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Computer-Aided Instructional Sequence for Biomechanics of Human Movement*

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A microcomputer laboratory has been developed at The University of Texas at Austin to train students in the biomechanics of human movement. The prototype system is based on an enhanced IBM Personal Computer PC-AT with dual alphanumerics and graphics screens. Primary development of the software for this laboratory was accomplished using IBM Professional FORTRAN with the Graphical Kernel System (GKS). A sequence of ten computer-aided instruction (CAI) modules has been developed in the lab to train students in various aspects of biomechanics. The modules either display digitized data of filmed motion, simulate motion based on user input parameters, or instruct the student on some aspect related to the field. In each module, students proceed in a self-paced manner through a set of interactive assigments and communicate their results through a report at the end. The laboratory, consisting of six workstations, is a formal laboratory requirement for undergraduate Biomechanics courses in Mechanical Engineering and in Kinesiology. This paper summarizes CAI software modules that have been completed to date and outlines software modules currently in development.

INTRODUCTION

THE USE of computers to instruct students in the field of biomechanics of human movement is a relatively new development which has followed closely the use of computers in biomechanics research. The realization that human motion is too complex to allow accurate analysis by the human eye has precipitated the use of more quantitative, computerized measures. Typically today, human movement data are analyzed by a combination of cinematographic or video recordings, film digitization, data smoothing, kinematic and kinetic data extractions, spline interpolations, and computer graphics display techniques. These same techniques that have been used for movement analysis are now also being used for instructional purposes.

Initial use of the computer in the study of human motion is perhaps best exemplified by Plagenhoef's [1] programs in the late 1960s for obtaining kinetic data on a Control Data 3600 mainframe. Input was in the form of punched cards, and output was mainly in the form of printed numbers. As hardware became more flexible, pen plotting capabilities facilitated more visual interpretation of human motion analysis. Miller's [2] studies provided an option to portray a diver's body position in selected phases using a Calcomp pen plotter. Subsequent packages developed by Riley and Garrett [3], Hatze [4], Boysen *et al.* [5], and Barr, *et al.* [6] provided more interaction by displaying dynamic human motion on computer graphics display terminals. Recent conferences [7] on computer simulation in biomechanics have further shown the acceptance and attractiveness of interactive computer modeling to study a wide range of musculoskeletal functions.

A long-range objective of our group is to integrate research and teaching in human biomechanics through computer modeling and simulation. We also wish to increase availability of human motion analysis to students, faculty, clinicians, and coaches in a low-cost microcomputer laboratory environment. To accomplish this objective, a proposal was submitted to the Project Quest program, supported by the IBM Corporation, to develop a biomechanics laboratory and to explore how microcomputers can be used to enhance the learning experience in this particular field. The proposal was approved and development of the project was initiated in the 1986/87 academic year. While the laboratory instructional sequence has continued to evolve over the past three years, it has reached a level of maturity that warrants a systematic description of the instructional objectives and methods employed in the laboratory.

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HARDWARE CONFIGURATION

The laboratory consists of six student workstations, each based on an IBM PC-AT microcomputer with dual Enhanced Graphics (EGA) and Professional Graphics (PGA) Displays. This dual display mode has proven to be useful in separating written alphanumeric commands and responses from the graphical output and stick figures. Memory for each workstation has been expanded to include two 30 Mb fixed disks, and a 3072 kb main memory expansion board. A math co-processor resides in each machine to speed application program execution. Each workstation includes a six-pen plotter, and each pair of machines shares a Pro Printer. The typical workstation configuration is illustrated in Fig. 1.

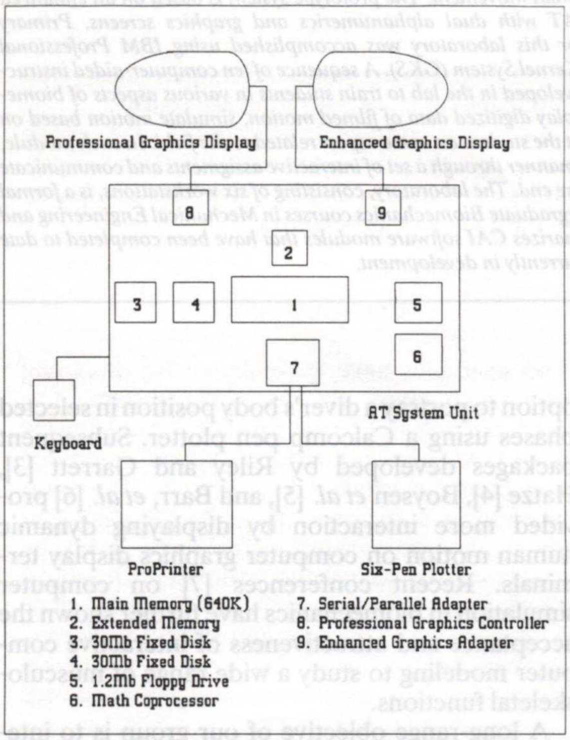


Fig. 1. The microcomputer system hardware configuration used for the laboratory is based on the IBM PC-AT with dual displays, extended memory, and two 30-Mb fixed disks.

