Chapter 3

# Image-Based Recording and Analysis Methods for the Assistance of Track and Field Coaches to Improve Athletics Training

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**Abstract**

The aim of the present scoping review was to present the image-based analysis methods that have being utilized to assist Track and Field coaches to observe the technique of their athletes aiming towards the optimization of performance. From the era of early photography till the current innovation of markerless motion analysis, sports and track and field athletes in particular are the field where the technological advances in image capturing and analysis are implemented for both practical, as well as for scientific purposes. The outcome of the blending of technology and sports science is the better understanding of human motion, the exploitation of its movement abilities, and its ideal segmentation when teaching sport techniques that has led to the optimization of sport performance and the identification of the unique prospects of human performance as presented by elite athletes. The chapter is comprised by a short description of the evolution in motion analysis methods, its contribution in the understanding sport techniques, its exploitation to create tools to effectively teach sport technique, and the presentation of the technological innovations that will assist track and field coaches in the future.

## INTRODUCTION

The repetitive, commonly acknowledged manner in which forces are applied in relation with the way the body and its segments move in

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the environment to achieve a specific task is called technique of human movement. While there is a common format for the movement in each sport, an athlete's technique is not something predetermined, common and stable, but something that is constantly changing, depending on the phase of his athletic development (Kollias, 2019).

The teaching of sport techniques in Physical Education, the daily practice in athletics training, as well as for scientific research in sports provoke certain challenges, such as:

- the understanding of the mechanisms involved in the movement of the human body,
- the manipulation of these mechanisms aiming to improve the movement of the human body in the environment,
- the exploitation of the positive effects and/or the minimization of the disadvantages when the human body interacts with the environment,
- the definition, the identification, and the classification of the factors comprising the effective pattern adopted by "talented" individuals that result in the optimized execution of the movement.

The search for the answers in the above questions is suggested to trigger the process to teach sport technique in a way that others could adopt or personalize these factors in order to achieve enhanced performance by executing the desired movement in an efficient manner (Kollias, 2019).

## METHODOLOGY

### METHODOLOGICAL ASPECTS OF SPORT TECHNIQUE TRAINING

Techniques in athletics are complex. It has been suggested that for effectively teaching novices an athletic technique, simple deterministic models should be constructed depicting the basic features of the event (Dick, 1992, see an example in Figure 1). The simplest descriptive model of sport movement takes the form as a simple description. e.g., in the long jump "the athlete runs - steps on the take-off board - jumps - lands with his feet on the sand pit" (Kollias, 2019).

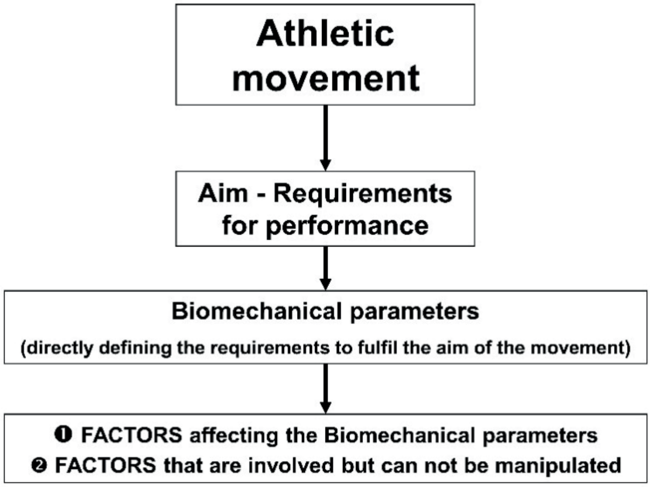


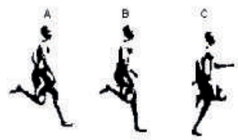

***Figure 1. Flow chart of the elements to construct a deterministic model (adopted from Kollias, 2019).***

The visualization (commonly in the form of demonstration, Rink, 2006; Silverman, 1991) and feedback (Gallahue & Donnelly, 2003) are embedded in the learning process. Due to the complexity of athletics technique, errors are common. Thus, their identification and actions to correct them are essential in the training process. Error analysis is a process that includes movement observation and error analysis, as well as the identification-interpretation-correction of technical errors by the coach (Martin, Carl, & Lehnertz, 1993). For this reason, effective methods to ensure an objective control and error correction are necessary (Matveyev, 1981). However, the high speeds at which the movements of the body parts are carried out to perform the sports technique have made the use of visual media an essential training tool (Tidow, 1989). Athletics coaches are highly recommended (Schmolinsky, 1983) to present a series of photographs or films, both for learning and for the evaluation of their athletes' technique. Recent research revealed that this approach is effective (Kyriakidis et al., 2022a; 2022b). Nevertheless, the implementation of the results of biomechanical reports of elite athletes to novices or lower-level athletes without "filtering" this information through the model depicted in Figure 1 is not the most appropriate approach to effectively use the image-based information in the training/learning process.

