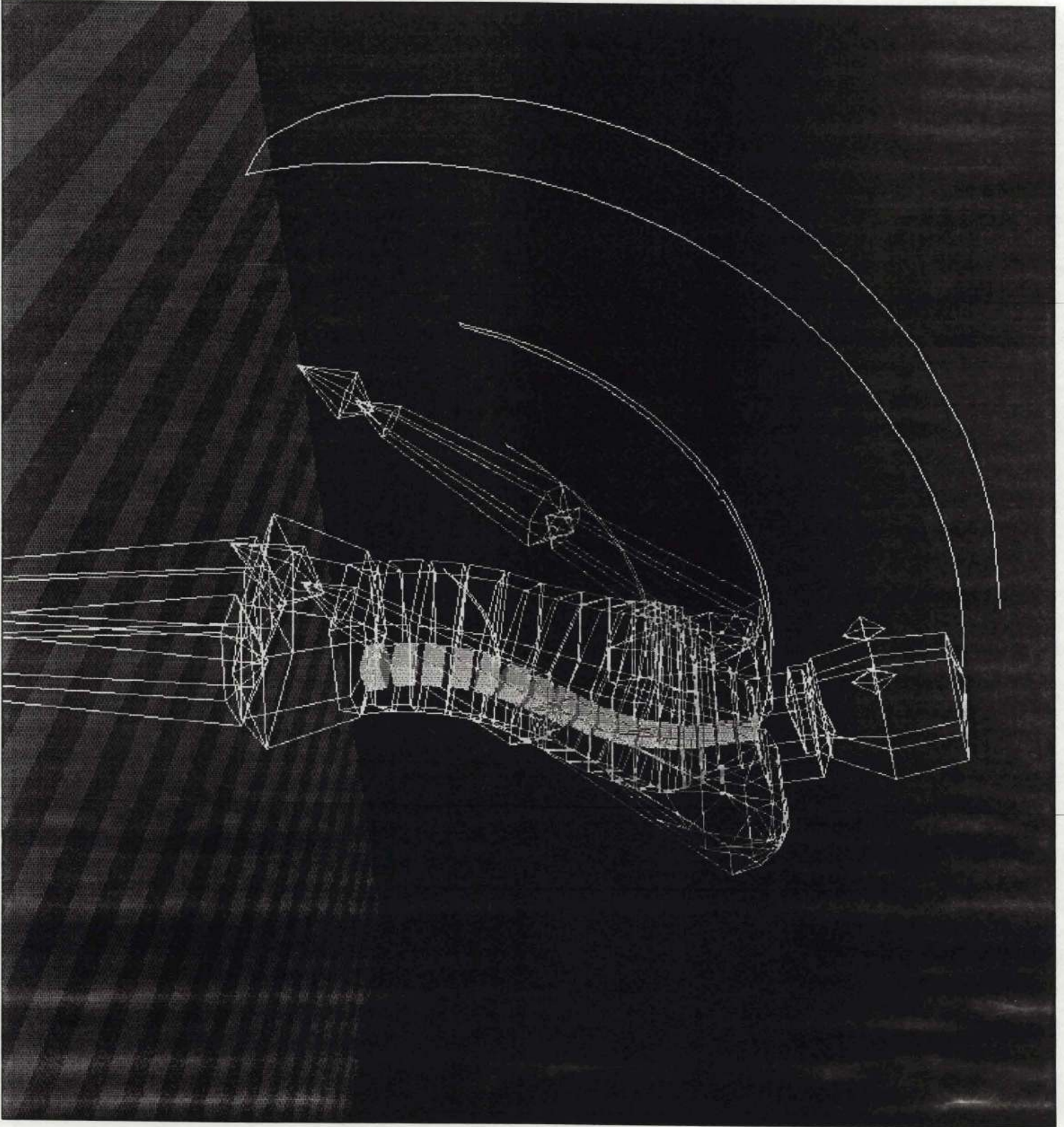
Figure 10
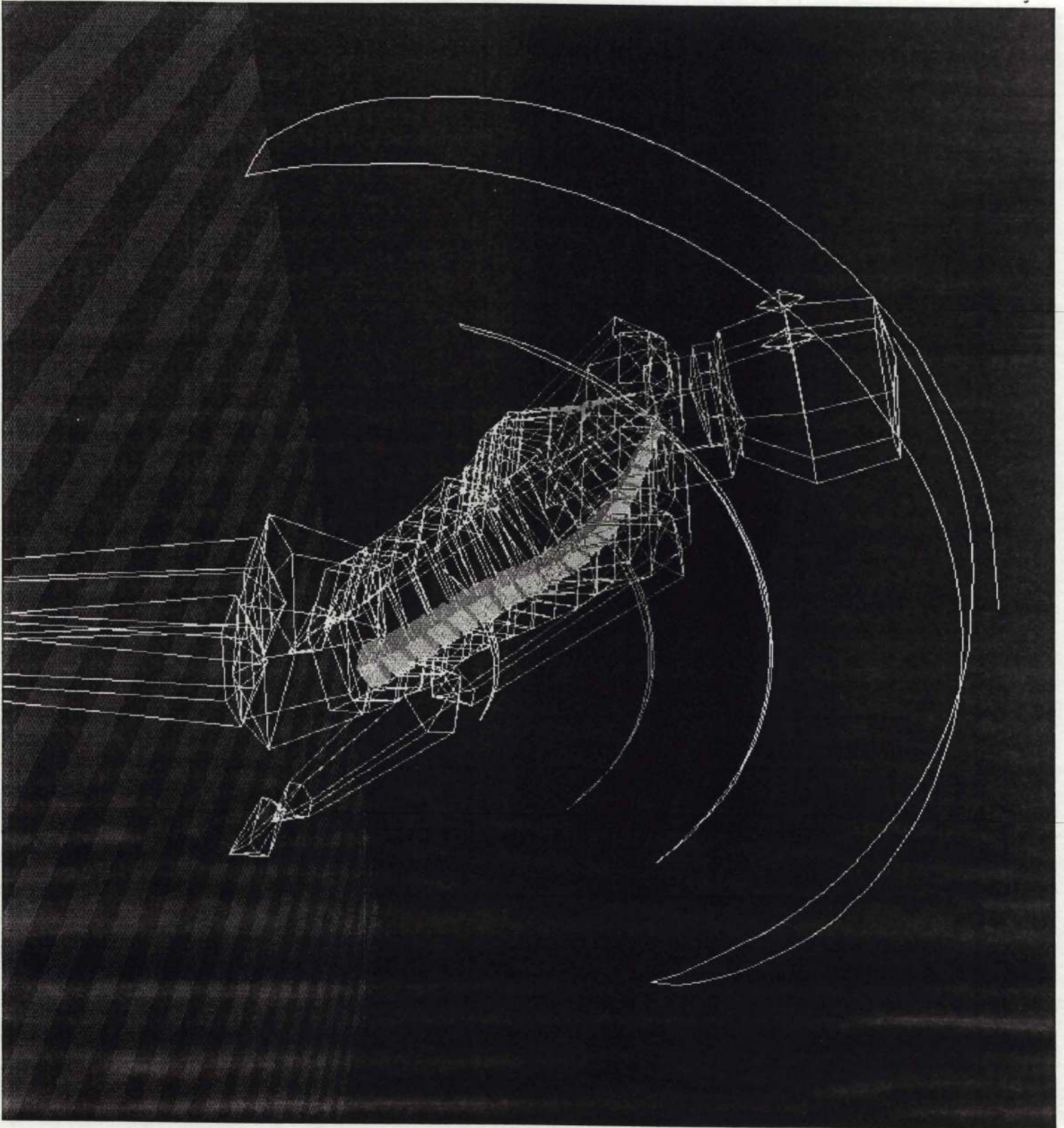