SOFTWARE CONFIGURATION

Primary development of the software was accomplished using IBM Professional FORTRAN with the Graphical Kernel System (GKS). The Graphical Kernel System, implemented as a library of subroutines, is a tool designed for the development of portable graphical applications. GKS uses drawing primitives as basic building blocks in a user-defined (world) coordinate system which is mapped to a normalized device viewport. Each primitive is controlled by a definable set of attributes (line style, width, color). Using segments or groups of primitives, subpictures can be transformed as one entity or stored for later use. GKS also permits the use of graphics text for annotation and has various area fill modes. This system has proven to be very useful in animating simulations and provides excellent flexibility for interactive applications.

INSTRUCTIONAL MODULES

The instructional software developed for the biomechanics laboratory was designed to parallel lecture material in class and focuses on general biomechanical principles in kinematics, anthropometrics, muscle mechanics, kinetics, modeling, and simulation. Currently, ten instructional modules have been completed or are in progress. These modules and the biomechanical categories that they address are listed in Table 1. Each module provides for ample user interaction, including establishing parameters, choosing data files, making modifications to parameters, and choosing display modes. The output of each module is a graphical display on the CRT screen and, in some cases, a hardcopy table from the printer or a plot from the pen plotter. In all cases, the student has an assignment at the end which requires a brief technical report and some data charts or tables. The following section summarizes the development and pedagogical objectives of each instructional module.

Table 1. The currently available modules for analysis of human movement in the biomechanics laboratory

Module Title	Biomechanical Category
1. Stick Figure Plotting	Kinematics
2. Digitizing and Smoothing	Kinematics
3. Whole Body Center of Gravity	Anthropometrics
4. Muscle Modeling	Muscle Mechanics
5. Static Elbow Flexion	Kinetics
6. Dynamics of Running	Kinetics
7. Vertical Jumping	Kinetics
8. Baseball Pitching	Simulation
9. Pole Vaulting	Simulation
10. Tennis Serve	Simulation

Kinematics: stick figure observations

The first module introduces the student to the IBM PC-AT workstation and permits the student to study a variety of human motions using two-dimensional stick figure displays. The files originate from a broad spectrum of sporting events that had been earlier filmed at the University of Texas and which were hand-digitized for use in this laboratory. Some of the many motions available for user observation include: football punting, distance running, swimming start, shot put, discus throw, javelin throw, weightlifting, hurdling, and ballet. The files may be displayed with variable time intervals between stick figures and with a selected point highlighted. As part of the exercise, students are required to obtain several hardcopy plots of the stick figures. An example of one typical plot is shown in Fig. 2. Following the laboratory, the students are required to hand calculate and plot velocities and accelerations of a key tracked point, using finite difference, for two different events. This differentiation exercise assists the students in evaluating kinematic features that contribute to the success of the athletic motion, but which may not be readily observable in the stick figure motion itself. Doing the calculation by hand also makes the students appreciate the data processing capabilities of the microcomputer exhibited in the next module.

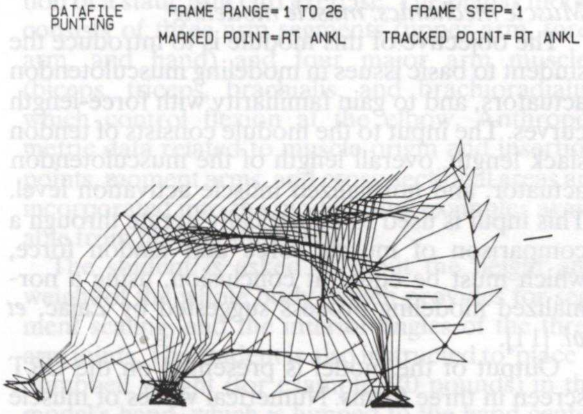
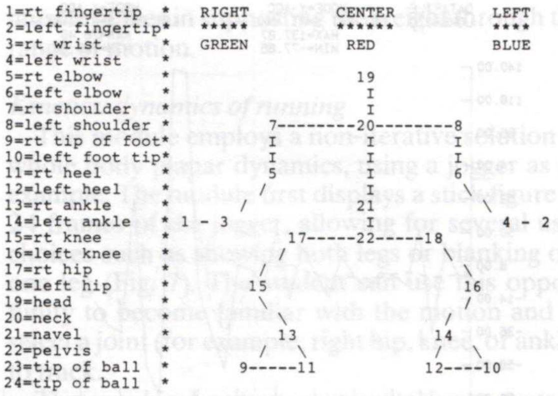


Fig. 2. A typical stick figure plot obtained in the lab shows a punter with the right ankle of the kicking leg being tracked with a marker.