For the aid of the coaches in practice, the concept of Model Technique Analysis Sheet (Figure 2) was proposed (Tidow, 1989). The Model Technique Analysis Sheet is comprised by the structure (namely, the phases of the technique) of the movement with the corresponding illustrations (sketch or photograph) and a short description (containing the appropriate criteria) of the ideal technique (Tidow, 1989). A phase of the technique is defined as a complete movement that begins at some characteristic time instant, ends at another characteristic time instant and has a specific purpose, with the above being common to all (e.g., the approach in the long jump - Kollias, 2019). An important factor for the efficient use of the Model Technique Analysis Sheet is to provide the ability for immediate feedback and for iterative execution based on a goal. For this reason, the description of exercises and criteria must be clear, with short sentences and simple-to-understand terminology (Panoutsakopoulos & Kollias, 2008). For the construction of criteria assessment form, suitable for the evaluation of the phases of the technique, the following steps are required (Ferro Sánchez & Floría Martín, 2007, Panoutsakopoulos & Kollias, 2008):

- the collection of information regarding the movement,
- the definition of the aim of the movement in terms of an objective evaluation,
- the distinction of movement into distinct, separate phases,
- the determination of the biomechanical parameters fulfilling the aim of each phase,
- the identification of the critical elements used by coaches to improve the technique their athletes,
- to match the coaches' critical elements with specific biomechanical parameters,
- to set the evaluation criteria for each variable
- the determination of the form of documenting the results of the observation.

**MODEL TECHNIQUE ANALYSIS SHEET 2.1: SPRINT RUNNING**

| SPRINT RUNNING | PHASE | CODE | REFERENCE | CRITERION ASSESSMENT |
|---|---|---|---|---|
|   | (1) FRONT STANCE PHASE | AB1 | Lead leg | Active movement downwards/"*pawing motion*" |
| | | B2 | Lead foot | Compliant support/"*active*" |
| | | B3 | Foot | Touchdown at the front part/near the projection of the body center of mass (BCM) |
| | | C4 | Heel | Recedes slightly/no ground contact |
| | | C5 | knee | Slight flexion |
| | | C6 | Hips | Fast movement over the stance point |
| | | ABC7 | Torso | Almost vertical (forward lean 5°-10°)/Torso, head and shoulder muscles: relaxed |
| | | ABC8 | Upper limbs | Contralateral swing in the sprinting direction/ elbows: 90° flexed/movement is generated from the shoulders |
|   | (2) REAR STANCE PHASE | DE9 | Support leg | explosive push-off/effort to avoid great vertical BCM displacement |
| | | DE10 | Support leg | Ankle, knee, and hip joints extend |
| | | F11 | Support leg - knee | Not fully extended |
| | | DEF12 | Duration of impulse | The shortest possible |
| | | DEF13 | Torso | Almost vertical (forward lean 5°-10°)/Torso, head and shoulder muscles: relaxed |
| | | DEF14 | Upper limbs | Contralateral swing in the sprinting direction/elbows: 90° flexed/movement is generated from the shoulders |
|   | (3) REAR SWING PHASE | GH15 | Rear leg | Movement forward and upwards/relaxed |
| | | HI16 | Knee | Flexed |
| | | I17 | Heel | Near the glutes |
| | | GHI18 | Swing leg | Fast swing forward |
| | | GHI19 | Torso | Almost vertical (forward lean 5°-10°)/Torso, head and shoulder muscles: relaxed |
| | | GHI20 | Upper Limbs | Contralateral swing in the sprinting direction/ elbows: 90° flexed/movement is generated from the shoulders |
|   | (4) FRONT SWING PHASE | J21 | Swing leg - thigh | Fast upward lift |
| | | K22 | Swing leg - thigh | 15°-25° lower than the horizontal level |
| | | KL23 | Swing leg - shank | Fast forward movement/relaxed |
| | | KL24 | Swing leg - foot | Fast forward movement/relaxed |
| | | L25 | Swing leg - thigh | Downward movement/preparation for active landing/movement is generated from the hips |
| | | L26 | Swing leg - shank | Downward movement/preparation for active landing/no kicking action |
| | | L27 | Swing leg - foot | Downward movement/preparation for active landing/toes point upwards |
| | | JKL28 | Torso | Almost vertical (forward lean 5°-10°)/Torso, head and shoulder muscles: relaxed |
| | | JKL29 | Upper limbs | Contralateral swing in the sprinting direction/ elbows: 90° flexed/movement is generated from the shoulders |

*This Model Technique Analysis Sheet was created based on Kartalidis & Papaiakovou (2000) and Saraslanidis (2007)*

***Figure 2. Model Technique Analysis Sheet (with permission from Panoutsakopoulos & Kollias, 2008).***

The main advantages of the creation of Model Technique Analysis Sheet for the evaluation of the techniques are (Ferro Sánchez & Floría Martín, 2007; Panoutsakopoulos & Kollias, 2008):

- the "translation" of the biomechanical parameters into "coaching language",
- the objective evaluation of the technique,
- the ability to gather all the information that exists in the literature, thus contributing to the provision of new solutions to a specific movement problem,
- the possibility of choosing goals for conducting the training/learning process with the method of mutual teaching and the method of self-control,

- the possibility of using the Model Technique Analysis Sheet to apply interdisciplinarity in the training/learning process (e.g., understanding the factors that influence the long jump and what kind of training should be done through the retraction of the principles of Physics taught in Education).

From the above, support is provided to the argument that images that are recorded either as photos or as videos or even extracted from image-based recording and analysis systems are of importance for the training process in track and field and, consequently, in the augmentation of performance in the athletics events.

