APPLICATION IN SPORTS OF THE "ELITE": A SYSTEM FOR REAL TIME PROCESSING OF TV SIGNALS

Roberto ASSENTE and Giancarlo FERRIGNO

Centro di Bioingegneria - Fondazione Pro Juventute
Via Gozzadini, 7
20148 MILANO ITALY

Antonio PEDOTTI and Renato RODANO

Antonio Pedotti
Politecnico di Milano - Dipartimento di Elettronica
P.zza L. da Vinci, 32
20133 MILANO ITALY

Competitive sport requires a deep engagement of the athletes that have to improve continuously physical and technical qualities with heavy programs of training. The help of the coaches is an important tool both to plan the training and to perform it correctly. The coach evaluates the work of the athlete with quantitative and qualitative inspections. Quantitatively he measures the actual performance or useful parameters (time, length, height) obtaining information on the total efficiency of the athlete. Qualitatively he analyzes the technical aspects of the sport. The analysis is done by a direct visual inspection or by video tape records. The final result is a synthesis of sensations that, through experience and knowledge, becomes practical suggestions. When the same analysis is quantitative, the intervention may be more complete as the coach is supported by powerful information: knowledge of quantities not easy or possible to be detected by visual inspection (velocities, accelerations, forces), accurate description of each phase of the movement, data storage allowing objective comparison in time.

Examples of quantitative analysis of several sports are widely reported in literature but, up to now, many of the method proposed by the researchers did not find an extensive application in practical activities.

Many are the reasons and some of them are represented by the lacking of useful answers to the main requests arising from athletes and coaches when a method has to be applied. The method has to allow a complete freedom of movement and must not to modify strongly the environmental conditions of training; the equipment to use has to be simple and the results must be available in a short time.

High speed filming is a method that partially satisfies these requests as it gives an accurate description of the movement without limiting the freedom of the athlete. Data collection is performed by an operator which analyzing each frame, recognizes the markers placed on the body of the subject and digitizes handling a pointer their x, y coordinates. Unfortunately the human intervention, so convenient for markers recognition, slows down the data acquisition and, despite of the help of the computer, a long time is required to obtain the final results.

Recently a new generation of instruments has been designed to analyze automatically the human movement. In this paper will be described a new device, ELITE, able to reach this goal in agreement with the needs of the sport world.

KINEMATIC DATA COLLECTION

Apparata for kinematic data collection must satisfy several requirements coming from experience of people involved in this kind of analysis. As cited above, they must not interfere with the movements of the subject in order to not modify the natural evolution of the movement itself. Systems employed for routinary use must allow a real time or at least on line check of the reliability of the measure, and they must present preliminary results as soon as possible in order to evaluate if the experimental set-up is suitable for a given application. Furthermore, a good motion analyser must be easy to use, requiring a limited intervention by the operator. Optical systems, based on different kinds of electronic cameras, better fit the first requirement because of their non-contact nature and for this reason they are widely used in movement analysis. Their use furthermore becomes obligatory in sport performances evaluation where wide and swift movements are involved stressing the need of freedom of the subject under analysis. The on-line presentation of the results and the limited operator interventions are obtainable only by using automatic systems, thus overcoming manual coordinates reading of films or recorded tapes furthermore improving the accuracy and repeatability of the measure. Assuming body segments as constant length links, the movement can be described knowing, instantaneously, the spatial position of each link end. This latters can be identified by applying them suitable markers to be recognized by the automatic system for kinematic analysis. Depending on the optical sensors used, these markers can be passive or active, affecting these latter subjects movements because of the presence of power supply wiring. Transducers used in optical systems vary from TV cameras (Cheng et al. 1975; Jarret et al. 1976; Cheng 1979) to lateral effect photodiodes (Woltring 1974; Woltring 1976; Woltring et al. 1980) of rectangular or linear shape and to linear CCD arrays (Leo and Macellari 1979). Spatial accuracy, sampling rate and image distortion vary depending on the kind of transducer used, as well as the nature of the errors due to markers detection

