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To cite this article: M.R. Yeadon & J.H. Challis (1994) The future of performance-related sports biomechanics research, Journal of Sports Sciences, 12:1, 3-32, DOI: [10.1080/02640419408732156](https://doi.org/10.1080/02640419408732156)

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Published online: 01 Feb 2008.



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The future of performance-related sports biomechanics research

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Accepted 11 August 1993

An overview of performance-related research in sports biomechanics is presented describing the relevant techniques of data analysis and data processing together with the methods used in experimental and theoretical studies. Advances in data collection and processing techniques which are necessary for the future development of sports biomechanics research are identified. The difficulties associated with experimental studies in sports biomechanics are described with examples of the different approaches that have been used. The strengths and weaknesses of theoretical studies are discussed with examples drawn from a number of sports. It is concluded that progress in performance-related research will result from the application of a suitable combination of theoretical and experimental approaches to those sports in which technique is the primary requirement for success.

Keywords: Sports biomechanics, review, data collection, data processing, experiment, computer simulation.

Introduction

The word 'biomechanics' is derived from the Greek *bios* meaning life and *mekhaniki* meaning mechanics, so that biomechanics may be said to be the study of the mechanics of life forms. The extent of this subject area is evident in the publications on the biomechanics of plants, insects, reptiles, dinosaurs, birds, fish, whales, elephants, kangaroos and humans (Alexander, 1968, 1975, 1989). In the biomechanics of humans, topics range from the mechanics of bone, tooth, muscle, tendon, ligament, cartilage, skin, prostheses, blood flow, air flow, eye movement, joint movement to whole body movement (Fung *et al.*, 1972; Huijskes *et al.*, 1982). In human movement biomechanics, topics include injury, clinical assessment, rehabilitation, ergonomics and sport.

Sports biomechanics has two main branches – the study of sport-related injuries and the understanding of performance in sport. The focus of this paper is performance-related research, which poses questions such as: What is the best run-up speed for a particular high jumper? How should foot placement be modified for faster approach runs? Why is it beneficial to use a curved approach in high jumping? These questions are of the form: What is done? How is it done? Why does it

work? The answers to What? How? and Why? are important to the athlete, coach and scientist, respectively.

One method of seeking answers to such questions is to use an experimental approach. This may take the form of direct intervention in the activity which may meet some understandable resistance from athlete and coach. More often the experiment is invisible to the athlete and is purely a matter of the way in which the biomechanist selects the data. By obtaining movement data on an individual athlete, it may be possible to identify those elements of technique which are associated with the better performances. This may indicate how the individual can improve personal performance. By obtaining data on a number of athletes and identifying the characteristics of the better athletes, it may be possible to gain insight into how training should be structured.

Another method of investigation is to use a theoretical approach. This takes the form of an idealization of the activity using a theoretical model. Hypothetical data are generated by using the model in specified situations. For example, with a model of aerial movement, it is a simple matter to determine how much faster a diver will somersault when moving from a straight position to a closed pike. A theoretical model may also be able to provide a general description of movement which can lead to a more complete understanding than that provided by a number of particular examples.

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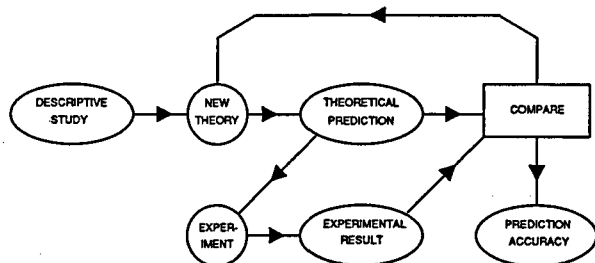


Figure 1 The theory-experiment cycle of scientific method.

Although the experimental and theoretical approaches appear to be quite different in nature, they are both an integral part of *scientific method*. Initially, a scientific investigation will probably take the form of a descriptive study which provides a record of what happens. The data may suggest a possible theory. Such a theory may be used to predict the outcome in a given situation. An experiment can then be conducted to determine the actual outcome. A comparison of theoretical and experimental outcomes can then establish the accuracy with which the theory models the activity. This will indicate the level of confidence that can be given to theoretical predictions and may suggest how the theory can be modified. The cycle of theory-prediction-experiment-modified theory is shown in Fig. 1.

Similar diagrams showing the structure of scientific method are given by Beck (1960), Heath (1970) and Davies (1973). Davies suggested that initial testing of theoretical predictions may be accomplished using available observational data, while the subsequent testing of refined theories may require carefully designed experiments. In a similar vein, Heath distinguished between *observational science* and *experimental science*. While there may be some variation in the descriptions of scientific method, there is always the common element of testing a well-defined theory using a comparison of predicted and experimental results.

Sciences may be described as *experimental sciences* or *theoretical sciences* according to the relative degrees to which they rely on experiment and theory. Sciences can vary from the data dominant, such as botany, to the theory dominant, such as philosophy. Sports biomechanics should be a balanced mix of experimental data and theoretical modelling if a realistic understanding is to be achieved. Both experiment and theory pose their own particular problems in sports biomechanics research and these will be addressed in subsequent sections.

Fundamental research in biomechanics, such as the mechanics of skeletal muscle, can enable specific applied research projects to be undertaken in particular sports. Applied research provides the basis for interpreting the results of data collection and thereby makes possible support services to sports. The understanding gained from applied research is a prime resource for coach

education, although, with the passage of time, acceptance of original ideas transforms them into common knowledge whose origins are often forgotten.

This paper will consider the future of performance-related sports biomechanics research by looking at the strengths and weaknesses of the methods presently in use and identifying areas for improvement and development. The paper is structured so as to consider the areas of data collection, data processing, experimental studies and theoretical studies. This order reflects both the chronology of individual studies as well as the historical development of sports biomechanics. *Data collection* and *data processing* in themselves do not constitute sports biomechanics research but govern the extent and form of such research. In these sections, the particular requirements of applied research in sports biomechanics are used as a basis for identifying necessary developments in these data acquisition techniques. In the sections on *experimental studies* and *theoretical studies*, the strengths and weaknesses of each approach are considered, and recommendations are made for the approaches to be used in future research in sports biomechanics.

Data collection

While the coach will use a subjective qualitative analysis of sporting movement in order to determine what advice to give, the researcher in sports biomechanics must make use of objective quantitative data (Watkins, 1987a, b). The methods of data collection in sports biomechanics are those generally employed in other areas of biomechanics (Atha, 1984; Bartlett, 1992). Sports biomechanics introduces additional problems to the measurement process due to the nature of the activities being examined, these problems being further exacerbated if the measurements are to be taken during competition. This section will examine those data collection techniques relevant to the analysis of sporting activities with a view to identifying their weaknesses, strengths and potentials.

Biomechanical analyses of human movement require information on kinematics, inertia parameters, and internal and external forces. Data collection techniques in each of these areas will be considered including manual and automatic film and video systems, accelerometers, force platforms, pressure sensors and electromyography systems. In sports biomechanics, the most common means of obtaining data has been the manual digitizing of film or video recordings. The methods for reconstructing the locations of points of the body from their recorded images will be reviewed in the section on data processing.

Two-dimensional cinematography and video

Many researchers have performed analyses of sports movements in two dimensions using a single cine or video camera. The coordinates of points are measured from the recorded image, using a projector and digitizing tablet for film, or using a video player and image capture for video (Shapiro *et al.*, 1987). These coordinates are transformed from the image reference frame to a reference frame in the activity or movement space. Two-dimensional analyses have been used for a variety of sporting movements such as kicking (Putnam and Dunn, 1987) and long jumping (Hay, 1988).

In two-dimensional studies, the movements are analysed by projecting points onto the sagittal plane or plane of progression. Such studies ignore movements away from that plane, suggesting that such movements have no significance for the activity being performed. Unfortunately, this assumption may not be justified and should be investigated using a three-dimensional analysis. Many sporting movements which may appear to be essentially two-dimensional in nature require three-dimensional data collection techniques if their full features are to be revealed, as for example in long jumping (Smith *et al.*, 1988). The increased study of movement in three dimensions should highlight those activities which can be justifiably and profitably analysed in two dimensions.

Three-dimensional cinematography and video

Three-dimensional analysis techniques generally require at least two cine or video cameras (Miller *et al.*, 1980). Ideally, the points of interest should be visible in two or more simultaneously recorded images before they can be located in the three-dimensional movement space. Moving from two-dimensional to three-dimensional analysis involves a significant increase in complexity to derive the positional data, as will be discussed in the section on data processing. Three-dimensional techniques have been used to study a variety of sporting movements such as field hockey (Elliot and Chivers, 1988) and baseball pitching (Feltner and Dapena, 1986). To date, 16 mm film has dominated as the medium used to record movement, but with the rapid development in technology it is anticipated that video will be used increasingly for data collection in sports biomechanics. At the present time, video systems generally offer lower spatial resolution than film-based systems (Kennedy *et al.*, 1989; Angulo and Dapena, 1992). This lower resolution does not seem to be a consequence of the poorer video image but arises because the video-digitizer coordinates are limited to integral pixel values. Improved resolution could be obtained either by

allowing the cursor to move across the captured image in fractions of a pixel using anti-aliasing techniques, or by using a standard high-resolution film digitizer tablet in conjunction with a video projector.

Both cine and video systems have the problem that the measurement of information from the image (data reduction) is often performed manually, involving frame-by-frame digitization of body landmarks. The labour-intensive and time-consuming nature of manual digitization has led to the development of automatic systems which greatly reduce the time required for analysis but also necessitate the attachment of markers to body segments. Manual digitizing will therefore continue to be used when data have to be collected at major sporting events.

Automatic motion analysis

Woltring (1987) classified automatic systems into three groups: those that are video-based, those using light-emitting diodes (LEDs) and those using scanning mirrors. Video-based systems use markers covered in retro-reflective tape in conjunction with camera ring lighting which is often stroboscopic using infrared LEDs (e.g. VICON, ELITE, MotionAnalysis). The advantages of these passive markers are that no wires and batteries are needed and they are inexpensive to replace. The disadvantages of such systems are the limited image resolution at sample rates higher than 50 or 60 Hz, the interference caused by sunlight and the difficulty in automatically identifying markers. These systems have been used in sports such as weightlifting (Whittle *et al.*, 1988) in which the movement is simple and confined to a small volume.

Light-emitting diode-based measurement systems (e.g. Selspot, Watsmart) generally rely on the lateral photo-effect (Woltring and Marsolais, 1980). The LEDs flash in a given sequence, controlled by a unit attached to the subject, and a photo-detector registers the coordinates of the light pulse of each of the LEDs, using the lateral photo-effect. The sequencing of the LED activity permits automatic identification of the markers. Another advantage over video-based systems is the good resolution at high sampling rates. The disadvantages include the interference caused by reflections and the need to carry a power supply and wiring for the LEDs. Typical sporting applications have been in rifle shooting (Zatsiorsky and Aktov, 1990), where the whole body movement is limited.

The third type of system (CODA) is based on scanning mirrors and coloured retro-reflective prismatic markers (Mitchelson, 1988). The rotating mirrors sweep fans of white light at 300 Hz through the movement space so that coloured light is reflected back

by each retro-reflective prism. The advantage of this type of scanning system is that the markers are passive but can be uniquely identified using their colour spectra. The main disadvantage is that the number of landmarks that can be used is limited due to difficulties in distinguishing the different spectra. This limitation probably accounts for the relatively few systems in use and the fact that one laboratory modified the system to use photodiodes rather than reflective markers (van Weeren *et al.*, 1992). So far the use of this system in sports biomechanics has been limited to events such as archery (Stuart and Atha, 1990), in which there is little movement and only a few markers are needed.

