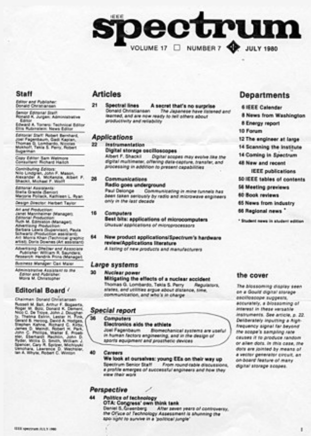
Electronics aids the athlete

Biomechanical systems are useful in human factors engineering, and in the design of sports equipment and prosthetic devices



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IEEE Spectrum July 1980 Synopsis

This issue of the IEEE Spectrum from July 1980 covers a range of topics including nuclear power, digital storage oscilloscopes, underground radio communication, and the applications of microcomputers.

One of the key articles discusses how electronics are aiding athletes. The article explores how biomechanical systems are being used in human factors engineering and in the design of sports equipment and prosthetic devices. The technology is being used by athletes to analyze their performances and find ways to improve them. The software and computer systems analyze slow-motion movies of an athlete's movements and estimate bone and muscle stresses in relation to the movements. This information is then used to suggest optimum movements that might help an athlete break an existing record.

The issue also includes a special report on how digital storage oscilloscopes are evolving, offering data-capture, transfer, and processing in addition to their present capabilities.

Other topics covered in this issue include the politics of technology, the effects of a nuclear accident, and the use of microprocessors in unusual applications.

The article discusses the use of biomechanical analysis in sports, particularly tennis and golf. It explains how researchers use a piezoelectric crystal force platform to measure the impact forces applied to a tennis racket, the angular velocity of the player's arm and racket, and the impact duration. The data is then processed and analyzed to yield parameters for magnitudes, time interval, and impulses for any position of the force components. The article also discusses the concept of the "sweet spot" on a tennis racket and how it can be calculated. In golf, the article discusses how biomechanical data can be used to analyze the efficiency of a player's swing. The article concludes by discussing the potential applications of biomechanical analysis in other fields, such as shoe design and the development of prostheses.

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Below find a reprint of the 6 relevant pages of the article "Electronics aids the athlete" in "IEEE Spectrum":

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Articles

Departments

the cover

The blossoming display seen on a Gould digital storage oscilloscope suggests, accurately, a blossoming of interest in these versatile instruments. See article, p. 22. Deliberately inputting a high-frequency signal far beyond the scope's sampling rate causes it to produce random or alien dots. In this case, the dots are jointed by means of a vector generator circuit, an on-board feature of many digital storage scopes.

Electronics aids the athlete

Biomechanical systems are useful in human factors engineering, and in the design of sports equipment and prosthetic devices

Olympic athletes intent on breaking world records are turning to sophisticated software programs and high-speed computer systems to plot their performances and find ways to improve them. The software and computer systems analyze slow-motion movies of an athlete's movements and estimate bone and muscle stresses in relation to the movements. From this information, it is possible to postulate some optimum movements that might help an athlete break an existing record.

Runners, shot-putters, javelin throwers, swimmers, weight lifters, and others are taking advantage of this approach. The same technology is also being used by manufacturers as an aid in the design of such sports equipment as exercise machines, tennis rackets, golf clubs, ski boots, and jogging shoes.

The laws of physics apply to any system in motion, man or machine. Like a machine made of mechanical members, the parts of the human body form a link system consisting of the foot, shank, thigh, trunk, hand and arm, shoulders, neck, and head. Joints serve as fulcrums, and the contracting skeletal muscles exert forces on the segments.

In analyzing human motion, the researchers are using a computer-controlled digitizer. System programming breaks down the total body motion into center-of-gravity points; velocities and accelerations; horizontal, vertical, and resultant forces of body segments; and timing between segments. The athlete gets quantitative measures of motion. The biomechanical systems calculate body movements in minutes from data provided by the digitizer.

One researcher, Gideon Ariel, vice president and research director for Computerized Biomechanical Analysis Inc. in Amherst, Mass., uses a biomechanical system that does the following: obtains and digitizes motion-picture data, measures the athlete's movements, uses computer algorithms to quantify the performance, and finally, analyzes the results. The system, however, is not fully automatic, and the operator is the most important instrument in the process.

