THE SIMULATION OF HUMAN MOVEMENT.

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ABSTRACT.

The simulation of human movement is a challenging intellectual and computational problem. The general approaches to simulation and animation of human movement are reviewed in terms of the necessary input environment, simulation model and output environment. Although both dynamic and kinematic systems are discussed, emphasis is on the kinematic and the system developed at Simon Fraser University (SFU) is described in some detail to illustrate the trade-offs which are necessary. The SFU system accepts either analytic inputs from a combination of movement notation and movement macros or descriptive kinematic inputs from instrumentation such as goniometers. This leads to a complete kinematic simulation and produces animated output in the form of stick or fleshed out figures on vector or raster graphic displays.

KEYWORDS: Animation; Human body simulation; Movement notation; Dance notation; Human body displays.

1. Overview.

Human movement is simulated for many different reasons and in many different ways. Animation systems used for cartoons aim to provide an illusion of reality but make no pretence to accuracy. Systems to recreate movement patterns from dance notation also seek to create a visual representation of moving figures but in this case there is more emphasis on accuracy and less on the reality of the illusion. Similar requirements exist for systems to test the compatibility of a workplace to moving human bodies. All of these applications are limited to kinematic effects and contrast with the needs of a dynamic simulation. Since dynamic simulation involves solving the equations of motion for the human body the cost is several orders of magnitude higher than for a kinematic simulation. It is probably 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 of a quality comparable to real figures on commercial t-v. However, the complexity and cost of solving this problem would likely exceed that of developing a training simulator for jet aircraft. It is unlikely that funds of the order of $10 million will be made available to develop a comprehensive system for human movement simulation and thus, of necessity, any systems implemented in the next decade will involve compromises. In this context, the general features of a simulation system for human movement are discussed in terms of the three major components: the input environment, the system model and the output environment.

At Simon Fraser University (SFU), we have developed a system for kinematic simulation (1,2,3). The system accepts as input data from movement notation (Labanotation) or analog instrumentation (electrogoniometers) and interfaces with output modules which produce stick or fleshed out figures on vector or raster graphics displays. The simulation software is portable and runs on a number of different computers. To highlight the compromises necessary in the design of a movement simulation system, our own development will be used to provide parenthetic examples. We will also refer to parallel developments by Badler and his colleagues at the University of Pennsylvania (4,5,6), Herbison-Evans at the University of Sydney (7) and Savage and others at the University of Waterloo (8).

2. System Models.

Kinematic and dynamic models of human movement can be classified according to their generality, complexity, constraints, dimensionality and implementation restrictions.

Generality: the degree to which a model is designed with features which are completely general as opposed to class specific or problem specific. Cartoon animation and dynamic simulation systems are often very specific whereas some kinematic simulation systems are quite general in principle, although the output processor may be specific to a particular body.

SFU System: 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. Also, the spatial meaning of the command symbols of the movement notation input are defined at run-time by a data file. In retrospect, such generality is seen to be unnecessary. While it is certainly necessary to be able to specify different body sizes the topology is essentially invariant. How many times does a researcher interested in dance want to simulate a spider?

Complexity: a function of the number of independent body segments and the number of joints. A reasonable representation of the human body can be obtained with about 23 segments if the details of the hands and feet are omitted.

SFU System: The body which is simulated comprises 23 joints and 22 independent segments grouped together as 10 complex limbs.

Limbs:	*Complex limbs:*
torso - 5	*neck and head*
neck - 2	*upper torso and head*
head - 1	*whole torso and head*
arms - 2 each	*hips, torso and head*
hands - 1 "	*lower arm and hand*
legs - 2 "	*whole arm and hand*
feet - 1 "	*whole leg.*

Constraints: anatomical and physical constraints limit the scope of feasible movements; e.g. knees and elbows cannot be hyperextended and feet should not pass through the floor. In dynamic simulations there are additional biomechanical limits which can be applied.

SFU System. The current version of our model incorporates no constraints of this type. Earlier versions incorporated constraints but these were removed when it was found that they sometimes resulted in unnatural movement patterns. The conclusion drawn was that if constraints are included then it is necessary to incorporate a sophisticated feedback correction system which results in natural movement patterns when the notated movement is not possible. With such a sophisticated feedback system it would also be possible to incorporate other natural features of human movement such as, for example, a balance control which would adjust the body orientation if the centre of gravity moved too far from the centre-line.

Dimensionality: any complete simulation must be carried out in three dimensions but any display is usually limited to two dimensions. Thus there is a point between the actual simulation process and the output process where a transition can be made which 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. As discussed below, most displays are effectively "2½" dimensional.