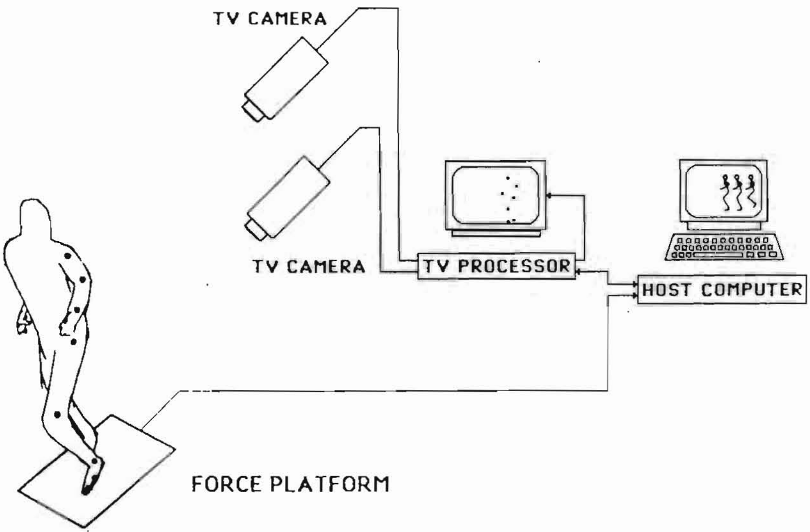

Figure 1 - ELITE system for kinematic analysis of sport performances.

missing. All these factors play an important role in space coordinates evaluation, affecting also all derived kinematic variables, from space displacements to angles variations, linear and angular velocities and accelerations.
The system used to collect data presented in this paper and called ELITE is a TV camera based one, employing passive markers recognized by their shape, thus achieving a high detection reliability even in outdoor applications. This characteristic is obtained by computing in real time the cross correlation between the picked up image and a reference mask which matches the shape chosen for marker. It is evident the difference between this approach and the threshold detection typical of similar systems which does not allow the use in critical environments. Thanks to a particular algorithm the spatial accuracy of the system reaches 1/2500 of the field of view.

INSTRUMENTATION

The architecture of the ELITE system (Ferrigno and Pedotti 1985) for the kinematic and dynamic analysis of the sport performances is reported in fig. 1. One or more TV cameras shoot the subject and send his image to a particular processor which recognizes markers and computes their coordinates, sending these latters to a general purpose computer which provides for their storage, processing and for graphic representation of the results. A force plate, fitted in the pathway on which the subject is moving, collects information about dynamics of the movement. The platform is connected to the computer where dynamic data are combined with kinematics in order to compute derivate quantities, such as moments.

Markers

The relevant points of the subject, the coordinate of which must be measured, are marked by using small hemispheric markers coated with reflective material. The weight of these markers is negligible at all, and they can be easily fixed to the body by adhesive tape. Reflective material covering marker casts back light within a narrow angle (15 degrees) so they must be lit up by a lamp as near as possible to the optical axis of the TV camera. This can be accomplished by placing a lamp very close to the TV camera when the subject is sufficiently far away from the lense, or by using a I.R. LED ring around lenses in close range applications. Being the recognition of the markers, as we will see below, accomplished by using information about their shape, the image of the subject must be frozen through very short exposure. The system actually works at 50 Hz of sampling rate, although preliminary good results at 100 Hz have been obtained, as well a fast shuttering of the image is necessary in order to avoid shape distortion which may cause markers missing.
The shuttering has been performed in two different ways: by using a rotating disk with a limited transparent area in front of the lenses when lamp is used and by flashing the I.R. LEDS when the lighting ring is adopted. Both methods reach the goal in their particular application, however, in future, the mechanical shutter will be included in the TV camera behind the lenses, in order to make the complete interface to the environment (TV camera, shutter, lamp) more handy.

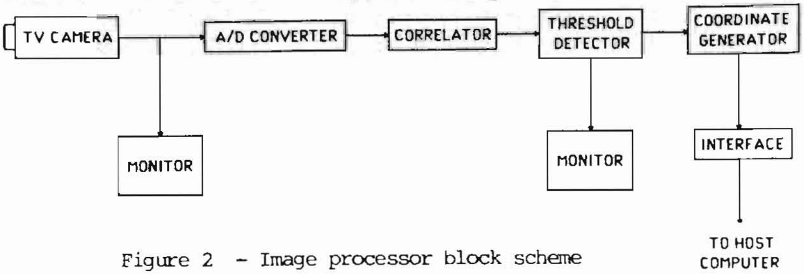

Figure 2 - Image processor block scheme

The markers dimensions vary with the distance from the TV cameras and with the lenses adopetd, however 7 mm in diameter are commonly used at 7 meters from a TV camera equipped with a 25 mm lens. The particular shape of the markers, makes them visible also when they rotate up to 60 degrees around their axis. This last characteristic is necessary in normal 2D applications, but becomes crucial in 3D analysis where a single marker must be seen by at least two TV cameras laying in different standpoints.