Kinematics: digitizing, smoothing and differentiation techniques

In order to introduce the student to the data gathering aspect of biomechanics, a screen-based digitizing module has been developed using football punting data. Each of the frames of the full punting motion are displayed one at a time on the CRT screen. Since the motion is presented from a profile view, and essentially appears to occur in a two-dimensional plane, some difficulty exists in distinguishing between left and right body points during digitizing. To overcome this digitizing difficulty, a color coding scheme is used: the right limbs are presented in green, central points are in red, and left body points are blue. This monitor display detailing the color coding scheme and numbering of key body points for digitizing is shown in Fig. 3. The student uses the screen cursor to locate and digitize key body points (for instance, ankle of the kicking foot) on the stick figure. This procedure, across all frames, results in a raw digitized file which is ready for processing.



```
1=rt fingertip  *   RIGHT         CENTER          LEFT
2=left fingertip*   *****         ******          ****
3=rt wrist      *   GREEN          RED            BLUE
4=left wrist    *
5=rt elbow      *                   19
6=left elbow    *                    I
7=rt shoulder   *                    I
8=left shoulder *          7--------20--------8
9=rt tip of foot*          I         I        I
10=left foot tip*          I         I        I
11=rt heel      *          5         I        6
12=left heel    *         /          I         \
13=rt ankle     *       /           21           \
14=left ankle   * 1 - 3              I             4 - 2
15=rt knee      *            17-----22-----18
16=left knee    *           /                \
17=rt hip       *         /                    \
18=left hip     *        15                    16
19=head         *         \                    /
20=neck         *           \                /
21=navel        *           13              14
22=pelvis       *         /   \             /   \
23=tip of ball  *       9-----11           12----10
24=tip of ball  *
```

Fig. 3. The body joint numbering system for on-screen digitizing consists of 22 body points, as shown to the left of the figure, plus 2 points for the ball.

From the raw digitized data, velocity and acceleration curves can be calculated directly using finite difference methods. However, the digitizing process introduces errors which become amplified in these derivative calculations. Hence, the module is further used to demonstrate this inherent error in digitizing, and to introduce smoothing techniques for noisy biomechanics data. The overall smoothing process as developed by Schryver *et al.* [8] is illustrated in Fig. 4, and involves both digital filtering and spline fitting techniques. For this case, the available smoothing techniques include:

1. Finite Difference,
2. Quintic Spline, and
3. Digital Filtering (Pre- and Post-).

Various combinations of the options are investigated by the students, for example prefiltered finite difference versus unfiltered finite difference, as well as comparison of the spline routine which calculates velocities and accelerations by straightforward differentiation of the polynomial equation. Such a comparison is illustrated in Fig. 5. For the quintic spline, a method for auto-determination of the smoothing coefficient is being incorporated into the package as a new feature.

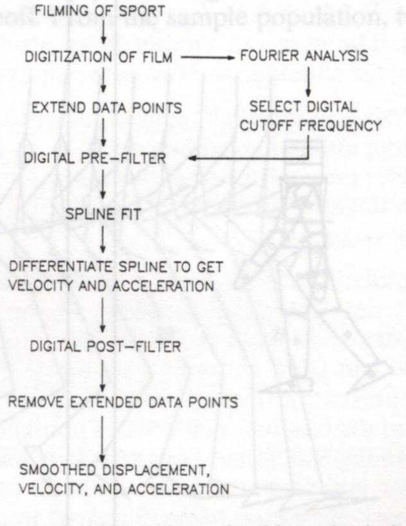


Fig. 4. The smoothing process for biomechanical analysis begins with digitization of filmed or video-taped movement data. The data can then be further processed using digital filters and splines to yield velocity and acceleration profiles.

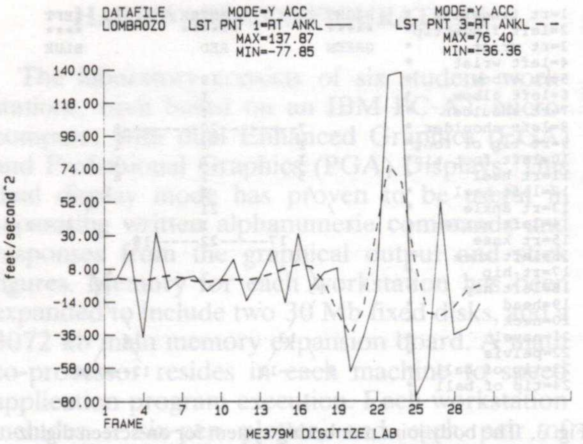


Fig. 5. Comparison of raw (solid line) and smoothed (dashed line) biomechanics data helps to demonstrate the influence of digitizing error in data interpretation.

For the digital filtering routines, a fixed 6 Hz lowpass cutoff frequency is used, so the student does not have the Fourier analysis option. However recent research by our group [9] suggests that this 6 Hz cutoff may be too low for generalized motion in sports biomechanics, and incorporation of this input parameter may be included in future development.

Anthropometrics: whole body center of gravity

Anthropometric realism of human body segmentation and mass centers is emphasized in this laboratory module. A three-dimensional wireframe model of the human body (Fig. 6) is displayed on the screen. The display consists of three views: a frontal orthographic view, a right profile view, and an isometric pictorial. The user is asked to input the model's body weight and height, and estimates of the locations of the center of gravity and mass of each segment are solved using standard anthropometric data [10]. The whole-body center of gravity is calculated in a straightforward fashion for the default stance, and is displayed on the screen using a GKS marker.

