Evaluation of Movement in Sport by Means of Vectograms

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INTRODUCTION

Standard techniques, such as filming (Terauds, 1983), automatic TV digitation (Pedotti and Ferrigno, 1985), or optoelectric procedures (Leo and Macellari, 1981; Woltring and Marsolayis, 1980) are effective in describing movement. A complete understanding of dynamics, however, may be of critical importance in order to explain performance, identify muscular interplay patterns and estimate loads acting across joints and tendons.

Mathematical models may be the right approach to body dynamics evaluation (Pedotti, Krishnan and Stark, 1978; Hatze, 1981; Ramey, 1983) but the complex experimental procedures and the considerable computing work they involve prevented them from being widely used in studying movement in sport.

Despite its partial informative content, the ground reaction force provides a more direct access to the study of body dynamics. This force, ensuring equilibrium based on Newton's third law, depends on the dynamics of body as a whole and provides a highly significant synthesis of movement.

Ground reaction force is measured by means of force plates, ie mechanical structures with transducers (strain gauges or piezoelectric cells) arranged to identify the three cartesian coordinates of the force and, possibly, to compute the coordinates of its point of application.

Ground reaction force is entirely represented by the three cartesian components and the spatial coordinates of the application point versus time (Cunningham, 1958) or, most effectively, by the evolution of the vector on the support plane (Elftman, 1939).

Ground reaction force may be also considered as the spatial-temporal evolution of the vector being projected on the sagittal plane and frontal plane. This type of representation, named «vectogram» (Cappozzo et al., 1973) proved to be instrumental in evaluating normal and pathological gait in biomechanical terms (Cova et al., 1980, Pedotti and Santambrogio, 1981, Gualtieri et al., 1981). Its potential found confirmation also in the light of correlations with kinematic, dynamic and neuromuscular quantities studied in analyzing the ambulation of spastic patients (Crenna and Frigo, 1985).

As far as the movement in sports is concerned, several studies conducted on the basis of the three components of the ground reaction force are reported in the literature (Kulov, 1973; Ramey, 1973; Bosco and Kami, 1973; Payne, 1983). With this procedure the authors supplemented information obtained by components with the measurement of kinematic quantities to increase the contents in terms of biomechanics.

Examples of a vectorial representation of ground reaction force in running with particular reference to its application point were reported by Cavanagh and Lafortune (1980), while Payne (1979) related the vector to the athlete's kinematics in race walking and running.

The vectograms obtained in the plane of advance were widely used to illustrate biomechanics of different movements in sport disciplines (Boccardi et al., 1978; Pedotti and Rodano, 1978; Pedotti et al., 1983; Pedotti and Rodano, 1985).

These studies stressed the potential of this representation as a self-contained tool for biomechanical research purposes. The aim of this paper is to provide, by means of a set of paradigmatic examples regarding athletics, a first key to better understanding vectograms so that both the researcher and the trainer may correctly use them for practical purposes too. Vectograms are utilized to:

— illustrate the typical dynamic characteristics of some sport disciplines;
— document changes in motor coordination induced by training and by the type of discipline which virtually different athlets are engaged in;
— evaluate the stage of recovery from accidents;
— evaluate the influence of tools (shoes) on motor coordination.

METHOD AND PROCEDURES

Subjects

The dynamic of more than two hundred subjects (83% male) was analyzed with vectograms during the last nine years. The athletes belonged to three main categories:
— members of the Italian track and field team;
— athletes competing in regional athletic events;
— young athletes beginning their sporting activity.

Data Collection

The ground rection force was measured by means of a piezoelectric force platform (Kistler 9261A type). As the disciplines studied required different environmental conditions, the force plate was placed into the floor in three different environments:
— at two thirds of the 18-meter long walk-way of the Bioengineering Center's Gait Analysis Laboratory for race walking and tests of motor coordination;
— in a 40×24 meter gymnasium for running and high jump disciplines
— on the outdoor track for long and high jump.

Two photocells, one meter from one another, were usually placed at hip height immediately before the force plate in order to measure the speed of the subject. The photocells were used to control the start and stop of a specially designed threshold chronometer. The threshold was set on the time of photocell darkening in order to avoid undesidered starts and stops of timer due to arms crossing the beam and then to exactly measure the speed of pelvis.

