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Advances in the application of information technology to sport performance

DARIO G. LIEBERMANN,[1] LARRY KATZ,[2] MIKE D. HUGHES,[3] ROGER M. BARTLETT,[4] JIM McCLEMENTS[5] and IAN M. FRANKS[6]*

Abstract

This paper overviews the diverse information technologies that are used to provide athletes with relevant feedback. Examples taken from various sports are used to illustrate selected applications of technology-based feedback. Several feedback systems are discussed, including vision, audition and proprioception. Each technology described here is based on the assumption that feedback would eventually enhance skill acquisition and sport performance and, as such, its usefulness to athletes and coaches in training is critically evaluated.

Keywords: feedback, information technology, skill acquisition, sport, training.

Introduction

It is well documented that when feedback is provided in an appropriate manner, motor skill acquisition improves significantly (see Schmidt and Lee, 1999, for a review). Consequently, feedback is a major factor in the improvement of sport skill performance. Recently, advances in information technology have made it possible to augment and improve the feedback athletes receive during training and competition. Moreover, modern technology has had such a profound impact on sport that many athletes and coaches now consider information derived from technological advances to be invaluable. This might be related to the concept of feedback that originated in mechanical control theory. In accordance with such engineering models, close-loop systems were designed to keep homeostasis or equilibrium around a reference value, which, in turn, would allow the work of a main actuator (Shannon and Weaver, 1949). Deviations from the steady-state reference were coded as error, which would then drive the system to compensate or correct. That is, in movement science, feedback information about movement was generally expected to allow systematic corrections in the performance. However, feedback will be relevant to the human learner if, and only if, the individual knows the performance goal and perceives the need to carry out corrections relative to some expected outcome. Under such assumptions, a coach should strive to provide an environment that is conducive to optimum learning by augmenting the feedback that athletes receive. Feedback should thus enable athletes to modify their movements and produce optimum performance.

In this paper, we provide several sport examples of how performance feedback can be augmented by the use of modern technology. The examples are discussed and further used to bridge the theory of motor skill acquisition and the practice of coaching. Our main goal is to describe and evaluate technological advances applied to sports that could be potentially useful, provided they are based on an appropriate exploitation of the sensory and cognitive feedback resources available to the performer. However, it should be realized that this paper is not intended to be a comprehensive review of all the factors that affect the learning of motor skills.

* Address all correspondence to Ian M. Franks, School of Human Kinetics, University of British Columbia, 210 War Memorial Gym, 6081 University Boulevard, British Columbia V6T 1Z1, Canada. e-mail: ifranks@interchange.ubc.ca

Video information in training

In normal conditions during training, athletes are active in correcting errors. However, on some occasions, coaches use alternative aids to provide extrinsic (external) visual feedback, for example videotaped replays of the performance. In this context, video technology has significantly influenced training methods. Although video technology originated in the 1950s, its use in coaching is an innovation less than two decades old. Its attractions for use in training are its relatively low cost, accessibility and portability. It is affordable for most field workers and, perhaps, already the most popular technology used in sport. However, using this medium requires performers to adopt a passive attitude. Individuals watching their performances cannot always control the feedback information received during a video presentation. This feedback is delayed until the task is complete and, therefore, cannot always be associated with the internal sensory information at the time of motor execution. Moreover, the information available may often exceed the athlete's processing ability; thus, additional guidance may be required, particularly with inexperienced or young athletes. In such cases, the coach's role is to guide and help in associating the visual feedback generated by the presentation of the video movie with the expected results.

Video-based motion analysis systems, although significantly more expensive, are also used to facilitate feedback about performance kinematics. Lately, these systems (e.g. APAS, Ariel Inc., http://www.arielnet.com; Silicon Coach, SiliconCOACH Ltd, http://www.siliconcoach.com) have become more accessible, often being available over the Internet. They are adaptable to any common technology – most PC platforms, video camera systems and frame grabbing technologies are supported – and affordable for the coach. A combination of common digital technologies allows video recording in field conditions, for example during a golf match. Images can be downloaded from any digital video camera via Firewire™ to hand-held computers (e.g. HP Jornada Series). They can then be transmitted in a compressed image format to a remote server through GPS (Global Position System satellite service) or directly by a cellular phone to the same server (see hand-held APAS, Ariel Inc.). The video data can be redistributed and analysed by researchers in any of the available server locations providing the service around the world. Very basic kinematic profiles and tabulated results – such as shot release speed, angle, height and phase durations through the put – can be returned to the performer or coach in the field in minutes. These can be accompanied by similar data from world ranked experts for comparison, retrieved from a library of profiles in the specific sport.

Video is also recognized as an appropriate medium for obtaining qualitative information about the performance. Video, in combination with TV technology (http://www.orad.co.il), is suitable for enhancement of feedback using replays, real-time three-dimensional simulations or superposition of vector graphics. It can be further used for individual notational analysis and game statistics in remote locations. Less abstract and important information can be obtained from video playback technology; for example, for on-site immediate comparison between one's performance and that of other athletes. One interesting technology used for this process is based on a superposition of video sequences appropriately transformed and graphically enhanced (scaled, translated and rotated for comparison). Such a superposition of two footages (one from an expert and another from a less-experienced individual) is presented simultaneously. This allows the recognition of essential differences between the two performances (http://www.dartfish.com/technologies/technologies_simulcam.html) and, in this way, visual qualitative and meaningful feedback is provided to the performer. The underlying assumption of such a motor learning strategy is based on imitation. Humans and other primates imitate movements from birth (e.g. facial or hand; Meltzoff and Moore, 1977) and continue throughout life bypassing the need to extract abstract kinetic or kinematic information to learn a motor skill. Based on the human and animal models, the potential of learning by demonstration is recognized and implemented in robot motor learning (see Schaal, 1999).

Other video analysis systems, such as the 'coach-friendly' Silicon Coach and Quintic (http:/www.quintic.com), emphasize this type of comparative feedback and imitation. However, a note of caution about this type of learning activity has been raised by Bartlett (1999): one person's optimal performance is unlikely to be the same as that of another.

One further drawback with all video analysis systems is the time taken to record manually and accurately the coordinates of the joints of the body and other points important in the analysis (see, for example, Ay and Kubo, 1999). This precludes immediate feedback of anything other than the video images themselves and restricts fast feedback to simple kinematic and temporal data as noted above. More detailed kinematic analysis takes time.

Automatic tracking systems (e.g. Expert Vision Analysis [EVA], Motion Analysis Corp., http://www.motionanalysis.com; Vicon, Oxford Metrics, http://www.vicon.com; CODA, Charnwood Dynamics, http://charndyn.com) use several different technologies to track and record movements, some in real time. The systems that use passive markers and pulsed light arrays with simultaneous sampling from multiple cameras (e.g.