## METHODOLOGICAL ASPECTS OF IMAGE-BASED RECORDING AND ANALYSIS METHODS

A vast percentage of the obtained information obtained by humans are images and technology aids the perception of information in a direct and objective manner (Xu & Chen, (2022). It is not paradox that contemporary scholars study and debate on the identification of the track and field techniques in the antiquity using as reference the sport related depictions of ancient athletics that serve as artistic work on ancient amphoras, kylixes, kraters, tondoes, cups, etc. - Maras, 2017; Mouratidis, 2012).

There is a variety of both measurement systems and analyses methods. However, the instrumentation to record and analyze athletics techniques should be affordable, valid, reliable and objective (Kollias, 2019). Regarding the analysis methods, it is extremely difficult to conduct analysis during an athletics event using image-based analysis methods, as the instrumentation should be placed in locations not interfering with the competitors and judges, the calibration procedure cannot be conducted during the event, the environmental factors may not favor the recording, and athletes might not consent to the measurement. Under this perspective, the image-based recording and analysis methods are epigrammatically presented.

Photography

Initially, photography is the exact representation of an object that is depicted on a light-sensitive material in the form of an image (Kollias, 2019). Nowadays, digital photographs are created by computer-based photoelectric and mechanical techniques that exploit the arrays of electronic photodetectors of the digital cameras. As digital cameras are embedded in smartphones, digital photography can be considered as the most affordable image-based recording and analysis method for assisting coaches to capture, evaluate, identify the technical errors and provide feedback related to the technique to their athletes. Nevertheless, the use of photography to assess athletics technique is replicating the same problem to coaches as scholars studying sports in antiquity: the still image can be circumstantial and random at the same time, thus depriving the opportunity to either get the information for the specific phase of the technique or getting an abstract segment of the desired information (Figure 3).

***Figure 3. Single photo of middle distance runners. For the leading runner, the flight phase is recorded. For the trailing athlete, the instant before the midstance is shown. If the case was to study the runners regarding the technique elements of the push-off phase and to assess their technique using a Model Technique Analysis Sheet, this photo was not depicting the desired information for both runners.***

The problem imposed by the single photography can be partially solved by using either the continuous shooting mode (mentioned also as burst shot) or using strobe photography. The former allows the recording of multiple images at once. This enables the capability to acquire images containing the desired depiction of the technical elements of interest with a greater chance (Figure 4). An early example of this concept by Eadweard Muybridge in the 19th century can be viewed at http://en.wikipedia.org/wiki/Eadweard_Muybridge.

***Figure 4. Images acquired using the continuous shooting model (60 pictures/s; this synthesis contains every 15th photo taken).***

The strobe photography is the blending of photos depicting the movement into a single image (Figure 5). It can be created by either merging a series of continuous photos by overlaying all the photos in one, or either capturing an image using a device commonly called as strobe, which is used to produce regular flashes of light, giving the impression of acquiring the movement in slow motion. This photographic technique was developed in the 1930s and required the execution of the movement in a dark room where strobe lighting was periodically illuminating the place by flashing up to several hundred times/s (Kollias, 2019). Beside the awkwardness to perform an athletics technique in a dark room, the frequent alterations of darkness and bright flashing could result to discomfort, disorientation, and consequently, to injury.


*Figure 5. Strobe photography of the hurdle clearance. As the markers are placed in pre-defined positions, spatial parameters can be extracted. Also, joint angles can be measured. This strobe image was created using the APAS Wizzard v.1.2.59 software (Ariel Dynamics Inc., Trabuco Canyon, CA).*

Another strobe photography technique used in the past was to attached lights (i.e., "active markers") on specific joints and to record, via continuous photos, their trajectory. This technique required capturing images in dim light or a dark room, a "slow" photographic film (i.e., 16-19 DIN) and batteries attached to the body (Kollias, 2019). All these factors again result in discomfort and to the inability to perform the technique optimally. Finally, a disadvantage of the strobe photography by blending the continuous photos into one is that the background should not be altered during the capturing of the series of photos. In addition, although the fact of capturing the technique in more time-instances, the same limitation as the single photograph applies, as it is possible to miss recording the desired image. Blending additional images from the series of continuous photos might not solve these mishaps, as then the image gets blur due to the overlaying the images on each other that eventually results to the difficulty to identify the body segment with the corresponding time instance.

In general, due to the disadvantages and the limitations of the photographic methods to capture and to analyze athletics technique, their usage is limited for qualitative approaches or artistic depictions of sport movement.

Cinematographic- and video-recording methods

The motion-based analysis methods are based on the fact that the recordings accurately capture the movement in a predetermined rate (Kollias, 2019). Thus, the motion can be “freezed” and a detailed observation can be conducted by the frame-by-frame viewing of the recordings. In addition, the basis of these methods, namely the spatiotemporal depiction of the recorded movement, provides the ability to conduct a kinematical analysis on the planar plane (2D) or even in the 3D space (Figure 6).