In general, researchers film the body movements at speeds ranging from 64 to 200 frames per second, with a one-quarter-open shutter (this depends on surrounding conditions) to prevent fast-moving segments from blurring. They project the film on a screen that has strip microphone sensors along its width (x) and length (y). Using a sonic pen manually in conjunction with the computer-fed digitizer, the researchers locate the body joint centers on the film. Each time they touch the screen with the pen, the sensors transmit the exact coordinates through the digitizer into the computer and then on to a display. The x-y coordinates of the body joint centers are stored and changed into numerical data by a computer program.

With the film speed and the displacement of the joint centers known, the researchers can use software programs to calculate the velocity and accelerations of different body segments. The programs break down this information into body motion parameters. These include the resultant forces, angle of application of resultant force, moments of force, forces at ground contact points, and the coordination of motion between various body segments.

All of this information provides a quantitative measure of the body movements. For example, the moments of force indicate the magnitude of the muscle action at each joint, and the athlete uses this information to perfect his activity.

Individual sports analyzed

Consider the application of this technology to the kinetic analysis of a world-record javelin throw in 1968 by Janus Lusis, a Russian athlete (he won a silver medal in 1972). From a film shot at 64 frames per second, Dr. Ariel located the javelin thrower's joint centers with a sonic pen, and the results appeared on a computer display (Fig. 1). This tracing showed the position of each joint center in the various body segments. The data, when processed, yielded velocity and acceleration curves (Fig. 2). From the curves, one can observe that, in the best throws of the javelin, the velocity of the last body segment is at its maximum just prior to release, rather than at the instant of release. This velocity is achieved by rapid deceleration of other body segments prior to release. With proper timing of critical motion through alteration of vertical and horizontal forces, a javelin thrower can improve performance. At this time, researchers can identify some of these motions, but there is a need for further investigation to conclusively quantify these characteristics. In one movement, for example, by keeping his feet flat against the ground throughout the whole throwing motion, the javelin athlete can achieve maximum distance. If he lost contact with the ground at any instant prior to release, the throw would be less successful.

Examination of the curves shows the successful throws are related to a continuous displacement of the body's center of gravity. If the thrower's feet leave the ground, there is a discontinuity in this placement. This same principle also applies to shot-putters.

Just how much improvement in performance can be achieved by any athlete is not clearly understood at present. The mathematics to spell this out is not yet fully developed.

Moment curves indicate the dominant forces at issue in the javelin throw and the effect of one body segment on adjoining segments. If muscle action moves one segment clockwise, for example, it will tend to move an adjoining segment counterclockwise. In any human movement, one body segment can affect the adjoining one in a way that is undetectable by the human eye. In a deep knee bend, for instance, the direction of the moment depends upon the angles of the body segments and the dynamic forces. With a relatively upright trunk, the main muscle action at the knee involves the extensors. However, if the trunk is bent forward slightly, the knee flexors become the dominant muscles at

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that joint.

In a similar way, researchers have analyzed data for center-of-gravity displacement relating to two shot-puts by Randy Matson, of the U.S., a former Olympic record holder. For one throw of 21.35 m, the computer shows that the horizontal and vertical displacement of the center-of-gravity movement was continuous through the release. If the horizontal displacement of the center of gravity is halted at any instant prior to release, the throw is less successful, as was evident in a second attempt, a 19.83-m throw. The display shows that the displacement occurred just as the thrower's two feet lost contact with the ground. Contact with the ground during the entire throw enables the athlete to continue to displace his center of gravity uniformly.

High jump. In the high jump, it is important to build up enough vertical force to counteract gravity. To increase the upward force resulting from simply pushing off the ground (during a jump), high jumpers direct their horizontal momentum (caused by running) into a vertical direction. This movement by the athlete requires a sudden deceleration as the athlete brakes his forward progress to change direction. Biomedical analyses of high jumpers show that, during the jump, maximum deceleration of the arms just before takeoff helps the knee extensors optimize the jump. Timing of the deceleration of one body part can aid the movement of other body segments.

Several factors are critical to achieve this maximum vertical force. According to computerized data, about 60 percent of the power can be contributed from the free-swinging leg and arms. Researchers analyzing Valery Brumel, the Soviet high jumper who formerly held the world record (using a straddle jump style) and 1968 gold medalist Dick Fosbury, indicate they all produce roughly the same force by using their free legs and arms.

The computer motion diagrams, however, revealed that Brumel's straddle demands much more backward force in order for him to change his horizontal drive into a vertical one. He has to spend a considerable amount of power. On the other hand, there are other jumpers who utilize less muscular effort more efficiently, wasting much less backward force.