The student now has the option to perform controlled rotations of certain body segments, and to observe how these new segment positions affect the location of the overall whole-body center of gravity, as seen on the updated display. In the future, we plan to further develop the module, which would incorporate some partitioning algorithms for major muscle groups, allowing the students to observe changes in the activity of these muscle groups to maintain postural control as the whole body center of gravity deviates significantly from the normal default stance.

Muscle mechanics: muscle modeling

The objective of this module is to introduce the student to basic issues in modeling musculotendon actuators, and to gain familiarity with force-length curves. The input to the module consists of tendon slack length, overall length of the musculotendon actuator, and normalized muscle activation level. This input is used to numerically iterate through a comparison of muscle force and tendon force, which must be equal at conclusion, using a normalized modeling process suggested by Zajac, *et al.* [11].

Output of the model is presented on the CRT screen in three forms. Numerical values of muscle length, tendon length, and normalized musculotendon force are displayed in the upper left quadrant. The normalized muscle force-length curve is next drawn in the upper right quadrant and the current operating point is highlighted with a GKS marker. A pseudo image of the muscle and tendon

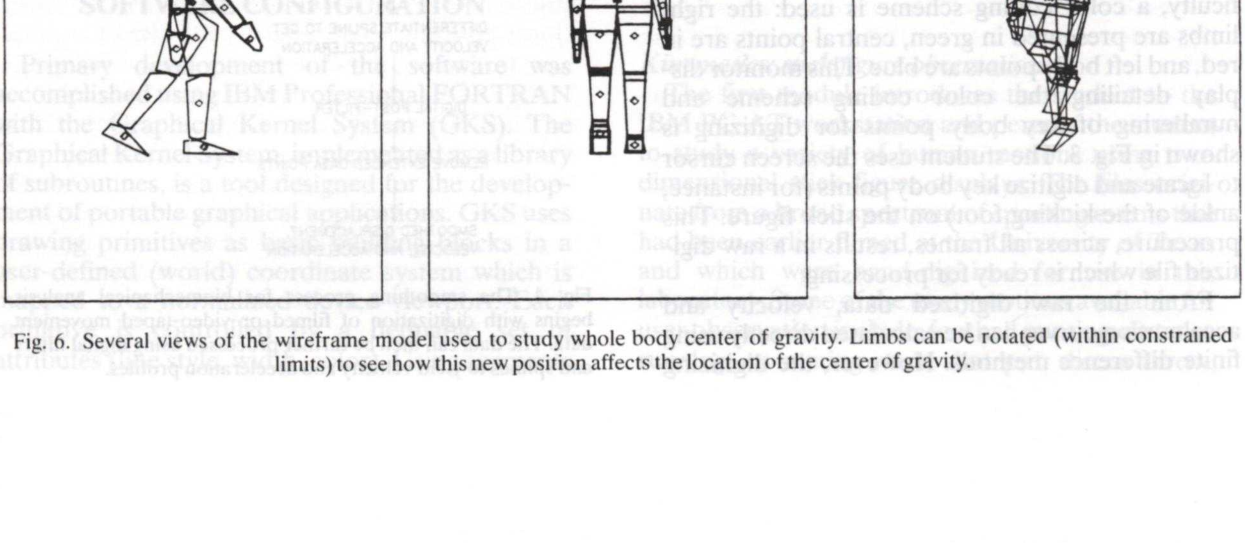


Fig. 6. Several views of the wireframe model used to study whole body center of gravity. Limbs can be rotated (within constrained limits) to see how this new position affects the location of the center of gravity.

is drawn on the bottom of the screen. The image is geometrically scaled to the calculated lengths and the red color shading of the muscle belly is varied according to its relation to maximum normalized force. By varying the selected input parameters, students can track the output force along the force-length curve.

Currently, the optimal normalized musculotendon length is fixed at 12 inches, pinnation angle is assumed to be zero, and electrical activation patterns are set to a unit step function. Future additions to the module will include a more detailed modeling algorithm which permits the user to scale musculotendon parameters even more realistically.

Kinetics: static elbow flexion

This module introduces the student to a simple muscle force partitioning problem through simulation of a static arm curl exercise. The planar model consists of three arm segments (upper arm, forearm, and hand) and four major arm muscles (biceps, triceps, brachialis, and brachioradialis) which control flexion at the elbow. Anthropometric data related to muscle origin and insertion points, moment arms, and cross-sectional areas are incorporated into the model using examples available from the literature [12].

The student is asked to input the height and weight of the whole body, which provides for segment scaling, and the interior angles of the three arm joints. The student is also instructed to 'place' a dumbbell weight (for example, 20 pounds) in the model's hand, which is lumped to the hand center of mass. The module then performs the muscle torque partitioning problem for this static position by assuming equal distribution of stress, and displays the results on the bottom of the screen for the four muscles. The graphical output also includes a color stick figure display of the arm with the current input position angles and muscle attachments. By iterating through a logical sequence of elbow flexion/extension angles, the students are able to observe and track the contribution that each muscle makes in supporting the weight through the range of motion.