SFU System. 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. With the move to fleshed out figures, where limb cross-sections may be non-uniform (e.g. hands, feet), this additional output is necessary and is being added.

The principal dichotomy in simulation systems is between the kinematic and the dynamic. Realistic and reasonably accurate animation is possible with kinematic simulation provided that the body is almost always in contact with the ground and accurate kinematic descriptions are provided as inputs. The output will be most 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 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. It becomes almost impossible to handle complicated jumps and somersaults.

Without a dynamic simulation 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 (9,10,11) and in studies of human function under stress such as in an automobile crash (12) or in competitive athletics (13). There are also clinical studies underway to relate joint forces to muscular and skeletal abnormalities and to dysfunction in general (14). The movement patterns being simulated are generally quite specific and of limited duration; thus this work puts relatively little emphasis on displays. Some typical biomechanical studies include those of Hemami (15), who investigated idealized models of biped dynamics, Paul (16), Morrison (17), Pierrynowski (18), Hardt (11) and others who investigated the dynamic division of force among muscles during locomotion; and Hatze (9) who has developed a comprehensive model to study optimal control of human movement. Such simulations require extensive computation; Pierrynowski required 30 minutes of computer time (IBM 4341) to simulate 1 second of real time and Hatze used 24 hours of time on a major computer to optimize and simulate the movement of a lower limb during a single kick!

SFU System. All simulation is kinematic. Dynamic simulation has been considered for ballistic movements such as jumps, but at this stage the computational costs would be excessive.

3. The Input Environment.

In any simulation system the input can be specified in one of a number of ways. For many purposes the most natural input 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 the use of a movement notation system. A different approach involves the use of kinematic specifications derived either from the specifications of a user or from instrumentation. These will be discussed in turn.

Movement Notation: Although a number of systems have been proposed, the only three in common use are Benesh Notation (19), Eshkol-Wachmann Notation (20) and Labanotation (21), All three have been used to record dance. Benesh being the most popular in the U.K. and Labanotation in North America. In addition, Labanotation has been used in industrial time and motion study, Benesh has been used to record movement clinically (25) and Eshkol-Wachman has been used to record behavioral patterns in animals (23). At least three groups are using Labanotation as input to a kinematic simulation system and Herbison-Evans is using a system based on Benesh Notation (29). It is generally agreed that Labanotation is more general and analytic and thus is more suitable than Benesh for input to a computer based system, although Benesh notation is particularly suited to the stylized movements of ballet. Eshkol-Wachman Notation is also analytic and general but is less useful since it is less widely used.

Labanotation allows a complete kinematic description of any gesture. Thus either the actual symbols or an alphanumeric equivalent can be entered into the system model as input. In contrast to gestures, changes of support such as arise in walking, running or jumping are indicated by a shorthand which shows only the direction and level of the support limb while it is on the ground and the time that the support limb is out of contact with the ground. Thus the input processor must interpret the pattern of support changes and call a preprogrammed sequence or macro from a library. As noted above in the discussion of dynamics simulation, the potential number of such macros is quite large, although a limited number can cover the common steps in everyday human activities.

Macros can also be used to conveniently prestore any sequence of Labanotation commands which may 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. The use of such macros can substantially shorten the notation of a movement sequence. In fact, this represents an intermediate step between simple notation and a higher level more natural language. We have suggested the form a high level language might take (24).

Kinematic Description: As distinct from notation or a higher level language, both of which represent an analysis of the movement patterns, a direct kinematic input which is descriptive can be provided. This descriptive input can be derived from high-speed cinematography, video, ultrasonic or polarized light instrumentation or more directly from goniometers attached to the joints (25). At least for the lower limbs, relatively simple instrumentation is available for this purpose;

joint angles are available as voltages which can be fed into a computer through a multiplexed analog/digital converter. A subject wearing bilateral lower limb goniometers is shown in Figure 1.

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). This would allow an animator to derive some aspects of an animation from direct measurements on a moving subject and then to add other movements with notation. We have suggested that this approach holds promise for clinical applications.

A side benefit of a system which 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 which is produced is to be optimal, but in any case it will be accurate. At present instrumentation does not exist to provide simultaneous measurements of all joint angles for a free moving human subject. However, this is probably technically feasible and a preliminary study has suggested that a body stocking with integral strain-gauges could be developed.

SFU System. Although a screen oriented Labanotation editor and input system has been developed, it has been found more convenient to use an alphanumeric representation of Labanotation as the standard input. Input sequences typically involve a combination of macros and individually notated gestures. A library of 50 macros now exists. Input can also be derived from the analog outputs of an electrogoniometer. Currently inputs can be recorded and digitized simultaneously from 16 of the 18 axes of rotation available for the three joints (hip, knee and ankle) of each lower limb. These inputs from instrumentation are easily combined with notation inputs; for example it is straightforward to add arm movements with notation to walking movements of the legs derived from the goniometer.