Further interesting results were found when sports trainers studied the computer simulation of Brumel, jumping flop style. The simulation employed such information as Brumel's horizontal velocity, the speed of segments of his body, his leg lengths, and the muscular force that he had developed during some of his leaps. When Brumel flop jumped, his backward force was reduced considerably to a point that permitted him to clear the high bar at 2.41 m (7 ft 11 in), almost 12.7 cm (5 in) more than the world record. From the computer software calculations, the force built up by the takeoff leg in a 2.1 m (7 ft) jump approximates seven times the body weight, about 598.5 kg (1330 lbs) for an athlete who weighs 85.5 kg (190 lbs).

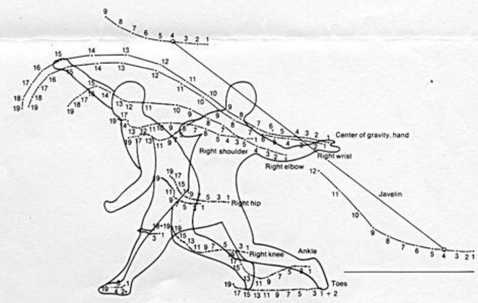
Long jump. The long or broad jump combines the athletes' motions (for both the sprint and the high jump) in a sum of horizontal and vertical forces. Investigations by some researchers indicate that the sum of these forces can be optimized at an angle somewhat less than 30 degrees from the horizontal. Theoretically, the best ballistic angle, they note, is 45 degrees, but the angle in case of a jumper must be less because an erect athlete starts his movement with his center-of-gravity point already several meters off the ground.

Sports trainers who were trying to discover what makes near perfection in the long jump studied the performance by Bob Beamon of the U.S. at Mexico City in 1968. He jumped 8.90 m (29 ft 2.50 in), or more than 0.30 m beyond anything done before.

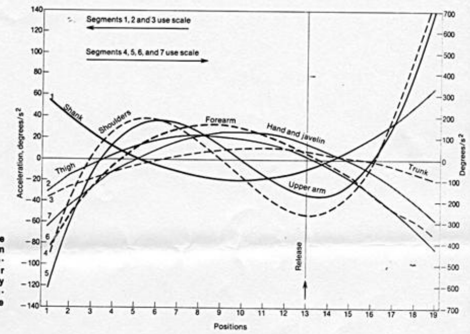
Using films of Beamon's jump, they compared him on the computer with Randy Williams, the 1972 gold medalist. Beamon's final stride was 3.81 cm (1.50 in) longer than that of Williams. Beamon, according to the computer analysis, had achieved extremely high velocity just prior to takeoff. As he transmitted his horizontal force into vertical force, the films show that he kept the trunk of his body very rigid. Typically, sports trainers say that long jumpers collapse the trunk slightly as they absorb the shock at takeoff.

Beamon's ability to jump without absorbing the forces in his joints appears to allow him to optimize his performance. His swinging arms served two functions. Prior to lift-off, he decelerated them to add more force, as with his free leg. During his flight, his arms added no power, but helped him retain his balance. These results are still being studied to quantify the movement and timing relationship necessary to improve performance.

Other sports that researchers have studied, using electronic systems for biomechanical analysis, include long-distance and sprint running, kayak maneuvering, diving, figure skating, hammer throwing, discus throwing, golf, and tennis.



[1] A computerized biomechanical analysis of the javelin throw. This cinematographical data is obtained from the film at a speed of 64 frames per second. The joint centers, which are marked by points, are traced by the computer-fed digitizer.



[2] Acceleration curves of the javelin throw plotted from computer-processed biomechanical data. Particular curves relating to various body segments are shown, including the instant of release of the javelin from the hand.

Long-distance running. Long-distance running is generally considered to be a cardiovascular activity, but computer analysis indicates that biomechanical factors are important. Speed depends on the length and frequency of the runner's stride. While long strides mean fewer strides per km, there is also a drawback. Biomechanical data show that each stride is associated with a braking force that momentarily stops the forward motion of the athlete. How much braking there will be depends on where the body's center of gravity is at the moment of foot contact. Computer analysis reveals that, for some athletes, the optimal stride length is one in which the braking force is at a minimum.