Once each subject had grown accustomed to the experimental requirements, he performed the same movement as many times as the recording of at least four «right vectograms» required. «Right vectogram» means a vectogram obtained when general and specific conditions are respected.

The general conditions are:
— all foot inside the force plate
— stride not evidently adjusted for foot to land on it.

The specific conditions were defined in each group of tests by considering the movement and the aim of the research. Some examples:
— steady state in race walking and long distance running
— take-off in high jump with bar overcoming

— high and long jump take-off judged to be technically correct by a trainer.
— heights of vertical jumps similar to those obtained by the athlete during periodical tests.

Computation of vectograms

As already said, the vectogram is assumed to be the ground reaction force projected on a vertical plane. The vectograms obtained with the simultaneous projection on two orthogonal planes completely define the ground reaction vector. Usually zy and zx are the planes taken into consideration (see Figure 1a). GR (zy) and GR (zx) are computed as follows:

(1) $GR(zy) = \sqrt{Rz^2 + Ry^2}$
(2) $GR(zx) = \sqrt{Rz^2 + Rx^2}$
where
(3) $Rz = f_{1z} + f_{2z} + f_{3z} + f_{4z}$
(4) $Ry = f_{1y} + f_{2y} + f_{3y} + f_{4y}$
(5) $Rx = f_{1x} + f_{2x} + f_{3x} + f_{4x}$

and where fi (see Figure 1) is the portion of reaction measured by each transducer.

The coordinates of the application point (Px and Py) are computed through the equilibrium of moments (Figure 1b and 1c).

(6) $$Yp = \frac{fz_{(3,4)}}{Rz \cdot Ly}$$

(7) $$Xp = \frac{fz_{(1,4)}}{Rz \cdot Lx}$$

where

(8) $fz_{(3,4)} = f_{3z} + f_{4z}$
(9) $fz_{(1,4)} = f_{1z} + f_{4z}$

and Ly and Lx respectively are the distance between the transducer couples considered.

Two computational procedures may be adopted. The first, suggested by Pedotti (1977), is based on-line display of vectograms through a completely hardware implemented processing of signals coming from the

