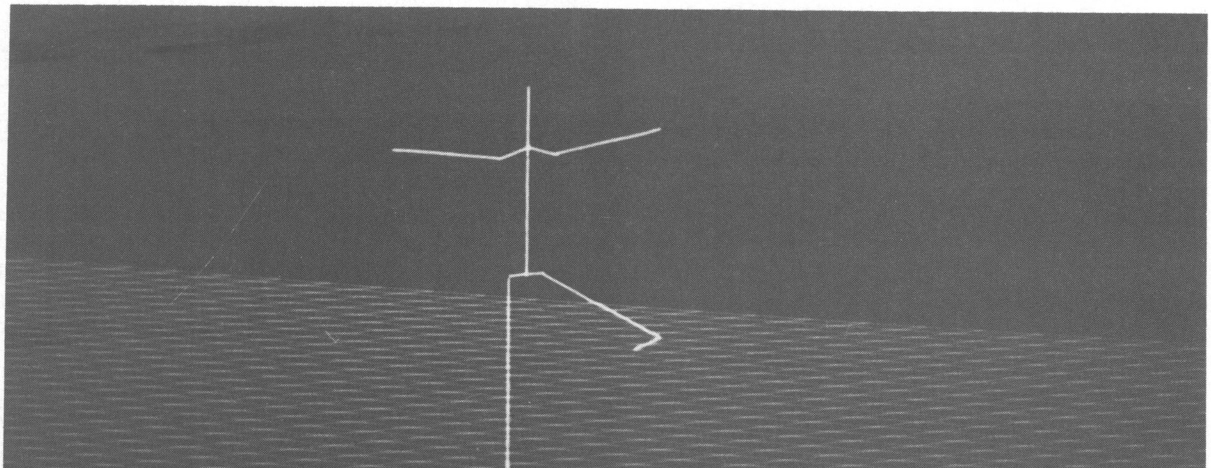
A kinematic simulation model allows realistic animation of the human body—provided the body is in contact with the ground and input data is accurate.

Aspects of the Kinematic Simulation of Human Movement

T. W. Calvert and J. Chapman
Simon Fraser University

A. Patla
University of Waterloo



Human movement is simulated to meet different needs within a number of fields, including aesthetics, entertainment, scientific research, and clinical diagnosis. Animation systems used in cartooning, for example, provide an illusion of reality without pretense to accuracy. Systems recreating movement patterns from dance notation also seek to create a visual representation of moving figures—but with more emphasis on accuracy and less on illusion. The clinical analysis of abnormal movement patterns for medical diagnosis and the analysis of normal movement for ergonomic design of workplaces also require the accurate simulation of the body in action.

All of these applications are limited to kinematic effects, contrasting with dynamic simulations where movements are calculated from patterns of applied forces. Since dynamic simulation, unlike kinematic simulation, involves solving the equations of motion for the human body, the cost is several orders of magnitude higher.

Whatever the nature of the simulation, many users place greatest importance on the quality of the output, whether it is the hand-painted bodies of cartoon characters on broadcast video systems, or the stick figures, or primitive fleshed-out figures on vector or raster graphic displays. Because the computational load increases with the fidelity of the movement representation and with the quality of the display, high-quality images will generally have relatively crude movement patterns and vice versa.

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It might be technically feasible to implement a dynamic simulation of multiple human bodies with a real-time video output of realistic fleshed-out, clothed, textured, and shaded figures comparable in quality to the images of actual people who have been filmed or videotaped for commercial TV. However, the complexity and cost of solving this problem would probably exceed those of developing a training simulator for a jet aircraft. Since it is unlikely that funds of such magnitude will be made available to develop a comprehensive system for human movement simulation, any systems implemented in the next decade will necessarily involve compromises.

In this context, we will discuss the general features of simulation system for human movement in terms of three major components: the input environment, the system model, and the output environment.

We will also describe the kinematic simulation system developed at Simon Fraser University.[1-4] Accepting data from movement notation (Labanotation) or analog instrumentation (electrogoniometers) as input, this system interfaces with output modules driving both vector and raster graphics displays with stick or fleshed-out figures. It also has an output module that can be used to control a robot manipulator arm. The system's simulation software is portable and runs on a number of different computers. Additionally, we will refer to parallel developments by Badler and his colleagues at the University of Pennsylvania; Herbison-Evans at the University of Sydney; Savage, Officer, and Ryman at the University of Waterloo; Sealey at the University of Iowa; Dombrower at UCLA; Zeltzer at Ohio State; and Kingsley, Schofield, and Case in the UK.[5-14]

The block diagram of Figure 1 introduces the elements of the simulation problem. Although, in practice, solutions are often dominated by the nature of the input and output environments, it is conceptually more convenient to discuss the system model first.

System model

Simulation models can be classified according to their generality, complexity, constraints, dimensionality, and whether they involve dynamic calculations.

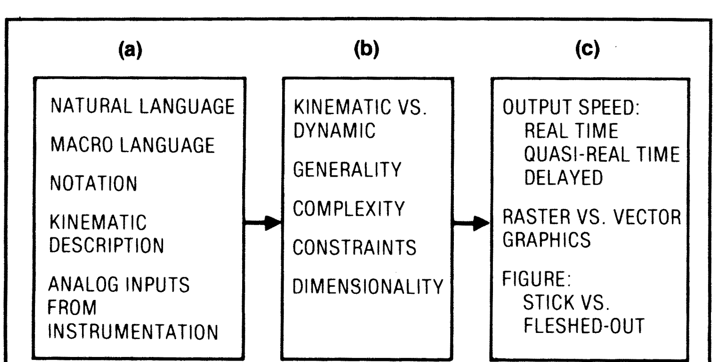

Figure 1. Simulation of human movement involves three elements: (a) the input environment, (b) the system model, and (c) the output environment.