All three types of motion analysis system are limited by the requirement for markers to be attached to the subject, the LED systems being further restricted by the need to carry power and wiring. If the fixing of markers to the subject is not a problem, then the LED-based systems generally offer higher spatial and temporal resolution and have automatic marker identification. All the systems have the advantage that the data are available much quicker than with manual digitization. It must be remembered, however, that automatic systems can only give the locations of the surface placed markers, whereas joint centre locations can be estimated by the operator when using a manual system. All of the automatic systems have problems if the markers become obscured for too many of the sensors at the same time, whereas during manual digitization the operator can estimate the locations of obscured points. In the analysis of many sporting activities, it can be seen that these automated systems have the potential for increasing the number of trials that could be analysed, although their use is obviously precluded in competition.

Angle measurement

Joint angles may be determined using any of the motion analysis techniques described. An alternative way of measuring joint angles is to use goniometers which range from simple two-dimensional goniometers to the more complex triaxial goniometers (Chao, 1980). Signals from these devices can be recorded using a telemetry system or a data logger carried by the subject, reducing the encumbrance to the subject and making field operation possible. Nicol (1988) presented a flexible triaxial goniometer in which strain gauges measure the bend in terms of an angular change, and this may be more suitable for the analysis of sporting activities than the rigid devices usually employed. Despite the fact that goniometers need to be attached to the subject, they have the advantage of being relatively cheap to buy or manufacture and can be used on-line to provide the subject with immediate feedback.

Magnetic tracking systems

An *et al.* (1988) used a source which emitted low-frequency magnetic fields together with a sensor for six degree of freedom measurement of joint motion and for tracking movement over a distance of 2 m. Multiple sensor systems using the Earth's magnetic field as a source have the potential for quantifying segment configuration and body orientation for general human movement (Kolen *et al.*, 1993). Further development of such systems is to be expected over the next few years, although there is the disadvantage of interference from ferromagnetic materials within 1 m of the subject as well as the limitations associated with active marker systems.

Acceleration measurement

Accelerometers detect accelerations by quantifying the forces that are applied to a small mass using a strain gauge, piezoresistive, piezoelectric or inductive force transducer. Since it is the effect of force that is measured, accelerometers are affected by gravitational forces. It is possible to determine the position and attitude of a single rigid body using six suitably orientated accelerometers (Morris, 1973), although some researchers have found that the double integration of acceleration values can lead to large errors (Nigg and Yeadon, 1987). Padgaonkar *et al.* (1975) have demonstrated that using nine rather than six accelerometers per body segment reduces the influence of experimental error on the measurements. Since there are other motion analysis systems available which require fewer units to be attached to the body, it is likely that the main use of accelerometers will continue to be the measurement of acceleration.

There are problems associated with mounting the accelerometers on the human body. Gross and Nelson (1988) used skin-mounted accelerometers to examine the landing from a vertical jump, whereas Lafortune (1991) used accelerometers attached directly to the tibia with cortical pins in order to examine tibial accelerations during walking and running. Ziegert and Lewis (1979) evaluated different methods of affixing accelerometers to the tibia, and found that the measured acceleration depends upon the mounting used. With skin-mounted accelerometers, there can be significant noise added to the signal due to soft tissue movement, while the use of cortical pins circumvents this problem but is an invasive procedure. Ladin and Wu (1991) have presented an evaluation of an approach where the data from a single triaxial accelerometer are combined with positional data for the estimation of net joint forces. Their evaluation reported that superior estimates of joint force could be obtained using a combined approach rather than using the standard inverse dynamics procedure based on the

differentiation of displacement data. Using such an approach means that high-frequency components of the signal are not ignored when determining joint moments. Given the nature of many sporting activities, such a procedure may find significant use.

Anthropometry

Mechanical analyses of human movement require a knowledge of the inertial properties of the segments making up the human body. There are a number of methods which calculate body segment inertia parameters from a set of anthropometric measurements. These include geometric models (Hatze, 1980; Yeadon, 1990b), regression equations (Hinrichs, 1985), non-linear regression equations (Yeadon and Morlock, 1989) and the scaling of cadaver inertia values (Forwood *et al.*, 1985). These methods vary in achievable accuracy and in the time and number of measurements required. For many of these procedures, it may not be possible to have access to an athlete for long enough to take the measurements. For example, the model of Hatze, which requires 242 anthropometric measurements to be taken, needs the extended cooperation of the subject. A practical solution to this problem may be to take the anthropometric measurements using a photogrammetric system (e.g. Jensen, 1978), where the necessary measurements for customizing the model are made from photographic images of the subject.

The applicability of the different procedures for the determination of body segment inertia parameters to sports biomechanics is considered in the section on data processing.

Force measurement

Force is generally quantified via the deformation of transducer elements such as piezoelectric devices which generate a charge proportional to the force causing the deformation. The most common force measurement device used in biomechanics is the force platform, which can measure the three orthogonal components of the net force and the three components of the net moment. A rectangular platform is supported by four force transducers, which are typically either piezoelectric cells (e.g. Kistler) or strain gauges (e.g. AMTI, Bertec). The key design features are that the platform should be large enough to measure the contact force of the movement of interest, and have a natural frequency sufficiently high so that vibrations of the platform do not interfere with the signal of interest (Antonsson and Mann, 1985; Kerwin and Chapman, 1988). Although these platforms have been used predominantly to examine gait (e.g. Winter, 1983), they have also been used to provide the ground reaction forces for the calculation of resultant

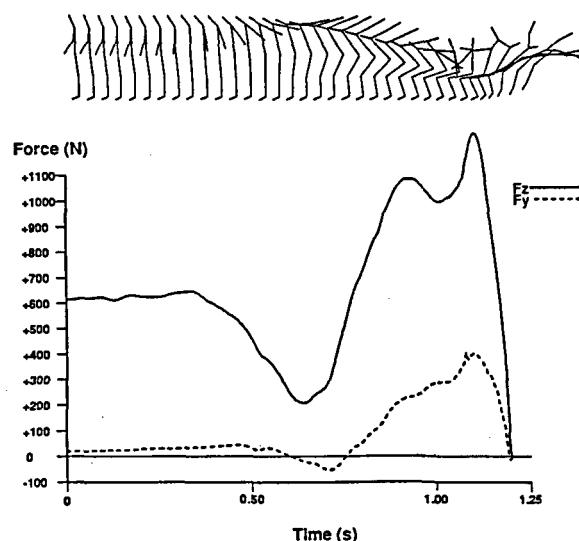


Figure 2 Vertical (F_z) and anterior-posterior (F_y) forces recorded by a force platform during the take-off for a flic-flac.

joint moments during a somersault take-off (Nicol and Watkins, 1987), and to trace the movement of the centre of pressure during running (Cavanagh and Lafortune, 1980). Figure 2 shows the ground reaction force recorded by a force platform during the execution of flic-flac. Bobbert and Schamhardt (1990) found that the calculation of centre of pressure locations from three Kistler force platforms (type 9287) contained systematic errors, since the contact plate deformed under impact and did not load each transducer centrally. They produced an algorithm which may be used to reduce this systematic error, for plates of the same type, without additional calibration.

Miller *et al.* (1989) measured reaction forces during take-offs using a force platform mounted in the 10 m platform at the 1986 World Diving Championships. The force platform lay directly beneath the top surface of the diving platform. In situations such as this, it is worth checking that the force transferred away from the force platform due to lateral cross-bridging is small. In the case of ski jumping, force platforms covered by 0.4 m of packed snow may be expected to register only part of the normal force applied to the snow surface (Virmavirta and Komi, 1989). The deformation of point elastic surfaces, such as synthetic track, will affect the transferred forces only slightly, since the mass of the deformed surface is small (Nigg and Yeadon, 1987).

To be able to examine the forces acting during a sporting activity often requires a force measuring device which offers more flexibility than a force platform. In order to quantify the forces acting on sporting equipment, appropriate instrumentation is required. For example, Robertson *et al.* (1985) instrumented many of the pieces of gymnastics apparatus, using load trans-

ducers, so they could measure the applied forces, while Ruby *et al.* (1992) used a pedal dynamometer to measure normal and tangential pedal forces during cycling. The measurement of forces using a force transducer of some variety is appealing, but the essential calibration of the force measuring device is often problematic.

In an attempt to understand the neuromuscular factors influencing performance, the forces exerted by muscles have been measured *in vivo* using buckle transducers. Although this technique is more commonly used with animals that are sacrificed to facilitate calibration, Gregor *et al.* (1991) have measured the forces acting on the Achilles tendon during cycling. Studies such as this have the potential to provide insight into human movement, but the application of such a protocol is limited by the difficulty of calibration and the number of muscles whose tendons can be easily accessed. Other considerations are whether the forces are affected by the measurement procedure and whether such an invasive technique is ethical.

Pressure measurement

Devices are now available which permit the measurement of the pressure distribution beneath the foot. These take the form of either pressure plates placed on the ground or pressure insoles placed in the footwear (Lord, 1981). The use of pressure plates for research in sports biomechanics is likely to remain limited, since these devices are small and the pressure is redistributed if the plate is covered by an appropriate sports surface. Pressure insole systems have much greater potential, since they measure pressure at the foot-shoe interface, collect data for more than just a single foot contact, avoid the targeting associated with pressure plate use and can be used in a wide range of activities. These pressure measurement systems may be based on capacitance devices, strain gauges, force-sensing resistors, piezoelectric transducers or magneto-resistive devices (Cavanagh *et al.*, 1992). In discrete systems where individual transducers are used, the conditions at the foot-shoe interface may be altered if the transducers are too thick. Matrix systems consisting of numerous pressure-sensing elements arranged in rows and columns permit the pressure normal to the entire plantar surface of the foot to be monitored (Nicol and Hennig, 1976).

The limitations of these systems include sensitivity to temperature, humidity and repeated stress, non-linear response, unidirectionality, susceptibility to mechanical breakage, the need for trailing wires and the fact that the matrix insole itself may redistribute pressure. Researchers should not be content to accept manufacturers' specifications for these devices, but should carry out a series of calibrations on each element of the matrix and should determine the effects of temperature,

humidity and repeated stress on the transducer output. Bartlett *et al.* (1991) found differences in the net vertical reaction forces during discus throwing as measured by EMED pressure insoles and by force platform. Such differences arise primarily because there is a threshold level for pressure transducer elements below which zero force is registered, although the fact that the transducer elements are aligned normal to the interface rather than vertically also produces differences. Future developments in this type of technology should include simultaneous measurement of all three components of stress, improvements in reliability and portability, and the extension to the hand-equipment interface.

Electromyography

Electromyography (EMG) is the analysis of muscle function via the measurement of the electrical activity of muscles using either surface electrodes or indwelling electrodes. The EMG signal sampled is dependent on the type of electrodes, their placement and the distance between the electrodes. Surface electrodes are more commonly used in sports biomechanics, since they are less invasive, but they require that the skin is prepared to reduce impedance (Okamoto *et al.*, 1987) and suffer from cross-talk due to the activity of other muscles.

Using an EMG telemetry system, or by having the subject carry a data logger, it is possible to measure the electrical activity in a range of sports without constraining the subject. Indeed, with adequate preparation it is possible to measure EMG patterns for a wide range of different sporting activities. Clarys *et al.* (1985) used telemetry when measuring EMG signals from 25 muscles during front crawl swimming, while de Koning *et al.* (1988) used a telemetry system to obtain the EMG signals from 10 muscles during speed skating.

For a more extensive discussion of the collection of EMG signals, the reader is directed to Bartlett (1992) and Clarys (1987).

Future directions

This section has discussed the major methods of measurement used in sports biomechanics covering the measurement of position and orientation of rigid bodies, acceleration, anthropometry, force, pressure distribution and EMG. It should be recognized, however, that there are other methods used to collect data in sports biomechanics. These vary from the simple calculation of speed using photo-electric sensors to obtain times (Komi, 1987) to the more complex use of wind tunnels to examine the aerodynamic characteristics of bodies (e.g. Dal Monte *et al.*, 1987). With the current rapid increase in technology, the development of more accurate and varied methods of measurement should be anticipated.