Kinetics: dynamics of running

This module employs a non-iterative solution to whole body planar dynamics, using a jogger as an example. The module first displays a stick figure of 24 frames of the jogger, allowing for several user choices such as showing both legs or blanking out one leg (Fig. 7). The student can use this opportunity to become familiar with the motion and to select a joint (for example, right hip, knee, or ankle) to track.

The graphical output next switches to a static frontal figure with color-coded indicators of the net force and torque at each body joint. Beside the static figure is a side view of the current frame being analyzed. Hence, using the color-coded indicators, the student can obtain a qualitative feel of the changes in joint dynamics as he paces the stick figure through the 24 frames. Also available are quantitative printouts of the actual force and torque values. In this manner, the student can observe the dynamics of the full range of motion (one whole stride) and can plot this information as part of the assignment, as illustrated in Fig. 8. Students are required to relate the key features of the joint force and torque histories to the ongoing movement, which provides for the development of a true understanding of body dynamics.

Kinetics: vertical jumping

The vertical jumping module is designed to illustrate a primary biomechanical factor in optimum performance, namely the contribution of the arm motion to the vertical takeoff velocity of the center of gravity. Data were gathered from filmed records of elite female college athletes [13] while they performed a maximal height vertical jump using four different styles of arm motion: (1) arm swing; (2) no arm swing; (3) arm swing with a block of motion at takeoff; and (4) arm swing with a reversal of motion at takeoff. From the sample population, two trials

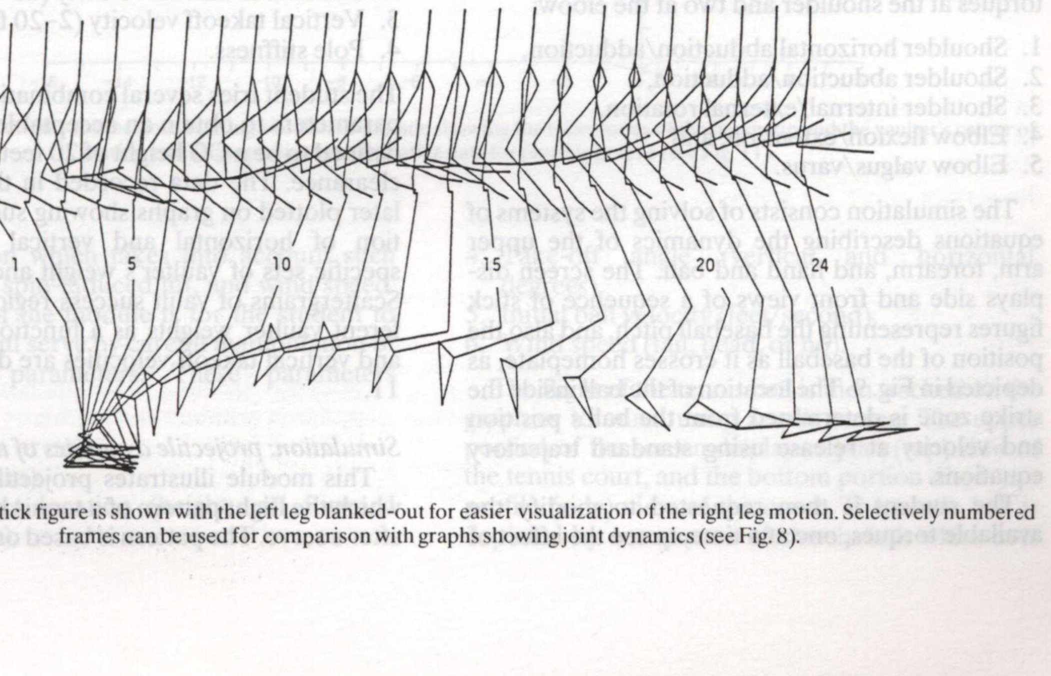


Fig. 7. The jogger stick figure is shown with the left leg blanked-out for easier visualization of the right leg motion. Selectively numbered frames can be used for comparison with graphs showing joint dynamics (see Fig. 8).

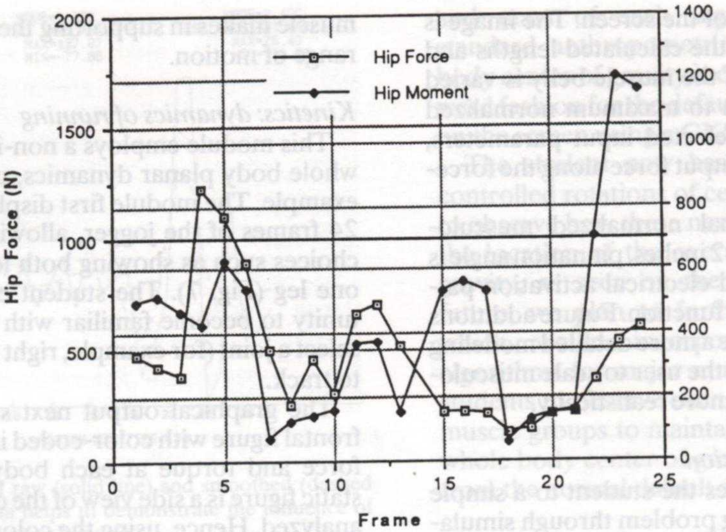


Fig. 8. Force and torque distribution in the right hip of the jogger (see Fig. 7) are plotted for one full stride.

for each jumping style were chosen and placed into a lookup table.