Leaning forward slightly at the hip joint also contributes to running efficiency, analysis shows, as does landing on the ball of the foot rather than on the heel. Another factor enhancing efficiency is the capacity of the leg muscles to absorb physiological energy elastically. This indicates that training for long-distance running should consist of endurance exercise as well as specific muscular training to develop the elastic capacity of the muscles. Sports researchers note that arm movement during running counteracts torque due to hip rotation. Furthermore, they have discovered that spiked shoes limit athletic competitors. The shoes are designed to compensate for slippage. However, every time a runner's spiked shoes dig into the track, force is wasted in pulling them out.

Weight lifting. Analysis of the motions of Bulgarian, Soviet, and German weight lifters with the biomechanical system shows that the coordinated techniques they use allow them to get under the weight when the barbell is at a relatively low point. That this technique is successful is supported by findings with the biomechanical computer system. One might think that lifting weights is a simple matter—just bend over and pick up the weight. However, researchers who have analyzed the motions say the proper technique in lifting heavy weights is first to lower oneself to the ground, while keeping the feet firmly planted flat against the ground. Next, with the hand firmly grasped around the barbell, the athlete quickly pulls up on the weight, accelerating upward while positioning the rest of the body directly under the barbell. This movement exerts the greatest upward force on the barbell and also allows the body stress to be dissipated in the legs instead of the lower back.

U.S. athletes, it was found, were delaying in getting under the barbell until the barbell began to accelerate downward. This prevented them from lifting record loads. Once the weight starts to descend, the lifter has to overcome both the inertial forces and the weight of the bar.

Hammer throw. At one time, U.S. athletes dominated the hammer throw event. In recent years, however, the U.S. competitors have failed to throw the hammer as far as entrants from the Soviet bloc. At the qualifying events for the Montreal Olympic Games, no American exceeded the qualifying standard of 68.9 m, while the Russians had more than 25 athletes capable of heaving the hammer that distance. A computer analysis explains why. The shorter throws of U.S. athletes resulted from relatively low velocities during turns of the body and low linear velocities (of the hammer) during the delivery phase. The computer-fed digitizer showed that these low velocities resulted from an inefficient center of gravity displacement of the American throwers. To correct this problem, trainers suggested that throwers pull hard on the hammer handle to accelerate the hammer. The movement is similar to pulling on a door knob to open a stuck door.

Tennis forces plotted. Ball/racket interaction tests are providing new insight into the mechanics of tennis. A biomechanical analysis of this activity involves tests performed and displayed each time a machine fires a tennis ball into a racket. The racket is held by simulated hand grip and mounted on a force platform.

The electronic data show that, with a forehand stroke, the tennis ball velocity is about 72.4 km/h prior to impact. For both forehand and overhead smash strokes, the tennis player's arm is almost perfectly straight before and after impact. Researchers view the arm as a rigid system of links. Outputs from a piezoelectric crystal force platform are amplified and fed into a computer, where the signals are stored. Tests are repeated, so that subsequent curves can be compared to assure statistical significance.

The x, y, and z force curves are stored in a computer memory for later processing. The computer program processes the data, reduces the number of points per curve, and calculates additional curve values as needed. The processed data yield parameters for magnitudes, time interval, and impulses for any position of the force components. Another program processes the curve files, and the data are plotted on display.

The tests are determining the impact forces applied to the racket, the angular velocity of the arm and racket, and the impact duration. For the forehand stroke, the impact force at 72 km/h is 400 N, the angular velocity of the arm is 4.9 rad/s and the impulse duration is 4.0 ms. Impulse duration depends on several variables such as ball hardness and racket stiffness. For the overhead smash stroke, the kinetic and kinematic data show an impact force of 1350 N, an arm angular velocity of 8.55 rad/s and an impulse duration of 4.0 ms.

For each stroke, three analyses are performed. The first assumes the wrist as the fixed point; the second: the elbow as the fixed point, with the wrist as a rigid connection; the third: the shoulder as the fixed point, with the elbow and wrist as rigid connections. In this way, the reaction forces at each body joint are found.

In the smash stroke analysis, the angle of each joint is part of a segment that is considered fixed. The "residence time" of the tennis ball—how long the ball is in contact with the racket—during these tests ranges between 3.8 and 4.2 ms. Since human reaction time is approximately 70 ms, it is not the ball on the racket that is felt by the tennis player, but rather the racket's reaction to the impact. Just as the ball leaves the racket, the racket head begins to move.

Another interesting point revealed by tennis players is that as much as five times the body weight is absorbed in the knee and ankle joints during play. In other words, players weighing 67.5 kg subject their knees and angles to forces of as much as 337 kg. Tennis shoes and courts must be designed to account for this energy absorption.