EVA, Vicon) are particularly attractive for rapid feedback in non-competitive sport settings. Hubbard and Alaways (1989) reported the early use of the EVA system to measure release conditions in the javelin throw quickly enough for the thrower to 'improve performance' in the next throw. This system incorporated an optimization of javelin flight for that thrower with the same release speed, and then fed back information on optimal release angle, angle of attack and pitch rate compared with values for the actual throw. As with much technologically driven information on the provision of immediate feedback, no attention was paid to whether the immediate feedback of such information could improve performance. In this case, we expect, from over a decade's experience, that athletes need information on how to change their techniques to effect changes in release angles and that this information is best provided with non-immediacy.

Automatic tracking systems have not yet been widely used in athlete feedback, probably because of their high cost, their use frequently being limited to indoors and not providing a video image, although this can be done with separate and synchronized video cameras. However, because of the increasing frame rates of these systems (the latest Motion Analysis Eagle digital cameras capture at 500 Hz), real-time display not only of stick figures but also of joint kinematics and even of solid body models through packages such as SIMM (Software for Interactive Musculoskeletal Modeling) suggest wider applications in indoor training.

Training in three-dimensional virtual environments

Visual feedback inherently carries information about the perceived relationship between the individual and the environment. Self-motion relative to the surroundings initiates perception of the moving environment as a precursor to action (Gibson, 1979; Michaels and Carello, 1981). To exploit the link between perception and action, computer applications create virtual environments by using different visual effects. This relationship is implicit in simulation trainers that are accompanied by three-dimensional displays. Stereovision is a common technique used to create such a three-dimensional effect, based on the principle that each eye receives a slightly different view of the same visual object. Fusion of the two views and further interpretation of the three-dimensional image occurs at higher brain centres. Red-green or red-blue (passive) filters, or polarized (active) glasses synchronized with a monitor (see http://www.3d-video.de), are among the earliest techniques to show different images to the two eyes. They have been used in semi-real environments or in completely immersed virtual-reality settings (see http://www.sgi.com/virtual_reality/, Immerse Reality). A more recent technology uses glasses that provide a complete TV display that is slightly different for each eye (see http://www.i-glasses.com). A simpler and more popular way to provide a three-dimensional experience is by showing superimposed objects, appropriately scaled and put in perspective, by creating movement and shading effects in the planar display. This is the case in TV-video games such as Nintendo™ and Sony Play Station™.

In a simulated three-dimensional virtual environment, the coach may regulate important factors that influence perception, such as speed, orientation and directional changes, simply by operating a joystick or a keyboard. Thus, skill may result as a by-product of training in controlled simulated three-dimensional virtual environments. Some technologies today have been developed for training in conditions that simulate the real surroundings. These technologies are setting a standard for indoor coaching in, for example, bicycle riding (CompuTrainer™, RaceMate Inc.), golf (Part-T-Golf™, Part-T-Golf Marketing Company), windsurfing (Force[4] WindSurf Simulator, Force[4] Enterprises Inc.) and other sports.

Kelly and Hubbard (2000) reported the design and construction of a bobsled simulator for driver training. The system comprised a bobsled cockpit, motion control system and graphics workstation. The shape of the track being simulated was derived from construction specifications. The driver's view of the simulated track was presented to him on a monitor mounted in the cockpit, synchronized to roll angle and steering force feedback through the motion control system. Interestingly, this development was intended not only to help train the US bobsled team, but also to provide a 'tourist attraction' to increase interest in the sport. Whether it succeeded in either intention was not reported.

A recent concept is that of remote coaching via the Internet. People carry out a computerized exercise program while a third party supervises the routines and controls the mechanism. For example, a 'servo valve' may be controlled in a remote mode to adjust speed, resistance and other parameters during a bench press or a knee extension on an isokinetic machine (see Ariel Dynamics Ltd, http://www.arielnet.com). The feedback is provided by the computer as a graphic display of selected movement parameters plus statistics such as peak and mean results of the performances during the workout. Similarly, on-line coaching can be done for running on a treadmill, cycling or training on a stepper (see NetAthlon™ or UltraCOACH VR® software, IFT Ltd, http://www.fitcentric.com). The performer can train in a virtual environment showing scenery of preference that is displayed on a screen while jogging on a treadmill. Wearing appropriate glasses allows also stereovision and, thus, the environment may be seen in three dimensions. The same technology allows athletes to train and compete on–line even at remote distances. Web racing is a promising innovation that has been introduced, for example, in diverse sports like bicycle riding, wheelchair racing and rowing (see http://www.ultracch.com).

The potential for such technologies is great, certainly for recreational purposes and for initial learning of a skill. However, this depends on the feedback information that can only be used effectively if it is associated with the actual movements. Current research suggests that visual feedback presented during training in a virtual environment may accelerate the learning process compared with standard coaching techniques (see Todorov *et al.*, 1997, for a table tennis example). In other cases, when individuals are asked to estimate where a ball would land, judgements based on the information presented in a three–dimensional virtual environment may lead to a different visual search strategy than the one used in real settings (Zaal and Michaels, 1999). This, in turn, might slow the skill learning process. Thus, as far as motor performance is concerned, further research is required to support the general use of such virtual settings for training.

The potential advantage is that when three–dimensional virtual environments are used, exteroceptive feedback, in combination with internal feedback, may be manipulated to acquire a new skill or to improve an old one. Sometimes, the advantage of virtual reality settings is that such environments may be used to enhance indirectly the acquisition of a skill by allowing pre–practice in simulated unknown conditions. For example, in non–sporting motor activities, virtual reality is widely used in combination with actual simulations. Pilot training involves practising in simulators that combine visual and kinaesthetic feedback to emulate flight conditions, thus making the training process more realistic and effective without taking risks (Boeing 727 and Airbus commercial liners; Quadrant Systems Ltd).

The training of car–driving responses using simulators is another example (DTS Driver Training Simulator, Digitran, Inc.). In such settings, a driver is confronted with unexpected events (e.g. a dog suddenly crossing the roadway) that require appropriate actions. Driving simulators allow for adjustments of the different parameters during learning of the braking response. These parameters include driving speed, tailgating distance, the rate of increase of the optic expansion after the brake action and the moment the brake lights will turn on. The advantages are various considering that simulators are relatively inexpensive and safe compared with the risks of training such skills in real conditions. Figure 1 shows the set–up used to train cyclists in an environment that allows for control of feedback through a virtual reality simulation.