The students are required to make on-screen observations from stick figures and to plot on-screen kinematic data related to each trial. From these observations, they are required to complete a table relating peak upward velocity and vertical takeoff velocity to height achieved at the center of gravity. These results can be represented nicely by comparative bar charts. They are also asked to perform brief kinetic and potential energy balances, and to compare their analytically-predicted heights with those observed from the experimental data displayed on the screen. Finally, students are required to explain the contribution the arm motion makes to the vertical height achieved.

Simulation: baseball pitching

This program generates a simulation of a baseball pitch from kinematic and kinetic data that have been modified from field data [14], which serves as a default. The user can modify three anatomical torques at the shoulder and two at the elbow:

1. Shoulder horizontal abduction/adduction,
2. Shoulder abduction/adduction,
3. Shoulder internal/external rotation,
4. Elbow flexion/extension, and
5. Elbow valgus/varus.

The simulation consists of solving the systems of equations describing the dynamics of the upper arm, forearm, and hand and ball. The screen displays side and front views of a sequence of stick figures representing the baseball pitch, and also the position of the baseball as it crosses homeplate, as depicted in Fig. 9. The location of the ball inside the strike zone is determined from the ball's position and velocity at release using standard trajectory equations.

The student is then requested to modify the available torques, one at a time, to see the effect of that modified torque on the control of the pitch. This modification is performed using values in both increasing and decreasing directions from the default norm, with instructions to move the ball to specified portions of the strike zone. Students learn about the intricacies of forward dynamic solutions in link systems by attempting to control the pitch location in the strike zone.

Simulation: pole vaulting

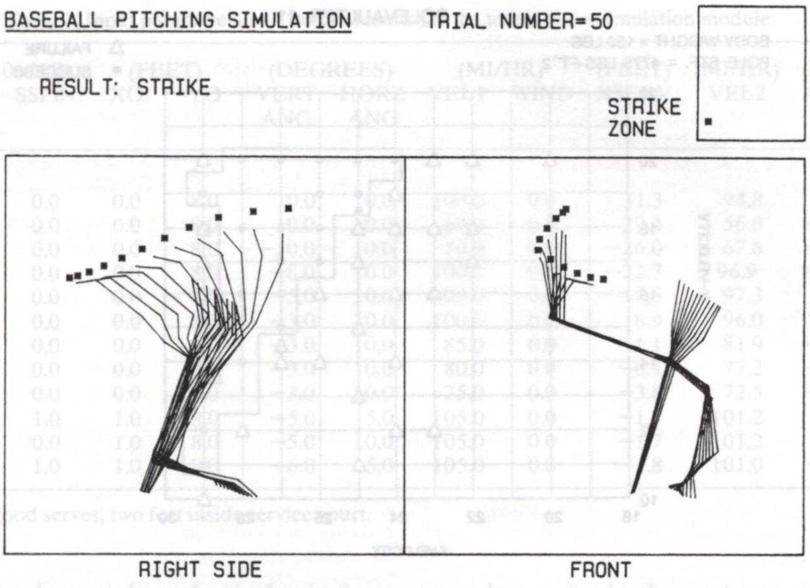
In order to study the mechanics of energy storage and transfer, the students observe a controlled simulation of pole vaulting. The simulation process employs a numerical integration technique adapted after Walker and Kirmser's [15] solution with time-fixed moment of inertia. The output of the simulation is a temporal graph showing the positions of the vaulter's center of gravity (CG) and pole grip, as illustrated in Figure 10. The user initiates the simulation by inputting four parameters:

1. Vaulter's weight (145–175 lbs.),
2. Horizontal takeoff velocity (15–30 ft/sec.),
3. Vertical takeoff velocity (2–20 ft/sec.), and
4. Pole stiffness.

The student tries several combinations of the input parameters to obtain an acceptable vault, which is defined to be a CG height of 20 feet or higher at bar clearance. The data recorded in the lab are then later plotted on graphs showing success as a function of horizontal and vertical velocities, for specific sets of vaulter's weight and pole stiffness. Scattergrams of vault success regions for two different vaulter weights as a function of horizontal and vertical takeoff velocities are displayed in Fig. 11.