The computer-fed digitizer system indicates that an overhead smash stroke results in shear forces at the shoulder that are more than four times higher (than those present during a free swing of the racket). At the elbow, shear forces caused by ball impact are more than three times higher and at the wrist two times higher. In the more common forehand stroke, the impact reaction forces at the shoulder are more than three times greater than the normal swing motion at the shoulder, more than two times greater at the elbow, and more than two and a half times greater at the wrist.

A term often heard on tennis courts is the "sweet spot" of the racket. It refers to the center of percussion when the ball hits the racket and can be calculated mathematically. It is usually found to be somewhere between the center of the strings and the throat of the racket. This measurement assumes the pivot point of the arm to be at the player's hand, where he grips the racket. Analysis of film shot at 10,000 frames per second, however, shows that the handle-wrist-hand connection is fairly rigid, and that the pivot point is actually the player's shoulder. As a result, the center of percussion has been pinpointed slightly above the wrist.

Golf. In golf, the aim of the player is to translate maximum body effort and complex timing sequences to the ball so it will travel far and straight. To achieve this maximum impact—which must occur within approximately 1.2 ms, according to the biomechanical data—the body motion must be coordinated. The forces of all body segments from the feet to the hands are coordinated and transmitted from the feet to the hands and are coordinated and transmitted to the club head. With proper timing, maximum kinetic energy will be transmitted to the golf ball.

Dr. Ariel has studied the golf drives of Jack Nicklaus and former President Gerald R. Ford. The data shows it took Ford 0.2 s to complete a swing—that is, from the first movement of the club in the direction of the ball through impact. The same stroke phase for Nicklaus required 0.18 s. At impact, Ford's club was positioned approximately 300 degrees from the right horizontal and Nicklaus' approximately 270 degrees. In other words, at impact velocities, Nicklaus' club was vertical, while Ford's had already passed the vertical position. One of the most important differences between the two golfers, according to the data, is that Nicklaus has greater separation in the timing of the peak velocity among the sequences of the different arm segments. This separation or delay makes for a more efficient interaction between Nicklaus and his club.

Far-reaching implications

Kinetic analysis of whole body motion can be applied in any field of human performance. The possibilities for application of biomechanical analysis are far reaching.

Total body motion analysis is yielding the magnitude and direction of forces on the shoe for each activity, in addition to the total body center of gravity corresponding to force data. The information is being used by some manufacturers to design better shoes. While the stylist considers the esthetic qualities of the shoe, the engineer is concerned with physical components, such as slip equation, strength of the material, and durability. At the same time, the researcher must take into account the person in the shoe and the sports activities involved.

In the design of synthetic material for playing surfaces, biomechanical data can help specify the material properties of polymer compounds. Dynamic stiffness, hysteresis or damping efficiency, and deformation of the compounds can be assessed by analysis of the forces produced by human performance.

Further use of biomechanical analysis is being investigated in the development of prostheses to duplicate the functions of normal human limbs, and the potential for analysis of human motions to standardize the characteristics of disabilities is of interest to the United States Veterans Administration and insurance companies.

For further reading

For a more detailed physiological analysis of human performance by a computer, the following two selections from the World Congress on Sports Medicine are suggested: "Biomechanical Analysis of the Knee Joint During Deep Knee Bend with Heavy Load," XXth World Congress in Sports Medicine, *Congress Proceedings*, 1975, pp. 71–79, and "Computerized Biomechanical Analysis of Human Performance," XXth World Congress in Sports Medicine, *Congress Proceedings*, 1975, pp. 53–60.

Considering the applications of computer analysis to javelin throwers (by athletic trainers) as the subject of an article in the *Track and Field Quarterly Review:* "Computerized Biomechanical Analysis of Throwers at the 1975 Olympic Javelin Camp," Vol. 76, 1976, pp. 45–50.

For those who are interested in using biomechanical systems to design sport equipment, a paper presented by Dr. Gideon Ariel is suggested: "Computerized biomechanical Analysis of Athlete Shoes," *V International Congress of Biomechanics, Abstracts*, Jyvaskyla, Finland, 1975, p. 5. An interesting treatment of this technology is also presented in: "Computerized Biomechanical Analysis of Human Performance," Thomas P. Martin, *Biomechanics of Sport*, State University of New York at Brockport, 1975, pp. 228–229. ◆