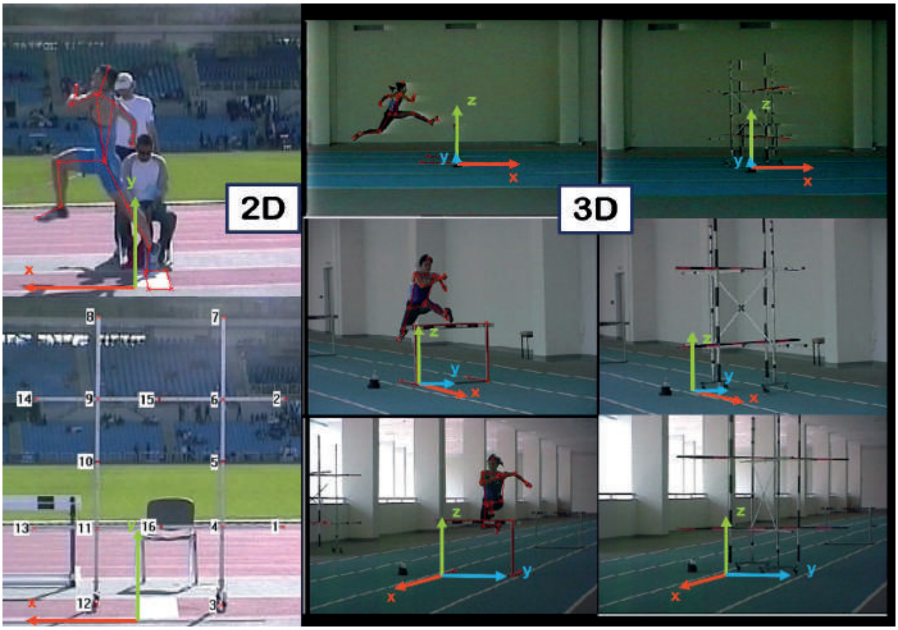



***Figure 6. Views, axis of movement and calibration for 2D-DLT and 3D-DLT kinematic analysis.***

As a furhter technological step to the work of Muybridge, cinematography was used. The main advantages of cinematography compared to photography was the increased sampling frequency, the resolution and the ability to study the athletic technique as it evolves spatiotemporaly. At first, their sampling frequency was not satisfactory, but this was improved over time. Nevetheless, there were some disandvantages: i) the motor that rotated the film to capture high-speed cine-film was noisy and this imposed possible troubles when recording athletes in competition, ii) there was no instant reviewing of the captured film (i.e., if the view of recording recorded the whole ranged of the motion of interest), as the film could not be developed on cite, and iii) the analysis of the recorded film required additional equimpent such as the projection machine and the digitizer (Kollias, 2019).

To overcome some of the above-mentioned problems that characterized the cinematographic recording and analysis of athletics technique, the video-recording method emerged in the 1980s. It was cheaper, more user-friendly and less time consuming in terms of the time-gap from recording to the initiation of the analysis (Kollias, 2019). At first, the resolution of the recorded videos and the size of the depicting object of interest in the image were lower than the cinematographic method and researchers debated whether the video-based analysis techniques were comparable in terms of accuracy to cinematographic methods (Angulo & Dapena, 1992; Kennedy, Wright, & Smith, 1989). The technological innovations regarding the improvements in the resolution (both in the recording camera and the display screen for the digitization) and the sampling frequency, besides the elimination of the barrel-like distortion of the image with the use of flat screens, led to the abandonment of cinematography.

Along with the technological innovations, researchers developed techniques to record and analyze athletic movement not only with stationary cameras, which is the standard method to conduct the recording and the analysis of sports movement, but with panning cameras (Figure 7) as well (Gervais et al., 1989; Yu, Koh, & Hay, 1993).

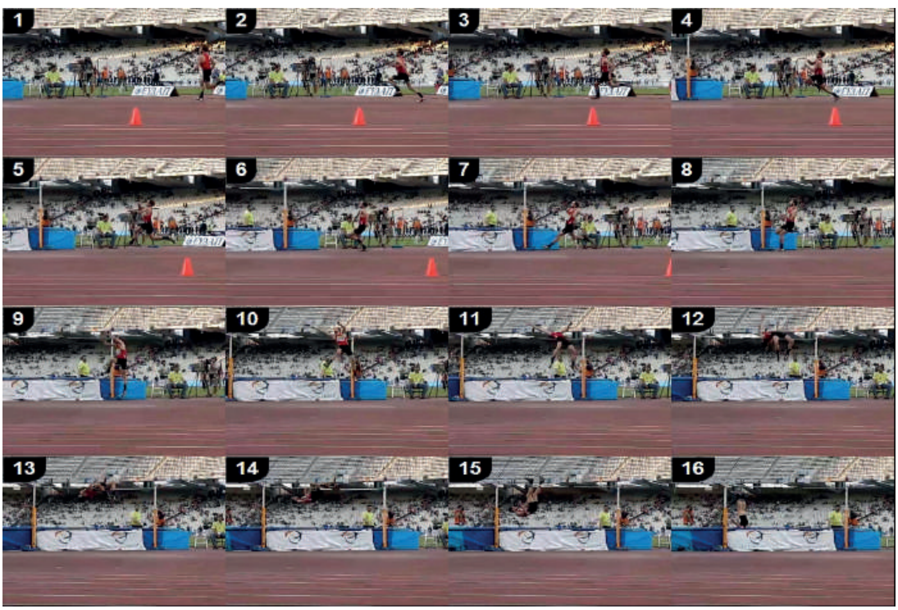



***Figure 7. Summary of a video recorded with panning technique. The sequence was created using the Kinovea 0.9.4 (©2021: Joan Charmant and the Kinovea Community) software.***