4. Output Environment.

As in most computer graphics, output displays for a human movement simulation system are characterized by their quality, speed, and cost with trade-offs possible among them. Display speed can be described in terms of both the delay before the display starts and the speed at which frames can be generated once it has started. If a frame-rate of about 12 per second cannot be maintained then either the display will miss out significant segments of the movement patterns or the display speed will be slower than realtime; in either case the flicker rate will be objectionable. (A frame-rate of 12 will avoid objectionable flicker on most displays if "twoing" is used, i.e. each of the computed frames is displayed twice.)

Display quality depends on the nature of the display terminal and on the complexity of the image which is generated. Whereas the vector graphics terminal allows relatively complex line drawings it does not lend itself to filling in areas with shading or color. 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 very high. The simplest and thus computationally most efficient display for the human body is a stick-figure. For many purposes this 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 it is possible to rotate the viewpoint in realtime. Nevertheless, the stick-figure is hardly realistic (normally it would be completely unacceptable for cartoon animation) and many naive users find it distracting.

While there have been a number of proposals for representation of the human body in biomechanics (e.g. Hanavan (26)),few of these approaches are computationally efficient. Recently two new and efficient approaches have been developed, one of which is best suited to vector graphics and the other to raster graphics. Herbison-Evans' Nudes program (7) results in a body with the limbs of the body represented by ellipsoids (Sausage Woman). This has the advantage that it leads to an efficient technique for hidden line removal but the disadvantage that after the display image has been computed the viewpoint is fixed and cannot be changed by the user. An example of this output is shown in Figure 2. The method developed by Badler, O'Rourke and Toltzis (27) for raster graphics relies on modelling the body with spheres (Bubble Man). These have the advantage of having a circular projection for any orientation. If the disks which are to be displayed are sorted by depth a "2½" dimensional display results and it is possible to vary intensity with depth and/or adopt the

Figure 1. Electrogoniometers similar to that shown here are to be used to measure the three angles of rotation at the three joints on each leg (25).

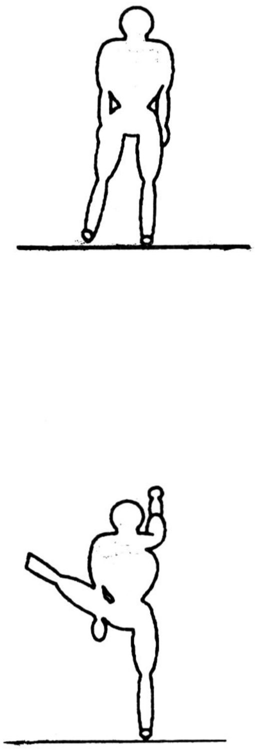

Figure 2. Two examples of a fleshed out figure produced on a vector graphics terminal using Herbison-Evans "Nudes" technique (29).

technique proposed by Knowlton (28) to outline and shade the limbs. The principal advantage of the "bubble man" is that it is computationally efficient and gives reasonable quality. An example produced on an Apple II monitor is shown in Figure 3. While neither the "bubble man" nor the "sausage woman" is of high quality by the standards of cartoon animation they are probably close to the best that can be expected with current hardware and funding. An accurate model of a fully fleshed out, clothed, textured and colored human body comparable to the images on commercial t-v must wait for the next generation of hardware, at least as far as realtime animation is concerned.

SFU System. Output is produced on an Evans and Sutherland Picture System 1 driven by a PDP 11/34, on a 512x256x1 raster graphics display driven by a combined Pascal Microengine and Z80 and also on an Apple II microcomputer running Pascal and with a black and white monitor (280x192x1). All development of production animation is carried out using a stick-figure output similar to that shown in Figure 4. A number of movies have been made using a frame by frame approach, and while in the past they have all featured stick-figures, we are currently using the "sausage woman" on the Evans and Sutherland and expect to make others with the "bubble man" on the new Pascal Microengine system.

5. Conclusions.

The systems in use today are essentially research tools and as such are unsuited for a production use in animation, interpretation of dance notation or the characterization of clinical abnormalities. While it has been possible for some time to produce a portable standalone system for kinematic simulation and display, to our knowledge this has not been seriously attempted, probably because the costs were prohibitive. However, within the last two years 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 reasonable price. A prototype system is currently being tested which will give a stick-figure output at a frame rate of 12 frames/second although the rate at which this output can be calculated by the simulator will be only 2 frames/second. It remains to be seen whether such a system with a reasonably powerful input editor will be seen as attractive by potential users.