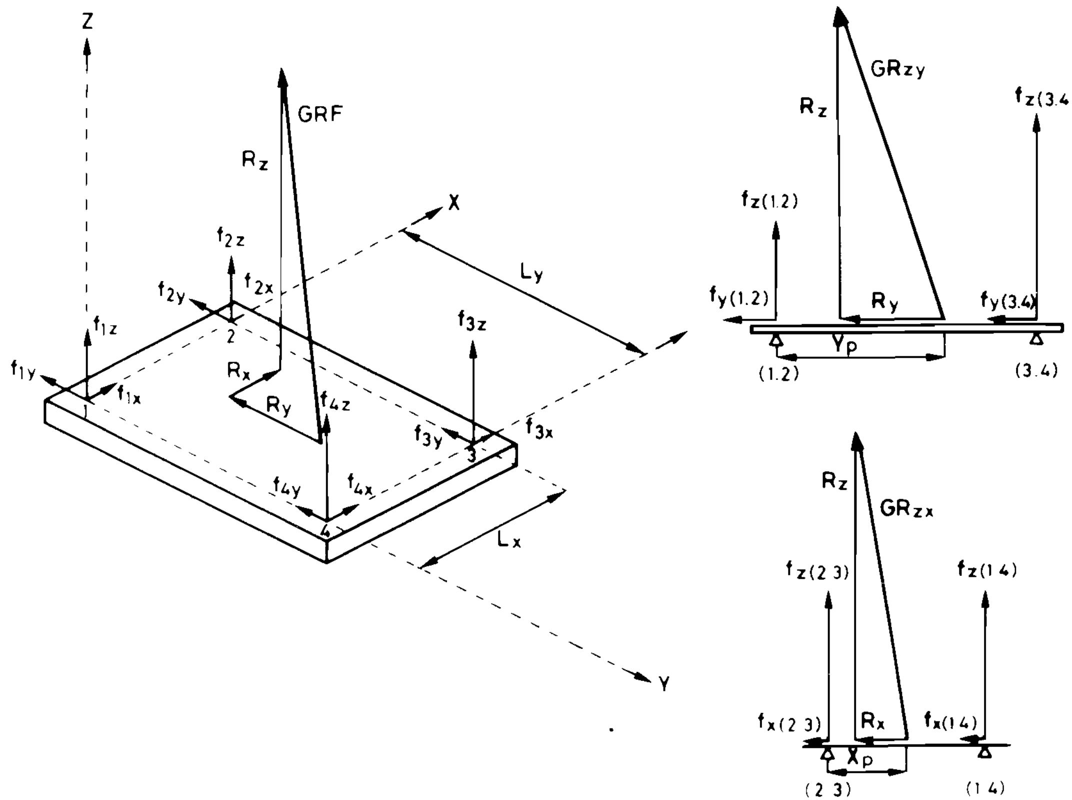

Fig. 1 Scheme of the force plate used to compute the vectograms.

force plate. The second procedure is based on computer data processing. The computer performs the analog to digital conversion of signals, mathematical computation and vectogram plotting.

The results reported herein were obtained with both procedures.

Conventions

The zy plane is considered as the «plane of advance» because the force plate was always placed to superimpose this plane to the athlete's plane of progression during the experiments. In analyzing the take-off in high jump, the plane of advance was assumed to be the plane passing through the trajectory of the center of gravity during the flight. This plane was estimated by considering the take-off and landing areas, and superimposition was obtained by suitably rotating the bar supports by an angle based on the athlete's run up. Vectograms projected on the plane of advanced (VAP) are presented with the direction of progression from the left to the right. Vectors inclined contrary to the direction of progression mean a negative horizontal force, ie a negative horizontal acceleration of the center of gravity.

The zx plane is referred to as the «frontal plane» and the vectograms projected on it (VFP) refer to the athlete seen from behind.

The meaning of the inclination of VFP vectors depends on the foot in contact. Right-hand vectors point out subsequent medial reactions on the left foot and vice-versa with the right foot.

The yx plane is referred to as the «ground plane» and the evolution of the vectors' point of application (APD) refers to the force plate seen from the top.

Scales

Force scales: The same scale applies to vertical and horizontal forces. Consequently, the inclination of the vector displayed equals the actual reaction at recording time.

A vertical segment is indicated near the vectograms, its amplitude being proportional to the subject's body weight.

Time scale: the sampling frequency of vectors is a choice made by the operator and depends on the time of contact.

If the sampling frequency is too low there is a loss of information but, on the contrary, if it is too high the interpretation of the vectogram may become difficult.

Experience suggests that 100 Hz are an optimum for practical applications regarding track and fields events. Obviously, frequency needs to be increased or decreased when faster or slower phenomena are analyzed.

Reading keys

For a vectogram to be correctly interpreted, in addition to what has been specified regarding conventions and scales, some basic points should be kept in mind:

a) as regards VAP and the progression from left to right, the vectors on the far right coincide with the area where the foot tip contacts the force platform, whereby the contact of the whole foot may be approximately defined even if kinematic data are lacking.

b) the coordinates of the application point of vectograms concerning the contact of a single foot always fall within the projection of the foot on the platform, even if that area of the foot is not in contact with the ground at the time. At any rate, the position of the vector permits most loaded areas to be located.

RESULTS

Comparison of athletic acts

Figure 2 shows the vectograms of four different athletic acts: race walking, slow and spring running, and long jump. The diagrams, in their different projections, were obtained as a result of computer data collection and processing. Notices in the lower right sector report some data relating to the test: BW = subject's body weight; SF = supporting foot; FL = actual foot lenght; V = velocity; SD = support phase duration.

The arrow under the baseline connects the start support vector with the end support one.

As a result of the information supplied also by the components, maximum amplitudes of the reaction force are identified, which change considerably as a function of the athletic act: from BW 1.56 in race walking to BW 5.8 in long jump. The support phase duration is also dependent on the act, which is highlighted by the number of vectors that for each act were sampled at 10 msec intervals.