Motion analysis systems

As already described, the imaged-based recording and analysis methods are related to the technological advances. One such advance was the introduction of optoelectronic motion capture systems. A series of sophisticated cameras that emit invisible infrared light trace constantly within the recording space (i.e., "volume") the reflective markers (i.e., "passive markers") that attached to the object/examinee at predefined points (Figure 8). The coordinates of these points (joints and segments) are automatically stored in a computer. Then, the motion analysis system provides an estimation of the position and pose (orientation) of the examinee across image sequences. The greatest advantage of the motion analysis systems is that the kinematic parameters that interpret the examined movement is almost immediately available (Kollias, 2019). This is because of the automatization of the system compared to the manual, field by field, digitizing of the anatomical points and other markers of interest in the cinematographic- and video-recording methods (Colyer, Evans, Cosker, & Salo, 2018).

***Figure 8. Reflective marker positioning on a participant in a pilot study using an optoelectronic motion analysis system in an indoor track. The study examined the resisted sprinting biomechanics when pulling a weighted sled.***

Despite the disadvantage of the possible marker misalignment with the joint in the case of rapid movements, the accuracy of the optoelectronic motion capture systems is documented (Richards, 1999; Topley & Richards, 2020) and found to be superior compared to other motion analysis systems (Van der Kruk & Reijne, 2018). However, the optoelectronic motion capture systems are mostly designed for the indoor measurements of slow movements conducted in a limited space; all circumstances that are not characteristic of sport (Van der Kruk & Reijne, 2018) and track and field in particular. In addition, these systems cost considerably higher than the previously mentioned analysis methods. Among other disadvantages, markers need to be attached on the athletes with the above-described discomfort, resulting in limited use of this method during competition. In addition, a considerable time to prepare the examinee is required in order to attach the markers (Colyer et al., 2018).

Markerless Motion Analysis Systems

The latest innovation in the field of image-based recording and analysis methods is the automatic, non-invasive, markerless motion capture systems. An advantage of the markerless motion analysis systems is that there is no use of markers that may provoke discomfort and disturbance in the execution of the sport technique (Kollias, 2019). Another advantage is the availability to retrieve information both indoors and outdoors, during training and competition, in testing and in general in any aspect of the training procedure. The major elements of a markerless motion analysis system are the camera systems, the body model, the image features used and calculation (algorithms) of the shape, pose, and location of the object of interest. However, in order markerless motion analysis systems to provide accurate results, the same mishaps are recorded alike the optoelectronic motion capture systems, added the high-resolution cameras required to assist the identification of the body segments. Readers are referred to the work of Colyer et al. (2018) for an in-depth presentation of this technology.

## RESULTS

Regardless the image-based recording and analysis method, coaches can be benefited by retrieving both qualitative and quantitative information.

Qualitative analysis

In terms of the qualitative assessment of athletics technique, coaches can compare the image(s) depicting their athletes with the ideal technique presented in a Model Technique Analysis Sheet.

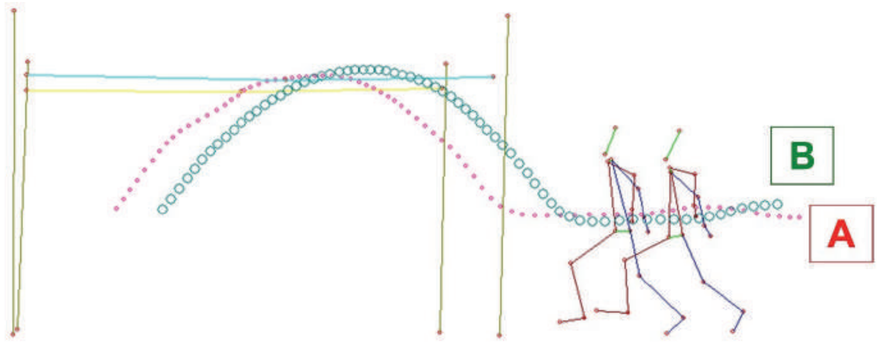



***Figure 9. Stickfigures of the same high-jumper in a longitudinal biomechanical analysis of his technique. The 3D-DLT analysis was conducted using the APAS v.14.1.0.5 software (Ariel Dynamics Inc., Trabuco Canyon, CA).***

In this concept, not only a picture, but also a stick-figure, either by itself, or over-imposed with another stickfigure (Figure 9) and/or on a captured image of the athlete's technique (Figure 10), could add details in the information provided to the coaches. It can be also a useful tool to provide feedback to his/her athletes.