In particular, the use of automatic motion analysis systems will permit a significant increase in the number of trials that can be analysed in a laboratory or training environment, and reduce the time required to provide feedback. Similarly, the use of pressure distribution transducers will enable the recording of forces at the interfaces of athlete and equipment in sports as diverse as skiing, weightlifting and throwing activities. Unfortunately, many of the techniques described in this section cannot be used during competition, and for biomechanical analyses in such circumstances reliance will still have to be placed on film- and video-based techniques.

Data processing

The previous section reviewed the data collection techniques that are frequently used in sports biomechanics. This section examines how the data are processed for use in sports biomechanics analyses with a view to identifying areas for future development. Guidelines have been published in Canada (Dainty and Norman, 1987) and Britain (Bartlett, 1992) reviewing most of the basic methodologies for biomechanical data collection and data processing for sporting activities. The order in which the data processing techniques are discussed relates to the order used in the section on data collection. One additional area considered is the analysis of error in the parameters and variables determined during data processing.

Two-dimensional cinematographic and video reconstruction

The motion analysis technology has been identified whereby the locations of points in the field of view of a single camera can be measured in a two-dimensional image reference frame. The transformation from image coordinates to a plane defined in the movement space is commonly performed with a linear transformation using scale information recorded in the field of view (Doolittle, 1971). Such procedures usually require that the image plane is parallel to the movement plane and this may not be possible in certain environments. A more flexible approach is provided by the two-dimensional direct linear transformation, where the attitude of the image plane to the object space plane is not restricted (Walton, 1981). During many sporting activities, the athlete may cover a significant distance and it may be necessary to pan the camera in order to have a sufficiently large image size for subsequent digitization. For the reconstruction of body points, it is necessary to digitize control points in each film frame so that the panning angle can be calculated (Gervais *et al.*, 1989).

The advantages of two-dimensional analyses are that only a single camera is required and the procedures can be simple. While some activities may be justifiably examined in two dimensions, the majority of analyses are now three-dimensional, despite the increased information and processing requirements.

Three-dimensional cinematographic and video reconstruction

In this subsection, some key areas in the processing of data for three-dimensional film and video analysis are discussed. The areas of focus are the synchronization of images recorded from different cameras, the techniques used to reconstruct the position of points in three-dimensional space, the ways to circumvent the need for a large calibration object, the use of panning cameras, the reconstruction assessment, and the relationship between accuracy and camera positioning.

The ability to locate a point in three dimensions generally requires that the image coordinates of that point are measured simultaneously from at least two (camera) views. Today, 16 mm cameras can be phase-locked and video cameras gen-locked so that the recorded images are synchronized. The physical connection between cameras necessary for phase-locking may not be possible in certain environments, necessitating another technique. A mirror may be used to enable two images to be recorded on the same film (Marchand *et al.*, 1983), although the size of the image is effectively reduced, the mirror can introduce distortions, and for many activities a very large mirror would be required.

If the exposures made with two cameras are not simultaneous, synchronization may be effected by interpolating the separately recorded data sets over the same time base. Walton (1981) used a timer in view of both cameras to establish times for each frame and then linearly interpolated the data of the faster camera over the time base of the slower. Dapena (1979) used a timer to obtain the start and end times of the activity and assumed that the framing rate was constant between these two points. This gave frame times for each camera, and then an interpolating cubic spline was used to time-match the data. When the placement of a timing device in the view of the cameras is not possible, synchronization can be achieved using the digitized film data. Yeadon (1989) synchronized films of ski jumping at take-off by assuming that the centre of mass of the body was in the vertical plane bisecting the in-run. At landing no such assumption was made, but it was necessary for the velocity vector of the ski jumper to make a sufficiently large angle with the plane defined by the positions of the athlete and the two cameras. Such synchronization methods, which are based on information available from the recording of the activity, are

useful when data are collected at competitions, since it is not always possible to have cameras physically linked or to have a timing mechanism in view of all cameras. The accuracy of synchronization using such methods is dependent upon the camera calibration accuracy, since errors in the estimated camera locations can lead to poor synchronization. Technological developments mean that it is possible for a common time to be recorded on a film or video image, using microwave links, so that the cameras do not have to be physically connected. Unfortunately, such devices are currently sufficiently expensive to prohibit their use in sports biomechanics.

Given the images of points from two synchronized recordings, the two-dimensional image coordinates of these points are used to reconstruct the points in a three-dimensional movement space reference frame. This may be done by explicitly reconstructing rays from each camera directed towards the landmark of interest. These techniques impose restrictions, such as the optical axes of the cameras having to intersect (Cappozzo, 1983), or the cameras being in known locations (Penrose *et al.*, 1976). Techniques where the cameras must be in known locations or have optical axes intersecting may be too restrictive for many environments where sporting activities are to be examined.

The most common reconstruction technique used in sports biomechanics is the direct linear transformation (DLT), which permits arbitrary camera placement but requires that control points with known locations must be distributed throughout the activity space (Abdel-Aziz and Karara, 1971). This is usually achieved using a calibration frame which contains a number of control points that fill or surround the volume within which the activity will take place. In sports biomechanics, it can be difficult to construct such a large calibration structure and often a small frame is used which leads to larger reconstruction errors for the points lying outside the calibrated volume (Wood and Marshall, 1986).

Hatze (1988) implemented a modified form of DLT in which the shear factor of the transformation was constrained to be zero. He obtained a better fit to 30 control points (RMS = 0.8 mm in a 2 m field) compared with the conventional DLT procedure (RMS = 4.8 mm). Whether such a large improvement is due solely to the reduction from 11 unknowns to 10 is unclear, as different numerical algorithms were used for the parameter determination. Since back-calculation from the DLT parameters gives less accurate estimates of the camera location and principal point of the lens when the calibration frame is small, a method incorporating constraints on these parameters should permit extrapolation outside the volume spanned by the calibration frame.

The problems associated with the use of small calibration structures and the need for extrapolation

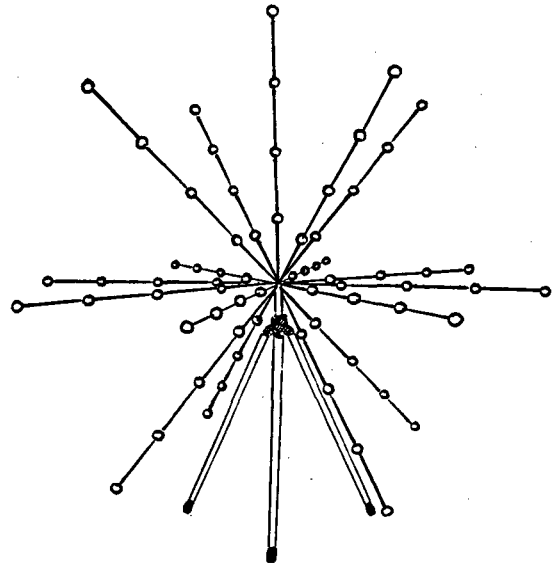


Figure 3 A calibration frame for three-dimensional reconstruction.

outside the calibration volume may be exacerbated by the design of the calibration frame. It is necessary that the control points are distributed evenly throughout the calibration volume. If a disproportionately large number of points are clustered in a particular region, the corresponding DLT parameters will produce an increased reconstruction accuracy in this region at the expense of poorer reconstruction elsewhere. Figure 3 shows a typical portable calibration frame with four control points equally spaced on each of 17 rods emanating from a central hub. Half of these control points lie within the innermost one-eighth of the control volume and so digitizing each of the 68 points in the calibration procedure will not produce an even reconstruction accuracy throughout the calibration volume. There is a strong case for the repeated digitization of fewer points which are more evenly distributed throughout the calibration volume.

A number of three-dimensional reconstruction procedures have been developed which require calibration objects of reduced size. Woltring (1978, 1980) developed a technique which required multiple views of a two-dimensional calibration structure to perform a three-dimensional calibration. Dapena *et al.* (1982) simplified the calibration frame to the ultimate and moved a pole of known length throughout the movement space to calculate the external camera parameters. Ball and Pierrynowski (1988) used a modified version of the DLT, in which a small three-dimensional calibration frame was moved throughout the volume to be calibrated. The disadvantages of these techniques are that it may be difficult to position the frame throughout the volume and the number of control points to be

digitized is much greater than for a single calibration frame for the same level of accuracy.

Woltring *et al.* (1989) effected calibration using a rigid configuration of four markers on each body segment. This has the advantages that the control points are distributed throughout the movement volume and that no additional digitization is necessary, since the marker information is needed for the analysis of segment movement. The disadvantages of this technique are the requirement of a rigid marker configuration and the decrease in calibration accuracy as the field of view increases. The rigid marker requirement could be relaxed by using the known segment link lengths with the method of Dapena *et al.* (1982), so that the moving athlete would calibrate the movement space. This idea is very attractive, although it remains to be seen whether segment link lengths will provide sufficient information to enable accurate calibration. Further development in calibration methods is necessary to produce a convenient but accurate procedure which may be used in a general sporting environment, as this will extend the range of sports which can be analysed and the environments in which data collection can proceed.

Three-dimensional panning techniques

The projected image for film or video analysis must be large enough to make the identification of key body landmarks feasible. If an activity occurs in a large volume, one camera in a fixed orientation may not result in a large enough image, while using a number of cameras to cover the desired field of view introduces many practical and computational problems. If a camera with a smaller field of view could be rotated to follow the activity of interest, the problems of image size and requirement for additional cameras would be overcome. Dapena (1978) used three-dimensional reconstruction techniques where two cameras were free to rotate about their vertical axes, allowing horizontal panning. Yeadon (1989) presented a method for studying ski jumping where the cameras were free to rotate about both vertical and horizontal axes, using a tripod head which allowed pan and tilt. Both techniques required the cameras to be in known locations and two control points to be identified and digitized in each film frame.

Yu *et al.* (1993) extended the DLT method for use with two panning cameras by placing a black and white tape permanently in the field of view and calibrating a $24 \times 2 \times 2$ m volume with a 68-point control object in 10 different positions. An 'accuracy' of 0.017 m was obtained, although this value does not reflect any errors made in the 10 placements of the control structure. The disadvantage of the method is the need to digitize 680 points for the calibration. The advantages are that there is no need to survey the camera locations and that no

assumptions are made about internal camera parameters.

Panning techniques are essential for the analysis of a number of sports, and therefore further effort should be invested in developing simple, accurate and reliable techniques for the measurement of body positions using panning cameras.

Measurement accuracy

To assess the value of a methodology for measuring the positions of points of a body segment, three factors must be considered: accuracy, precision and resolution of the measurement system (Taylor, 1982). Measurement accuracy is the difference between the measured values and the true values of criterion data, while precision is the difference between the measured value and the expected mean value, and resolution is the least discernible change that the measurement system can measure. For systems which employ the manual digitization of images, some of these factors are operator-dependent, and should be assessed for each operator. Lanshammar (1980) presented formulae which permit the calculation of the expected precision of data after smoothing and differentiation. Analysis of these formulae indicates that a suitable measure of temporo-spatial precision for comparing systems is the product of the sampling interval and the variance of the noise in the measured displacement data. The formulae of Lanshammar illustrate that increased spatial and temporal resolution can improve the precision of the displacement data and their derivatives, so when assessing specification of a system consideration should be given to both.

Reconstruction accuracy is affected by the positions of the cameras used for the reconstruction (Wood and Marshall, 1986). In a theoretical analysis, Abdel-Aziz (1974) examined the accuracy of movement space reconstruction for a two-camera condition and showed how the angle of convergence between the cameras affected reconstruction accuracy, there being an optimum angle of convergence for maximum reconstruction accuracy for any given camera position. Although appropriate camera positioning can theoretically result in improved accuracy, positioning must also reflect the need for a clear view of all the control points and the need to identify the markers or body landmarks to be digitized. For certain sporting activities, the positioning of cameras may be restricted, particularly if the activity is to be filmed in competition. Camera positioning must therefore consider optimum configuration for viewing of the markers or significant body landmarks, the theoretical optimum for maximum accuracy, and the constraints imposed by the location and type of sporting event.