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, there is a unifying theme in the duplication of human function and as methods become more sophisticated the solutions converge. Thus, as it is realized that kinematic solutions must be supplemented by dynamic simulations, the methods of biomechanics merge with the methods of animation.

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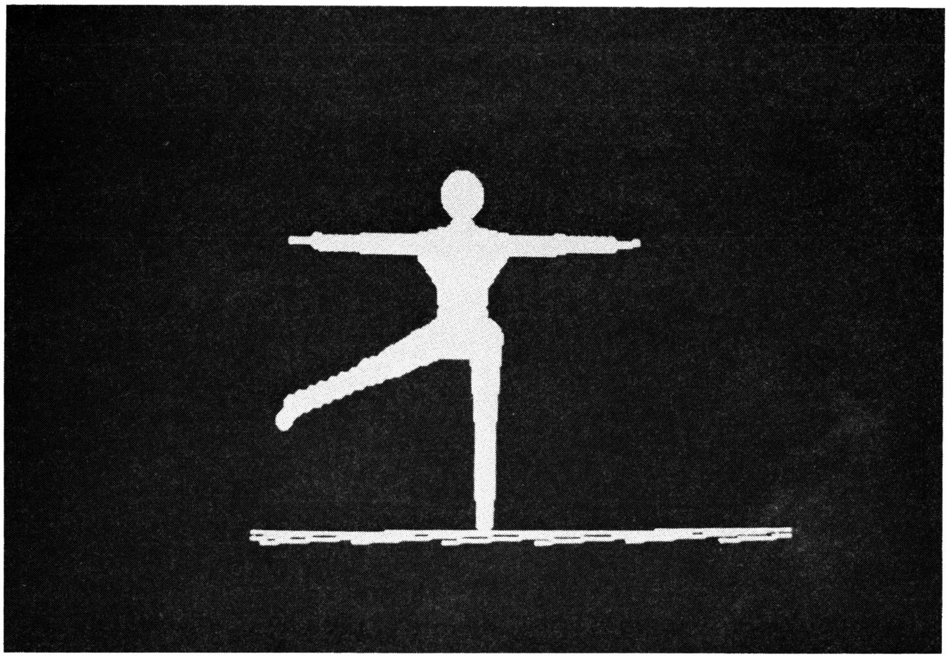

Figure 3. A figure generated on a raster graphics terminal (Apple II) where the body is modelled with spheres (27, 28).

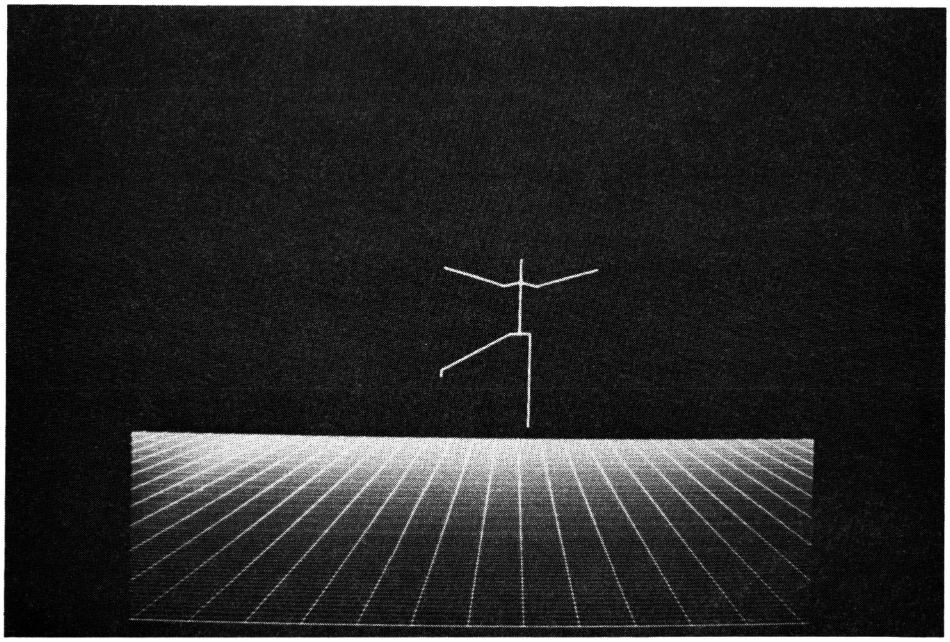

Figure 4. A stick figure display generated on the Evans and Sutherland Picture System 1.

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