The use of intrinsic feedback under vibration conditions for enhancing muscular capacity training

It has been acknowledged that vibrations generated by low–voltage alternate current may act directly on

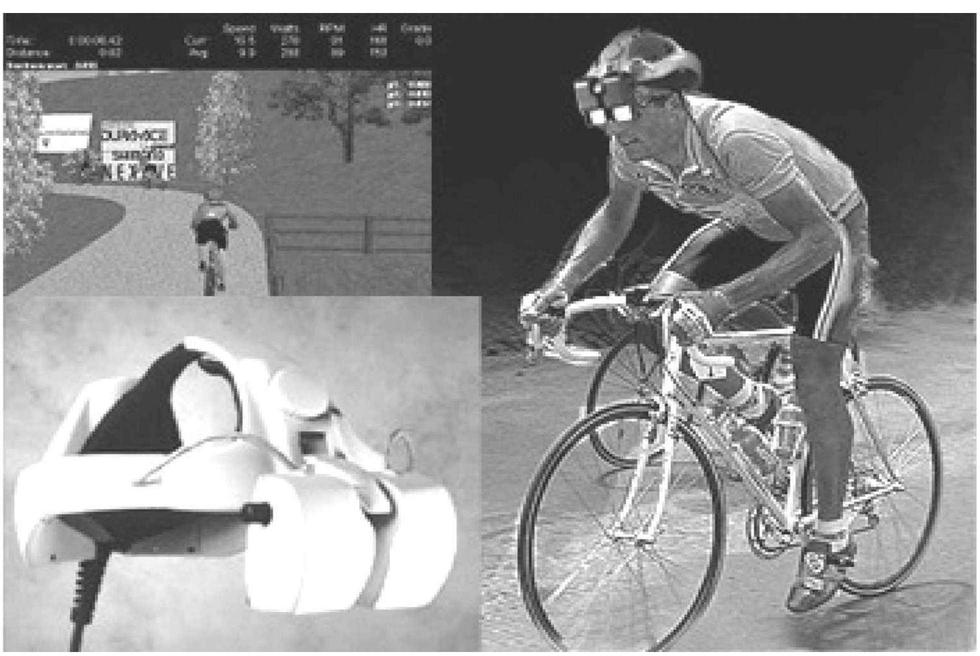

Fig. 1. Cycling simulation in a virtual reality environment.

motor units, spindles and pain receptors (Lundeberg *et al.*, 1984), reducing pain and causing muscular relaxation. Nazarov and Spivak (1987) suggested that vibratory stimulation of proprioceptors might also have positive effects in training muscle elasticity in sports. More recently, mechanical segmental vibrations during simple arm lifting movements were used by Liebermann and Issurin (1997) to investigate empirically the effect of vibration on muscle effort perception and muscular force generation. They hypothesized that a momentary sensory conflict might help to increase muscle force output. That is, people would have the feeling of lifting fewer loads during vibration conditions and, thus, would lift heavier loads. The findings of Liebermann and Issurin showed that participants consistently perceived that movements against a load appear 'easier' when vibrations (44 Hz and 3 mm amplitude) were applied. This confirmed that a perceptual factor was involved in the process. Stretch reflexes could certainly have been activated by the stimulation of the muscle spindles and the following reflexive contractions could have summed to change perception and allowed stronger voluntary muscle contraction in the direction of the movement. The results of this experiment also showed that participants lifted somewhat heavier loads and, consequently, that the ratio of training time to output could, in principle, increase. This could make a training unit more efficient. Does the increase in loading capacity by using vibratory stimuli justify its use? As far as acquisition of a skill or improvement of an old one is concerned (particularly when the skill demands accuracy), vibration might have a negative influence. After a muscle or tendon is vibrated there are after-effects, such as significant changes in position and velocity sensing (Goodwin *et al.*, 1972; Sittig *et al.*, 1985, 1987). These movement 'illusions' or distortions may cause undershooting or overshooting during limb displacements without the participant being aware of them. It is always preferable to train and tune proprioception to the correct movement patterns. But considering that success in competitive sport implies an increase in muscle capability as well as mastering a skill, a manipulation of intrinsic feedback by applying vibrations might lead to positive results in the final performance. We suggest that coaches should critically weigh the benefits of vibration training against potential risks on muscles or against the altered kinematic patterns that might result as a consequence of the perceptual–sensory conflict created.

Some technologies suggest the use of whole-body, as opposed to segmental, vibrations. Vibration devices adapted to sports might be incorporated to learn and adapt to conditions in which the skill requires damped vibrations, such as windsurfing, alpine skiing and mountain biking (Mester, 1999). Mester reported that positive effects of whole-body vibrations might be attributed merely to practice in a simulated environment where these vibrations are controlled. Intrinsic feedback is used in such cases to learn to cope with such vibrations. This is illustrated in Fig. 2.

It has been shown that long exposure to whole-body vibrations can pose health hazards in some occupations – truck drivers suffer from back pain and industrial workers suffer from loss of sensitivity in the fingers. Once again, the coach should evaluate the use of vibration training in light of the risks inherent in the method

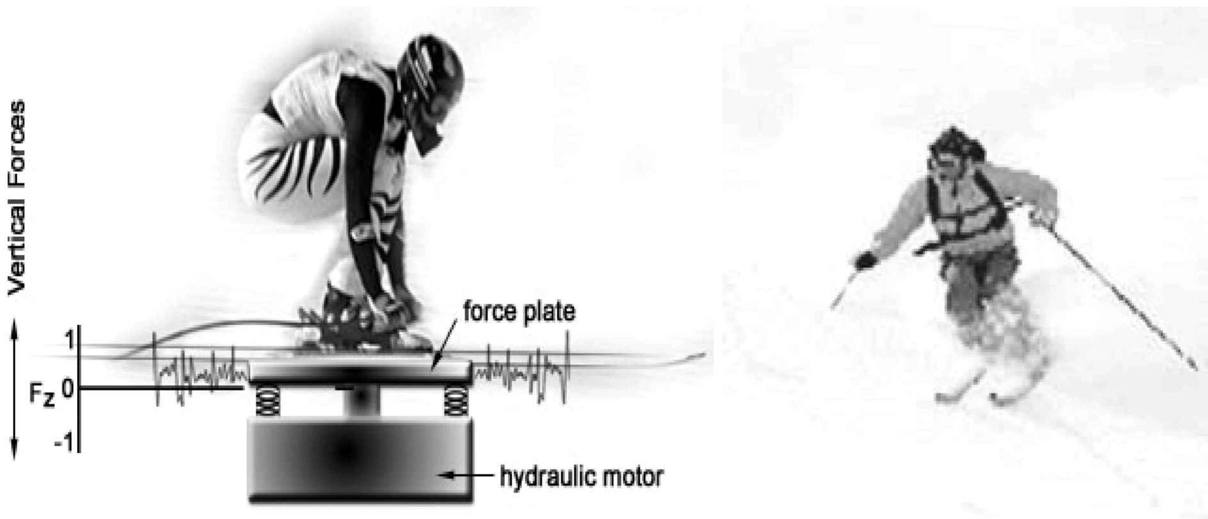

Fig. 2. Floor irregularities and high speeds in downhill skiing cause vibrations that challenge the musculoskeletal structures and control of movement.