Automatic motion analysis tracking

As outlined in the section on data collection, automatic motion analysis systems employing passive markers have problems in identifying and tracking markers when they become obscured. This problem increases with the number of markers and with the complexity of the movement. In sports biomechanics studies, whole body data are often required for analyses of complex athletic or gymnastic movements which are more taxing than clinical gait analysis for which many of the systems were designed. In order to realize the potential of automatic motion analysis systems in the study of sporting movements, it will be necessary to keep track of a relatively large number of markers in order to obtain coordinate data for whole body movement. There is evidence that algorithms based upon a link-system model of the athlete can enable the automatic identification, tracking and interpolation of marker trajectories (Morgan, 1991). Such a tracking system must be developed before automated motion analysis systems can be used routinely in a sporting context for more activities.

Image recognition

Rather than using an automatic system that requires markers to be attached to body segments, there exists the possibility of using video-based image recognition for tracing body segments. While many techniques are based on the recognition of straight lines and vertices (Tsui and Chan, 1989), some work has been done on the recognition of three-dimensional curved objects from multiple two-dimensional images (Liu and Tsai, 1990). The extension of such an approach to the recognition of body segments will be a non-trivial task, since body segments are not rigid bodies and the boundaries between adjacent segments are not well-defined. A first step could be the tracking of a subject wearing a 'harlequin' suit, in which each body segment has a different colour, against a neutral background. Such a system could probably be produced using existing knowledge, but it will be many more years before video recordings of competitive sporting events can be routinely analysed using an automatic image recognition system.

Curve fitting and differentiation routines

Measurements made using an image-based motion analysis system are contaminated with noise generated during the recording and digitizing procedures. The sampled signal can be considered to be the sum of the true signal, systematic noise and the random noise. The

true signal can never be deduced from the measurements; only the best estimate of the signal, the systematic uncertainty and the random uncertainty. The sources of systematic noise include lens distortion, incorrect marker placement, errors in calibration objects, and skin and marker movement. In general, the sources of systematic noise should be identified and minimized. For example, in order to reduce the effect of skin movement on marker position for horses, van den Bogert *et al.* (1990) used a correction algorithm. Due to the nature of numerical differentiation, unless the random noise is reduced it may be amplified to such an extent that the estimated derivative values may contain more error than signal. There have been a number of techniques advanced for the reduction of noise and the differentiation of displacement data, including Butterworth filters and finite difference formulae (Pezzack *et al.*, 1977; Lees, 1980), truncated Fourier series (Hatze, 1981a), quintic splines (Wood and Jennings, 1979) and cross-validated splines (Woltring, 1985). Each of these techniques uses a mathematical function to approximate the displacement data. Finite differencing is equivalent to using a local polynomial fit, Fourier series uses a trigonometric fit, and a quintic spline comprises a sequence of fifth degree polynomials which are joined smoothly to form a single approximating function. The precise frequency components of the true signal underlying a sampled signal are rarely known in sports biomechanics and some procedure must be adopted for the determination of the filter cut-off, or other smoothing parameter. The techniques adopted to specify cut-off frequencies include the use of previously published values (Winter *et al.*, 1974), and manual adjustment of the degree of smoothing after visual inspection of the fitted curves (Vaughan, 1982). A poor choice of smoothing parameter may corrupt the data, treating vibrations as noise and leading to the erroneous results of Komi and Mero (1985) as reported in Best and Bartlett (1988b).

For biomechanical analysis to have genuine validity, an objective repeatable process is required for selecting the degree of smoothing. The procedure of Hatze (1981a) for fitting a Fourier series and the generalized cross-validated spline of Woltring (1985) both use automatic algorithms to select the degree of smoothing, while the method of Yeadon (1990a) requires repeated digitization to determine the closeness of fit for a natural quintic spline.

When selecting a curve-fitting and differentiating technique, consideration must be given to the nature of the technique used, as well as to how the degree of smoothing is selected. Fourier sine series and natural cubic splines constrain the second derivatives at the endpoints to zero, while natural quintic splines constrain the endpoint third derivatives to zero. Challis and Kerwin (1988) have shown that the quintic spline gives

more accurate first and second derivatives than the other commonly used techniques.

When a curve-fitting package is used in conjunction with displacement data obtained in a repeated impact activity such as running, errors will be introduced due to oversmoothing near the times of impact, especially when the camera framing rates are low. The researcher should be aware of this problem and investigate the extent of the data corruption rather than expecting the software package to produce reasonable results. Horizontal speed during running is best reported as a mean value over an integral number of strides rather than as a time history of instantaneous values that reflects the properties of the curve-fitting routine more than the changes in the speed of the athlete.

The need still remains for a data-smoothing and differentiation package that will cope with rapid accelerations such as those associated with foot strike in running. In addition, estimates of the uncertainties in calculated velocities and accelerations are required if these values are to be interpreted sensibly.

Joint angles and segment orientation

If a sporting activity is studied in two dimensions, a joint angle may be defined as the angle between two lines which define the proximal and distal segments (Winter, 1979). In three dimensions, the process is somewhat more complex. For example, Craig (1986) identified 24 different conventions for the angles describing the relative orientation of two articulating (quasi-) rigid bodies. These angle conventions all have singularities at which angles are not defined or spurious values are obtained (e.g. Codmans paradox: Kapandji, 1982). Singularities may be avoided by using Euler parameters (Huston *et al.*, 1978) or the angle system devised by Woltring (1991).

However the angles are defined, the selection of segment-fixed reference frames can influence the values of the angles determined (e.g. Blankevoort *et al.*, 1988). A lack of uniformity of conventions across studies makes the comparison of results difficult. Suggestions have been made for standardizing the reporting of kinematic data (Cavanagh, 1992; Wu, 1992), although no single system can always provide the most appropriate means of describing every configurational change of the body. The use of computer graphics to supplement configurational data may be beneficial in aiding a full appreciation of three-dimensional movement.

In three dimensions, the attitude and position of a rigid body are normally determined simultaneously. To do this, the locations of at least three non-colinear points must be known in an inertial reference frame, and relative to a reference frame fixed in the rigid body. The transformation matrix from one reference frame to the

other supplies enough information from which to determine both the position and attitude of one reference frame relative to the other. There are a variety of techniques available for determining these matrices. Least-squares techniques (e.g. Spoor and Veldpaus, 1980; Veldpaus *et al.*, 1988) are to be preferred as these make some allowance for the errors arising in marker position estimates. These errors arise due to imperfect photogrammetric models, mistakes made during digitizing and the non-rigidity of the body segment to which the markers are fixed. During sporting movements involving impacts, significant deformation of the assumed rigid body may occur, and the use of a least-squares technique will not account for all of the error arising due to these deformations. Further attempts to quantify marker movement and lack of segment rigidity are required, particularly for sporting movements.

Segmental inertia parameters

Accurate values for the inertia parameters of body segments are needed for many biomechanical analyses. Methods for the determination of these parameters include water immersion for obtaining segment volumes (Plagenhoef *et al.*, 1983), reaction board measurements for mass centre locations (Drillis *et al.*, 1964) and oscillation techniques for moments of inertia (Hatze, 1975). Experimental techniques such as these are time-consuming and are not suitable for obtaining inertia parameters of central segments such as the pelvis. These problems are overcome by a number of techniques which estimate inertia parameters from a set of anthropometric measurements. Some are based directly on cadaver data (e.g. Hinrichs, 1985; Yeadon and Morlock, 1989) and should be viewed with caution, since the age and former health of the few individuals in the cadaver samples makes extrapolation to a live athlete population questionable. Other techniques are based on cadaver data to a smaller extent, such as the density values used in the geometrical solid models of Hatze (1980), Jensen (1978) and Yeadon (1990b). In their review of segmental inertia parameter determination, Reid and Jensen (1990) recommended the use of such mathematical models, although the lack of information on density distributions of both male and female athletes introduces a measure of uncertainty in the estimated values. The current development of techniques such as computer-aided tomography (Huang and Wu, 1976) and magnetic resonance imaging (Martin *et al.*, 1989) may circumvent the reliance on cadaver data or provide a means for evaluating these models.

At sports competitions there may be restricted access to athletes, but the need for individualized segmental parameters remains. In such a situation, segment

lengths may be obtained from the three-dimensional film analysis of the movement and could be supplemented by a small number of perimeter measurements if reasonable correlations can be established with the remaining measurements required as input to an inertia model. There is a need for a method of calculating individualized inertia values from a set of anthropometric measurements which requires minimum intervention time.

Electromyography

There are many methodological problems and considerations associated with obtaining a reliable and quantifiable EMG signal (Hof, 1984; Bigland-Ritchie, 1981). Once a raw EMG signal is obtained, it can be processed in a variety of ways, including use of a linear envelope, rectification and integration, root mean square methods and power spectrum analysis. A comprehensive review of EMG processing techniques was provided by Bas-majian and de Luca (1985). Raw or rectified EMG signals are often normalized to reduce the variability of the signal. Confusingly, the normalization is often performed to different reference values, such as the highest amplitude in maximal isometric contraction or the highest amplitude in the activity examined (Yang and Winter, 1984). No consensus at present exists on how to elicit a maximum voluntary contraction (Clarys and Cabri, 1993).

The most popular procedure is the rectification and integration of the signal over a short time period, as used by Lippold (1952), who suggested that the integrated EMG is linearly proportional to the muscle force for isometric contractions. This relationship has subsequently been supported by Komi (1973) and Hagberg (1979), and by Hof and van den Berg (1981a) for dynamic muscle actions. A linear relationship between force and rectified integrated EMG for isometric actions has been questioned by some researchers, such as Simons and Zuniga (1970) and Rau and Vredenburg (1973), who claimed that the relationship is quadratic. Since the relationship between the EMG signal and muscle force is not clear, particularly for the fast, voluntary movements found in many sporting activities, the role of EMG in sports biomechanics will continue to be limited to the identification of the muscles that are active and those that are inactive for a given movement.

To illustrate the different ways in which EMG signals are processed, two studies are compared. Hof and van den Berg (1981a, b, c, d) band-pass filtered their EMG signals (30–600 Hz), whereas Olney and Winter (1985) used a low-pass filter, with the highest cut-off frequency for the EMG signal for any one of the muscles being 2.8 Hz. To be able to compare EMG signals across studies, consistency is required in EMG signal collec-

tion and processing. A number of recommendations in this respect are provided by Winter *et al.* (1980).

Error analysis

Error analysis is the study and evaluation of uncertainty in measurement (Taylor, 1982). Since any measurement made in biomechanics cannot be free from uncertainty, the likely error associated with the measurement should be quantified before the value can be assessed. After calibration of the measuring device, some unbiased assessment of the accuracy of the measurement system should be performed. Where possible assessment should also be made of the precision of the measurements. For curve-fitting and differentiating routines, the formulae of Lanshammar (1980) can be used to estimate the maximum possible precision of the derivative values. The velocity and acceleration values calculated using numerical differentiation are often used in conjunction with segmental parameters to derive other variables, such as segmental energies and resultant joint moments. It must be appreciated that it is difficult to assess the accuracy of parameters such as those defining the inertial properties of a body segment, but the propagated errors arising from uncertainties in anthropometric measurements can be calculated.

Although it may not always be possible to estimate the accuracy of all parameters and variables, where possible estimates should be made of the uncertainty with which all variables and parameters are determined. Quinn and Mote (1992) examined the forces and moments acting in the leg during skiing. To determine the uncertainties in these variables, they estimated the uncertainties in the experimental measures used to compute these variables, and error propagation formulae (e.g. Holman, 1989) were then used to determine the uncertainties in the forces and moments. Cappozzo (1991) has discussed the influence of many of the errors and uncertainties arising from the procedures and models used in gait analysis. Kadaba *et al.* (1990) assessed the influence of error in the reconstruction of embedded reference frames on the calculation of resultant joint moments during gait. The unique nature of many sporting activities means that errors and uncertainties in the analysis of these activities may be different from those in gait analysis, warranting further analysis of the errors associated with these variables.