Generality. Generality is the degree to which a model is designed with general features as opposed to class-specific or problem-specific ones. Cartoon animation and dynamic simulation systems are often very specific. On the other hand, some kinematic simulation systems are quite general in principle, although the output processor can be specific to a particular body and the ouput interface can be specific to a particular display technology. Parameters which result in loss of generality when they are built into the model include body topology, body size (i.e., limb lengths), body shape (i.e., the contours of limbs in fleshed-out figures), stereotyped movement patterns, and constraints on movement at joints.

The advantage of generality is that new problems can be handled without changing the simulation system; however, this asset must be balanced against the added costs of system design when specific features such as body topology and body shape cannot be built in. For example, a researcher interested in dance needs a system capable of simulating the movements of dancers with different body sizes, but how often does he want to simulate a spider?

Complexity. This is a function of the independent bodies being simulated. Each body's complexity depends on the number of independent body segments, the number of joints, and the number of limbs connected to each joint. Usually the connectivity will be restricted to simply connected limbs—that is, there should not be a closed ring of connected limbs (normally not a problem for real bodies). A reasonable representation of the human body can be obtained with about 23 segments if the details of the hands and feet are omitted. Computation time depends principally on the number of independent limb segments.

Constraints. Constraints can be anatomical or imposed by the physical environment. In either case, they limit the scope of feasible movements. For example, knees and elbows cannot be hyperextended, and feet should not pass through the floor. In dynamic simulations, additional biomechanical limits can be applied.

If constraints are included in the model, impossible instructions will not be implemented; however, complexity would be increased since the ambiguities of impossible situations must be resolved. How this is handled really depends on the application. In cartoon animation, for instance, the illusion must suggest natural movement. In industrial applications, a robot manipulator arm could be damaged if given an impossible command. On the other hand, in notating a dance or studying the results of an automobile crash, it is probably important to know whether "impossible" movements may result. To be completely general, constraints must be applied as part of the simulation model, but it is also possible to detect illegal commands in the input module and to handle some inappropriate output patterns in the display module.

Dimensionality. Computational cost is linearly related to dimensionality. Any complete simulation must be carried out in three dimensions, but displays are usually limited to two dimensions. Thus, a point occurs between the actual simulation process and the output process where a transition can be made that saves computation. There are obvious advantages if the user can select the viewpoint in real time, but economies can be achieved if this is predetermined. Most displays are effectively 2½-dimensional—that is, the objects in the display are stored as flat parallel surfaces which can cover each other.

Kinematic vs. dynamic. The principal dichotomy in simulation systems is between the kinematic and the dynamic. Realistic and reasonably accurate animation is possible with kinematic simulation, provided the body is always in contact with the ground and accurate kinematic descriptions are provided as input. With this type of simulation, the output is realistic for slow movements but cannot account for ballistic movements except to the extent that they are accurately described in the input. This simulation approach is used for cartoon animation, for visualization of clinical records and dances recorded in notation, and for studies of man-machine interactions in the workplace. The disadvantage to it is that a very large library of kinematic descriptions must be built up if a variety of movements are to be handled at different speeds. As a consequence, handling complicated jumps and somersaults becomes almost impossible.

Without a dynamic simulation, however, no information can be obtained on any forces within the body or between the body and the external environment. Such simulations are needed in fundamental research on human biomechanics[15-17] and in studies of human function under stress, such as in an automobile crash[18] or in athletics.[19] Furthermore, clinical studies are underway that relate joint forces to muscular and skeletal abnormalities and to dysfunction in general.[20] Since the movement patterns simulated are usually quite specific and of limited duration, this work puts relatively little emphasis on displays. Typical biomechanical studies include those by Hemami,[21] who investigated idealized models of biped dynamics; Paul,[22] Morrison,[23] Pierrynowski,[24] Hardt,[17] and others, who investigated the dynamic division of force among muscles during locomotion; and Hatze,[15] who has developed a comprehensive model to study optimal control of human movement. Such simulations involve extensive computation. For example, Pierrynowski required 30 minutes of computer time on an IBM 4341 to simulate one second of real time, and Hatze used 24 hours on a major computer to optimize and simulate the movement of a lower limb during a single kick.

Input environment

In any simulation system the input can be specified in a number of ways. The most natural input for many purposes would be in the form of behavioral statements in natural language. The closest approach to this which has been developed to any degree of sophistication involves a movement notation system. Another involves kinematic specifications derived either from user specifications or from instrumentation.

Movement notation systems. Although a number of movement notation systems have been proposed, the only three in common use are Benesh notation, Eshkol-Wachman notation, and Labanotation[25-27] All three have been used in recording dance, Benesh being the most popular in the UK and Labanotation in North America. In addition, Labanotation has been used in industrial time and motion studies, Benesh has been used clinically to record movement,[28] and Eshkol-Wachman has been used to record behavioral patterns in animals.[29] At least three groups are using Labanotation as input to a kinematic simulation system, while Herbison-Evans[30] and Ryman[10] are using systems based on Benesh notation. In comparisons with Benesh, Labanotation is considered the more general and analytic, thus the more suitable for input to a computer-based system. However, Benesh notation is particularly suited to the stylized movements of ballet. Eshkol-Wachman notation—also analytic and general—is not as useful since it is less widely used. The examples given in this article will involve Labanotation; however, the notation will not be described since it has been extensively covered elsewhere.[2,7,27]

Labanotation. Because Labanotation allows a complete kinematic description of any gesture, either the actual symbols or an alphanumeric equivalent can be entered into the system model as input.