The analysis of VAD clearly points out the biomechanic. In race walking, the behaviour of vectors is similar to the one typical of normal

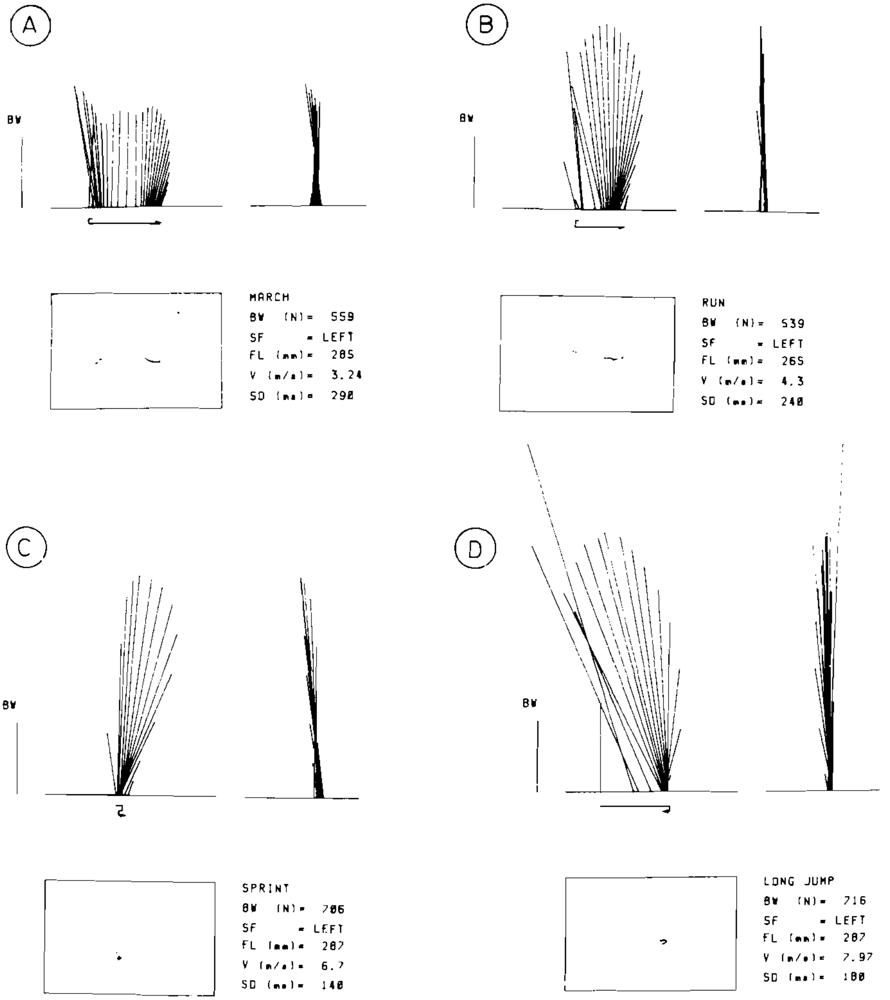

Fig. 2 Full vectograms of four athletic movements. A: race walking, B: long distance run, C: sprint run, D: long jump take off. Components sampled at 100 Hz.

ambulation (Boccardi et al., 1977), with two definite maxima corresponding to the braking and trusting phases. The higher dynamics of the walking act results in an impact peak, located in the heel area, which is higher than in normal ambulation. Load transfer to the forefoot is very rapid (highly spaced central vectors) and thrust involves the forefoot homogeneously. After the minimum there is a fast increase of the vectors, related to the motor coordination imposed by the technique, that tray to reduce the not convenient downward displacement of the gravity center.

In long distance running, the rearfoot support phase duration decreases considerably. A peak vector corresponding to the impact phase is present in this area. Braking (vectors inclined contrary to the direction of progression) involves the rearfoot and forefoot whereas thrust involves the forefoot only.

The VAP relating to sprint was obtained with a platform placed 15 meters after the starting line, and the inclination in the direction of progression of all vectors demonstrates that the athlete is in the acceleration phase. The impact peak typical of long-distance running is absent because the athlete only uses his forefoot as a support.