Future directions

This section has considered the processing techniques for the major methods of measurement used in sports biomechanics. The analysis of sports often introduces problems which are unique to the biomechanist working in the sport environment, thereby requiring the de-

velopment of novel or ingenious data-processing techniques.

Sports biomechanics would benefit from developments in a number of data-processing areas. These include the development of a portable and accurate three-dimensional camera calibration system, the analysis of algorithms for tracking markers on a link system, the examination of procedures for data smoothing and differentiation (particularly for impacts) and, finally, the development of a simple procedure for determining segmental inertias.

It must be remembered that data collection equipment and data-processing techniques are only able to produce numbers. All too often researchers are ignorant of the underlying technologies and principles and, as a consequence, they are also unaware of the limitations inherent in these hardware systems and software packages. The sports biomechanist should retain a healthy scepticism and not rely on manufacturers' claims or expect automatic algorithms to take appropriate action in all situations.

Experimental studies

As mentioned in the Introduction, both experimental and theoretical approaches are an integral part of scientific method, and although separate sections are devoted to experimental studies and theoretical studies, it should be recognized that this division is traditional rather than fundamental. There is a large body of literature describing the design and analysis of scientific experiments and most sports biomechanists would benefit from reading more widely on this subject (e.g. Finney, 1960; John and Quenouille, 1977; Hicks, 1982; Rothstein, 1985; Maxwell and Delaney, 1990; Cox, 1992).

The experiment

The question that an experiment will aim to answer must be clearly identified. Suppose that technique in high jumping is of interest. The question could take the form: How does the approach in the high jump affect the height jumped? The independent variable is manipulated by the biomechanist to produce the experiment and in this example would be some aspect of the approach, such as *the horizontal speed over the last stride*. The dependent variable describes the outcome of an experiment and in this example would be a measure of the height jumped, such as *the maximum height reached by the mass centre*. The research hypothesis is a statement whose validity the experiment will test. In the present case, the hypothesis could be: *If differing*

approach speeds are used, then the maximum heights reached will differ.

Experimental design

The requirements of a good experiment are that systematic error should be avoided, that precision should be maximized, that the conclusions should have a wide range of applicability, that the experiment should be as simple as possible, and that the uncertainty in the conclusions should be assessable (Cox, 1992).

Systematic error

Statistical tests investigate whether the differences in the mean values of the dependent variable for different conditions can be accounted for by random errors. If the statistical conclusion is that the means are (significantly) different, the issue is whether the difference (in height reached) was a result of the differences in the independent variable (approach speed) or of other factors. In an ideal experiment, the conditions should differ only in the independent variable, and so experiments should be designed to eliminate systematic differences which are considered to be 'threats to internal validity' (Maxwell and Delaney, 1990). Such threats are typically problems where another variable may be responsible for an apparent relationship between dependent and independent variables. Ways of minimizing such problems will be considered under the topic of precision.

Rothstein (1985) identified other threats to internal validity. In the high jumping experiment, examples of these could be: rain during the period of data collection (history), fatigue due to repeated attempts (maturation), awareness of the experiment (Hawthorne effect), inconsistency of the camera framing rate (instrumentation) and missing data values (mortality). Only careful consideration of such threats in the design of an experiment will guard against extraneous factors affecting the result.

Precision

In the high jumping example, an experiment is conducted to determine the variation in the maximum height reached (dependent variable) produced by changes in the approach speed (independent variable). This effect variance may not be detectable if the variation arising from other sources is too great. The measurement system will inevitably introduce errors. If the mass centre of the body is calculated from digitized coordinates of body landmarks, there will be random errors introduced by the resolution of the hardware and the judgements made by the person digitizing. Such error variance needs to be minimized. In the case of manual digitization, for example, inter-operator and

intra-operator measures of reliability can be used to assess and improve performance.

Variation arising from variables not accounted for in the design of the study is known as extraneous variance. Again, if this variation is not controlled sufficiently, the effect that the experiment is investigating may be masked. In the high jumping example, variables such as the angle at which the leg is planted will also affect the height reached.

There are a number of methods of controlling such extraneous variance. The variable could be added as another independent variable. This has the advantage of preserving a wide range of applicability, but will necessitate an increase in the number of trials to ensure adequate numbers in each experimental condition. Alternatively, the variable could be eliminated by selection to ensure that the variation in this variable is small. This may be difficult to achieve with technique variables such as the angle of plant, and even if it is achieved there remains the disadvantage of limiting the generality of the conclusions. The advantage is that the size of the experiment can be kept relatively small. Another possibility is to match subjects with respect to their leg plant angles. One group would use a low approach speed and the other group would use a high approach speed. This might circumvent the problems of variance due to variations in the leg plant angle. The use of two distinct groups can, however, introduce a host of possible variables which may influence the outcome and there are a number of advantages for using repeated measures with the same athlete or group of athletes. In this case, there may be carry-over effects from one condition (low approach speed) to the other (high approach speed). This problem may be overcome by randomizing the order of conditions in the experiment.

The purpose of reducing the extraneous and error variance is to enable the effect variance to be detected. This aim may also be achieved by making conditions as different as possible so that the effect variance is maximized.

Applicability

Once the study has been designed in order to minimize systematic errors and to maximize precision, the external validity of the study must be considered. This is the extent to which the conclusions will have general applications to other settings and populations. The requirements of internal and external validity are in conflict. For internal validity the researcher must impose control of the experimental setting, but this may reduce the range of applicability of the findings. Moore (1951) used plaster casts to restrict the mobility of body segments during twisting somersaults on the trampoline. He found that as more body segments were immobilized, the twisting during contact with the

trampoline bed became greater. The problem with such imposed control is that the environment created may be quite different from that of an unconstrained movement and the results obtained from this artificial situation may reveal little about a free movement. Typically in the initial stages of exploring a topic, emphasis will be given to the control of factors affecting the internal validity of the experiment, whereas in subsequent stages efforts will be made to widen the applicability.

A central concern for external validity is that the sample population used in the study should be representative. Subjects should be selected on this basis rather than using those that are conveniently available. In order to make statements about techniques used by elite athletes in competition, it is necessary to select from this population. The Hawthorne effect that knowledge of participation in an experiment can affect the outcome has been identified previously as a threat to internal validity. Its relevance for external validity is clear, since the subjects may perform differently outside the experimental setting.

Maxwell and Delaney (1990) identified the key principle for protecting against threats to external validity as heteromethod replication. The idea here is that experiments should be replicated but with the procedural details that are deemed theoretically irrelevant being changed. If the findings can be replicated under these varied circumstances, there can be more confidence in the generality of the findings.

Simplicity

In the first stages of an investigation it is important to keep experiments simple, since initial ideas may have to be revised in the light of early results. Complicated experiments tend to be large, time-consuming affairs which may be abandoned rather than completed if a more promising line of enquiry becomes evident. In later stages more complicated experiments may be devised, but it is a matter of judgement and experience to decide how safe it is to go with any particular application (Cox, 1992).

Estimates of uncertainty

In order to make a statement about the differences in the dependent variable arising from two experimental conditions, it is necessary to have a measure such as the standard error of the difference between the means. This allows the limits for the true difference to be calculated at any required level of probability and the statistical significance to be measured. Since conclusions are made on a statistical basis, there is no certainty that the conclusions are correct. The probability that random variation will produce an apparent difference between conditions is known as the level of significance. Concluding falsely that there is a relationship when in fact

there is none constitutes a type I error. The sports biomechanist may restrict this type of error by setting the level of significance more stringently. Doing this will increase the probability of a type II error, whereby it is falsely concluded that there is no relationship. The power of a test is its ability to detect relationships that exist and so is the complement of a type II error. The power of the test will increase with both the sample size and the size of effect produced by the different conditions. Another approach for increasing power is to use a homogeneous population to minimize variability. In *power analysis*, the sample size for a particular power is calculated from the significance level and effect size (Cohen, 1988). DeVita and Bates (1988) calculated standard deviation curves for the vertical reaction force during running and concluded that a sample size of 25 trials was necessary to provide accurate data. Unfortunately, their data indicated that increasing the number of trials from 20 to 25 results in a reduction of the mean value of the standard deviation by a factor of 3. Since this is unlikely for distinct samples on statistical grounds and impossible on mathematical grounds when 5 trials are added to the initial 20 trials, it is clear that such a result must not be accepted at face value.

All too often in sports biomechanics, an arbitrary significance level is selected without any consideration of power and type II error. Bates (1989) cited an example with an estimated power of 0.25, which is equivalent to a probability of 0.75 of making a type II error. The danger of neglecting power considerations is that a false conclusion that there is no relationship may discourage further work in the area. When power is likely to be low for a significance level of 0.05 and when type I and type II errors are of equal importance, it may be more appropriate to select a significance level of 0.2 or 0.3 (Winer, 1971). These issues are discussed in Franks and Huck (1986), who have made recommendations on the selection and reporting of significance levels.

Effect size

As sample size increases, so does the power of a statistical test and it becomes possible to detect smaller and smaller differences between two conditions. Since it may be argued that there will always be some difference between two conditions (Bakan, 1966), whether a difference is found to be significant or not is purely a matter of sample size. Cohen (1990) suggested that the primary purpose of research should be to measure effect size rather than level of significance. A large effect size which is not statistically significant may lead to further research, whereas a failure to report effect size may discourage further research. Indeed, the question is really not one of 'Has an effect occurred?', but rather 'Is the effect of any importance?' Thomas *et al.* (1991)

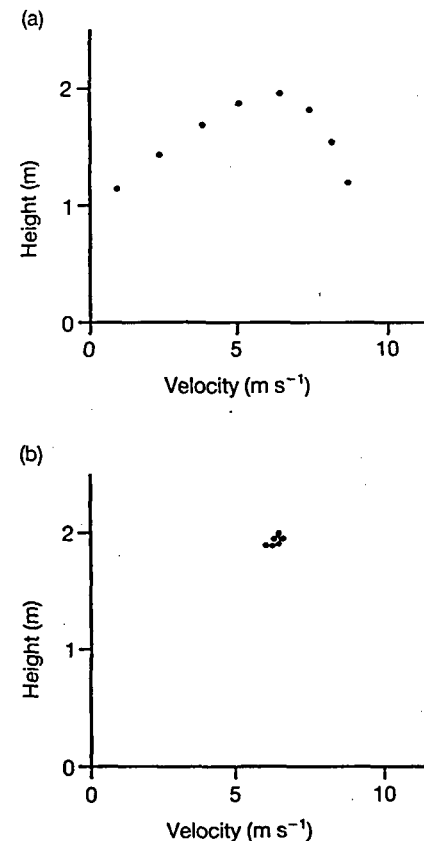


Figure 4 (a) Theoretical data set showing maximum height reached by the mass centre for different approach speeds of one high jumper; (b) actual data set for six jumps by one competitor at the WAAA Championships in 1991.

made a case for presenting sufficient information in research papers to enable the effect size to be calculated. In sports biomechanics sample sizes are often limited, since manual digitizing, for example, is a time-consuming process. As a result, it is important to present sufficient information for the reader to evaluate how meaningful the results are.