– as with any other, such as plyometric training. If the exposure to vibration is controlled and constrained to a limited time, the injury risk factor might be negligible. If the skill requires prolonged exposure to vibration conditions, however, alternative solutions should be searched. In fact, materials science and its applications to sport have developed enough to override some of the hazards posed by directly training sensory and muscular systems in vibratory conditions. 'Smart materials' may have become a smarter option. For example, in downhill skiing, which requires quick control of the limbs, or in long distance running, usually carried out over stiff surfaces, the negative vibration effects are counteracted by piezo-ceramic materials introduced in the construction of better skis. Such skis are equipped to detect and compensate for vibrations (http://www.techreview.com/articles/apr96/TrendSki.html) through the physical properties of the material. As pressure is applied to any part of the ceramic surface, piezoelectricity is generated (a static charge produced by elastic deformation) and converted into a force that attenuates the vibrations – the ski becomes stiffer as a function of the charge.

It is worth mentioning here that vibratory stimulation is an accepted treatment used in physical therapy. Astronaut physical training might also change as a consequence of such stimulation, since vibrations applied to skeletal bone present an increasingly positive effect in the reversal of osteoporosis (Rubin *et al.*, 2001), a problem encountered on prolonged space missions.

In summary, any training technologies that might develop as a consequence of vibratory stimulation research in sports should be critically evaluated. Technology has developed to overcome vibrations without requiring adaptation training. Materials science and damping mechanisms might be useful in specific sports.

Temporal feedback in skill training

One important element in skill performance is timing. Temporal variables are easily learned and retained with little attention (Liebermann *et al.*, 1988). The information conveyed in temporal structures or rhythms may sometimes override the use of spatial information. That is, while people are trained to perform a skill, the duration of the movement is perceived and learned better than some spatial aspects, even if the person pays attention to the latter only (Liebermann *et al.*, 1988). Temporal variables appear to be so robust and efficient for motor learning that coaches often use them intuitively. For example, they clap their hands at a pre-determined tempo encapsulating the rhythm of the action that best suits the spatial configuration of the skill. The performer listens and translates this into motor actions.

Temporal templates can be used to train individuals in aerobic workouts. The major technological innovation here is that performance can be monitored by interactive Personal Aerobic Training software (virtual PAT; Davis and Bobick, 1998) that has been developed at the Massachusetts Institute of Technology (MIT). The basis of the approach is a computer algorithm, which recognizes the silhouette (edges) of the performer situated in front of a wide back-projected infrared light source. The body eclipses the infrared source and the cameras filter out the images – a binary extraction of black from white background – to send them digitally to the computer. The pattern recognition algorithm captures changes in the silhouette – body motions – from frame to frame and temporally codes these changes. This is translated into auditory feedback, which, in turn, is activated either when performance of the exercise declines (negative feedback) or when performance is correct (positive feedback). The algorithm sets rhythmical musical patterns for the personalized aerobic workout. The tempo is adjusted interactively while performing and, thus, the computer-controlled temporal structure is synchronized with that of the performer.

The apparent complexity in the process of extracting the information during the motor performance does not imply that the feedback itself is complex. Quite the opposite: technology may help to reduce feedback to the most essential information units. For example, temporal information is simple and natural in any moving body, but may not be as accessible as other forms of movement information. However, once extracted, this information may be effectively delivered and used to enhance motor skill.

Providing feedback about team performance

Over the past few years, researchers in notational analysis have developed many sport analysis systems. These systems describe in detail not only the actions of athletes in competition, but also the behaviour of the coach during practice. Indeed, considerable effort is now being made to quantify accurately competition and practice performance (for a review of several analysis systems, see Hughes and Franks, 1997). Sport analysis systems, many of which are computer-aided, are designed to describe in detail the movements and technical actions of the athlete.

Information derived from this type of computer-aided system can be used for several purposes: (i) immediate feedback; (ii) development of a database; (iii) indication of areas requiring performance improvement; (iv) evaluation; and (v) as a mechanism for selective searching through a video recording of the game. All of these functions are of paramount importance to the coaching process, which was the initial *raison d'ftre* of notational analysis.

One of the most exciting and potentially significant outgrowths of computer-aided sport analysis was the advent of computer interactive video technology. The ability of computers to control the video image made it possible to enhance existing sport-specific analytical procedures. An inexpensive IBM-based system was first described by Franks *et al.* (1989) and then applied to the analysis of team sport by Franks and Nagelkerke (1988). This computer-controlled system allowed the coach or the sports analyst to provide the athletes with digital and graphical data of team performance in addition to edited videotape instances of action that corresponded to these data.

The interactive video computer program accessed, from the stored database, the times of all specific events such as goals, shots and set plays. Then, from a menu of these events, the analyst could choose to view any or all of these events within one specific category. The computer was programmed to control the video such that it found the time of the event on the video and then played back that excerpt of game action. It was also possible to review the same excerpt with an extended 'lead in' or 'trail' time around that chosen event.

This type of interactive system has been the creative spark for more recent and commercially available analysis packages that offer a generic data-gathering system, which can be customized to any sport and interact with the on-line video (usually digital). A simple analysis of the data is available and the operator can have immediate access to edited highlights of the performance. The simplicity of the analyses and the lack of sophisticated editing facilities restrict these commercial applications at the moment, but the technology is advancing at a rapid pace.

Using computer-assisted video feedback and a specific algorithm for the statistics, Dufour (1993) evaluated players' and team performance in three fields: physical, technical and tactical. He demonstrated the ability of his computer-aided systems to provide accurate analysis and feedback for coaches on their players and teams.