Image Processor

The image processor provides for the analog to digital conversion of the TV signal, the cross correlation of the image with a reference shape, the threshold detection on the cross-correlation values and the coordinate generation. The block scheme of the device accomplishing all these functions is reported in fig. 2. The cross correlation block practically extracts, from the whole TV image, all the pixels group having a shape matching the one assigned for the markers. Each marker is represented, after this processing, by a cluster of high value pixels which are easily detected by the threshold detector block. It must be noted that, for example in outdoor applications, the threshold detector alone directly applied to the original TV image should not recognize the markers flooded by the background. The output from the threshold detector block triggers a coordinate generator and the actual coordinate of each pixel, together with its correlation value, are coded and sent to the host computer by the interface block. An important feature of the ELITE processor is that the recognized markers can be seen in real-time on a TV monitor (monitor block) so that the operator can immediately see if there are any missed or false marker. As it can be easily seen, the Elite system, in order to perform all the previous operations in real time that is to process a TV image every 20 ms, must present a high speed of processing of the order of 118 Millions of operations (multiplication and sum) per second. This performance of about 9 ns per operation has been obtained by using a parallel pipelined hardware devoted to this task. The actual sampling rate of the working system is 50 Hz, however succesful tests have been performed at 100 Hz, so the availability of the working system at 100 Hz is planned within one year. The quantization of the TV image is of 256x256 pixels; the final resolution of 1/2500 of the field of view is obtained by software elaboration of the cross correlation values of each pixel.

Force Platform

The force platform used to collect ground reaction forces when the subjects is in contact the floor is equipped with 12 piezoelectric sensors, 3 on each corner oriented along the x, y, z axes. Charge generated by the transducers is converted in voltage by Kistler charge amplifiers and then sent to the the A/D converter of the computer to be synchronously acquired with the kinematic data. By simple processing of these data, the 3 components and the point of application of the ground reaction vector are computed in order to be used for movements analysis (Pedotti 1977).

Computer Processing

The computer provides for the following operations:

- data collection
- kinematic data enhancement
- space resection
- distortions correction
- modelling
- tracking and markers restoration
- graphic representations

- data filtering
- velocities computing
- correlation between kinematics and dynamics
- other processings

The computer used is a DEC PDP 11/73 that is a member of the DEC 16 BIT computer generation using the 22 BIT Q BUS. To perform the acquisition of the kinematic data it is equipped with a direct memory access interface DRV11 accomplishing a maximum data rate of 250 kword per second. Dynamic data (and eventually EMG) are collected by 16 channel A/D converter ADV11 presenting a maximum conversion rate of 47 KHz. The basic central memory of 1 Mbyte is large enough to store data of trials lasting several seconds without discharging data on the RD51 31Mbyte Whinchester disk.

The second function performed by the computer is the enhancement of the accuracy of the kinematic data by computing the centroids of the cluster of pixels referring to each marker. This processing has been proven to increase the accuracy up to 1/2500 of the field of view of the TV camera.

When two or more TV cameras are used to shoot the subject from different standpoints, the computer provides for space resection and space intersection, that is it computes the cameras parameters to be used in the intersection, or 3D reconstruction of coordinates. This task is achieved by an iterative least square procedure thus requiring a low accuracy in control object positioning. Another important task performed by the software is the correction of unavoidable optical and electronic distortion from which the TV cameras coordinates are affected. This task is achieved by computing a set of correcting coefficients calculated from the coordinates of a control grid of markers acquired by the system.

Markers are acquired contemporaneously on each frame without any indication about their correspondence with relative body location. This correspondence must be realized by means of a modelling procedure which knows, in some extent, the analysed object or subject.

The model is given to the computer by specifying the set of links and points by which it can be schematically represented. Operatively a couple of frames containing all markers belonging to the body are classified automatically or by the operator, depending on the model, and then an automatic tracking procedure starts and classifies the whole marker sequence reconstructing also the hidden points. From the right ordered coordinates, stick diagrams and trajectories are easily represented on graphic terminal or plotter. After a filtering procedure, the velocities and accelerations are computed by derivating the trajectories with respect to time.

APPLICATIONS AND RESULTS

Reliability of kinematic data acquiring through ELITE, flexibility of software applications and large availability of biomechanical data is described with the following examples. The examples refer to movements characterized by deep differences among trajectories and speeds of the body segments.