Inter- and intra-individual results

Consider high jumping as an example. The data on 12 jumps by Dwight Stones presented by Nigg (1974) suggests that for an individual the relationship between approach velocity and height reached by the centre of mass might be as shown in Fig. 4a. This figure depicts an optimum approach velocity, such that velocities smaller or larger result in less than maximum height. In competition, the range of approach velocities will be much smaller than that shown in Fig. 4a. Figure 4b shows the results for six jumps by one competitor at the WAAA National Championships in 1991. The results are not inconsistent with the idealized Fig. 4a, but could not be interpreted as a clear relationship between

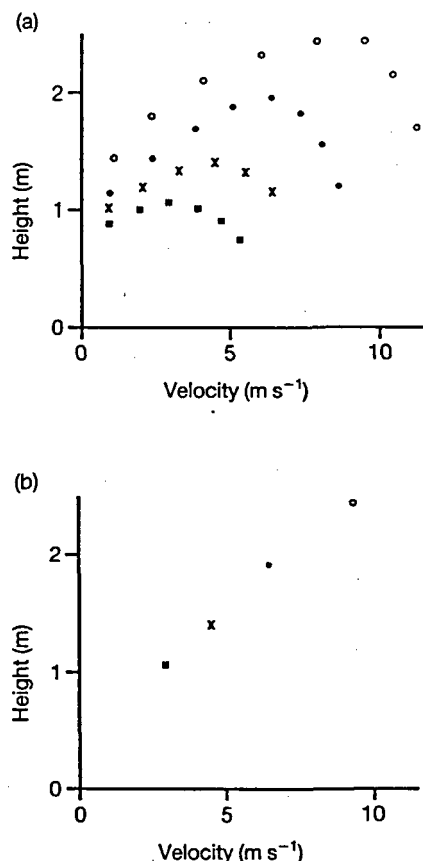


Figure 5 (a) Theoretical data set showing maximum height reached by the mass centre for different approach speeds of four high jumpers; (b) the best jump by each athlete in (a).

velocity and height. One reason is that the range of approach velocities is relatively small. Another is that if an athlete approaches at around his or her optimum velocity, the resulting velocity–height graph will have little slope or curvature and it will take little variation to produce a random looking plot such as Fig. 4b.

Figure 5a shows individual relationships between velocity and height for a number of hypothetical jumpers. Each athlete has a different optimum approach velocity and a different maximum height. If the best jump of each athlete is selected, the relationship between velocity and height reached will be as shown in Fig. 5b. Thus the answer to the question ‘What is the relationship between approach velocity and height reached in high jumping?’, depends very much upon how the question is interpreted. The intra-individual (within-subject) variation of height with speed is given in Fig. 4a, while the inter-individual (between-subjects) variation is given in Fig. 5b. The differences between inter- and intra-individual studies are discussed in Hay (1985).

Dapena *et al.* (1990) were able to use the best available trial for each of 77 elite high jumpers in an inter-individual study in such a way that advice could be given for diagnosing individual technique shortcomings.

They concluded that the method would not always give the correct advice, but may suggest technique changes which the coach could test out on the individual athlete. An intra-individual study might be expected to give more information on a particular individual.

Hypothesis testing

The two most common statistical tests used in sports biomechanics are the *t*-test and the *F*-test, which are used for contrasting the means of two or more groups and for assessing the correlation between two or more variables. Both of these tests are based on a number of assumptions regarding the sample populations and these assumptions may not hold for the data obtained in a particular study. The assumptions are that the distributions from which samples are taken are normal, the variances of the distributions are equal, and that the scores used in the test have independent errors. Boneau (1960) investigated the effects of violating these assumptions using computer-generated pseudo-random numbers as data. He found that, for equal sample sizes from distributions of the same shape, the *t*-test was remarkably robust in the sense that the actual type I error rate was close to the nominal value, even for samples as small as five, when the assumptions of normality and equal variance did not hold. When sample sizes were not equal, however, violations of the equal variance assumption produced type I error rates markedly different from the nominal value. The effect of a higher type I error rate than expected is to increase type I error, whereas a lower type I error rate will lower the power of the test. For distributions of different shapes, the *t*-test was robust to violations of equal variance (and normality) providing sample sizes were equal and greater than 25.

Maxwell and Delaney (1990) discuss the robustness of the *F*-test. The *F*-test is generally robust to violations of the normality assumption and to moderate violations of the equal variance requirement providing sample sizes are equal and are at least five. For unequal sample sizes, however, even moderate differences in variance can produce actual type I error rates considerably different from the nominal value. The *F*-test is not robust to violations of error independence. For repeated-measures designs in which the same group of subjects is exposed to different conditions, the scores will be correlated and other procedures must be used.

Hypothesis testing is a weak aspect of sports biomechanics, which stems from a general ignorance of the techniques and their underlying assumptions. It is hoped that this brief discussion will stimulate the consideration of such issues in preference to the indiscriminate use of statistical packages.

Linear regression

The widespread availability of computer packages has greatly facilitated the calculation of linear regression equations. Sadly, this has often replaced the required thought that should have been brought to bear upon the analysis. At the very least, the data should be examined to see if a linear relationship is the most appropriate one to consider. In many circumstances, simple mechanical considerations may suggest that a non-linear relationship is to be expected. In such circumstances, a transformation of variables should be performed prior to using linear regression. An *ad-hoc* method for quantifying the best fit polynomial is given in Hayes (1970). Hubbard (1989) noted that research studies of throwing events have generally used linear regression equations to express range as a function of release velocity. Such indiscriminate selection demonstrates a lack of understanding of basic mechanics, since it is a simple matter to show that range is quadratic in velocity if air resistance is neglected.

It is important to note that the closeness with which an equation fits a data set is not a measure of goodness of fit. Increasing the number of variables in an equation will produce a closer fit to the particular data set from which the coefficients are calculated, but this will result in a poorer fit to an independent data set if too many variables are used. It may be appropriate to reduce the number of undetermined coefficients by forcing the regression line to pass through the origin if there are good reasons for expecting it to do so. It is recommended that an independent data set be used for evaluating goodness of fit and that at the very least an unbiased error estimate is used taking into account the number of degrees of freedom (Carnahan *et al.*, 1969).

Hay (1987) warned against using several trials of several athletes to compensate for a small number of subjects. The determination of the level of significance of the correlation coefficient is dependent upon the relative values for the variation within subjects and the variation between subjects. In such an experiment, the results would also reflect both the individual and group relationships and may reveal no overall relationship at all if no distinction is made between individuals (Fig. 5a). All data points should have the same level of independence unless some calculation is made for within and between factors. There are two groups of tests that can be used for this purpose – BLUP (Best Linear Unbiased Prediction) and REML (Residual Maximum Likelihood), described in Robinson (1991) and Robinson (1987), respectively.

Scheirman *et al.* (1988) reported that 9 out of 48 variables were found to be 'significantly correlated to long jump distance at the 0.05 level'. When more than one correlation is considered, the individual significance

level must be adjusted appropriately if the overall level is to be 0.05. Failure to do this will increase the type I error considerably. Extreme examples of this type report the expected number of random correlations as 'significant' (Williams *et al.*, 1988). The occasions when the individual significance level is given some thought (e.g. Takei *et al.*, 1992) are still rare. Regressions should only be used if there is a theory predicting that there should be a (directional) correlation between the variables.

Hierarchical modelling

Rather than correlating all available variables, a choice can usually be made on more rational grounds. The deterministic model, described in Hay and Reid (1982), uses a hierarchical structure to express the results of a performance in terms of a number of factors, each of which is further decomposed into factors. Figure 6 is an example of a hierarchical diagram for the triple jump given by Hay and Miller (1985). Each of the factors has a lower level of factors that should account for most of the variance in that factor. The use of such a model can help to ensure that all relevant factors are considered and that those selected for analysis are not logically dependent. This will help avoid the correlation of the performance criterion with a number of factors which are themselves highly correlated.

Information content of biomechanical data

There have been occasions when statistics were used in a novel way to analyse athletic performance. Lee *et al.* (1982) looked at the variation in foot placement during successive long jump approaches in order to determine the point at which the athlete started to modify stride length in order to hit the take-off board. They found that the variance in the distance from foot contact to the take-off board steadily increased until the athletes were about 6 m from the take-off board. From this point the variance decreased as the athletes adjusted their stride length, presumably on the basis of visual feedback of their location relative to the board. Hay (1988) used the same procedure and found that the maximum variance in foot placement for 19 long jumpers occurred from the 2nd last to the 9th last foot contacts with a mode at the 6th last foot contact. Such information provides a better understanding of the techniques used by athletes and subject-specific information of this type may be most useful in making adjustments in training.

Biofeedback

Biomechanical information can be provided as real-time feedback to athletes with a view to improving performance. Atha *et al.* (1985) used a device strapped to a swimmer to monitor velocity and acceleration and to

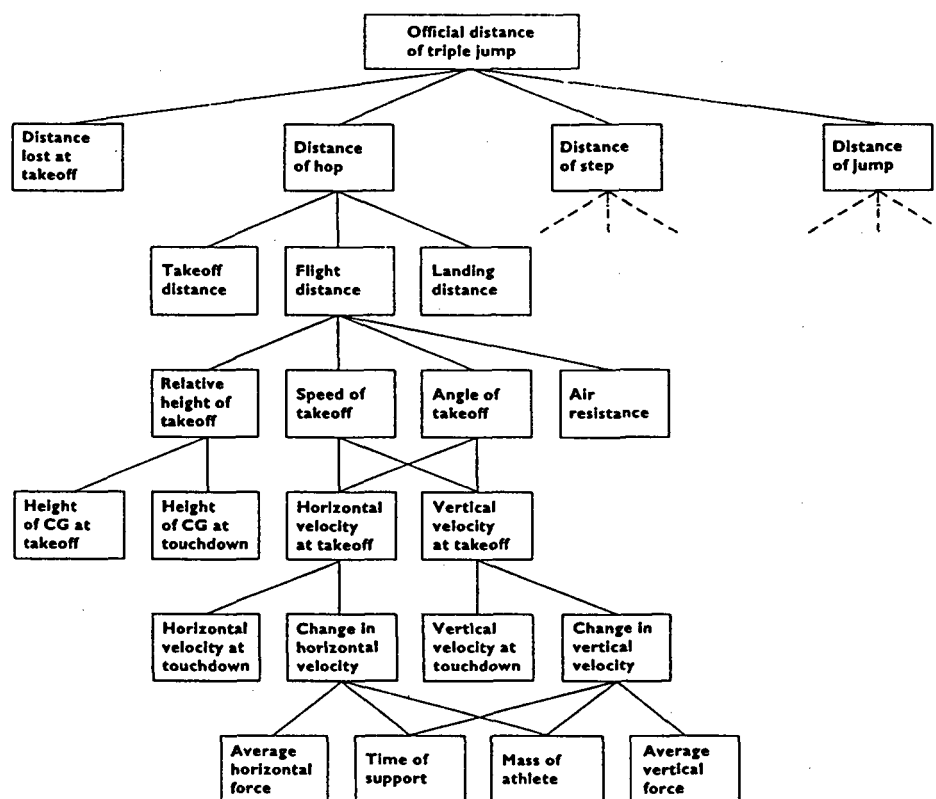


Figure 6 A hierarchical model for the triple jump (adapted from Hay and Miller, 1985).

convert these measurements into real-time auditory feedback signals to the swimmer. In general, the swimmers found that a compound signal containing both velocity and acceleration information was more useful than velocity information alone. Bauer (1991) designed an eight-seat rowing ergometer which simulated roll and propulsion feedback so that members of the team would feel the effect of the contributions of the other team members. It was found to be useful for the off-season training of high-performance rowers. Huffman *et al.* (1993) used a bobsled simulator which responded to steering input to give real-time simulation of a particular bobsled run. This simulator has been used by the USA team as an alternative to travelling to actual bobsled runs. There is great scope for research into identifying the feedback mechanisms that are used by athletes and evaluating the use of supplementary real-time feedback signals.

Future directions

It may be said that the majority of research into sports biomechanics has taken the form of descriptive studies

rather than investigations designed to answer specific questions. As indicated in the Introduction, a descriptive study is often a useful first step in the process of scientific investigation, which should lead to more carefully designed experiments. Many of the studies that can properly be described as experimental often have not made appropriate use of available knowledge of mechanics, suitable experimental design, correct statistical procedures and, as a consequence, have been limited in the contribution they have made. In order for progress to be made in this area, sports biomechanists should endeavour to gain a better understanding of experimental research design and statistical analysis.

Although there are difficulties inherent in undertaking experimental studies (such as the problem of obtaining sufficiently large data sets), the acquisition and analysis of real data will always be an integral part of research in sports biomechanics. The number of trials analysed in many studies has been limited by the necessity to digitize the film records manually. The advent of automatic motion analysis systems should permit this problem to be overcome in the future. Since there are inherent limitations in a purely experimental

approach, it should be a priority to incorporate a theoretical element into research studies in the form of a mechanically based mathematical model, as discussed in the next section.