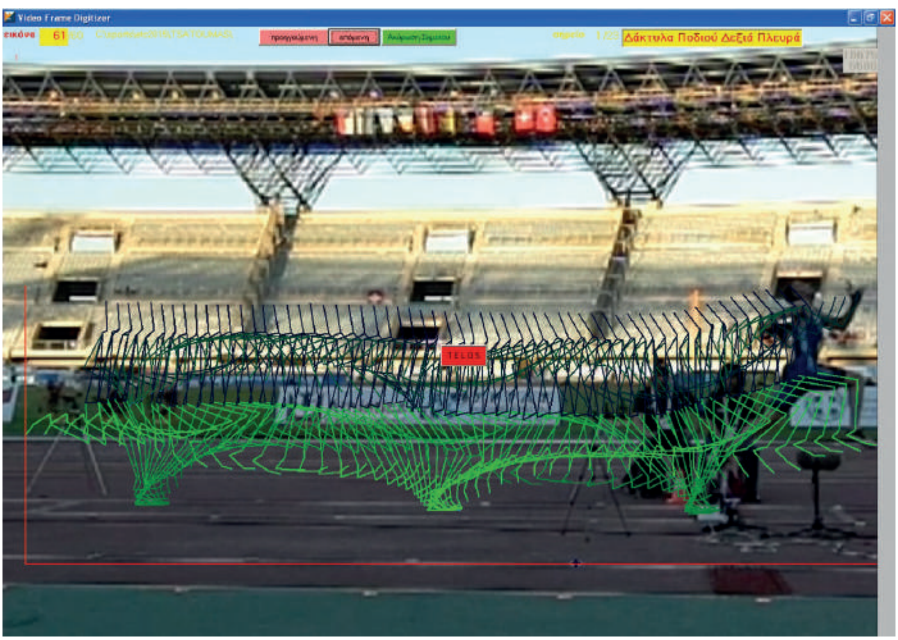



***Figure 10. Stickfigure imposed on a field of the video used to conduct the 2D-DLT analysis using the K-Motion v.15 software (Kinvent, Orsay, France).***

Quantitative analysis

When considering the quantitative information that can be given to track & field coaches, kinematic analysis can take the form of presenting values in a form of a table, graph, and/or combined in an infographic material (Figure 11). In addition, the results can be depicted in graphs in relation with previous results of the same athlete or other athletes for a comparison and ranking. Another form of presentation is the time-curve of a parameter of interest. Finally, the deterministic model as presented in Figure 1 can be enriched by providing the correlation/regression scores of a certain athlete after analyzing a cohort of his/her attempts (Figure 12).

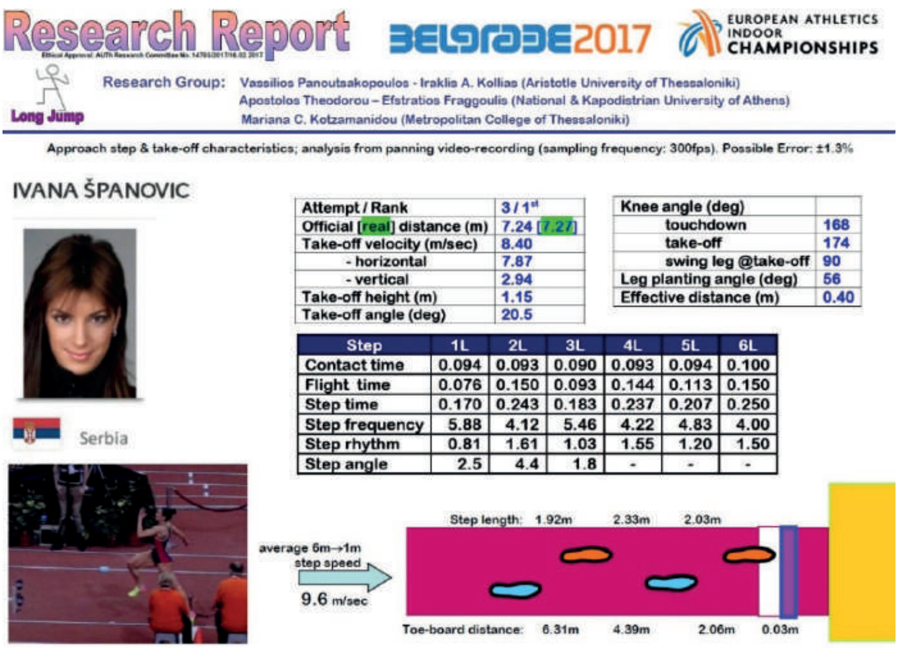



***Figure 11. Summary of a qualitative report of a video-based kinematic analysis conducted for attempts performed in a major athletics competition.***