Rugby

One of the winning components of a rugby team is the effectiveness of its scrummage. The task of the scrum is to maximize the push against the opponents to conquer the ball. This push is the result of the muscular action of each athlete and depends on many parameters: the arrangement and the coordination of the group, the physical qualities and the position assumed by the single athlete. If the push of each athlete is measurable the coach may found the most effective body position of the single to optimize the total effect. Moreover the knowledge of the motor coordination adopted increases the possibility to set up an optimal program of training. ELITE system has been used to investigate the push of rugby players.

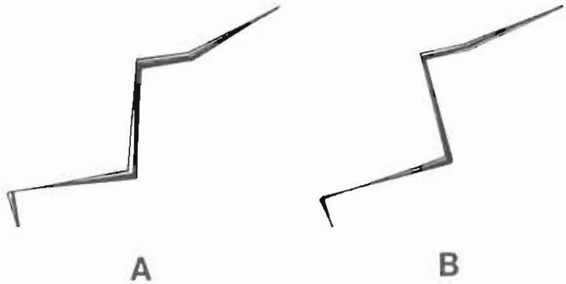

Figure 3 - Stick diagrams of rugby player during continuous push of 5 sec. A is from a push performed with the feet disposed on a line parallel to the shoulder one, B is from a push performed with the right foot forward displaced.

ANGLES IN DEGREES

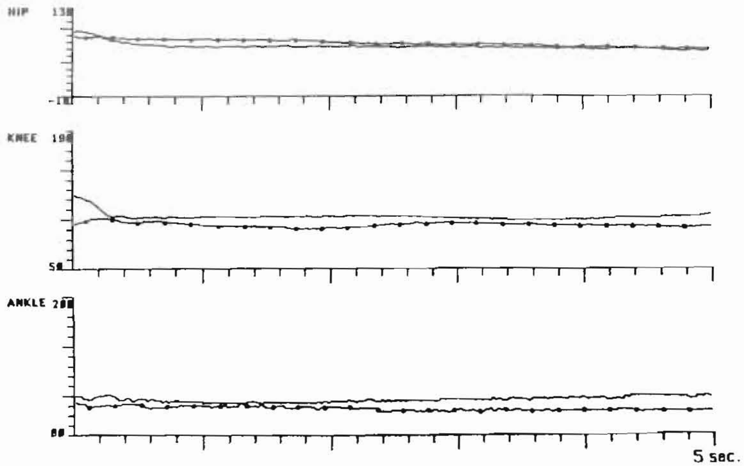

Figure 4 - Angles of hip, knee and ankle joints measured on the subject of figure 3. Dark lines are from condition A, dark-dotted lines from condition B.

During the experiments each athlete was requested to exert different kind of pushes against a specially designed structure simulating the opponent. The mechanical characteristics of the structure were known and costant during time. Two force plates were used to measure, simultaneously, the ground reaction forces acting on each foot. The x, y coordinates of six markers, placed on the right side of the subject, were recorded. The markers were positioned on the rotation centres of shoulder, hip, knee, ankle, and on iliac crest and fifth methatarsal head. The sum of the horizontal force components (y axis) has been used to evaluate the push of the athlete.
Fig. 3 is the stick diagram representation of two records of the same athlete during continuous maximal push of five seconds, performed respectively with both the feet at the same distance from the shoulders (A) and with the right foot advanced (B). The change of position induced angular modifications at the three lower limb joints as reported in fig. 4. By considering the curves after 0.4 sec coordinate (steady state) relatively small differences are evident: when the foot is advanced the dorsiflection of the ankle

encreases (5 - 15 degrees) and the flexion of knee too (7 - 12 degrees). The hip start more flexed (10 degrees) and reaches the same value of position A at the end of the action.
In spite of the small angular modifications, the dynamics of the push is influenced by the position of the right limb.

In fig. 5A and 5B are shown the horizontal components of the ground reaction forces versus time. The total force exerted in position A up to 3.5 sec is almost constant (1450 N) and then increases, reaching the maximum of 1700 N at 5 sec. In position B appreciable variations of force (between 1400 and 1700 N) during the first half of the action are evident, while in the second half the variations are strongly reduced and the mean value of this last phase is about 1450 N. The total push produced by assuming the two position is similar but the time evolution is different, and these differences may be used to reach at the best one of the goals required by the tactis of play.
By analyzing the intervention of each limb it is possible to observe that the position drastically influences the load distribution. Condition A shows a balanced action of the two limbs with a final increase of the right one. Position B shows two phases: at the beginning there is a strong action of the left limb (approximately two times those of the right one), that reaches the maximum of force while simultaneously the right has a minimum. After 2.5 sec the forces become similar on the two side and are so maintained up to the end.
Fig. 6 is the graphic of the muscular moments responsable of the push. Both position A and B involve the muscular groups that provides the extention of the hip and knee joint and the plantar flexion of the ankle but, by considering the right limb, the amplitude and time course of their intervention is strongly different. In particular the hip moment underlines an overload of the muscles when position B is assumed.