The only difficulty is that Labanotation has a rather clumsy way of representing small angular differences, so it is convenient to superimpose actual angle changes on the symbols, as shown in Figure 2. Changes in support—such as those that arise in walking, running, or jumping—are indicated by a shorthand showing the direction and level of the support limb while it is on the ground and the time that the support limb is not in contact with the ground. Consequently, the input processor must interpret the pattern of support changes and call a preprogrammed sequence, or macro, from a library.

The potential number of macros is quite large, although a limited number can cover the common steps in everyday human activities. In the macro for a step from a walk (illustrated in Figure 2), the simple symbols on the left show the changes in support for the left and right feet as they move forward sequentially in one step of a walk. Shown on the right is the corresponding notation necessary to kinematically define a reasonably accurate sequence of limb segment movements producing a step.

Macros can also conveniently store any sequence of Labanotation commands that can be used more than once. Simple parameters can be used so that the sequence is conditionally assembled for different numbers of repetitions, directions, and style, for example. Such macros can substantially shorten the notation of a movement sequence and represent an intermediate step between the base notation and a more natural higher level language. Elsewhere[4] we have suggested the form a high-level language might take.

Kinematic specifications. As an alternative to notation or a higher level language—both of which represent an analysis of the movement patterns—a direct, descriptive kinematic input can also be provided. This descriptive input can be derived from high-speed cinematography, video, ultrasonic, or polarized light instrumentation, or more directly from electrogoniometers attached to the joints.[28] Relatively simple instrumentation is available for this purpose, at least for the lower limbs (see Figure 3). Joint angles, available as voltages, can be fed into a computer through a multiplexed analog/digital converter.

Integrated inputs. If a simulation can accept both direct input from instrumentation and indirect input from notation, the possibility of integrating these two forms of input exists.[3] Integration would allow an animator to derive some aspects of an animation from direct measurements on a moving subject and to add other movements with notation. This approach holds promise for clinical applications.

A side benefit of a system that can integrate direct inputs from instrumentation with inputs from notation is that it becomes quite straightforward to automatically generate notation from the instrumentation inputs. The processor must have some intelligence added if the notation produced is to be optimal, but in any case it will be accurate. At present, no goniometers exist to provide simultaneous measurements of all joint angles for a free-moving human subject. However, this is probably technically feasible. A preliminary study has suggested that a body stocking with integral strain-gauges could be developed.

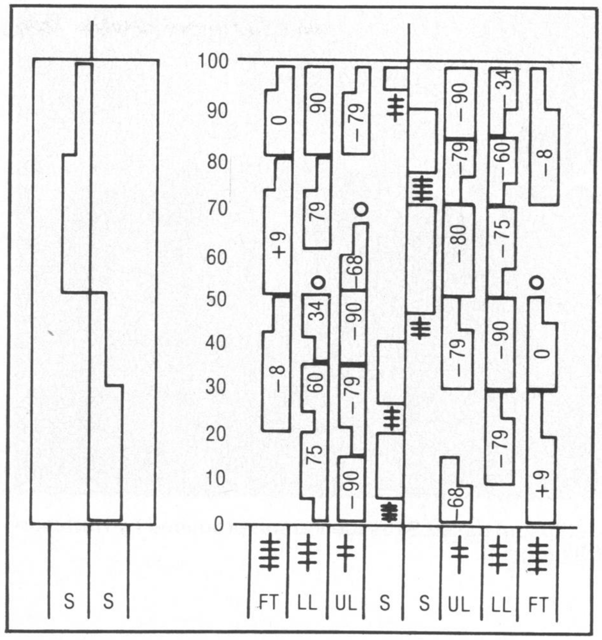

Figure 2. In the Labanotation for the WALKRL macro, the normal shorthand symbols on the left show only the change of support. The notation on the right shows the detailed commands necessary to produce reasonably accurate angle changes in the upper leg, lower leg, and foot.

Output environment

As in most computer graphics, output displays for a human movement simulation system are characterized by their speed, quality, and cost, with trade-offs possible between these three criteria. In considering display speed, the delay before a display starts and the frame rate after it has started must be distinguished. If a frame rate of about 12 frames per second cannot be maintained, then the display will either miss significant segments of the movement patterns or its speed will be slower than real time. In either case, the flicker rate will be objectionable. (A frame rate of 12 will avoid objectionable flicker on most displays if double framing is used—that is, if each of the computed frames is displayed twice.)

Display quality depends on the nature of the display terminal and on the complexity of the generated image. Although the vector graphics terminal allows relatively complex line drawings, it does not lend itself to filling in areas with shading or color. On the other hand, a raster graphics terminal makes it easy to fill in areas and use color but gives a poor representation of lines unless the definition is high. To make best use of a raster display, an antialiasing technique should be applied.[31]

The simplest and thus most computationally efficient display representation of the human body is a stick figure. For many purposes the stick figure is quite adequate since the movements of all independent body segments can be observed. A minor disadvantage is that it may not be possible to distinguish whether a limb is behind or in front of the body, but this problem is minimized if a perspective