Simulation: projectile dynamics of the tennis serve

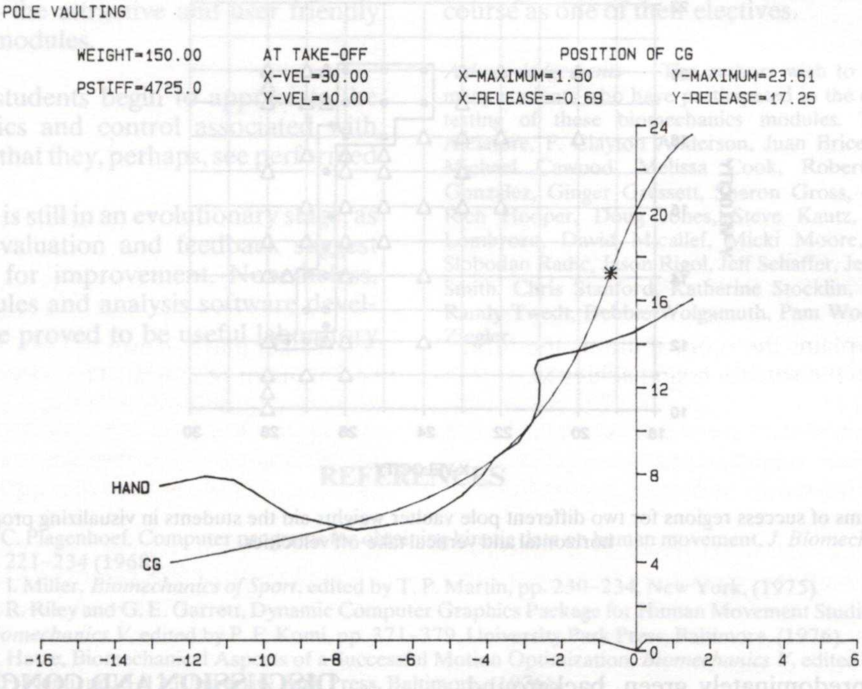
This module illustrates projectile dynamics, in which the flight pattern of a tennis ball is simulated after a serve. The pattern is based on an empirically



```
BASEBALL PITCHING SIMULATION    TRIAL NUMBER= 50

      RESULT:  STRIKE
```

Fig. 9. The screen display for the pitching simulation module is divided into three areas showing the pitcher from the right side, from the front side, and the ball's relation to the strike zone.



```
POLE VAULTING

      WEIGHT=150.00       AT TAKE-OFF                      POSITION OF CG
                          X-VEL=30.00       X-MAXIMUM=1.50        Y-MAXIMUM=23.61
      PSTIFF=4725.0       Y-VEL=10.00       X-RELEASE=-0.69       Y-RELEASE=17.25
```

Fig. 10. The screen display for the pole vaulting simulation module showing the trajectories of the hand grip and the vaulter's center of gravity, and listing pertinent quantitative data for plotting graphs (see Fig. 11).

derived equation which takes into account such factors as drag, spin-induced lift, and wind speed. The objective of the module is for the student to make a successful serve by careful manipulation of several input parameters. These parameters include:

1. Top spin (yes or no),
2. Slice (yes or no),
3. Initial contact location (height and forward position, feet),
4. Take-off angle (vertical and horizontal, degrees),
5. Initial ball velocity (feet/second),
6. Wind speed (tail, head, or no).

The flight of the tennis ball is then tracked on the graphics terminal using a split screen. The upper portion of the screen displays a plan (top) view of the tennis court, and the bottom portion displays a profile (side) view of the court. The tennis ball is depicted by a sequence of closely-knit white dots