Physical Tests

Vertical jump is used in sportive practice to evaluate the power of the lower limbs of the athletes. In spite of the large number of studies made by researchers on the biomechanical parameters involved in the exercise, usually the coaches take into account just the vertical displacement of the athlete. Even if this parameter is very important a better knowledge of the motor coordination adopted to perform the jump may be an useful feedback to evaluate both the status of the athlete, and the modifications due to particular programs of training. In fig. 7 the angles of hip, knee and ankle joints of a sprinter and an high jumper obtained during a vertical jump are reported. Vertical displacement of the gravity center of the athletes were almost the same (H sprinter = 0,42 m; H jumper = 0,44 m). Obviously the course of the angles is similar: low flexion of the joints followed by a fast and large extention up to the end of the contact. In the frame of the common mechanism the sprinter shows a large flexion of the knee and mantains the maximal dorsiflexion of the ankle for a longer time.
This parameters influences the dynamics as shown in fig. 8. The ground reaction forces there reported and their vectorial representation suggest some considerations. The vertical components of the ground reaction force, physically responsible for the jump, point out the jumper has an active phase shorter than the sprinter (0,35 and 0,40sec). The most convenient shape of the curve during this phase is that related to the jumper as is underlined by a faster initial encrease and by the lack of the relative minimum before the absolute maximum. This is due to a different motor coordination well analizable by vector diagrams. Considering the sagittal vector diagrams (SVD) both the athletes move the vectors from the initial position of equilibrium first to the heel and then on the forefoot. Here they exert the burst of force corresponding to the absolute maximum of the vertical component. But, while the sprinter moves forward only the weight (i.e. does not displace vertically the center of gravity) the jumper begins the extention when the vector is on the heel (increasing of the vectors in this area). The frontal vector diagrams and the time course of the center of pressure point out the simmetric action of the jumper while the sprinter moves the loads forward by overloading the right limb.

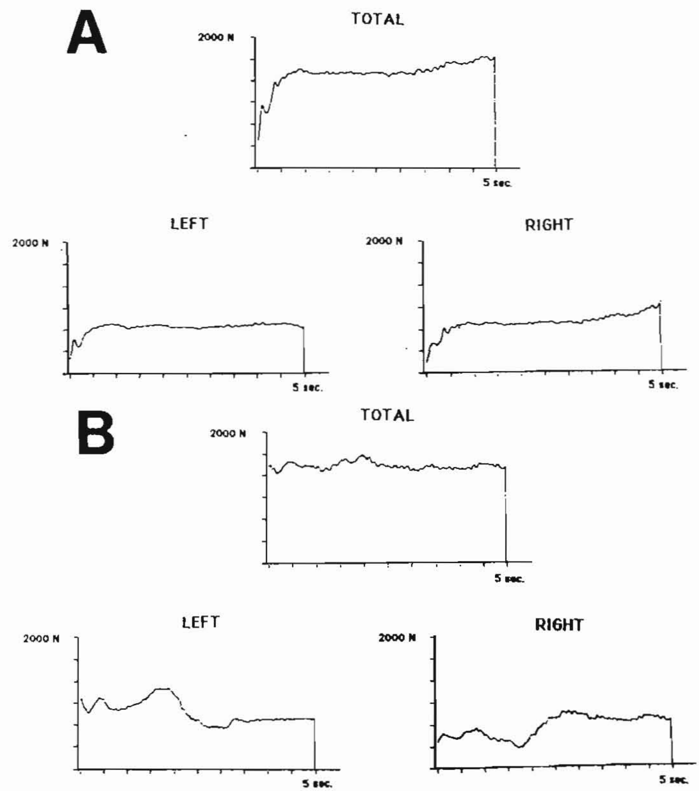

Figure 5 - Time course of the horizontal ground reaction forces exerted by the subject of fig. 3 during test A and B. For each test are shown the forces exerted by each foot and their sum.