It absorbs the impact of foot on the ground thanks to its highly resilient and articulated structure. In this case, the forefoot only acts as a support, as shown by the reduced distance between the first and the last vector (30 percent of the athlete's foot length).

The vectors do not move towards the forefoot in a continuous way as shown by the arrow.

In long jump VAP, vectors relating to impact phase move towards the forefoot in a continuous and very fast way.

The highest vector of impact grows at a distance from the last one that is approximately half the actual length of the foot. This means that the athlete load all the plantar surface of the foot to substain the maximum force.

After this phase, the load is displaced towards the forefoot, which supports the longest portion of the take-off phase. The inclination contrary to progression of all vectors depends on the mechanical need for the athlete to incline the speed of his center of gravity by an angle optimally suited for his jump. This inclination is obtained through a powerful braking action.

The analysis of VFP is complicated by mid-lateral shifts usually not continuous of the application point. In order to achieve a better understanding of VFP, it could be useful to provide a representation where the horizontal line proportional to the size of the platform is enlarged. Despite that limitation, VFP indicate how much force the athlete directs perpendicularly to motion. This mechanism may be due both to needs inherent to the performance and to technical deficiencies of the athlete. Thus it is possible to identify the limit values that, once overcome, suggest to the trainer an action on movement technique and to check its influence. Within the context, it is quite interesting to analyze the VDF of long jump, where vectors, almost all vertical, indicate an act controlled in the plane of advance, thus instrumental in terms of athletic performance and in agreement with the high technical level of the athlete examined. Even in the absence of a footprint indicating the stance on the platform, APD allows some significant considerations about the distribution of loads within the foot. The knowledge of the supporting foot is basic for APD analysis.

Taking into account that all data of fig. 2 relate to the left side, when race walking and running are compared, impact is found to occur in the side area of the heel with subsequent shift towards the inside foot. Whereas in running thrust moves towards the forefoot in an almost linear way, in running the load transfer between rearfoot and frontfoot occurs laterally and the final thrust phase involves the inside frontfoot. APD of sprint shows a first support of the lateral side of the foot, than the load transfer between lateral to medial side and the final trust becomes centered. In long jump the APD is approximately aligned with an axis parallel to the direction of progression up to the last vectors, slightly displaced laterally.

Training and motor coordination

As a rule, training results in changes in the physical and technical qualities of the athlete. Quantitative records of technical changes may be of great help to the trainer in view of relating the adopted procedures with the results obtained both in general and with a single athlete.

As an example of this aspect, Fig. 3 reports the VAP of the take-off of a high jumper obtained after winter training and during the summer competitions time. In all tests, the athlete passed the bar at 2.05 m. Both VAP couples indicate, due to their similarity, a considerable motor automation independent from training and due to the good technical ability of the athlete. During competitions time, vectors are more inclined and reach higher amplitude levels than during winter.

These data highlight the tendency towards a more marked verticalization of the exit speed as a result of muscle activity. The decreased speed