One innovative method of using video was described by Winkler (1996). He presented a comprehensive, objective and precise diagnosis of a player's performance in training and match-play using a computer-controlled dual video system. His system used computer-controlled assessment systems to assess physical fitness factors in training. In addition, he used two video cameras, interlinked by computer, to enable a total view of the playing surface area. This, in turn, enabled analysis of all the players in a team throughout the whole match, both on and off the ball – something that not many systems were able to produce at that time. More recently, this problem appears to have been overcome using the AMISCO system (Billi *et al.*, 1996; see http://www.videosports.fr). The researchers who have developed this particular system claim it is one of the more powerful tools for tactical match analysis. It is made up of various integrated technologies. A series of video cameras and sensors (approximately 4–6) is installed around the playing surface (usually in a stadium setting) to track the movements of all players, the ball and the officials. This is accomplished through sophisticated software development that compares predicted trajectories of players and ball with the acquired data. The AMISCO system provides a detailed analysis of each player's work rate, an interactive representation of all actions recorded during a match and a graphical reconstruction of all individual actions. More importantly, it can provide a digital replay of all the players and ball and synchronize this with a video replay from any one of the video positions. Therefore, it enables the researcher to describe not only the actions 'around the ball', but also the complete context in which the individual action was produced. Such complete analyses will enable sport scientists to investigate valid descriptions of game performance such as that described in McGarry *et al.* (2002, this issue). However, further research is still needed to test the reliability and utility of such comprehensive systems.

Providing feedback in aiming sports

For aiming sports that require accuracy and provision, such as Olympic shooting or archery, vision is a primary feedback channel. Consequently, diverse technologies have been developed to improve skill learning and performance in these sports. There are many examples in which augmented visual feedback is combined with sophisticated technology. Perhaps the most representative and clear example is in the use of laser-guided guns to train aiming skills in Olympic shooting. Laser technology, generally used in industry to detect displacements, allows performers to correct for deviations from the centre of a target during aiming within very narrow error margins and at long distances. Visual feedback, in combination with computer-generated auditory feedback, makes the training process very efficient in this case. It allows athletes to immediately correct posture before triggering while aiming (Noptel S-2000 Sport Shooter Trainer System; Noptel Oy Company, Finland; http://www.noptel.fi/nop_eng/shooter.html). The technical principle underlying such a system is that a laser beam attached to the rifle hits a laser-sensitive grid that generates an on–off pulse captured by a computer through an interface. The software transforms the pulses generated by those sensors that were hit into relevant coordinates. A graphic display of the deviations from the centre of the grid is provided on-line, together with an auditory feedback of proportionally higher pitch as the distance from the centre increases. A similar approach is used in training recreational hunting or in the military, where simulated changing environments are also integrated as part of the aiming task (Shot-Pro 2000 Shooting Simulator, Digitran Systems, Inc.; http://www.digitranhq.com/shoot.html). This is illustrated in Fig. 3.

The use of force platforms and force transducers in training

In sports that do not require spatial precision but require immediate knowledge of timing, radar technology has been adapted to obtain the relevant information. For example, sprinting athletes need to know their reaction times relative to the moment of triggering the start gun; they need to know their instantaneous and mean running speeds and the horizontal forces at the start of a sprint. In track sprinting, a device called the 'Saskatchewan Sprint Start Apparatus' has been developed at the University of Saskatchewan based on a radar-guided receiver and on force transducers. Sanderson *et al.* (1991) used this device to provide information to athletes immediately after they returned to the starting blocks. This information included reaction time, the resultant reaction force on the starting block and the linear speed of the athlete in the direction of the sprint. It was used to provide feedback and identify errors, information that the coach and athlete would not have available to them in normal training. Athletes could change their stance or try different techniques and immediately receive feedback on the change. This method of training had very positive effects in improving performance to a point where feedback evidence could be used by coaches or by the athletes on their own (McClements *et al.*, 1996). This is because the athletes receive immediate and simple knowledge of results that is visually displayed, allowing the athlete to compare the outcome of the performance with internal feedback at any instant.

Imagine a feedback system that relies on on-line auditory tones to calibrate the position of the centre of pressure with the desired target position. When the centre of pressure, also known as the point of force application, is far from some initial target location, an identifiable low-pitch tone follows. When it is close, it is accompanied by a high-pitch tone. Monitoring continuously the displacement of the centre of pressure below the feet in this way allows the association of muscle responses with the lack of stability during the standing posture. This can be done by using force or pressure plates.

These devices became very popular in biomechanical research. They are composed of upper and lower rectangular metal plates of known dimensions and are made of stiff but relatively light materials (aluminium alloys, graphite or titanium). The sensors are usually of

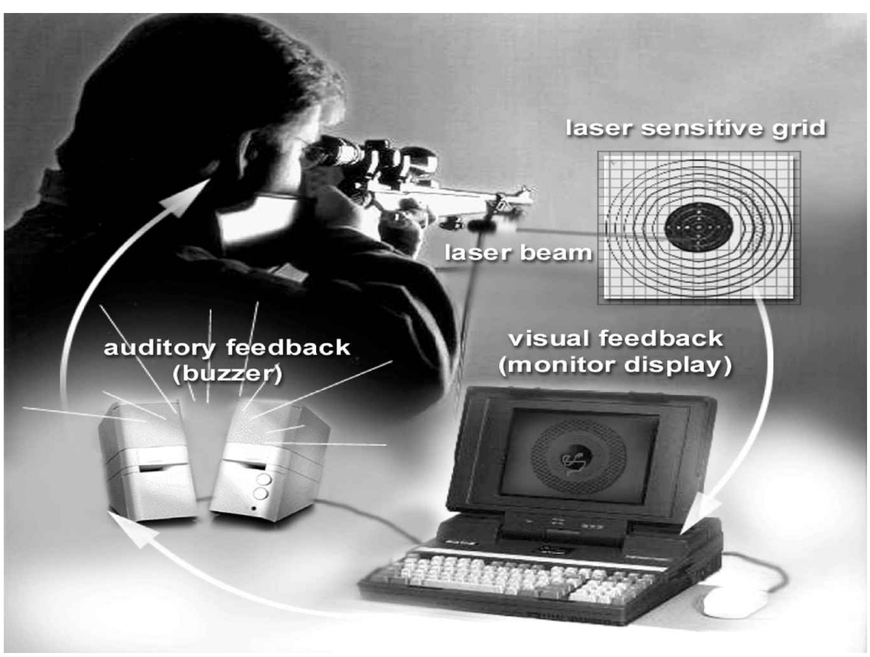

Fig. 3. Schematic illustration of laser-based guidance and feedback in Olympic shooting.

one of two types (strain gauges or piezoelectric crystals) and are installed in precisely engineered internal substructures. Generally, four sensors are used to measure forces on the vertical direction only or eight for measuring forces along all three orthogonal axes. Their purpose is to translate deformations caused by loading the upper plate into electrical signals that are amplified and calibrated to known external forces. If the distribution of force is equal across all points of the plate or for all sensors, the centre of pressure will be in the middle of the geometrical system. More importantly, if the centre of pressure is not moving, regardless of the position on the plate, the system rests in a stable balanced state. Olympic shooters need to train stability before pulling the trigger, as do gymnasts during floor exercises or when on the beam. The incorporation of computer-generated low-frequency tones (auditory feedback) may be used to associate stability (proprioceptive feedback) and centre of pressure displacements (visual feedback). Low-frequency sound or silence means that a relatively stable position is being achieved. Increasing higher-frequency sound means deviation from the stable position (auditory feedback). Thus, for example, the goal of a gymnast training to improve a skill requiring balance will be to maintain the system 'silent' for as long as required while keeping the correct body posture. Figure 4 shows two examples of one-legged standing before and after training with feedback. Note that displacement of the centre of pressure below the feet is less dispersed in Fig. 4b (right) than in Fig. 4a (left). This is indicated by the circular area surrounding the recorded planar displacement of the centre of pressure in static posture (20 s sampled at 20 Hz).