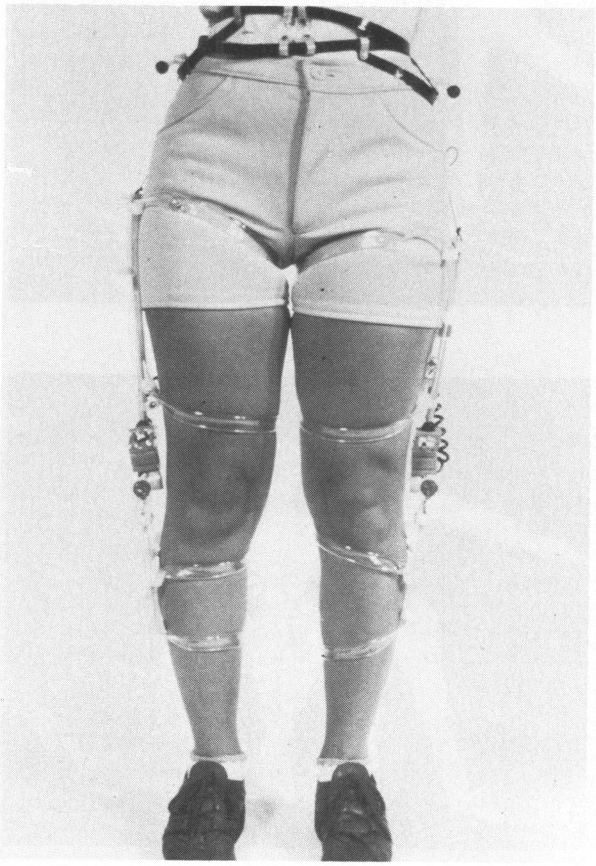

Figure 3. Electrogoniometers attached to the knee joints, providing direct kinematic input.

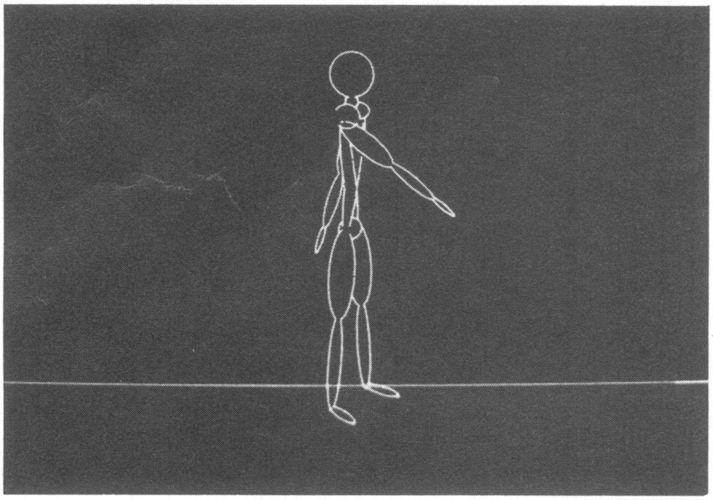

Figure 4. The ellipsoid-based Sausage Person produced by Herbison-Evans' NUDES program.

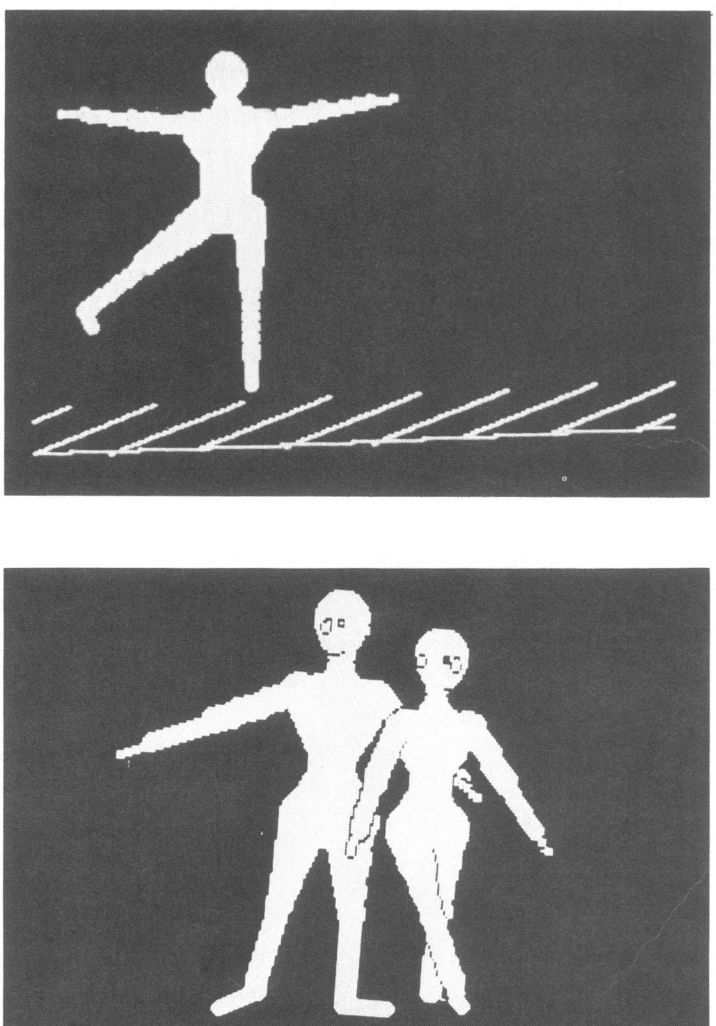

Figure 5. Examples of spheroid-based Bubble Persons produced on the Apple II.

view can be generated and the viewpoint rotated in real time. Nevertheless, the stick figure is hardly realistic—it is normally unacceptable for cartoon animation, for example—and many naive users find it distracting.

While a number of proposals have been made for representation of the human body in biomechanics (e.g., Hanavan,[32] few are computationally efficient. Recently, two efficient approaches have been developed, one best suited to vector graphics and the other to raster graphics.