Theoretical studies

As discussed in the Introduction, an essential element of scientific method is a theory or model that can be used to make predictions about the behaviour of the system under consideration. The model can then be evaluated by comparing these predictions with appropriate experimental data. In sports biomechanics, the motions of the mechanical systems studied are governed by Newton's laws of motion and so most models are mathematical formulations of Newtonian systems. Biomechanical models may be used to give *forward dynamics* analyses or *inverse dynamics* analyses (Zajac, 1993). In a forward dynamics analysis or simulation, the typical input consists of the forces acting on the system and the output is the resulting motion. In an inverse dynamics analysis, the kinematic data describing the motion are used as input and the model is used to calculate the applied forces or net joint moments. Inverse dynamics is useful for gaining an understanding of sports injuries, whereas simulations are prevalent in theoretical studies of sports performance and will form the focus of this section. Vaughan (1984) reviewed simulation modelling in a wide range of sporting activities.

Equipment simulations

Rather than modelling the human participant, some studies have chosen to model the motion of the sports equipment. This has the advantage that a simple model may be used. Hubbard and Rust (1984) modelled the javelin as an aerodynamic rigid body and simulated the flight. They found that the trajectory was extremely sensitive to the initial pitching angular velocity and speculated that it was this sensitivity that caused the large variability that occurs in javelin performance. Subsequently, Hubbard and Alaways (1989) developed a method of determining the initial release conditions from an actual throw using an automatic data acquisition system. This system enabled feedback to be given to an athlete within 2 min of a throw, indicating the characteristics of the throw and what modifications should be made for increased performance. The effects of javelin vibrations on the flight phase were determined by Hubbard and Bergman (1989) using simulations with the javelin modelled as an aerodynamic elastic beam. It

was found that both lift and drag forces were greatly increased by the vibrations, suggesting that a vibrating model was needed for accurate representations of javelin flight.

This example shows that a system which appears relatively simple to model at first sight may require much more complex modelling in order to provide accurate estimates of performance. As noted by Hubbard (1989), the aerodynamic 'data' of Terauds (1985), on which the model of Hubbard and Alaways (1989) was based, were not measured in wind tunnel experiments as suggested by the heading 'Javelin Aerodynamic Test' but were merely estimates based on observations of Javagun throws (Bartlett and Best, 1988). Although Hubbard (1989) thought that these estimates were probably not too inaccurate, the wind tunnel results of Best and Bartlett (1988a) indicated otherwise. The aerodynamic data of Terauds (1972) were obtained in a wind tunnel operating at three times the release speed of a world class javelin throw. Bartlett and Best (1988) identified large errors in these data as being partly responsible for the optimal range calculation of Hubbard (1984) being some 20 m greater than actually achieved. Additionally, a javelin model may neglect some element, such as the spin about the longitudinal axis, or errors in the estimation of the release parameters may lead to large errors in the simulated range (Best and Bartlett, 1988b). This underlines the need for an evaluation of the accuracy of the model before too much credence can be given to the conclusions obtained from theoretical simulations. The important issue of model evaluation will be considered in more detail in a subsequent subsection.

One danger likely to occur when concentrating efforts on modelling the equipment rather than the athlete is to neglect the dependence of the initial conditions on the athlete. In the javelin example, it is tempting to assume that the maximum speed an athlete can deliver a javelin is independent of the direction. To suppose otherwise would require knowledge of the athlete's capabilities rather than the relatively well-defined properties of the equipment. In determining optimal javelin trajectories, Hubbard (1984) incorporated such a constraint into his analysis using the experimentally determined relationship between release velocity and release angle obtained by Red and Zogaib (1977) for throwing a metal ball. Without this constraint, the optimal release angle for a javelin would be 30° rather than 42°. Since the introduction of this constraint changes the optimum release angle dramatically, it is important that the constraint equation should be an accurate representation of the relationship between release velocity and release angle. It would be an improvement, therefore, if such constraint information was to be based on throws of a javelin rather than a metal ball.

Human body models

Simple models have also been used to represent athletes. Hubbard and Trinkle (1985) modelled a high jumper as a rigid rod moving in a vertical plane. They assumed that the kinetic energy of the body during the approach may be arbitrarily redistributed during the take-off into energies associated with horizontal and vertical movement, and rotations. It was found that an optimal trajectory always consists of two brushes with the bar, near but not at the centre of the rod. In actual performances of Fosbury flops, the body is arched rather than straight and changes configuration during the flight over the bar so that the rigid rod model is clearly an oversimplification. Additionally, the assumption that a fixed amount of energy may be distributed between linear and rotational movements is unsubstantiated and so the relevance of the theoretical results to practice remains uncertain.

Eaves (1969) and Page (1974) modelled the body as a rigid rod in order to calculate the angular velocity a diver can obtain through toppling. They found that the angular velocity increased by a factor of four or more as contact was lost. Wilson (1977) correctly identified their error as a misuse of the principle of angular momentum conservation, since different axes were used before and after the moment of take-off. This example shows that mistakes are possible, even with very simple models, if the mechanics formulation is not well understood.

Alexander (1992) expressed concern that because the human body is complex, biomechanists often try to reproduce as much of this complexity as possible in the belief that more is better. Hubbard (1993) observed that the most fundamental understanding often comes from the simplest models. One advantage of a simple model is that it is sometimes possible to obtain analytical solutions (e.g. Yeadon, 1993a) and this can provide a general overview of all possible motions that is difficult to achieve when only numerical solutions are available. The weaknesses of a simple model are that the area of applicability may be unduly restrictive, important features may be omitted and the accuracy of the model may be poor. It should be realized that a complex model can simulate a simple model by the use of suitable constraints so that simplicity can be viewed as a property of the simulation design rather than the model itself.

Pike (1980) used a five-segment computer simulation model to show that it is theoretically possible to produce a full twist in a plain dive by means of asymmetrical arm movements. The advantage of using such a model is that it is possible to try out different hypothetical arm movements with confidence that the model will make the required changes and no others. This is in contrast to the problems of experimentation with real divers who may make additional changes to those requested. The

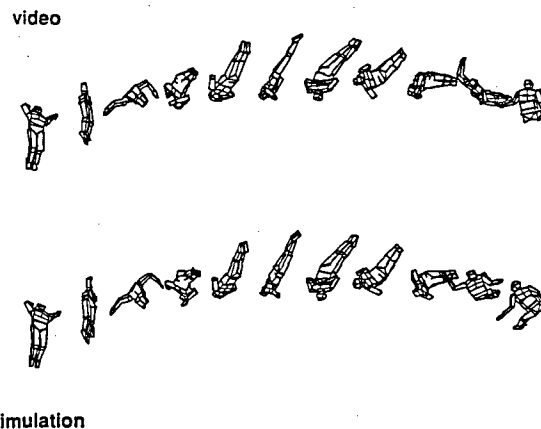


Figure 7 Evaluation of the accuracy of a simulation.

weakness of such a model is that the level of accuracy of the model is unknown and it may be that the model is inappropriate in some way or that an error has been made in computer coding.

Model evaluation

In order to overcome this shortcoming, van Gheluwe (1981) evaluated the accuracy of his six-segment computer simulation model of aerial movement using film data as input. He found that in three performances of backward somersaults with full twist from trampoline, the differences between simulation and film were less than 5% for somersault angles and less than 10% for twist angles. The angles describing body configuration were modified so as to keep the arms in a fixed position during flight. The corresponding simulations showed that little twist occurred under this condition. It was concluded that the twist was a result of the arm movements made during the aerial phase.

The method of van Gheluwe (1981) was extended by Yeadon *et al.* (1990), who used an 11-segment model to simulate aerial movement. Figure 7 compares the output of the simulation of a $2\frac{1}{2}$ twisting $1\frac{1}{2}$ somersault dive with a graphics sequence obtained from video data. It can be seen that, although the simulation closely follows the video sequence in the first part of the movement, the agreement eventually deteriorates. Beyond a certain point the simulation may lose touch with reality completely. For twisting somersaults this happens when the twist error reaches one-quarter of a revolution, since corrective movements in the final phase of the movement will not produce the same effect in the simulation

as they did in the actual movement. It is important to be aware of the accuracy limitations in a simulation in order that the results may be interpreted sensibly.

The use of models to simulate aerial movement have the advantage that in many cases air resistance may be safely neglected so that the only external force in the model is that of gravity. Additionally, it has been shown that it is not of advantage to make configurational changes as quickly as possible in twisting somersaults (Yeadon, 1993b, c). As a consequence, the limits to the speed with which the limbs can move are not of great importance in the search for the best twisting techniques.

Models with muscles

The simulation of movements where large forces are exerted on the body due to contact with the external world presents much greater problems. Not only are the equations of motion more complicated because external forces are involved, but it is also necessary to model the forces that can be exerted by the athlete. This requires the modelling of the muscles in order to produce insight into the system.

Alexander (1990) used a deceptively simple model of jumping comprising a thigh and shank with a single knee extensor muscle. This model was applied to the high jump and the long jump and was able to account for the relatively low approach velocities required for an optimum high jump take-off. While probably too simple in its present form to be of great use in the analysis of competitive performances, this model does show the operation of the mechanics of high jump technique and its dependence upon the properties of skeletal muscle.

Three models of throwing, each using two muscles, were used by Alexander (1991) to determine the optimum timing of the sequential contraction of muscles in different types of throwing. It was found that in each case there is an optimum delay, between activation of the more proximal muscle and the more distal one, that maximizes the speed at which the missile leaves the hand. It is not difficult to envisage further development of such modelling which could be applied to shot putting and baseball throwing. In order to model a cyclist, Yoshihuku and Herzog (1990) used five segments and seven muscle groups to represent the leg. The bicycle-rider parameters of crank length, pelvic inclination, seat height and pedalling rate were systematically varied until the muscles were able to produce their maximum power output. Although the model did not have a foot and therefore could not produce power with the calf muscles, the simulation produced reasonable results. A more sophisticated model of cycling in which the ankle pattern is optimized has been developed by van den Bogert and van Soest (1993).

These examples indicate the kinds of problems which can be tackled using models incorporating muscle. There are various levels of sophistication in the models described. These models vary in how the muscles crossing a joint are modelled and in the complexity of the model of the force-producing capabilities of the muscles. Alexander (1990, 1991) represented the muscles crossing a joint by a single muscle, the action of which was considered to be equivalent to that of all the muscles crossing a joint. In contrast, the model of Yoshihuku and Herzog (1990) had five muscles modelled for the knee joint.

The representations of the force-producing capabilities of the muscles are normally based on the model of Hill (1938), which can be conceptualized as a mechanical analogue of muscle. More recently, a number of Hill-like models have been developed with varying degrees of sophistication (Winters, 1990). In biomechanics applications, it is normally this type of muscle model which is used rather than the more complex type used by Huxley (1957).

These models vary in the number of components they contain. The muscle model of Yoshihuku and Herzog (1990) had a contractile component, where the force output of this component was dependent on the length and velocity of the muscle. The muscle model of Alexander (1990) consisted of an elastic component in series with a contractile component, the force produced by the latter component being dependent on the velocity of contraction only. Alexander (1991) extended this muscle model to account for the influence of the length of the contractile component on the force output of the muscles. Van den Bogert and van Soest (1993) modelled each muscle as a contractile component together with a parallel elastic element and a series elastic element. The activation dynamics of a muscle were modelled using an additional differential equation to account for time delays between activation and force. All of these models assumed that the control of the muscles was bang-bang, the muscles being considered to be either maximally active or producing no force, with the transition between the two states being immediate.