Figure 11

Figure 12

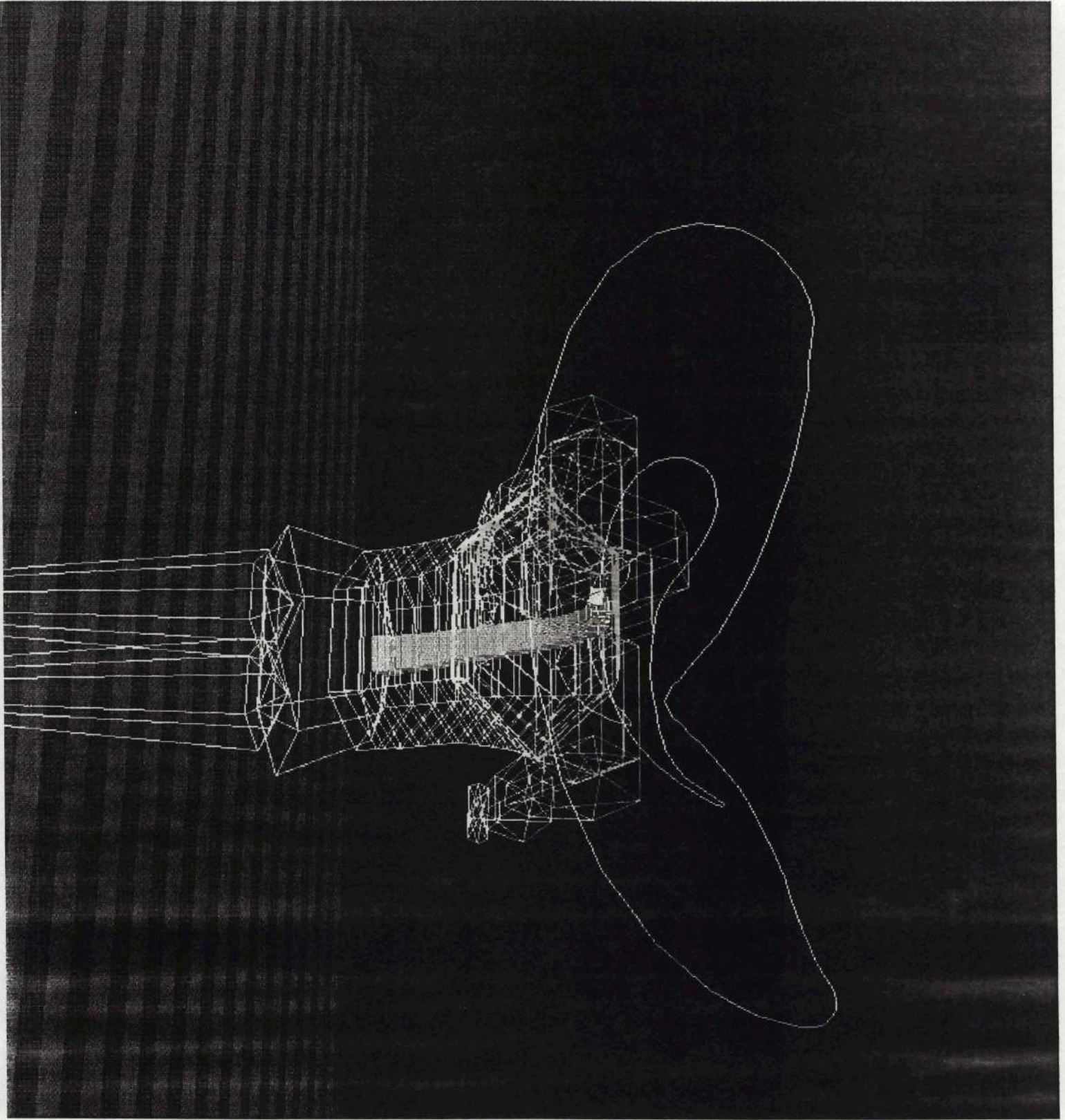Figures 13-14. Wireframe polygonal body performs circular motion.