Herbison-Evans' NUDES program[8] results in a body with limbs represented by ellipsoids—the Sausage Person. This method leads to an efficient technique for hidden line removal; however, after the display image has been computed, the viewpoint is fixed and cannot be changed by the user in real time. An example of this output is shown in Figure 4.

The method developed by Badler, O'Rourke, and Toltzis[33] for raster graphics relies on modeling the body with spheres, creating the Bubble Person. The advantage of spheres is that they have a circular projection for any orientation. If the disks to be displayed are sorted by depth, a 2½-dimensional display results. Then it is possible to vary intensity with depth or adopt the technique proposed by Knowlton[34] to outline and shade the limbs. The principal advantages of the Bubble Person are that it is computationally efficient and gives reasonable quality. Examples produced on an Apple II monitor are shown in Figure 5.

While the Bubble Person and the Sausage Person lack the high quality expected for cartoon animation, they are probably close to the best to be expected with current hardware. Achieving an accurate model of a fully fleshed-out, clothed, textured, and colored human body, comparable to the images on commercial TV, must wait for the next generation of hardware, at least as far as real-time animation is concerned.

The SFU kinematic simulation system

To illustrate the trade-offs made in implementing a practical system for kinematic simulation, we will briefly describe the system developed at Simon Fraser University.[1-4]

Generality. The simulation model is completely independent of the topology and size of the figure being simulated; this information is read in as part of a data file. Furthermore, the spatial meaning for the command symbols of the movement notation input are defined at runtime by a data file. In retrospect, such generality is unnecessary. While it is certainly necessary to be able to specify different body sizes, the topology is essentially invariant.

Complexity. The simulated body comprises 23 joints and 22 independent segments made up as follows: torso, 5; neck, 2; head, 1; arms, 2 each; hands, 1 each; legs, 2 each; and feet, 1 each. These are grouped together as the following 10 complex limbs: neck and head; upper torso and head; whole torso and head; hips, whole torso, and head; lower arm and hand; whole arm and hand; and whole leg. Although 23 different points (joints) move independently in the simulation, all of them are not necessarily shown in the output. Those not shown explicitly may result in distortions, for example, of the torso.

Constraints. The current version of our model incorporates no anatomical or physical constraints. The constraints in earlier versions were removed when it was found that they sometimes resulted in unnatural movement patterns. The conclusion drawn was that if constraints are to be included in the simulation model, then a sophisticated feedback correction system must be incorporated that results in natural movement patterns when the notated movement is not possible. With such a sophisticated feedback system, other natural features of human movement could also be included—such as a balance control to adjust the body orientation if the center of gravity moved too far from the center line. In clinical applications, however, where interest lies more in function that in an illusion of reality, the unusual movement patterns resulting from a lack of constraints serve a useful function since an abnormal condition may be indicated by this unusual pattern. Our current simulation model does not check any constraints, and natural movement patterns are obtained by carefully checking and editing the input code.

Dimensionality. The system model carries out all calculations in three dimensions. Since the initial system output was a stick figure, the angles of limb rotation were not included in the model output. However, with the move to fleshed-out figures, where limb cross-sections may be nonuniform (e.g., hands, feet), this necessary output is being added.

Kinematic vs. dynamic. All simulation in the SFU model is kinematic. Dynamic simulation has been considered for ballistic movements such as jumps, but at this stage the computational costs would be excessive. Long-term plans include incorporating a simplified dynamic simulation into the model in order to integrate the simulation system into ongoing research on human biomechanics and to improve the quality of animation for ballistic movements.

Input environment. A screen-oriented Labanotation editor and input system have been developed, and a comprehensive input editor designed by Smoliar and Weber[7] is available. However, using an alphanumeric representation of Labanotation as the standard input has been found to be more convenient. In this alphanumeric code, illustrated in Figure 6, each line has a one-to-one relationship to a Labanotation symbol. We have found it more convenient to work with this code than with Labanotation score because, first of all, the code can be directly stored and read by a computer and, secondly, it is easily generalized into macros which subsume many lines of elemental code. If necessary, a graphic display of a Labanotation score can be generated from this code. Input sequences typically involve a combination of macros and individually notated gestures. In the examples of simple macros found in Figure 6, the four submacros RLSTEPB, RLSTEPE, LLSTEPB, LLSTEPE are combined into the composite macro WALKRL for a full step of the walk.

A library of over 50 macros now exists at SFU. Input can also be derived from the analog outputs of an electrogoniometer. Currently, inputs can be recorded and digitized simultaneously from up to 16 of the 18 axes of rotation available for the three joints (hip, knee, and ankle) of each lower limb. These instrumentation inputs are converted into angle changes and stored in the same format used to represent the angular changes indicated by notation. Thus, the inputs from instrumentation and notation are easily combined. Arm movements from notation, for example, can be directly added to walking movements derived from the goniometer.

