THREE-DIMENSIONAL SPORT MOVEMENT ANALYSIS BY MEANS OF FREE FLOATING TV CAMERAS WITH VARIABLE OPTICS

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INTRODUCTION: Video analysis and off-line manual digitalization is usually used for 2-D and 3-D studies of human movement in sport science. The main advantage of this approach, with respect to the recourse to opto-electronic automatic motion analyzers, is the high flexibility in system set-up, the avoidance of marking procedures and the possibility of successful operation in a wide range of environmental situations. Such features turn out to be particularly important for recordings to be performed in the frame of high-level competition, when the experimental set-up must be adapted to a pre-defined competitive environment, without interfering with the performances of the athletes.
However, when methods proper to conventional close-range photogrammetry are used, most of the advantages offered by the flexibility of video analysis are not obtained. Particularly critical is the restriction of the useful calibrated volume to the field of view made possible by fixed pairs of TV cameras. In this case the useful sequence of images (where the dimension of the acquired subject allows one to limit macroscopic digitalization errors) is often insufficient for the analysis of a complete movement cycle.
This limitation hinders a fruitful application of video analysis in the frame of sport activities (alpine and Nordic skiing, swimming, track and field) in which the execution of the particular technical movement is performed within a large physical space.
A solution to the problem is proposed based on the use of free moving and zooming cameras. The corresponding dedicated software for repeated calibration based on Direct Linear Transformation (DLT)(Abdel Aziz and Karara, 1971) is described.
Results of recording performed in the laboratory are discussed aiming at the validation of the implemented method. The description of the methodology for the recording of sport activities and the presentation of the related results confirm the operational feasibility of the proposed method and the reliability of the resulting quantitative kinematics analysis.

METHODS: The recourse to panning cameras with variable optics implies two methodological consequences. The first is the availability of dedicated software tools for video analysis, specifically developed for repeated TV camera calibration. The second is the evaluation of suitable procedures for setting up the experimental apparatus and the disposition of the control points, in order to assure the highest accuracy in three-dimensional movement reconstruction, with a simultaneous speed of operation for the experiment preparation. In this frame, a dedicated software tool is presented for video analysis with free panning, tilting and zooming

TV cameras. The SW project, realized in C++ for Win16 environment and Win32 compatible, offers the necessary flexibility for separately performing repeated calibrations for each active TV camera. Calibration is performed by means of the DLT method, requiring a minimum of six control points describing a three-dimensional distribution. The calibration procedure can be activated and performed at the same time as the main subject digitalization, by selecting a cluster of points belonging to a unique global set of control points, whose three-dimensional coordinates are previously defined and stored in a plain ASCII file. Each performed calibration is uniquely associated to the specific sequence of frames and exploited during the automatic three-dimensional reconstruction.

Concerning the operational aspects, the requirement of repeated calibration imposes the distribution of references within the global acquisition volume, whose three-dimensional coordinates are known with respect to an absolute reference frame. Our experience, in line with previous results, reveals that the use of geodetic theodolites allows us to speed up the procedure of control points measurement, achieving a suitable trade-off between the effort of acquisition preparation and the methodical advantages of the repeated calibration method. However, it is necessary to have available methodologically validated guidelines and suitable procedures for setting up the experimental apparatus and the disposition of the control points, in order to assure the highest accuracy in three-dimensional movement reconstruction, with a contemporary speed of operation for the experiment preparation.

Accuracy evaluation in three-dimensional marker localization obtained through repeated calibrations has been based on laboratory acquisitions with free panning and zooming cameras capturing a moving rigid body (marked stick). The exploited accuracy index is defined as:

$$Accuracy = (SD / \sqrt{2}) / D_{MAX} * 100$$; (Pedotti and Ferrigno, 1995)

where D_{MAX} is the maximal dimension of the calibrated volume and *SD* is the standard deviation superimposed on the measured distance.

An analogous accuracy analysis has been performed on acquisitions made during Nordic ski competition (skating and classical technique) relative to two high-level athletes. In this case, body segments, supposed to be rigid and to be minimally subject to digitalization errors (segment's extremities always highly visible), have been taken in consideration and the same accuracy index has been calculated along the recording of approximately one movement cycle. Results relative to the right and left shank of both athletes are presented.