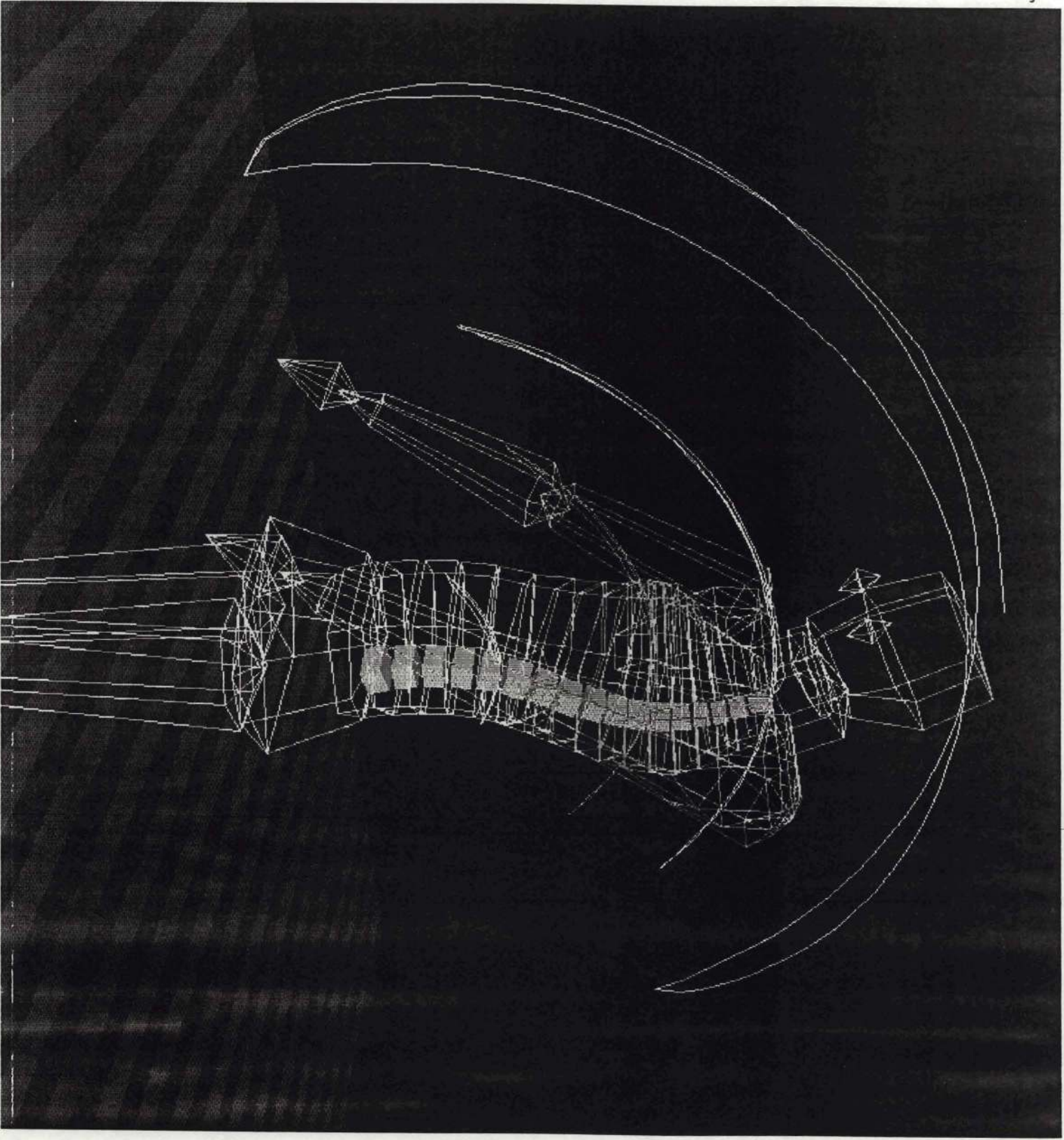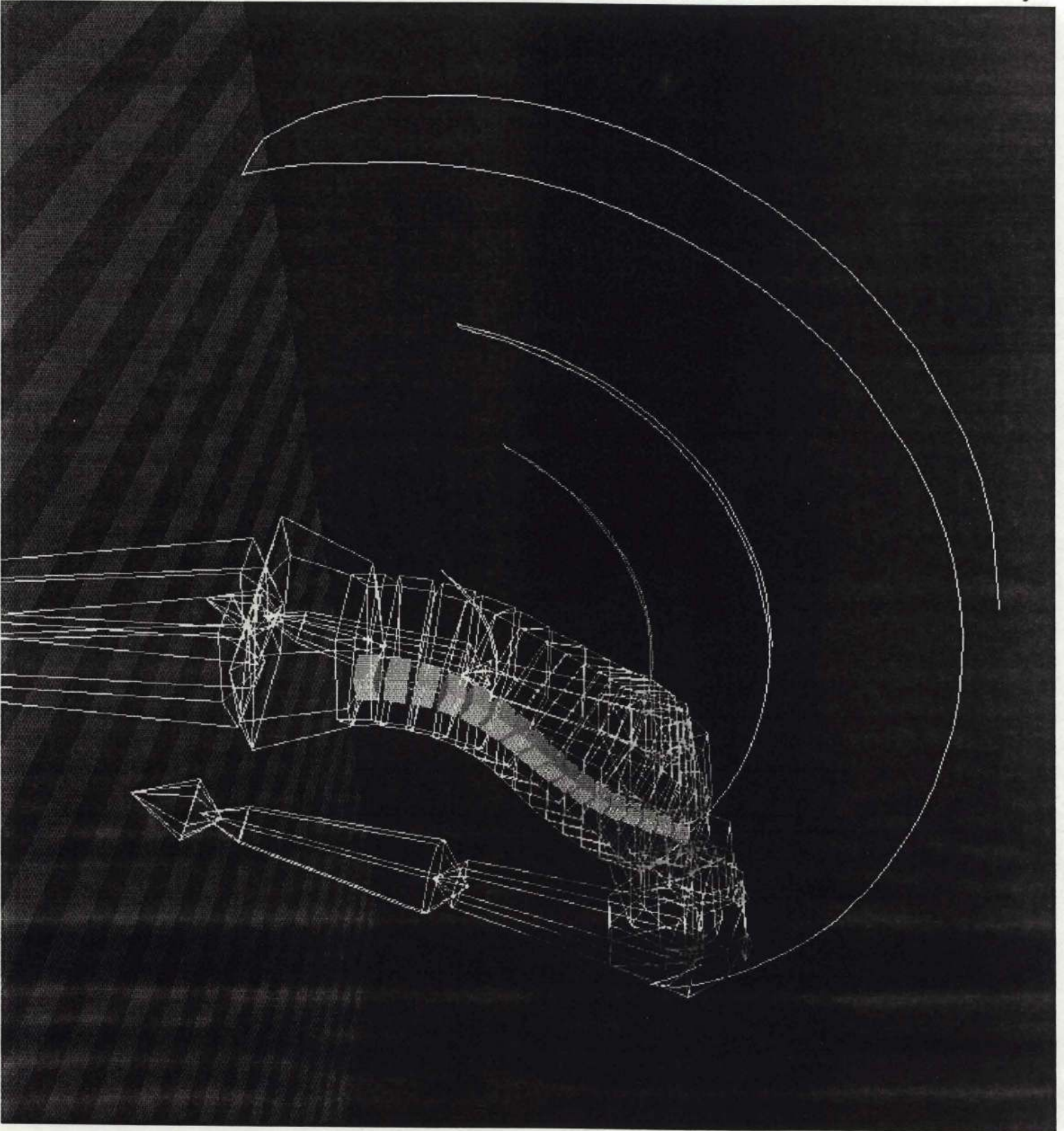