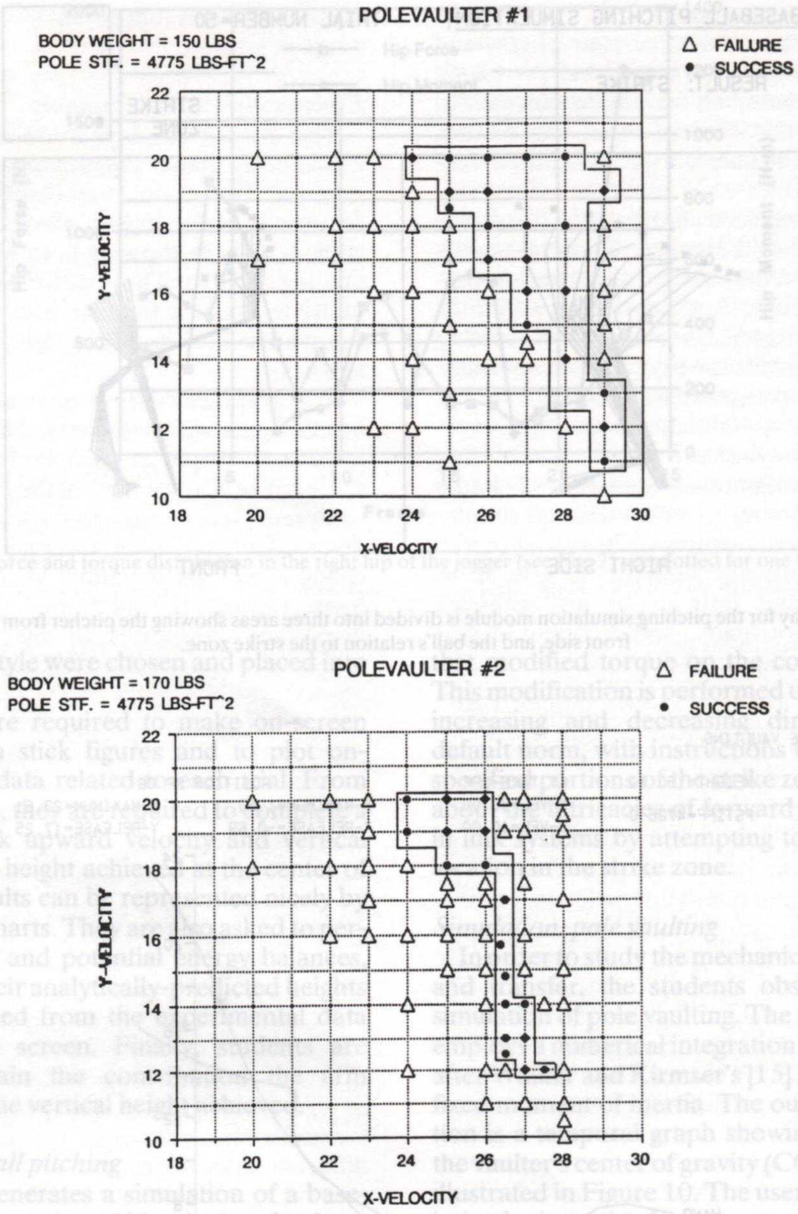


Fig. 11. Scattergrams of success regions for two different pole vaulter weights aid the students in visualizing proper combinations of horizontal and vertical take-off velocities.

on a colored, predominately green, background. The student can visually observe how high the ball clears the net, and the exact point of ball contact on the service court. By trying to obtain the optimal serve with different spins and under different wind conditions, the student should learn how each of the six input parameters affect the tennis serve. The student may wish to try many different combinations of input parameter values in order to gain experience on the combined effects of altering the service style. To receive feedback, a table of input parameter values and output results is maintained for the user, as shown in Table 2.

DISCUSSION AND CONCLUSIONS

A unique feature of this project has been the creation of a microcomputer laboratory that facilitates the integration of research and teaching through modeling and simulation of human biomechanics. When compared to other existing methods of experimentation and learning, the laboratory offers several significant innovative advantages:

1. Students are able to simulate many movement patterns without risking injury or incurring a learning delay;
2. Students receive immediate and quantitative feedback on their attempts and do not have to solely rely on qualitative judgements;

Table 2. Input parameters and output results for the tennis serve simulation module

	(1=YES	0=NO)	(FEET)		(DEGREES)		(MI/HR)		(FEET)	(MI/HR)	(DEG)	(FT)
TRIAL	TSPIN	SSPIN	XO	YO	VERT ANG	HORZ ANG	VEL1	WIND	XSERV	VEL2	ANGF	HNET
1	0.0	0.0	0.0	8.0	0.0	10.0	100.0	0.0	31.3	94.8	−8.2	3.3
2	0.0	0.0	0.0	8.0	10.0	0.0	60.0	0.0	29.4	56.0	−12.9	8.1
3	0.0	0.0	0.0	8.0	−10.0	10.0	70.0	0.0	−26.0	67.6	−15.9	0.0
4	0.0	0.0	0.0	8.0	−8.0	10.0	100.0	0.0	−22.7	96.9	−11.2	−1.8
5	0.0	0.0	0.0	8.0	−5.0	10.0	100.0	0.0	−19.6	97.3	−8.5	−0.2
6	0.0	0.0	0.0	8.0	−3.0	10.0	100.0	0.0	8.9	96.0	−9.1	1.2
7	0.0	0.0	0.0	8.0	−3.0	10.0	85.0	0.0	1.1	81.9	−10.4	0.8
8	0.0	0.0	0.0	8.0	−3.0	10.0	80.0	0.0	−0.1	77.2	−11.2	0.6
9	0.0	0.0	0.0	8.0	−3.0	10.0	75.0	0.0	−3.8	72.5	−11.7	0.4
*10	0.0	1.0	1.0	8.0	−5.0	5.0	105.0	0.0	−1.7	101.2	−9.6	0.0
*11	0.0	0.0	1.0	8.0	−5.0	10.0	105.0	0.0	−1.7	101.2	−9.6	0.0
*12	0.0	1.0	1.0	9.0	−6.0	5.0	105.0	0.0	−1.8	101.0	−10.6	0.4

* Deemed to be good serves, two feet inside service court.

3. Students learn fundamental mechanical principles in addition to their formal education in human movement; and
4. Students can progress at their own rate and are highly motivated to explore all available parameters due to the attractive and user friendly format of the modules.

In addition, the students begin to appreciate the intricate mechanics and control associated with body movements that they, perhaps, see performed every day.

The laboratory is still in an evolutionary stage, as student course evaluation and feedback suggest continuing ways for improvement. Nonetheless, the training modules and analysis software developed to date have proved to be useful laboratory experiences for undergraduate students in kinesiology, in mechanical engineering, and in biomedical engineering block options in electrical and chemical engineering. In addition, many graduate students have enrolled in this undergraduate course as one of their electives.

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