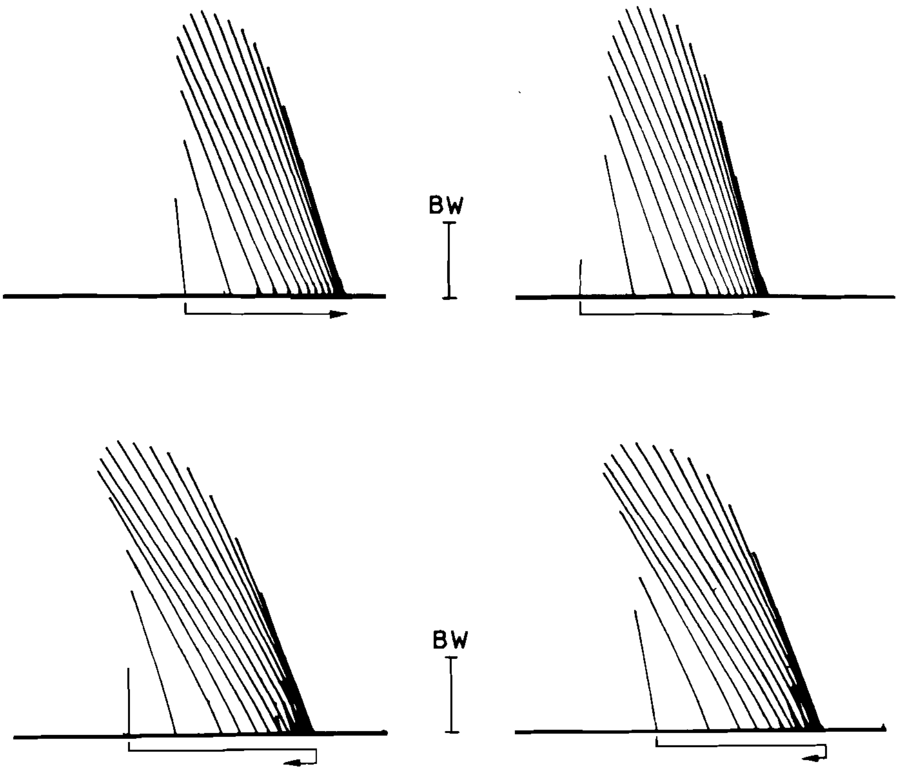

Fig. 3 Vectograms (VAP) of high-jump take-off Data from the same subject taken during winter (on the top) and during competition time (on the bottom). Frequency of sample 100 Hz.

detected at the beginning of take-off (7.5 down to 6.93 m/sec) suggests that the athlete exploited his motor abilities only in part when properly trained and relied on more dynamic actions when the jumping performance became more demanding. Such a hypothesis is supported by the increased duration of the take-off (170 to 190 m/sec), as evidenced by the number of vectors.

Motor coordination related to the discipline

Usually an athlete chooses a particular discipline that seems to be the best fit for his/her physiological qualities.

The trainers try to enhance these qualities to obtain the best performance.

Figure 4 is an example of how the discipline affects the motor coordination required to perform the same test. Vertical jumps, involving movement of arms, have been done by homogeneous groups of long

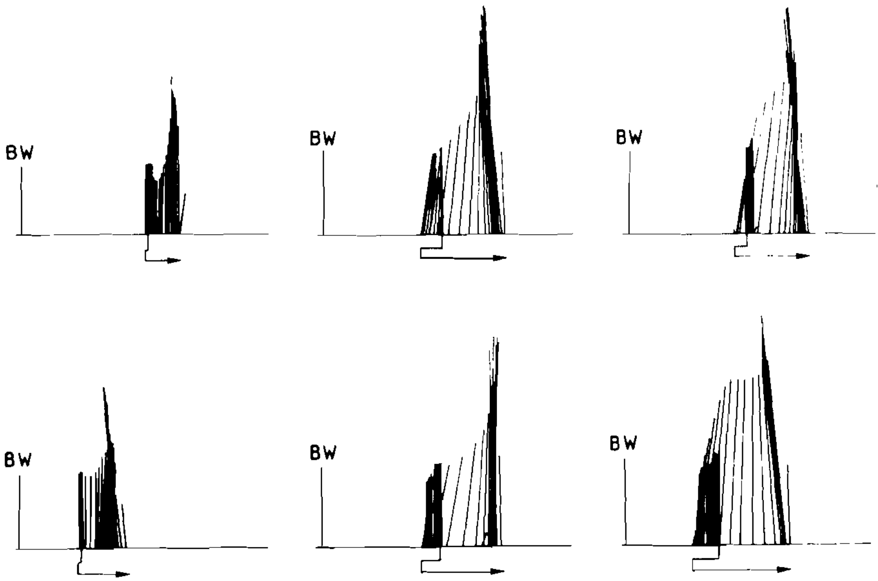

Fig. 4 Vectograms (VAP) of vertical jump. Data from athletes practicing different disciplines: long distance runners on the left, sprinters in the center and high jumpers on the right.
Frequency of sample 50 Hz.