The areas of the ellipses formed by surrounding the displacements may be easily calculated and compared. However, mere observation shows that, in feedback training conditions, standing static balance increases (Fig. 4b). The above illustration is an example that helps in understanding how technology provides information that is not normally available to the performer but is critical in the motor learning process.

Other force transducers have been used to provide feedback to athletes, from force pedals in cycling (e.g. Sanderson and Cavanagh, 1990; Broker *et al.*, 1993) to force transducers in the oar or oarlock for rowers (e.g. Dal Monte and Komar, 1988; Smith *et al.*, 1994). An interesting observation from the cycling research was that summary and immediate feedback were no different in the learning of modifications to pedalling technique by inexperienced cyclists (Broker *et al.*, 1993).

Information from oar forces has been considered to be important not only for evaluation of rowing technique, but also for crew selection (e.g. Gerber *et al.*, 1985). The focus until recently was on the forces applied to the oar by the rower, using the bending strain

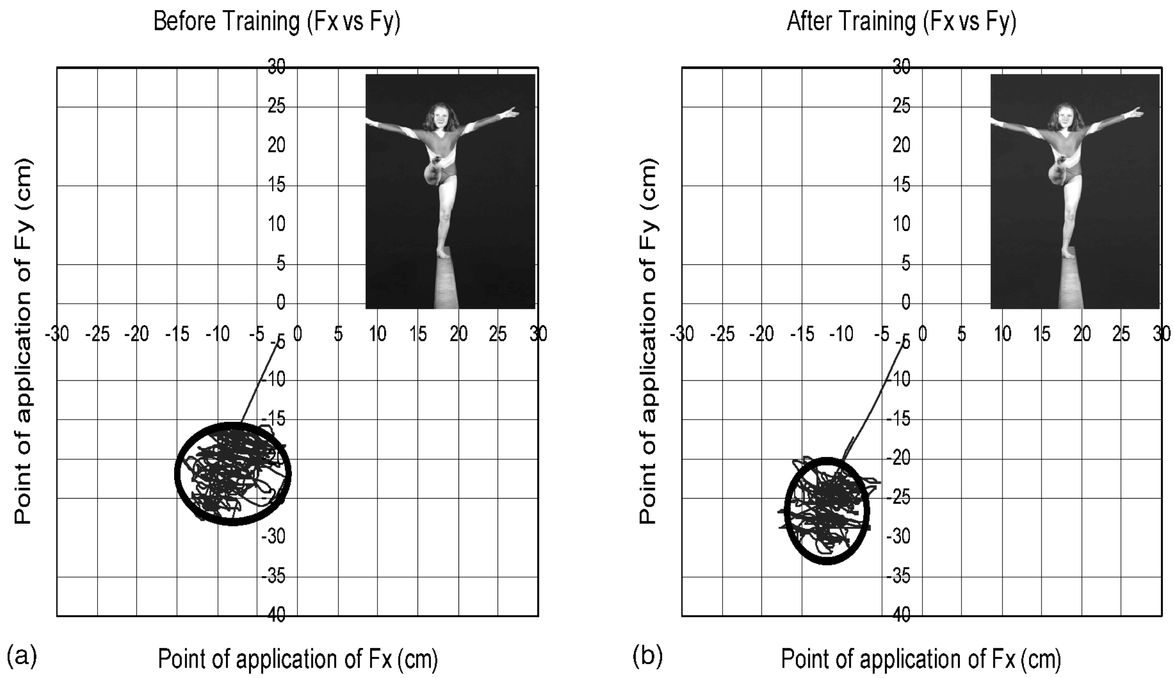

Fig. 4. Two-dimensional graphic representation of the centre of pressure excursions viewed from the top before feedback is available (a) and after feedback is allowed (b).

in the oar, which depends only on the normal oar force. As Smith and Loschner report in this issue (Smith and Loschner, 2002), a significant force, with a propulsive component, 'is transmitted along the long axis of the oar to the pin'; the stretcher force is also important. Recent technological developments now allow all forces that significantly affect boat speed to be measured (see Smith and Loschner, 2002, for details).

The use of eye movement technology in training

A popular line of recent research is based on eye-movement recording technology that determines where the athlete's gaze is focused. The underlying assumption of such research is that the fovea of the eye – a high-resolution area that is densely innervated – is specialized for the recognition of image contours, edges, junctions, colours and other features (Marr, 1982). Thus, the eye orbit moves to align the fovea in the retina with the projected image (Carpenter, 1988). This information is further processed in the brain and, consequently, the person sees, interprets and perceives. However, humans cannot see all images and, more importantly, cannot and do not need to look simultaneously at all images. Thus, a cognitive process allows scanning with the eyes of those aspects and features of objects in the environment that are more relevant to achieve a task goal. The assumptions underlying practical research applied to sport are, first, that expert athletes search for the relevant information during a performance (Abernethy, 1990). The second is that their eye movements (e.g. saccades) lock momentarily on what is perceived as the relevant information in a different way from non-experts (Tenenbaum *et al.*, 1996). However, that the eyes of the athlete focus on specific points, objects or events during skill performance does not imply a causal relationship between gaze, perception and conscious attention.

The expectation that eye movements of experts and their correlation to subsequent motor reactions might pinpoint the important foci of attention that lead to better performance (e.g. in the reception of a volleyball serve) is challenged by the finding that athletes might not even use all information available. Sometimes only visual information obtained at the beginning and end of the performance of fast events is enough to perform correctly, for example in cricket (Land and McLeod, 2000). In practice, the cricket player is able to predict and organize motor actions within the time constraints of the game and those of the visual information-processing system (see http://news.bbc.co.uk/hi/english/sci/tech/newsid_1032000/1032849.stm).