In both analyses data were previously filtered by means of a FIR (Finite Impulse Response) procedure (D'amico and Ferrigno, 1989).

RESULTS AND DISCUSSION: Among laboratory records, performed with 2 active TV cameras and characterized by 4 calibrations with 16 control points on each TV camera for a sequence of 36 images, the accuracy of the distance measurement signal was quantified as 0.22% of the maximal dimension of the calibrated volume (2388 mm). A maximal corresponding error of 5 millimeters in the landmark three-dimensional identification is mainly due to digitalization errors and confirms that no bias was induced by the repeated calibrations.

Figure 1 shows the stick diagram representation of half a movement cycle recorded during a Nordic ski high-level competition (skating technique) for an

Italian athlete. Fifty frames are represented (recording sample rate 50 Hz). In this case, for each frame, one calibration was performed, exploiting as control points geodetic references disposed in two parallel lines at each side of the slope. Actual three-dimensional co-ordinates of the control points were measured by means of a geodetic theodolite.

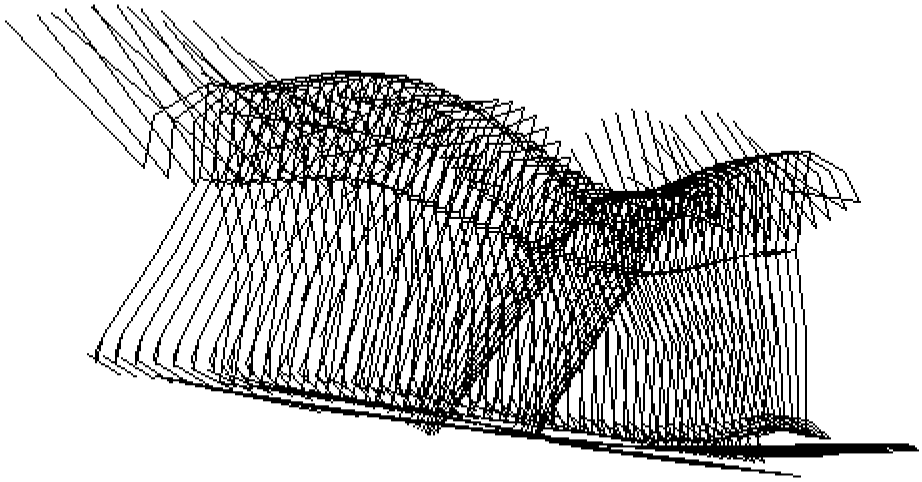

Figure 1. Stick diagram of a Nordic ski skating technique movement cycle

At each frame, a maximal number of 8 control points were included in the field of view of the TV cameras and could be used for the single calibration.
The same recording with the repeated calibration technique was used for the analysis of a second high-level athlete skiing with classical technique during an international competition. In this case, the control points could not be measured by means of a theodolite and were measured with a conventional technique. A maximal number of 13 control points could be used for the frame-by-frame calibrations.
Table I reports the obtained accuracy evaluation results in both cases.

Table 1. Results of accuracy evaluation

Ski technique	Body Segment	Frames	Distance measurement [mm]
Skating	right shank	50	494.4 ± 46.6
Skating	left shank	50	487.9 ± 35.7
Classical	right shank	50	435.6 ± 34.1
Classical	left shank	50	411.7±19.8

Among the reported results, in the worst case (right shank in skating technique) the error was quantified as 0.33% of he maximal calibrated dimension ($\cong 10^3$ mm).
Results confirm that the method of repeated calibrations with a reduced number of control points allows us to obtain an accuracy suitable for the three-dimensional quantitative characterization of the sport performance. The operational advantage during the digitalization process of having available the image of the subject with

considerable dimension allows us to overcome the inaccuracies of the reduced number of control points used for the calibration.

In conclusion, the use of panning and zooming cameras appears to be worthwhile for a systematic application in the analysis of sport activities. However, a suitable trade-off between the quality of the subject's image and the inclusion of a consistent number of control points in the field of view of each active TV camera must be found. In this case, the accuracy of the analysis could be further enhanced by the redundancy of information in the calibration procedure, and the most convenient choice of the control points configuration on each frame could be found (Challis and Kerwin, 1992).

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