Output environment. Output is produced on a number of systems, including an Evans & Sutherland Picture

```
7 RLSTEPB
4 0.0 50.0 UAR 180 85
4 0.0 50.0 LAR 180 89
4 0.0 50.0 UAL 360 79
4 0.0 50.0 LAL 360 70
1  0.00 15.00 ULR       PL   RFL
1  0.00 10.00 LLR       RBL  RBL  RBL  RBM
1  0.00 30.00 TOR       RFH  RFM  RFM  RFM  RFM  RFM
4 10.00 20.00 LLR       PL   PL   PL   RFL
1 15.00 15.00 ULR       PL   RFL
1 30.00 20.00 ULR       PL   PL   PL   RFL
1 30.00 20.00 LLR       PL
1 30.00 20.00  TOR      RFM
0 33.00  ANR
8
7 RLSTEPE
1 00.00 17.00 ULR       PL
1 00.00 20.00 LLR       PL   PL   RBL
1 00.00 20.00 TOR       RFM
0 00.00 ANR
1 17.00 18.00 ULR       PL   PL   PL   RBL
0 20.00 TOR
1 20.00 15.00 LLR       RBL  RBL  PL
1 20.00 30.00 TOR       RFL  RFM  RFM  RFM  RFM  RFM
4 35.00 15.00 ULR       PL   PL   PL   PL   RFL
1 35.00 15.00 LLR       RBL  RBL  RBL  RBM
8
7 LLSTEPB
4 0.0 50.0 UAL 180 85
4 0.0 50.0 LAL 180 89
4 0.0 50.0 UAR 0 79
4 0.0 50.0 LAR 0 70
1  0.00 15.00 ULL       PL   LFL
1  0.00 10.00  LLL      LBL  LBL  LBL  LBM
1  0.00 30.00 TOL       LFH  LFM  LFM  LFM  LFM  LFM
4 10.00 20.00 LLL       PL   PL   PL   LFL
1 15.00 15.00 ULL       PL   LFL
1 30.00 20.00 ULL       PL   PL   PL   LFL
1 30.00 20.00 LLL       PL
1 30.00 20.00 TOL       LFM
0 33.00 ANL
8
7 LLSTEPE
1 00.00 17.00 ULL       PL
1 00.00 20.00 LLL       PL   PL   LBL
1 00.00 20.00  TOL      LFM
0 00.00 ANL
1 17.00 18.00 ULL       PL   PL   PL   LBL
0 20.00 TOL
1 20.00 15.00 LLL       LBL  LBL  PL
1 20.00 30.00 TOL       LFL  LFM  LFM  LFM  LFM  LFM
4 35.00 15.00 ULL       PL   PL   PL   PL   LFL
1 35.00 15.00 LLL       LBL  LBL  LBL  LBM
8
7 WALKRL
6 0.00 1.00 LLSTEPB
6 0.00 1.00 RLSTEPE
6 1.00 1.00 LLSTEPE
6 1.00 1.00 RLSTEPB
8
```

Figure 6. The alphanumeric code for the WALKRL macro equivalent to the Labanotation shown in Figure 2. Note that the WALKRL macro is made up of four submacros.

System 1 driven by a PDP 11/34, a $512 \times 256 \times 1$ raster graphics display driven by a combined Pascal Microengine and Z80, and an Apple II microcomputer running Pascal with a black-and-white monitor ($280 \times 192 \times 1$ pixel display).

All development of production animation is carried out using a stick-figure output similar to that shown in Figure 7. Although a number of movies have been made using a frame-by-frame approach and featuring stick figures, we are currently using the Sausage Person on the Evans & Sutherland system and expect to make other movies with the Bubble Person on the Pascal Microengine system. The relative speeds of the systems are shown in Table 1.

Applications. We are experimenting with the use of this kinematic simulation system as a tool to assist in the notation of dance and as a tool for visualization of dance notation. Short movies have been made to illustrate the potential for visualization, and the first substantial segment of notation produced with the aid of the system is complete; the latter involves an improvisation sequence from the *Nutcracker* ballet.

The second major application is to the clinical assessment of movement abnormalities. The essence of this approach is that the kinematic patterns recorded with the aid of electrogoniometers can be supplemented with the notated judgments of a trained clinician. The composite clinical record is an animation sequence that can be viewed repeatedly from any angle.

A third application involves using the macrolanguage developed from animation of human figures to control a robot manipulator arm.

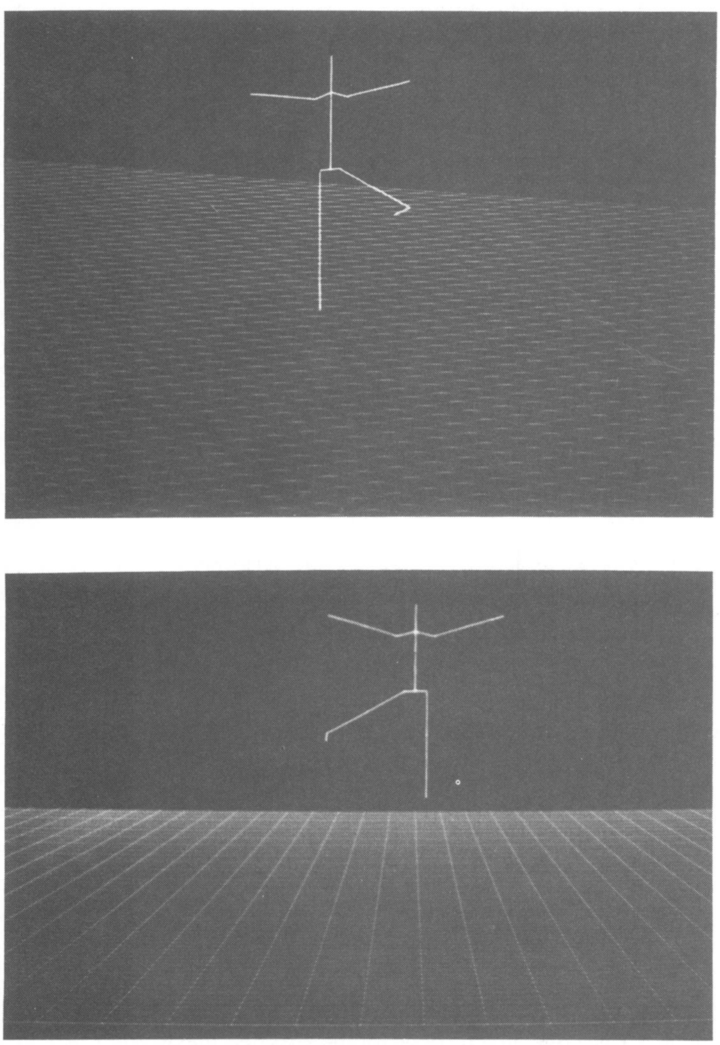

Figure 7. Two examples of stick figures produced on the Evans & Sutherland PS-1.