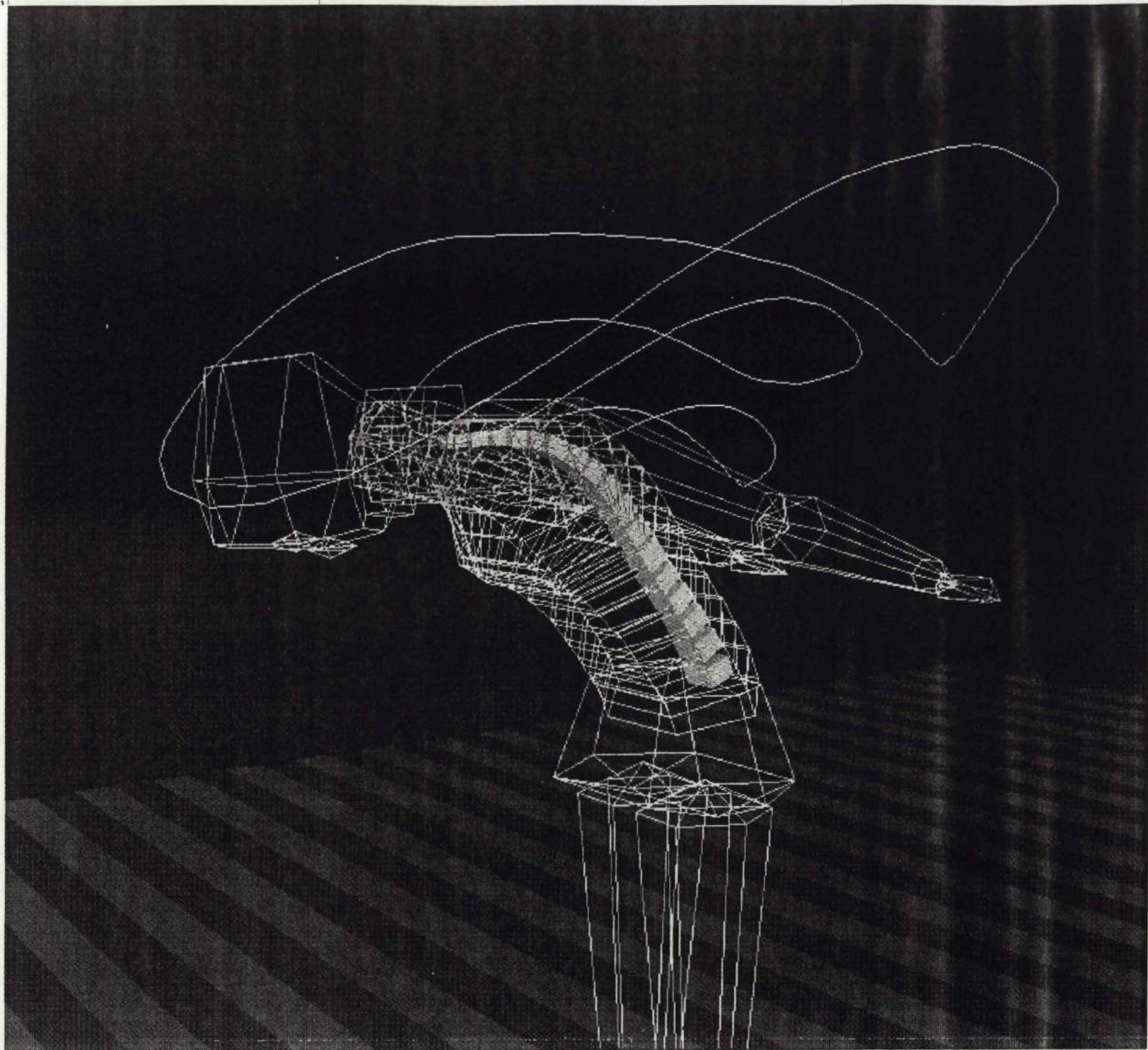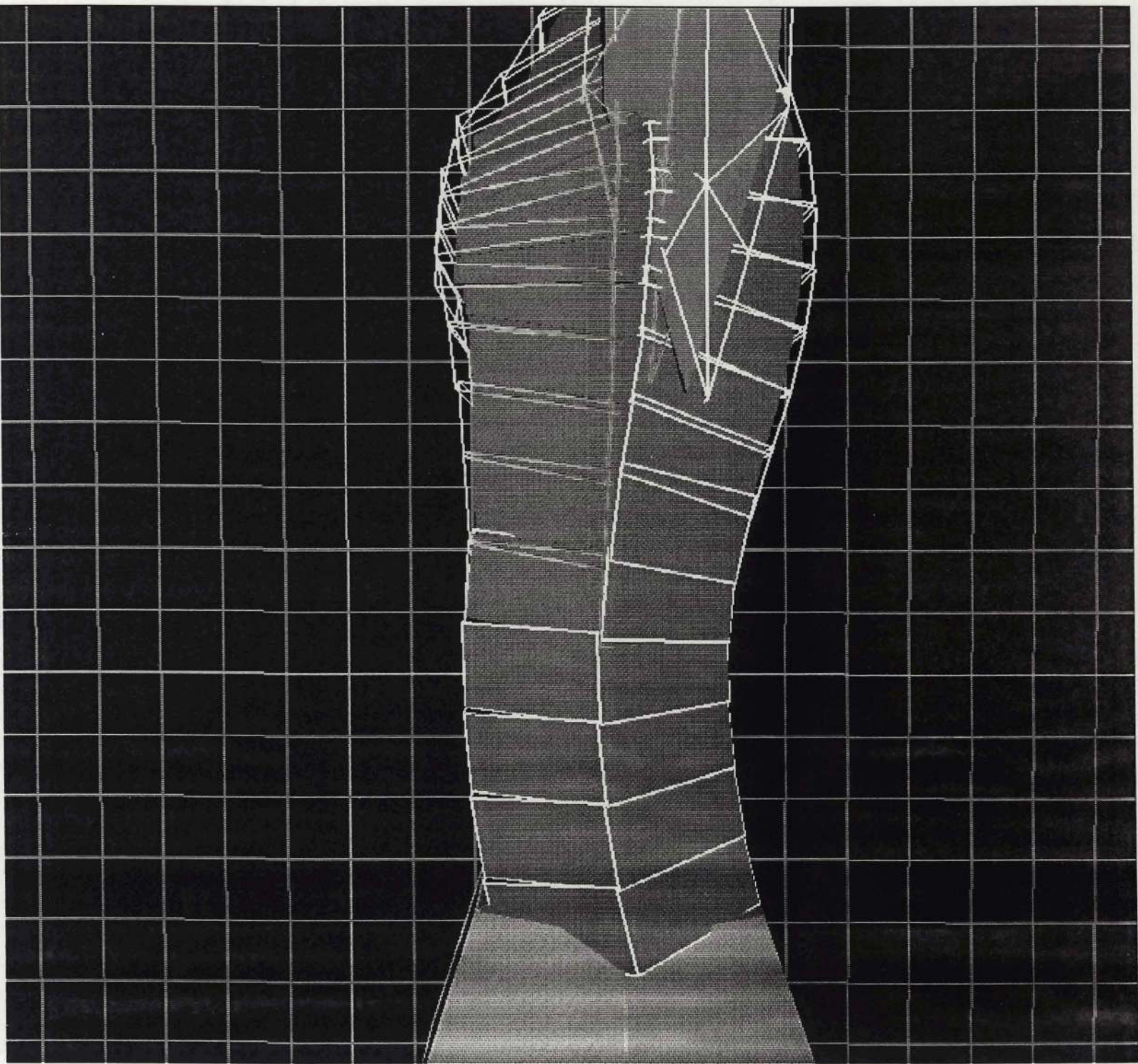
Figure 13

Figure 14

Figure 15. Breathing torso indicates movement over a 5.0 sec breath cycle. Green - 0.0 sec, red - 1.6 sec, yellow - 4.0 sec.