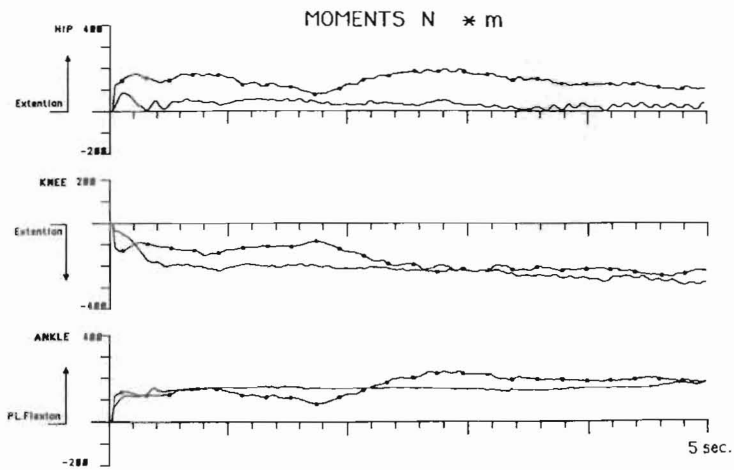

Figure 6. Hip, knee and ankle moments of the right limb measured during the push of a rugby player. Dark lines are from condition A, dark-dotted lines are Condition B.

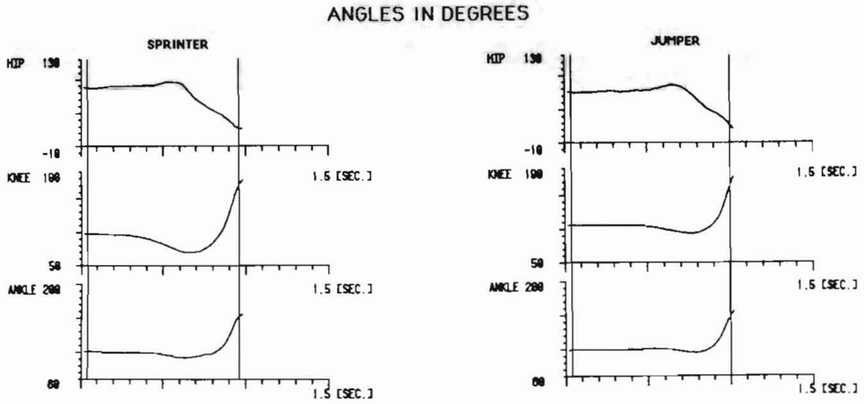

Figure 7 - Angles of hip, knee and ankle joints measured during vertical jumps performed by a sprinter and an high jumper.

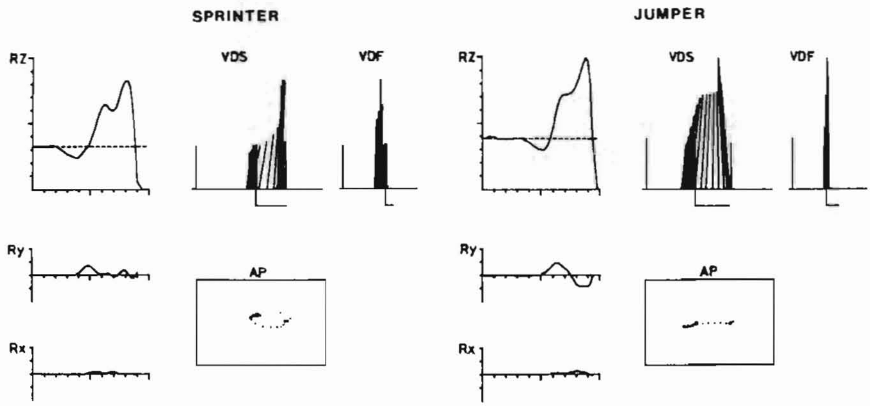

Figure 8 - Patterns of ground reaction forces measured during vertical jump of sprinter and high jumper. Rz, Ry, Rx are the time courses of the three components, VDS is the vector diagram projected on the sagittal plane (forefoot of the athlete on the left) VDF is the vector diagram projected on the frontal plane (right side of the athlete on the left), AP is the time course of application point on the force plate plane.