The systems in use today are essentially research tools. As such, they are unsuited for use as production tools in animation, the interpretation of dance notation, or the characterization of clinical abnormalities. Although producing a portable stand-alone system for kinematic simulation and display has been possible for some time, to our knowledge it has never been seriously attempted, probably because until recently costs were prohibitive. Within the last two years, however, the cost of hardware has dropped to the point where it is fairly easy to assemble a system which will give reasonable performance for a modest price. A prototype system currently being tested will give a stick-figure output at 12 frames per second, although the rate at which this output can be calculated by the simulator will be only two frames per second. It remains to be seen whether such a system with a reasonably powerful input editor will be attractive to potential users. The performance of this system in comparison to the others we use is also shown in Table 1.

The simulation of human movement represents a challenging intellectual and computational problem. Since the motivations for this work vary from aesthetics and entertainment to scientific research and clinical diagnosis, it is not surprising that many different approaches are used. Nevertheless, the unifying theme is the duplication of human function. As methods become more sophisticated, the solutions converge. As it is realized that kinematic solutions must be supplemented by dynamic simulation, the methods of biomechanics merge with the methods of animation. ■

Table 1.
Simulation and display speeds for three systems.

SYSTEM	FIGURE	SIMULATION (FRAMES)	DISPLAY (FRAMES)
EVANS & SUTHERLAND PS-1 WITH PDP-11/34	STICK	1/SEC.	9/SEC.
	ELLIPSE	1/SEC.	1/MIN.
PASCAL MICROENGINE WITH Z80	STICK	2/SEC.	12/SEC.
	ELLIPSE	2/SEC.	2/MIN.
	SPHERE	2/SEC.	1/SEC.
APPLE II	STICK	10/MIN.	30/MIN.
	SPHERE	10/MIN.	2/MIN.

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References

1. Z. Wolofsky, "Computer Interpretation of Selected Labanotation Commands," MS thesis, Kinesiology Dept., Simon Fraser University, 1974.
2. T. W. Calvert, J. Chapman, and J. Landis, "Notation of Dance with Computer Assistance," in *New Directions in Dance,* D. T. Taplin, ed., Pergamon Press, Toronto, 1979, pp. 169-178.
3. T. W. Calvert, J. Chapman, and A. Patla, "The Integration of Subjective and Objective Data in Animation of Human Movement," *Computer Graphics,* Vol. 14, No. 3, Aug. 1980, pp. 198-203.
4. T. W. Calvert and J. Chapman, "Notation of Movement with Computer Assistance," *Proc. ACM Ann. Conf.,* Vol. 2, 1978, pp. 731-736.
5. N. I. Badler and S. W. Smoliar, "Digital Representation of Human Movement," *Computing Surveys,* Vol. 11, No. 1, Mar. 1979, pp. 19-38.
6. L. Weber, S. W. Smoliar, and N. I. Badler, "An Architecture for the Simulation of Human Movement," *Proc. ACM Ann. Conf.,* Vol. 2, 1978, pp. 737-745.
7. S. W. Smoliar and L. Weber, "Using the Computer for a Semantic Representation of Labanotation," in *Computing and the Humanities,* S. Lusignan and J. S. North, eds., University of Waterloo Press, Waterloo, Ont., 1977, pp. 253-261.
8. D. Herbison-Evans, "NUDES 2: A Numeric Utility Displaying Ellipsoid Solids," *Computer Graphics,* Vol. 12, No. 3, Aug. 1978, pp. 354-356.
9. G. J. Savage and J. Officer, "Choreo: An Interactive Computer Model for Choreography," *Proc. 5th Man-Machine Comm. Conf.,* Calgary, Alta., 1977.
10. R. Ryman and B. Singh, "The Benesh Notation Computerized Editor," *Proc. Dance in Canada Conf.*, June 1982.
11. D. Sealey, "Recording Movement in Labanotation on Computer," Unpublished Users Manual, University of Iowa, 1979.
12. J. Menosky, "Video Graphics and Grand Jetes: Choreography by Computer," *Science 82,* Vol. 3, No. 4, May 1982, pp. 24-33.
13. D. Zeltzer, "Representation of Complex Animated Figures," *Proc. Graphics Interface 82 Conf.,* 1982, pp. 205-211.

14. E. C. Kingsley, N. Schofield, and K. Case, "SAMMIE—A Computer Aid for Man-Machine Modelling," *Computer Graphics,* Vol. 15, No. 3, Aug. 1981, pp. 163-169.

15. H. Hatze, *Myocybernetic Control Models of Skeletal Muscle,* University of South Africa Press, Pretoria, 1981.

16. D. B. Chaffin, "A Computerized Biomechanical Model—Development of and Use in Studying Gross Body Actions," *J. Biomechanics,* Vol. 2, 1969, pp. 429-441.

17. D. E. Hardt and R. W. Mann, "A Five-Body Three-Dimensional Dynamic Analysis of Walking," *J. Biomechanics,* Vol. 13, 1980, pp. 455-457.