distance runners, sprinters and jumpers. Height of jump, the performance usually recorded in this experiment, underlines a wide difference between runners and the other two groups. Nevertheless, no significant differences were found between jumpers and sprinters. VAP analysis affords detecting that runners move the application point directly from midfoot (starting stance) to forefoot where peak forces, allowing the center of gravity to displace vertically, are applied. Sprinters and jumpers, after the start, move the force on the heel (backward displacement of the application point) then quickly transfer it on the forefoot where maximal forces appear. The VAP confirm the results supplied by the height of jumps: runners shows lower and particular force patterns. Moreover, a more accurate analysis of vectograms permits to identify differences between jumpers and sprinters. The latter displace force on the forefoot without considerably increasing it. This implies that a stronger action of calf muscles is needed during limb extension. On the contrary, jumpers do show a significant increase in force when the vector is on the rear and midfoot. These patterns require a combined quadriceps and calf muscle action, whereby the final action on the forefoot becomes faster. The above considerations suggest that, results being equal, jumpers tend to use the available motor resources in a highly coordinated way.

Evaluation of recovery after injuries

Sometimes the athletes stop their activity due to musculoskeletal injuries. A recovery program needs to be started as soon as the clinical treatment is completed. The evaluation of the functional loss is important both to set up the optimum training procedure and to assess full recovery.

Vectograms may help the trainer during these steps. Figure 5 shows the VAP of a sprinter who underwent knee ligament surgery. The athlete was tested during drop jumps performed with the single limb. The vectogram on the left refers to the healthy limb and those on the right to the treated one. Motor coordination adopted to perform drop jumps is similar: backward displacement of body weight on rearfoot; limb bending during the forward displacement of the application point (as suggested by the decrease in vector amplitude), extension of the limb when force is concentrated in the forefoot.

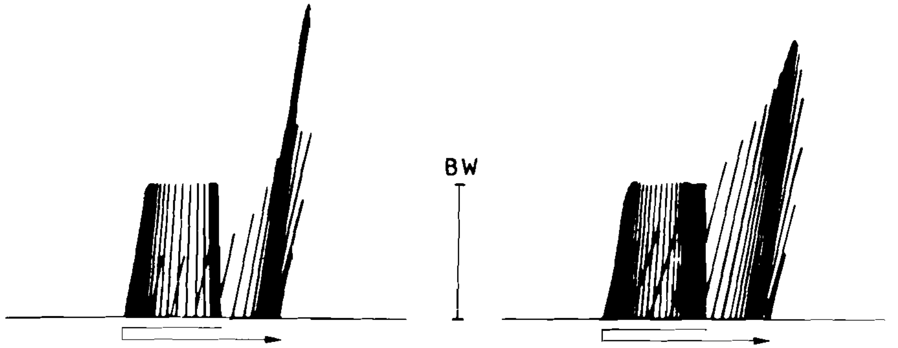

Fig. 5 Vectograms (VAP) of athlete who underwent knee ligament surgery on right limb. On the left VAP from left limb. Frequency of sample 50 Hz.

The clear asymmetry of the diagrams is related to different muscle actions. The healthy limb extends strongly and quickly when all loads are on the forefoot, where a wide concentration of high vectors is evident. The injured limb extension occurs earlier during the forward displacement. Vector concentration involves a wider area of the foot, while amplitude is definitely lower. This means that motor coordination gives an option: the best performance possible of the injured limb is obtained through a decrease in maximal loads on tendons and through the action of muscles that usually are less or differently involved in the movement to distribute the effort of the limb.

Evaluation of tools

The technological improvement of sports tools is highlighted by the evolution of playing surfaces and shoes. The theoretical help provided by new materials requires that a biomechanical survey is carried out in order to be able to identify benefits, if any, and possible changes in motor coordination.

Figure 6 shows some of these changes. Two athletes were examined while running at 3.4 m/sec. Both were two different pairs of training shoes, with low and high shock absorbing soles. As extensively reported in the literature (Nigg, 1986) high absorbing soles reduce forces exerted on the ground during the impact phase, during this phase, limb stiffness cannot be reduced by an active intervention of muscles. A correct control of impact forces is a way to prevent foot and muscles disorders. Despite the approximation due to sample frequency, vectograms confirm the action of soles: impact peak features the highest amplitude on the left (less absorbing sole).