In fig. 9 the muscular moments of three joint are reported. The moments summarize left and right limb action. The intervention of the extensors muscles is one more time underlined. As expected, the athletes differently use their potentialities:

- both show a similar muscular action at the hip characterized by two maxima during the active phase: the maxima are equilibrated for the sprinter while the jumper perform a strong initial action;
- the sprinter requires a big effort to the knee muscles and this effort is maintained for approximately a half of the active phase; the jumper progressively increases the moment and the maximum, appreciably lower than that of the sprinter, is reached during the last half of the extention;

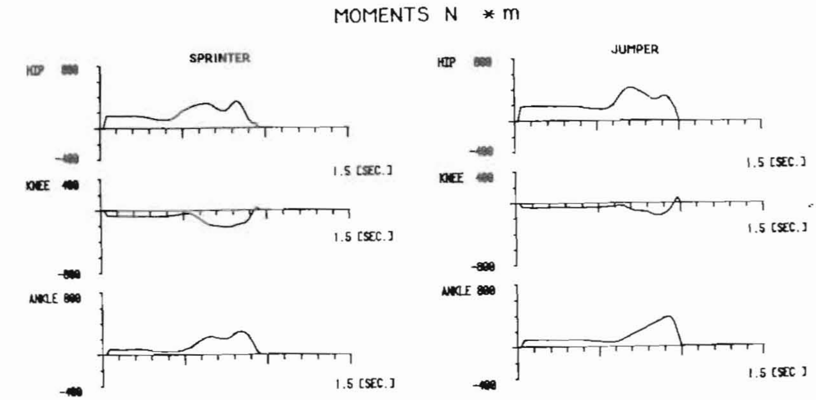

Figure 9 - Moments of hip, knee and ankle joints exerted during vertical jump by sprinter and high jumper.

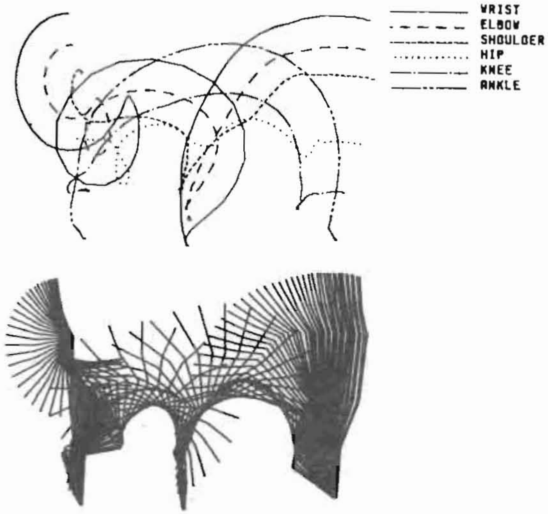

Figure 10 - Trejectories of the markers recorded during the backward somersault of a gymnast and stick representation of the body position. Start position on the left.

- completely different both for time course and amplitude are the muscular actions at the ankle. The sprinter activates the muscles in two phases, while the jumper progressively reach the final maximum.

Gymnastics

In some sport disciplines the goodness of the performance is evaluated through the opinion of a jury. One of these disciplines is gymnastics where the score is defined by the technical difficulty of the exercise and by a visual inspection of its execution. When the movement is very fast and complex it is possible to lose some aspects of the

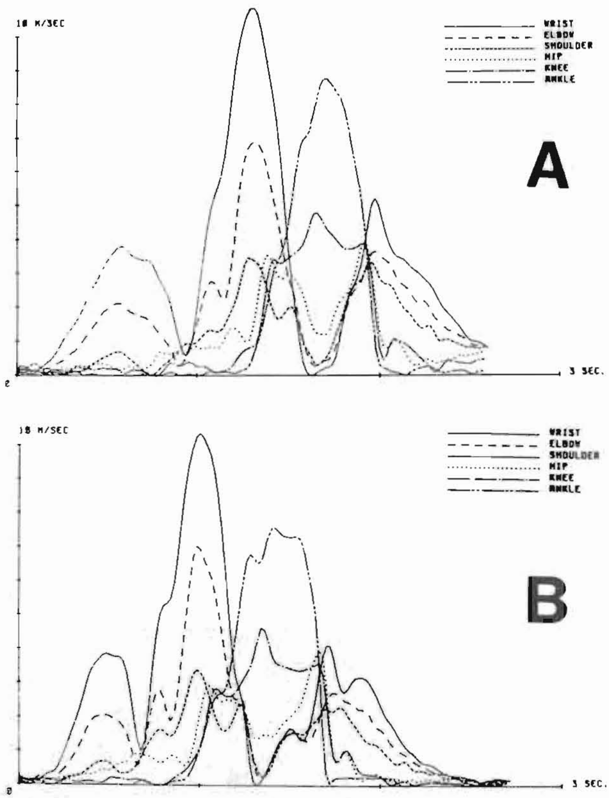

Figure 11 - Velocity (modulus) of the markers of two gymnasts. Both the athlete perform the same movement: backward somersault. The patterns A are tose of the athlete with higher technical level.