In fast-moving fast-reacting events, it cannot be expected that changes and differences in the way eyes move would help in designing better strategies to enhance motor skill acquisition simply because the 'in-between' information is irrelevant: in slow events, things might be different. The premise could then be that a visual search strategy might be extracted from studying the way experts use eye movements to look for the important visual information. Such 'expert' strategies might be developed further and used to train less experienced athletes about their eye movements.

This approach is reflected in the research of Vickers and co-workers (Vickers and Adolphe, 1997; Adolphe *et al.*, 1997) on eye movement in volleyball, which provides an example of information technology feedback in training selective gazing. Tracking of objects such as a ball with the eyes occurs without players being aware of it. Yet, expert volleyball players differ from near-experts in that the latter do not fixate their eyes on important events and locations for as long as experts (Vickers and Adolphe, 1997). This is labelled 'quiet eye' by Vickers (1996) and is defined as an objective spatial and temporal measure of gaze (eye fixation coordinates or tracking movements, onset, offset and duration). For example, in the reception of a volleyball floating serve – a relatively slow-motion event – near-experts start stepping towards the ball as the serve starts, but before the onset of the eye movements for tracking the ball. Experts, on the other hand, are presumably able to fixate their eyes and track specific locations, such as an area of the ball or the movement of the opponent, even before they initiate their own movements. However, in the context of this paper, it is most important to describe the technology used to record gaze while the participant is performing the motor skill. Vickers and co-workers used a mobile eye tracker device (Applied Sciences Laboratories-ASL 501) for this purpose. This device collected monocular horizontal and vertical gaze coordinates relative to a head-fixed reference frame defined by a helmet attached to the head of the performer. In addition, the information obtained was integrated with video-recorded scenes that were collected by micro-optics attached to the visor of the ASL eye tracker. This allows 'seeing' the scene from the point of view of performers, when the ball moves towards their eyes. Thus, the location of gaze can be mapped relative to the sport environment. The motor performance is videotaped using an external video camera placed in front of the participant. All systems collect data at a rate of 30 Hz, synchronized by a common time code and further edited off-line. The edited video combines gaze direction information (a small dot centred at the pupil and cornea), a view from the perspective of the athlete's eye and a front view of the performance.

Another example that uses the eye movement recorder in sport training can be found in the sport of

Association Football. Franks and Hanvey (1997) and Franks (2000) completed the first stage in the development and testing of a training programme for goalkeepers intended to help them improve their ability to save a penalty kick. Eight nationally ranked (Canadian youth, under 20 and under 23) goalkeepers were used in this study, which was designed to test the effectiveness of the training programme.

Pre- and post-tests involved each goalkeeper facing 40 penalty shots from four different penalty takers, each taking 10 shots. The information collected from these tests included goalkeeper movement (movement time, incorrect or correct prediction of ball placement, and save percentage), penalty taker's non-kicking foot placement, ball time and final ball position. After the pre-test, the goalkeepers were asked what strategies they used to predict the shot direction.

The intervention involved three components. First, the goalkeepers were shown how the response cue 'placement of the non-kicking foot' was reliable for detecting shot direction. This took the form of a video presentation in which a compilation of penalty kicks from previous World Cups was shown to the goalkeepers. It was made clear to the goalkeepers after this presentation and subsequent discussion that the problem with using this cue was that stimulus (response cue) identification and response (goalkeeper movement) initiation should be kept to an absolute minimum. Secondly, the goalkeepers were brought into the laboratory and given simulated training that involved them viewing a large screen videotape of a penalty taker approaching them. The screen would 'blank' at ball contact and the goalkeeper would move either his left or right arms as quickly as possible to indicate the direction in which he would dive. Each goalkeeper wore an eye movement recorder during this training intervention. The recorder provided the goalkeepers with feedback about their gaze control after every simulated penalty kick. This feedback was a video of their gaze pattern superimposed on the scene they were viewing during the penalty taker's run-up. Fixation on the non-kicking foot before that foot landed was stressed after each trial, as well as encouraging the goalkeepers to adopt a consistent strategy in where to look in the events leading up to the run-up.

Before the training intervention, visual scan paths within and between goalkeepers were variable, unreliable and inaccurate in optimum response cue (i.e. the penalty taker's non-kicking foot). It was important for the goalkeepers to fixate on the non-kicking foot before the shot to maximize the benefits of using the advanced response cue. With the aid of the feedback provided by the eye movement recorder, the goalkeepers were able to reduce the variability of their scan path and concentrate their gaze on the direction of the penalty taker's non-kicking foot. See Fig. 5 for an example of one goalkeeper's scan path before and after training.

In the third stage of the intervention, a more realistic set-up was used. Goalkeepers still wore the eye movement recorder and faced a real penalty. Unfortunately, because of the fragility and expense of the equipment and the possibility of injury, it was not possible to allow the goalkeeper to dive for the shot. Again, from a goalkeeper's 'ready stance' they were instructed to move their hands to the right or to the left as soon as they detected shot direction. Movement time and shot direction were measures used in this stage of the study. Also, visual fixations were recorded as a function of learning. In total, the goalkeeper faced 60 simulated and 120 real penalty shots in the entire study.

Before the feedback intervention, goalkeepers' ability to predict correct direction of the penalty kick was approximately 46%, similar to an earlier notation study of World Cup penalty shots by Franks and Hanvey (1997). After training, this figure improved significantly to 75%. It is clear that goalkeeper training in the use of advanced cues should exceed the 120 trials that were given in this study. However, the use of the eye movement recorder in helping them concentrate their gaze and adopt efficient and consistent perceptual strategies under considerable stress was successful.

Combining feedback technologies

During aiming tasks, such as archery and shooting, three steps must be performed correctly. First, a stable standing posture should be achieved where the athlete learns how to stabilize the body during aiming – breathing and heart beat are potential sources of variability. This stability may be reflected in the changes of the centre of pressure, as shown in Fig. 4. A second stage follows, during which the shooting device is to be maintained on the target for as long as needed. During this second stage, the training protocol should concentrate on visually stabilizing the rifle, gun or bow. Laser beams may serve this purpose. Also, as previously explained, these devices allow the athlete to point towards the centre of a visual target situated over a laser-sensitive grid connected to a computer. Any deviation from the centre of the grid – the maximal score – is accompanied by auditory tones of different frequencies. The performer can compare internal feedback with external feedback. When the centre of pressure is in the right position and the individual is aiming at the centre of the target (all auditory tones are silent), he or she can concentrate on the final stage. It is at this third and last stage that training gaze may be important in aiming before actual triggering (shooting or releasing

