Kiniesiology, the study of the physics of motion, is now a recognised tool in fields as diverse as orthopaedic surgery and sports training. The data it produces are graphs of linear and angular accelerations, displacements and forces (see Figure 1). These are all well and good but what do they mean?

For most of us, very little, unless they can be interpreted alongside a visual representation of what the body was doing at the time. Playing back the film or video from which the data was taken is one way of doing this but even in two-dimensional studies the original image is too complex to be helpful — a split screen image of two views, the basis of most 3-D work, is beyond comprehension for most of us.

Most commercial and scientific systems for motion analysis have recognised this problem. The traditional way to represent body motion has been the “stick man” image, representing the individual body segments as lines (see Figure 2). While this is better than nothing and may well suffice for two-dimensional motion, a three-dimensional stick-man display ends up looking more like a bad position in the old “pick up sticks” game. We have no real idea of the 3-D position of the limbs.

Humans are bipedal animals and walking is primarily a two dimensional activity, carried out on a more or less plane surface, the ground. However, human athletic performance — ballet, gymnastics, football, etc. utilizes capabilities which we have inherited from our ancestors, the primates (apes, monkeys, and lemurs). These are arboreal animals, spending most of their time in the trees. They move, feed and reproduce in a complex, three dimensional world. The human shoulder joint, for example, owes its marvellous range of motion to evolution through life in the trees.

Thus, for anyone interested in the evolution and functional anatomy of the human body, an ability to analyse motion in three dimensions, is a must. The rapid pace of advance in computer graphics now makes this — and much more — possible. In our laboratory, we are working in several areas which utilize these developments for visualizing such complex phenomena. We are further applying such techniques to reconstruction of the behaviour of species long extinct and, in the future, hope to use interactive computer graphics to experiment with evolution itself.

Our work began with the development of a three-dimensional motion analysis system. Like most previous systems, it uses as its source of information images from two video cameras: either standard 25 frames-per-second CCD cameras, or specialized high speed cameras capable of recording at over 1,000 frames per second. Depending on the photogrammetric reconstruction algorithm chosen, we can use cameras set at 90° to each other, or simply place them wherever convenient, recording the two images in split-screen format. Each individual field of the video is then converted to a bit-mapped image (Figure 3) using a digital framestore in a standard PC.

The PC (Figure 4) is linked by Ethernet to a cluster of three Hewlett-Packard series 9000 3-D Graphics workstations. Since each frame takes up 128 kbytes, 10 seconds of video requires almost 63 Mbytes of storage, provided by a combination of HP and PC hard disks and two magneto-optical drives to a maximum 1.6 Gbytes of local storage. Processing in the HP workstations is carried out by software written in C and at present uses the HP Starbase graphics library under HP Windows. (We intend to convert the system to run under the X-Windows standard as soon as PC UNIX standards become more settled.)

After conversion to HP graphics format, the operator uses a mouse to identify body markers such as joint centres on each half of the split-screen image. The three-dimensional coordinates are then calculated at each point, for every frame, with the program designed so that the operator is prompted by menus to choose how many segments to analyze. In this way, one can perform either a detailed study of motion of the fingers of the hand or the overall behaviour of the whole body, and the program needs no adaptation to analyze the movement of different species with different numbers of bones and joints.

This in itself is unusual and while the program produces standard graphs of the important mechanical parameters such as linear and angular accelerations of body segments, it is quite unique in the graphics display it produces to accompany them. Rather than representing each segment as a simple line, it uses primitives in the Starbase library to represent each segment as a three-dimensional solid — a truncated cone — with true perspective. This can be given further depth by shadows from up to six light sources and can be assigned any of a range of surface characteristics. We haven’t yet found a way of making our segments furry and would welcome any expert advice!

The depth cues all these features provide produce a realistic model of the subject (Figure 5), which gives the observer an unequivocal understanding of the three-dimensional position of the limb segments at any instant in a performance. The model can also be animated — either stepped through frame by frame (Figures 6-9), or played back at any speed including real-time. Any reference point may be selected, and the model “fixed” on that point, which remains still while all other parts move.

In many instances though, it is not enough to view the model from one angle. If, like us, you are interested in the role of individual muscles in producing motion, the performance needs to be analyzed from many different viewpoints, corresponding to the different planes of
The action of each individual muscle. The program therefore includes the capability to interactively rotate the observer’s viewpoint to any position with respect to the subject, and to zoom in on any area of interest (Figures 10-13). These functions are governed by controls on a knob-box so that no programming knowledge is required to operate the system (Figure 14).