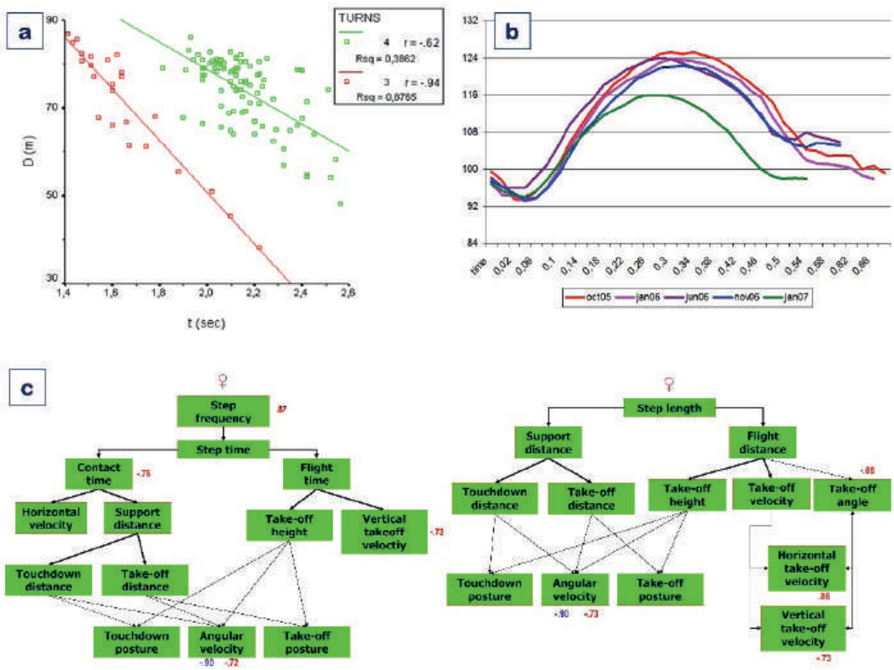


*Figure 12. Forms of providing quantitative information to coaches: a) comparison and ranking of hammer throw distance related to the duration of the throw, b) longitudinal time-curves of the body center of mass height during the hurdle clearance of a female hurdler (84 cm hurdle), and c) correlation coefficients of the factors comprising a deterministic model for sprinting (adapted from Hunter, Marshall, & McNair, 2004) with the 100 m sprint times of a female sprinter.*

## DISCUSSION

The image-based recording and analysis methods are beneficial for monitoring the evolvement of the athletics technique and can contribute to the augmentation of performance by optimizing the biomechanics of the sport movement, as well as by identifying technical errors with the potential risk of the ineffective exploitation of the athlete's capabilities or/and of provoking an injury. The technological advances provide affordable innovations and accurate instruments, with multidisciplinary applications that assist coaches to optimize the training process.

Despite the world-wide growing use of image-based recording instruments primarily among the track and field coaches' community and secondarily the seek for scientific evaluations with image-based analysis systems, some factors should be indicated for the optimal selection of the approach to acquire the desired information (Kollias, 2019):

- the trajectory of the movement: a basic analysis of the horizontal jumps and the sprinting/running events consider the movement as linear, thus just a camera is used and a 2D kinematic analysis is adequate to retrieve the desired information. However, if a large series of strides is the topic to retrieve useful information, then additional cameras are needed. In addition, if a rotation of the body or of a body segment or of an implement occurs in another plane of motion, then the technique in question should be examined with a 3D kinematic analysis, in which at least two (2) cameras are required. These alterations result in differences in the cost of the analysis and the time required to obtain the necessary results.
- the speed/frequency in which the movement is performed: the sampling frequency of the image-based capturing system should be in alignment with the duration of the investigated technique phase. For example, the support phase and the take-off in the sprint, jumping and high-hurdles events ranges from 0.08 to 0.18 s. Thus, the evaluation of the technique at this phase requires and adequate number of images. The common mobile phone camera's sampling frequency is 30 fps. In the above-mentioned example, this image-based capturing system can record just 3 to 6 images that are rather a small sample to extract accurately kinematic parameters such as linear velocity. Thus, a more specific and advanced camera is needed, that is more expensive, along with a reliable image-based analysis system.
- Recordings can be conducted during practice, but preferably during competition, where is believed that the optimization of performance occurs (Christensen, 2004). The successful recording assumes the knowledge of the proper settings of the motion analysis system, the avoidance of any obstructions in the field of view of the recording camera(s), and the effort to keep the background as neutral as possible.

Another topic is the compatibility of the image-based recording and analysis system with other measuring instruments, i.e., force-plates, electrodes for electromyography, spirometer, electrogoniometers, inertial measuring units, etc. The holistic approach of the examination of sport performance, although intriguing when multiple factors are considered, provides an ecological depiction of the concurrent status of the athlete and thus valid feedback for both coaches and practitioners.

To conclude, it is not an exaggeration to suggest that image-based recording and analysis methods are the basis for the introduction, progression, and maximization of performance in athletics via the visualization of the technical execution of the specific athletics technique, since humans are based on visual information to perceive. At this point, a couple of facts should also be mentioned. Firstly, despite the major importance of visual cues in athletics, an alternative approach should be followed when training visually impaired athletes, despite they were found to perceive time-to-contact to the take-off area regardless of the level of visual acuity (Panoutsakopoulos et al., 2015). Secondly, technology is rapidly involving in other measurement and assessment technologies such as inertial sensory, ultrasonic localization, and electromagnetic measurement systems (Van der Kruk & Reijne, 2018). Although different technologies compared to the motion analysis systems, their feasibility and affordability could add tools from which track and field coaches could benefit.

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## References

Angulo, R. M., & Dapena, J. (1992). Comparison of film and video techniques for estimating three-dimensional coordinates within a large field. *International Journal of Sport Biomechanics*, *8*(2), 145-151. https://doi.org/10.1123/ijsb.8.2.145

Christensen, B. (2004). Individual biomechanical profiles of changes in technique between practice and competition in seven collegiate pole vaulters. In M. Lamontagne, D. G. E. Robertson, & H. Sveistrup (Eds.), *Proceedings of the 22nd International Conference of Biomechanics in Sports* (pp. 527–530). Ottawa: I.S.B.S.