The VAP analysis indicates that the shoe material does not affect the impact peak alone. Actually, shoes with less absorbing soles induce athletes to concentrate the support on a smaller and forward area of the foot, in order to exploit the absorbing ability of the forefoot and to relieve stress on the rearfoot, which is less protected by the shoe.

This mechanism is pointed out by the shorter distance between the first and the last vector and by a quicker load transfer to the forefoot. In that way, the less absorbing shoe tends to cause an overload in the metatarsal area. This overload is confirmed by an increase in the amplitude (5 to 7 percent) of the corresponding vectors.

With low shock absorbing shoes, the minimum after impact is also found to be more marked. This depends on a definitely lowered center of gravity and could originate from a greater bending of the supporting limb

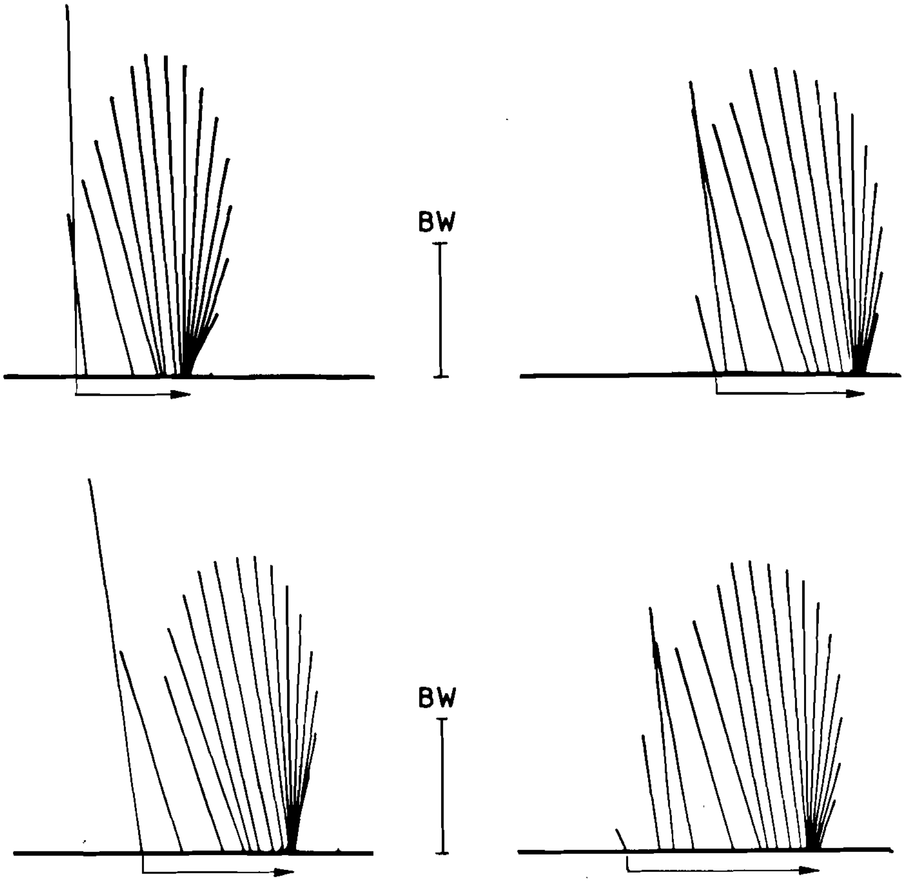

Fig. 6 Vectograms (VAP) of the left limb obtained from two athletes wearing running shoes with less (on the left) and more (on the right) absorbing soles. Frequency of sample 100 Hz.

performed as a reflex by the athlete in order to produce an immediate reduction of the high load perceived during the impact phase.

CONCLUSIONS

A few examples of vectograms concerning different applications in athletics were reported to stress the potential of this method.

Despite the lack of kinematic findings, vectograms can provide information to be used for a more accurate biomechanical and motor coordination analysis than the ground reaction versus time alone.

Vectograms proved to be sensitive to big and small changes in motor coordination.

The collection of the data obtained through a widespread application of this technique, represents a significant step towards the set up of a data bank to be used by the trainer to compare data concerning his athletes and improve his training action.

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