Further development of the program now permits us to enter data on limb measurements other than segment length, such as centre of gravity. These enable us, using a geometric model, to estimate the forces occurring in the subject during gait, without the experimental complexity of devices normally used for the measurement of external forces. The shape characteristics can be represented in the display, which also helps in our intuitive understanding of the force data.

Currently, we are experimenting with using a commercial dynamic modelling package, normally used in the design of production-line robots. This also uses the Starbase library, and allows us to construct a similar solid-rendered model, apply to it either known forces, or known movements, and calculate the other. We hope to use it, for example, to work out why some primates, such as the slender loris, while theoretically capable of leaping locomotion, move only by extremely slow quadrupedal walking or climbing. It may be that it is excessively expensive of energy, given their anatomical characteristics. Together with the data on real performances we can derive from living animals using our own system, we hope that this modeller will enable us to reconstruct animated models of the locomotion of extinct species, such as the earliest ape-man and some recently extinct lemurs from Madagascar so bizarre in their anatomical adaptations that there is no living analogue.

The same computer graphic techniques can be equally useful for the understanding of other body systems such as the teeth. The problem with analyzing the relationship between form and function of the teeth is that you can’t see it, as chewing is hidden from view by the cheeks and tongue, and the relief of the biting surface of teeth is irregular and rich in three-dimensional complexity. Chewing food, moreover, is an invention of the mammals — the birds, for example, just bolt their food, milling it down with stones in their gullet.

Moreover, the course of evolution in the dentition of mammals is hardly amenable to study. While one can make detailed, rigorous experimental studies of simple genetical changes in fast-breeding species such as the fruit fly, experimenting with evolution in mammals is neither practical nor ethical. Here, our three-dimensional data comes from a 3-D digitizing microscope from Reflex Instruments Ltd of Somerset, which uses interferometry to make 3-D measurements of the position of a light spot moved over the subject by the operator, using a trackball and joystick. Our version has the additional capability of making 3-D measurements from stereo-pair photographs of objects, so that we can travel to distant museum collections to photograph rare specimens and return to study...
them in our own laboratory.

In the system we are now developing, the 3-D data matrix produced by the microscope will then be passed by Ethernet to our graphics workstations and can then be reconstructed as a solid model, in the same way as our existing gait analysis system. Again, rotation and zooming of the object can be performed under knob-box control. What is more exciting to us is the prospect of animating paired sets of such reconstructions and programming them to follow the 3-D pathways that we can measure on living animals, using our 3-D motion analysis software. We will thus be able to see, in close detail, the way that the paired relief features of opposite teeth interact — something quite impossible previously.

Beyond this again, we intend to employ the capabilities of the Starbase system to interactively modify three-dimensional surfaces (Figure 15), using several extrusion techniques, such as fitting non-rational B-lines to nodes on the surface of our reconstructions. It will thus be possible to ask ‘what-if’ questions, such as ‘what will be the consequences for food reduction if the height of this cusp increases over evolutionary time?’ and ‘How will a change in the angle of this shearing crest change its interaction with the matching crest on the opposite tooth?’ Finite Elements analysis, another engineering technique, can also be applied to such manipulated reconstructions, to assess the changes in strength properties of the teeth under different loading regimes, as the morphology changes. Further developments again will include modelling the reduction of food particles between pairs of teeth, and of the effects of hardness of food particles on tooth wear — again utilising Finite Elements modelling. In all this, we are truly getting close to an ability to experiment with animal form in a way to which the most ardent animal-rights enthusiast could not object.

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Figure 1, page 11. The slender loris, Loris tardigradus; this is a nocturnal prosimian from Ceylon, and forms the subject in all videos enclosed. Photo by B Meier
Figure 2, page 12. An example of graphic output from our gait analysis system: velocity of an individual node in the z-direction
Figure 3, page 12. A traditional stick-man display: from work by Dr JB Wells
Figure 4, page 12. A bit mapped split screen frame showing the slender loris, Loris tardigradus walking on a pole.
Figure 5, page 12. VHS video, recorded via a special effects generator (right, front) is passed to a PC (centre) for conversion to a bit-mapped image using a digital framestore, and then sent via Ethernet to an HP graphics workstation (left)
Figure 6, page 12. A single-frame reconstruction of the link model of Loris (the segments are actually not cylinders but truncated cones, we have not put the segment centre of gravity data in at this stage)
Figures 7-10, pages 12 & 13. A series showing animation of different stages of one walking cycle in Loris: this skips some frames
Figures 11-14, page 13. Back, front, top and bottom views of the same animation
Figure 15, page 13. The knob box used to control viewpoint and zooming
Figure 16, page 13. An example of surface extraction (from an HP starbase demo)

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