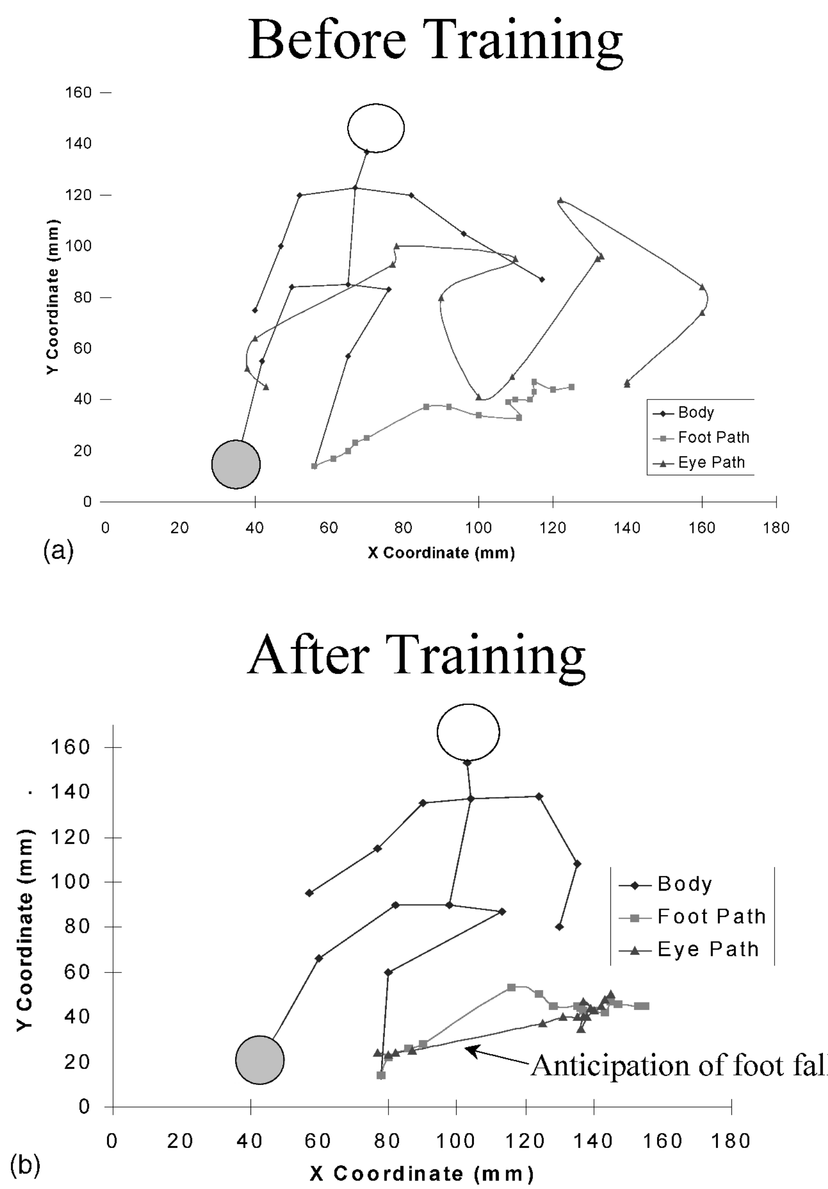

Fig. 5. A typical scan path of a goalkeeper's gaze compared with the position of the non-kicking foot during the penalty taker's run-up to kick the ball: (a) before the training intervention and (b) after the training intervention.

the bow). All these factors can only be measured using sophisticated technologies.

Is feedback always a prerequisite for acquisition of a skill?

Coaches often assume that using immediate feedback is always a valid way to improve skill. Thus, it is also assumed that technologies that provide immediate feedback are beneficial for learning. However, this may not always be the case. Sometimes it may be just as effective to give feedback information after some longer delay in a more specific and limited manner. This is because an over-exposure to feedback (too much information) might interfere with performance if it is provided but not needed (see Salmoni *et al.*, 1984, for a review). It should also be mentioned that training in the presence of immediate feedback might create a certain dependency on external information. However, as performers progress, they should become more independent and learn to rely on internal sources of information, which should then be used as the major error-correction facilitators.

We suggest, therefore, that the frequent use of different feedback sources is important and relevant at the beginning of the skill acquisition process, but less important later (Winstein and Schmidt, 1989; see also Hodges and Franks, 2002, this issue for a discussion of pre-practice information provided early in learning).

Any technology and device that is constructed around the idea of immediate feedback from diverse sources may be relevant for recreational, professional or amateur performers at the initial stages of the skill acquisition process. Initially, well-defined and understandable feedback will enhance learning. However, when experience is acquired, individuals are expected to rely on specific feedback from external sources and on intrinsic feedback. That is, they should become sensitive to their own mistakes in skill performance by focusing on relevant information and internal sensation. At this stage, excessive external feedback, even if provided immediately after performance, may interfere with the acquisition of skill. Feedback allowance should be reduced progressively as training proceeds and skill improves. At advanced standards of performance, the athlete should use specialized feedback from external sources that are specific to particular needs of the performer. It should also be mentioned that the ability to use internal feedback to improve performance is shadowed by a more common use of external feedback, which is more manageable. Intrinsic feedback is always with us. We cannot manipulate it easily from outside, thus it tends to be ignored. Technologies developed to enhance performance based on such intrinsic sensory information are rather specific and may depend on the type of skill and the learning phase. For example, in a balance maintenance task, internal feedback is not as effective as external-focus feedback and instructions (Shea and Wulf, 1999). However, during early phases of the acquisition of a skill, it has been suggested that external sources of feedback may be more effective. This will change from knowledge of results and verbal knowledge of performance during the initial cognitive stage to visual feedback during the associative stage. Only during the final autonomous stage might intrinsic proprioceptive and kinaesthetic feedback be more relevant to guide performance (see Magill, 1997). In fact, at advanced stages, elaborated 'summary feedback' might incorporate combined information from all feedback channels and have positive effects on performance (Schmidt *et al.*, 1990; Winstein and Schmidt, 1990). In light of the rather general character of technologies often built to train individuals, it is unlikely that they can adjust to meet a specific need for a feedback source. Hence, coaches should be aware of the differential needs of their athletes at the different stages of the training process.

Conclusions

Coaches strive constantly to improve the performance of athletes. The most important aspect of their role is to provide the athlete with a practice environment that is conducive to effective and efficient learning. The introduction of information technology into the sport performance environment appears to be a positive, although not always essential, step towards achieving this goal. When the athlete can compare internally the expected optimum performance with the actual movement outcome, the probability of learning increases. This review has focused on how information technology has been used to provide the athlete and coach with sophisticated, objective information about sport performance. For general purposes of motor learning, the impact of basic external feedback and collateral technologies – from simple video movies to complex simulators – are of major importance and should be seriously considered in the normal practice scheme.

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