Colyer, S. L., Evans, M., Cosker, D. P., & Salo, A. I. (2018). A review of the evolution of vision-based motion analysis and the integration of advanced computer vision methods towards developing a markerless system. *Sports Medicine-Open*, *4*(1), 1-15. https://doi.org/10.1186/s40798-018-0139-y

Dick, F. W. (1992). *Sports Training Principles* (2nd ed.). London: A & C Black Ltd.

Ferro Sánchez, A., & Floría Martín, P. (2007). Biomechanical applications of sport training based on qualitative and quantitative analysis. A purpose of discus throwing. *International Journal of Sport Science*, *7*, 49-80. https://doi.org/10.5232/ricyde2007.00705

Gallahue, D. L., & Donnelly, F. C. (2003). *Developmental physical education for all children* (4th ed.). Champaign, Il: Human Kinetics.

Gervais, P., Bedingfield, E. W., Wronko, C., Kollias, I., Marchiori, G., Kuntz, J., Way, N., & Kuiper, D. (1989). Kinematic measurement from panned cinematography. *Canadian Journal of Sports Science*, *14*(2), 107-111.

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2004). Interaction of step length and step rate during sprint running. *Medicine and Science in Sports and Exercise*, *36*(2), 261-271. https://doi.org/10.1249/01.MSS.0000113664.15777.53

Kennedy, P. W., Wright, D. L., & Smith, G. A. (1989). Comparison of film and video techniques for three-dimensional DLT repredictions. *International Journal of Sport Biomechanics*, *5*(4), 457-460. https://doi.org/10.1123/ijsb.5.4.457

Kollias, I. A. (2019). *Biomechanics of Sport Movement*. Thessaloniki: Kyriakidis Bros Publishers.

Kyriakidis, G., Chatzopoulos, D., Paraschos, I., Panoutsakopoulos, V., Kollias, I. A., & Papaiakovou, G. I. (2022a). The effect of blended learning new technologies and direct video feedback on the long jump technique in primary school students. *International Journal of Human–Computer Interaction*, *38*(6), 529-540. https://doi.org/10.1080/10447318.2021.1952378

Kyriakidis, G., Panoutsakopoulos, V., Paraschos, I., Chatzopoulos, D., Yiannakos, A., & Papaiakovou, G. (2022b). The impact of blended learning and direct video feedback on primary school students' three-step ball throwing technique. *International Journal of Computer Science in Sport*, *21*(2), 43-68. https://doi.org/10.2478/ijcss-2022-0010

Manas, A. (2017). On the jump of the ancient pentathlon. *International Journal of the History of Sport*, *34*(15), 1701-1702. https://doi.org/10.1080/09523367.2017.1413629

Martin, D., Carl, K., Lehnertz, K. (1993). *Handbuch Trainingslehre*. Schorndorf: Verlag Hofmann.

Matveyev, L. (1981). *Foundamentals of Sports Training*. Moscow: Progress Publishers.

Mouratidis, J. (2012). *On the jump of the ancient pentathlon*. Hildesheim: Weidmannsche Verlagsbuchhandlung.

Panoutsakopoulos, V., & Kollias, I. (2008). *Track and Field Technique Assessment Sheets* (Vol. 1). Thessaloniki: Aristotle University of Thessaloniki Publishing Service.

Panoutsakopoulos, V., Theodorou, A., Kotzamanidou, M. C., Skordilis, E., Plainis, S., & Kollias, I. A. (2015). Influence of visual impairment level on the regulatory mechanism used in the long jump. *New Studies in Athletics*, *30*(4), 17-31.

Richards, J. G. (1999). The measurement of human motion: A comparison of commercially available systems. *Human Movement Science*, *18*(5), 589-602. https://doi.org/10.1016/S0167-9457(99)00023-8

Rink, J. (2006). *Teaching physical education for learning* (5th ed.). Boston, MA: McGraw-Hill.

Schmolinsky, G. (1983). *Track and Field*. Berlin: Sportverlag.

Silverman, S. (1991). Research on teaching in physical education. *Research Quarterly for Exercise and Sport*, *62*(4), 352-364. https://doi.org/10.1080/02701367.1991.10607533

Tidow, G. (1989). Models for teaching techniques and assessing movements in athletics. *New Studies in Athletics*, *4*(3), 43-45.

Topley, M., & Richards, J. G. (2020). A comparison of currently available optoelectronic motion capture systems. *Journal of Biomechanics*, *106*, 109820. https://doi.org/10.1016/j.jbiomech.2020.109820

Van der Kruk, E., & Reijne, M. M. (2018). Accuracy of human motion capture systems for sport applications; state-of-the-art review. *European Journal of Sport Science*, *18*(6), 806-819. https://doi.org/10.1080/17461391.2018.1463397

Xu, S., & Chen, J. (2022). Application of multiprocessing technology of motion video image based on sensor technology in track and field sports. *Computational Intelligence and Neuroscience*, *2022*, 4430742. https://doi.org/10.1155/2022/4430742

Yu, B., Koh, T. J., & Hay, J. G. (1993). A panning DLT procedure for three-dimensional videography. *Journal of Biomechanics*, *26*(6), 741-751. https://doi.org/10.1016/0021-9290(93)90036-E