18. R. L. Huston, C. E. Passerello, R. E. Hessel, and M. W. Harlow, "On Human Body Dynamics," *Annals Biomedical Eng.,* Vol. 4, 1976, pp. 25-43.

19. M. Arcan, M. Brull, and A. Voloshin, "A New Development in Locomotion Analysis: The Integrated Gait Laboratory," *Proc. Biomechanics Sports, Games, and Sport Activities Conf.,* Wingate Inst., Israel, 1979, pp. 19-29.

20. F. Van Fassen, N. H. Molen, and W. Boon, "Biomechanics of the Normal and Pathological Gait," in *Biomechanics II,* J. Vredenbregt and J. Wartenweiler, eds., 1969, pp. 260-265.

21. H. Hemami, "A Feedback On-Off Model of Biped Dynamics," *IEEE Trans. Systems, Man, and Cybernetics,* Vol. SMC-10, July 1980, pp. 376-383.

22. J. P. Paul, "Comparison of EMG Signals from Leg Muscles with the Corresponding Force Actions Calculated from Walkpath Measurements," in *Human Locomotor Engineering,* Inst. Mech. Eng., London, 1974.

23. J. B. Morrison, "The Mechanics of Muscle Function in Locomotion," *J. Biomechanics,* Vol. 3, 1970, pp. 431-451.

24. M. R. Pierrynowski, "A Physiological Model for the Solution of Individual Muscle Forces during Normal Locomotion," PhD thesis, Simon Fraser University, Burnaby, B.C., Jan. 1982.

25. R. Benesh and J. Benesh, *An Introduction to Benesh Dance Notation,* A. C. Black, London, 1956.

26. N. Eshkol and A. Wachmann, *Movement Notation,* Weidenfeld and Nicholson, London, 1958.

27. A. Hutchinson, *Labanotation,* Theatre Arts Books, New York, 2nd ed., 1960.

28. R. E. Hannah, "Interpretation of Clinical Gait Data," *Proc. Special Conf. Canadian Soc. Biomechanics—Human Locomotion,* London, 1980, pp. 80-81.

29. I. Golani, "Homeostatic Motor Processes in Mammalian Interactions: A Choreography of Display," Chap. 2 in *Perspectives in Ethology,* P. P. G. Bateson and P. H. Klopfer, eds., Vol. 2, Plenum, New York, 1976.

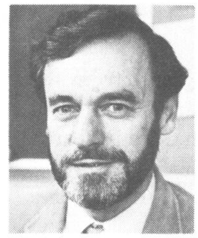
30. D. Herbison-Evans, "A Human Movement Language for Computer Animation," *Proc. Symp. Language Design and Programming Methodology,* University of Sydney, 1979, pp. 117-128.

31. M. T. Gupta and R. F. Sproull, "Filtering Edges for Gray-Scale Displays," *Computer Graphics,* Vol. 15, No. 3, Aug. 1981, pp. 1-5.

32. E. P. Hanavan, *A Mathematical Model of the Human Body,* Aerospace Medical Research Labs, Wright-Patterson AFB, Ohio, 1964.

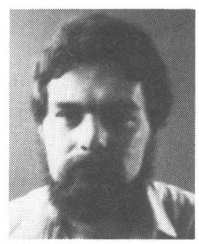
33. N. I. Badler, J. O'Rourke, and H. Toltzis, "A Spherical Representation of a Human Body for Visualizing Movement," *Proc. IEEE,* Vol. 67, No. 10, Oct. 1979, pp. 1397-1402.

34. K. Knowlton, "Computer-Aided Definition, Manipulation, and Depiction of Objects Composed of Spheres," *Computer Graphics,* Vol. 15, No. 2, Apr. 1981, pp. 48-71.



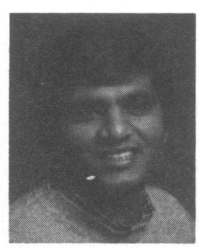
Thomas W. Calvert is a professor of kinesiology and computing science and dean of interdisciplinary studies at Simon Fraser University in Burnaby, British Columbia, Canada. A faculty member at SFU since 1972, he served as a director of engineering during 1980-81. He is currently on leave with Digital Productions in Los Angeles. His research interests include modeling and simulating human function with emphasis on the computer simulation and animation of human movement.

Calvert received the BSc in engineering from University College, London, in 1957, the MSEE from Wayne State University in 1964, and the PhD from Carnegie-Mellon University in 1967. He is a member of the Association of Professional Engineers of BC, ACM, the Canadian Medical and Biological Engineering Society, the Canadian Society for Computational Studies of Intelligence, and the Robotics International of the SME. From 1970-73, he served as associate editor for pattern recognition and artificial intelligence of the *IEEE Transactions on Computers.*



John Chapman has been engaged in the design and implementation of real-time and laboratory computer systems in a freelance capacity for the last ten years and has been actively engaged in researching the notation and animation of human movement for the last five years. His interests lie in computer graphics and languages.

Chapman completed the requirements for the BS degree in computer science at Simon Fraser University in 1982. He is a member of the ACM.



Aftab E. Patla is currently an assistant professor in the Department of Kinesiology at the University of Waterloo, Waterloo, Ontario. His research interests are in the areas of neural control of movement, nervous system modeling, and the clinical application of movement notation systems.

Patla received a BTech in electrical engineering from the Indian Institute of Technology, Kharagpur, India, in 1975; an MS in electrical engineering from University of New Brunswick, Fredericton, New Brunswick, in 1978; and a PhD in kinesiology from Simon Fraser University, Burnaby, British Columbia, in 1982.