The disadvantage of bang-bang control is that in a real human the control is not bang-bang. This raises the issue of increasing model complexity when it may not be required. For the dynamic activities examined above, finer control is probably not required, but for less dynamic movements graded control could be essential. The advantage of bang-bang control is that it minimizes the number of parameters needed to describe muscle activation and hence reduces the computing time required for an optimization. The evaluations of these models incorporating bang-bang control are fairly successful (e.g. van Soest *et al.*, 1993), and so this type of control is a useful model simplification. With the future

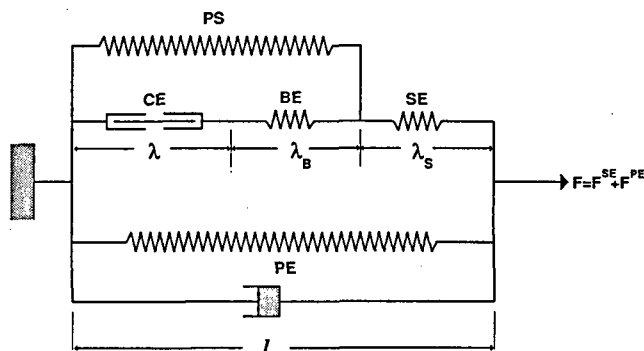


Figure 8 A model of muscle (adapted from Hatze, 1983). PS, parallel sarcomere elasticity; CE, contractile element; BE, cross-bridge elasticity; SE, series elasticity; PE, parallel elasticity; F , force output.

availability of increased computing power, it can be anticipated that graded control will be investigated as the demands on the computer will not be so prohibitive (Anderson *et al.*, 1993).

The muscle model of Hatze (1983) is more complex than those just described, as it has six elements (Fig. 8) and the force output of the contractile component is dependent on its length, velocity, and the previous and current activation of the muscle.

The human body model of Hatze (1981b) included 46 muscle groups and required neural control time histories as input variables. It was used to simulate a long jump performance by adjusting the control input until the required trajectory was produced. The ground reaction forces calculated by the simulation model were in good agreement with measured values, although the body configurations during take-off do not appear to be characteristic of a long jump. Since the model requires a very large number of parameters and inputs to be specified, there is an increased possibility of mimicking any given movement. As a consequence, a more thorough evaluation is needed involving comparison of all kinematic variables with actual data. It can be seen that it is difficult to evaluate the accuracy of models of extreme complexity, since the input is often unknown and it is insufficient to demonstrate that there exists some input for which some of the model output approaches reality.

Ideally muscles should be modelled with the simplest valid model, with as few parameters describing the model as possible. These parameters must be measurable using reasonable tests on the experimental subjects. The development of a sufficiently detailed model which can be shown to be an accurate and a usable representation of an athletic movement is not an easy task. In this area of research, in addition to accurate modelling, procedures are required for determining muscle model parameters *in vivo* (e.g. Wagmans *et al.*, 1990; Challis

and Kerwin, 1991), although some reliance on morphological data must be expected.

Multi-body dynamics

There are a number of packages which permit the automation of the simulation process (Schiehlen, 1990). Hubbard *et al.* (1989) automatically generated the equations of motion describing a ski jumper in flight using the symbolic manipulation package Macsyma. Other packages specifically generate a computer source code for simulating a user-specified system of rigid and elastic bodies (e.g. AUTOLEV; Schaehter and Levinson, 1988). Indeed, some of the packages will guide the user in the definition of the problem and provide most of the tools for the simulation (e.g. DADS; van den Bogert *et al.*, 1989). Such simulation packages can reduce the complexity of producing a model, but cannot help with the selection of the structure of the model.

Optimization

Since a simulation model may be used to determine the outcome of a given set of conditions, it is possible to investigate the conditions that will result in the best performance. Alexander (1990) determined the approach velocity and leg plant angle that maximized the height reached by the mass centre in high jumping. In this example, the approach velocity and plant angle are initial conditions which are constants or parameters of a simulation. With only two parameters, it is feasible to consider simulations over a range of values in each parameter and produce contour maps of height as a function of velocity and angle. This has the advantage of providing an overview of the solution space as well as locating an optimum. With more parameters the number of simulations required for a global view increases dramatically (Hubbard, 1984), and mathematical techniques are used to locate an optimum solution (Gill *et al.*, 1981). Such optimization methods typically iterate to a solution by using a gradient estimate to move 'uphill' at each step. The problem with numerical algorithms is that the solution obtained may not be a global optimum, merely the peak of a neighbouring foothill. It is necessary, therefore, to start the optimization from several different points to see if there are other local optima.

Since biomechanical structure and function have been optimized through evolution (Alexander, 1993), it would be fitting if similar methods could be used to determine optimum technique. Box (1957) used an evolutionary method based on the ideas of variation and natural selection to optimize industrial processes with some success. In such genetic algorithms, pseudo-random numbers are used to generate offspring which

die or survive according to their performance (Davis, 1987). The advantages of genetic algorithms are that they are robust, are intrinsically suited to parallel processing and can be applied to optimal control problems (Michalewicz *et al.*, 1992).

The determination of optimum muscle timing in throwing (Alexander, 1991) and jumping (van Soest *et al.*, 1993) requires the determination of control time histories rather than parameter values to produce maximum velocity. Such problems are usually simplified by restricting the form of such time histories so that they may be described using only a few parameters. In general, dynamic optimization techniques are required as in the muscular control required for optimal ski jumping (Hubbard *et al.*, 1989).

Sensitivity analysis

When an optimum is found using a simulation model, there is always some uncertainty associated with the values given to the model parameters not included in the optimization procedure. An investigation of the effect that such uncertainties have on a calculated optimum is known as a sensitivity analysis (Wilde and Beightler, 1967). Alexander (1990) showed that the optimum techniques for high and long jumps predicted by his simple model were remarkably insensitive to the values assigned to the muscle parameters. As a consequence, he was able to have some confidence in the ability of the model to account for differences in high jump and long jump technique, despite the fact that the model had not been evaluated.

The sensitivity of a performance measure to perturbations in the parameter values which produce an optimum also provides important information. If performance is not particularly sensitive to such perturbations, it means that techniques close to the optimum technique will still produce good performances. On the other hand, extreme sensitivity implies that very small deviations from optimum technique will result in performances that are appreciably less than optimum. In this case, achievement of the optimum is beyond the control of the athlete and will occur only rarely as a chance occurrence.

In general, sensitivity analyses are conspicuous by their absence from most simulation studies, as are the much needed simulation model evaluations. Without them little confidence should be placed in the results of simulation studies, particularly where optimum techniques are determined.

Future directions

The majority of models used in sports biomechanics suffer from a tendency to be divorced from the real

world. While computer simulation has enormous potential in the future development of sports biomechanics, this will only be realized if it is used in conjunction with data obtained from recordings of athletic movement. These data are needed to ensure that the model has sufficient accuracy and to provide realistic input data on which to base simulation analyses. Simulation packages, such as AUTOLEV and DADS, can reduce the complexity of producing a model, but cannot help with the selection of the structure of the model.

Although theoretical muscle models have been developed, the application to sports movements has been rather limited. In order that such application can be made, it will be necessary to establish the most appropriate type of muscle model for sports movements. For example, it may be more effective to use a torque-based model, the output of which is a function of the joint angle and angular velocity, rather than attempting to model the individual muscles crossing a joint. Additionally, the ability to obtain accurate individualized muscle parameters will have implications for the approach that should be taken.

The development of a whole body muscle-based computer simulation model, which may be customized to an individual, will permit the optimization of athletic performance. This will lead to specific applied research projects in a number of sports for the improvement of technique.

Summary

The primary methods of data collection in sports biomechanics have been identified as force measurement and film analysis. In the future, it may be expected that increasing use will be made of pressure measuring devices to obtain forces and force distributions between foot and footwear or hands and sports equipment. Video recordings are likely to be used in preference to 16 mm filming due to the advantages of loading, portability, costs and time. Once high-definition video comes into use, this medium may surpass film for the quality of data that can be obtained. Until such a time, care should be taken in research studies that accuracy is not sacrificed for the sake of convenience.

In data processing, the use of three-dimensional filming techniques has increased greatly in the past 10 years and is now the norm rather than the exception. Although much has already been done, there is still a need for the development of a simple but accurate procedure for calibrating large volumes of movement space. While there are a number of automatic systems commercially available, none appears to be capable of tracking many markers during a complex whole body movement. The development of a tracking procedure

which incorporates the constraints of a link system model will enable the application of these systems to sports movements. In the longer term, the recognition of body segments from video images should permit automatic three-dimensional reconstruction without the need for body markers.

The numerical differentiation of noisy data using cross-validated splines is a great improvement over earlier techniques, but is subject to the vagaries of automatic routines and there still remains a need for realistic error estimates of the derivatives obtained. While a number of models for obtaining personalized segmental inertial parameters have been developed, the majority of studies have failed to take advantage of these. The constraints imposed by time and athlete availability require that such methods are streamlined to enable individualized data to be obtained with a minimum of intervention. Thus there is a need for innovative developments in three-dimensional analysis, automatic tracking systems, data smoothing and differentiation routines, and segmental inertia models.

The problems associated with experimental and data-based studies have been identified as those of control, experimental design, small samples, choice of variables and statistical analysis. Although the literature abounds with studies in sports biomechanics, the vast majority have been limited by being descriptive in nature. In the Introduction, questions of the form *What? How? and Why?* were posed. Descriptive studies have been able to answer *What?* and some experimental studies have been able to answer *How?*, but few begin to tackle the question *Why?* Experimental studies are most profitable when they are combined with a theoretical approach.

The strength of the theoretical approach is that it is ideally suited to answering *How should it be done?* rather than *How is it done?*, and is also capable of providing insights into *Why does it work?* The weakness of a purely theoretical study needs to be avoided by evaluating models in the areas where they are to be applied and basing simulations on modifications to data acquired in the relevant environment (e.g. at competitions). Theoretical studies are most profitable when they are combined with an experimental approach. Although theoretical muscle models have been developed, their application to sport has been rather limited. In order for such application to be made, it will be necessary to establish the most appropriate type of muscle model and methods of parameter determination for sports movements.

The development of a whole body muscle-based computer simulation model which may be customized to an individual will permit the optimization of athletic performance. This will lead to specific applied research projects in a number of sports for the improvement of

technique. The advent of software packages for the development of mechanical models has opened the area of simulation to a much wider population. It may be anticipated that future advances in sports biomechanics research will stem from the application of whole body models to sports movements. There is a need to incorporate the advances that have been made in muscle modelling into such whole body models in a form which permits the majority of parameter estimations to be made from the analysis of the sports movements themselves.

Areas of fundamental research and development have been identified in data collection, data processing and research design. Applied research in sports biomechanics seeks to gain an understanding of performance in specific sports movements. Such an understanding may be used to improve performance by introducing modifications to technique or training. Success is likely to come more easily in those sports which are primarily biomechanical rather than physiological in nature. Sports in which dynamic strength and skill are needed, for example gymnastics and athletic field events, are well suited to the biomechanical analysis of technique, whereas endurance sports, such as marathon running, are more intractable to biomechanical investigations of technique. Sports such as swimming and speed skating require both technique and endurance. Although swimming may be considered a difficult activity to model realistically, in his review of biomechanics research in swimming, Martin (1989) concluded: 'Perhaps the greatest opportunity for a significant contribution to the biomechanics of swimming is in the development of a segmented analytical model which incorporates lift as a propulsive mechanism and has arms with multiple articulations.' The application of models which can be shown to accurately estimate the power expenditure and mechanical power production in sports with a strong physiological component will extend the range of sports to which biomechanics research can provide important insights.

One additional aspect that is a priority is that of innovation. Rather than merely repeating the methods and procedures used by other investigators in a different area of application, researchers should be encouraged to seek radical and new approaches if significant progress is to be made.

Acknowledgements

The support of the Sports Council in the preparation of this article is gratefully acknowledged, as is that of the members of the British Association of Sports Sciences Biomechanics Steering Group: Mike Lindsay (Chairperson), Professor Roger Bartlett, David Kerwin and Adrian Lees. The very

helpful comments of Russell Best, especially on the 'Experimental studies' section, are also acknowledged and have generally been incorporated.

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