fastest phases and to fix one's attention on the slower ones. By this way the final evaluation, in spite of the wide experience of the judges, may be influenced by defective data acquiring. A little bit easier is the task of the coaches as they can inspect many times slow motion filmed pictures to well understand the movement, to find mistakes and to propose new solutions. As previously underlined this approach does not give quantitative information, and the complex interchange of energy among the body segment in movement can not be measured.

The movement in gymnastics are severe tests for an automatic analysis, being hardware and software both deeply stressed.

In fig. 10 the stick diagrams and the trajectories of the markers as recorded with ELITE during a backward somersault of an athlete are reported. Large variations of the segment velocities, superimposition of the trajectories and reversals of body limbs are self explaining. The knowledge of the markers coordinates allows to compute other kinetic quantities. An example of the possible computations is reported in fig. 11 where markers velocities are plotted.

The patterns A are those obtained by the athletes with higher technical capabilities. The analysis of the velocities point out the common motor coordination used to perform the somersault. The distal markers (wrist and ankle) have patterns counter phased. The maximum velocity is reached by the wrist followed by the ankle and this may be explained by the larger mass of the lower limb.

Elbow and shoulder follow the time course of the wrist with reduced peaks of velocity. Similar behaviour is shown by the knee if referred to the ankle marker.
The hip acts as a movement controller: it reaches a first maximum between wrist and ankle maxima, contrarily to the knee shows a minimum at the same time of the ankle maximum, then increase the velocity up to its absolute maximum a little before the maxima of the arms markers.
The level of technical capabilities is confirmed if A and B data are compared. Athlete A prepares the somersault for a longer time (duration of the first arm movement). This probably allows him to perform a faster rotation as the high velocity peaks of wrist and ankle markers suggest. Furthermore athlete A has the basic trend of each velocity less affected by discontinuites, pointing out a more coordinate and smooth execution.

CONCLUSIONS

The use of ELITE system for the analysis of sport movements has been described through some applications. The results here reported that are just a part of those concerning programs of sport research performed at the Bioengineering Center of Milano, allow some considerations:

- the system may be used to inspect a large spectrum of sportive movements as underlined by the wide differences among the examples reported;
- freedom of movement is guaranteed to the athlete;
- the biomechanical parameters described allow, both to researchers and trainers, theoretical and practical analysis of the movement.

By this way ELITE seems to be an optimal instrument for application to sport analysis.

ACKNOWLEDGEMENTS

This work has been partially supported by Centro di Teoria dei Sistemi del CNR, Milano.

REFERENCES

1) H.J. Woltring, "New possibilities for human motion studies by a real time light spot position measurement", Biotelemetry, vol. 1, pp. 132-146, 1974.
2) I.S. Cheng, S.H. Koozekanani, M. Fatchi, "Computer-television interface system for gait analysis", IEEE trans. Biomed. Eng., vol. BME 22, p. 259, May 1975.
3) M.O. Jarret, B.J. Andrews J.P. Pau, "A television/computer system for the analysis of human locomotion", in IERE Conf. Proc., vol. 34, pp. 357-370, 1976.
4) A. Pedotti, "Simple equipment used in clinical practice for evaluation of locomotion", IEEE Trans., vol. BME 24, n. 5, pp. 456-461, 1977.
5) I.S. Cheng, "Computer television analysis of biped locomotion", Ph.D. Dissertatiuon, Dep. Elect. Eng., Ohio State Univ., Columbus, 1979.
6) T. Leo, V. Macellari, "On-line microprocessor system for gait analysis data acqisition, based on commercially available optoelectronic devices", in Biomechanics VII, Baltimore, MD: University Park Press, 1979.
7) H.J. Woltring, E.B. Marsolais, "Optoelectronic (SELSPOT) gait measurement in two and three dimensional space. A preliminary report", Bull. Prosth., vol. 17, pp. 46-52, 1980.
8) G. Ferrigno, A. Pedotti, "ELITE: a digital dedicated hardware system for movement analysis via real-time TV signal processing", IEEE Trans. on Biomed. Eng., vol. BME 32, n. 11, Bov. 1985.