INSTRUMENTATION AND MEASUREMENT METHODS APPLIED TO BIOMECHANICAL ANALYSIS AND EVALUATION OF POSTURAL STABILITY IN SHOOTING SPORTS

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The main problem of sport technique in precision sports consists in maintaining the body segments as stable as possible in position and orientation. Experimental data in shooting sports proved that the posture that shooters adopt is mechanically unstable as consequence of the interactions among the body segments. In this way shooters and archers try to make their posture more consistent and reproducible reducing the variability of their actions during the aiming and shooting. The object of this study is to present the basic consideration respect to biomechanical analysis and evaluation of postural stability in shooting sports. The proposed theoretical model and the designed measurement chain composed of a sonic digitizer, a force plate and an EMG system seems to be an efficient tool in order to describe and evaluate postural stability.

KEY WORDS: biomechanics, instrumentation, postural stability, shooting sports

INTRODUCTION: Sport Biomechanics one of the main fields of Biomechanics of Human Movement is in continuous expansion and consolidation in the wide field of Sport Sciences. Biomechanics of Human Movement is an interdisciplinary science that, with the support of other Biomedical Sciences, uses the knowledge of mechanics and different technologies to study the human body behavior under the mechanical loads that it can be subjected to. The development of Biomechanics, mainly during the second half of the last century, is consequence of its progressive applications in the fields medical and occupational and also in sports analyzing technique and designing sport gear of high quality. Nowadays, many applied research projects are orientated to the evaluation of the athletes' technique in the totality of the sports and sport modalities. Also, scientific research has contributed to design sport equipment with the highest quality standards. Furthermore the development of better measurement systems and/or instrumentation chains enables researchers to quantify with much more precision the biomechanical efficiency in sport activities, identifying the main characteristics of the most productive individual technique, the trainable factors that influence on the performance, and, the mechanical loads on muscle-skeletal system. Finally, the conception and design of technical solutions and aids for disabled help them to compete improving their quality of life. Methodological advances in Sport Biomechanics (Photo-instrumentation techniques, Force Plates, EMG, Modeling and Simulation techniques, etc.) allow for reaching a considerable level of scientific knowledge respect to the motor patterns displayed in most sport activities. However there are not so many research projects applied to the analysis and evaluation of sport technique in the precision sports, namely, shooting and archery. Even if more than thirty medals of the Olympic Program are shared among their modalities.

POSTURAL STABILITY: Shooting is a fine, steady and coordinated action of many physiological organs, like the visual organs, the proprioceptors, the motor effectors and systems like the neurogenic, respiratory, cardiovascular, endocrinous and locomotor system. Unlike to most sport activities, target sports like shooting and archery, require the elimination of any movement that could perturb the stability of the system shooter-gun/bow (S-G/B), to achieve the best performance on the target. According to many trainers, athletes and training books, postural stability is one of the most important factors that influence on the performance. In its turn postural stability is consequence of the interaction of the gravity with the mechanical properties of the locomotor system and the control process during aiming (Fig. 1). Despite the physiological or biomechanical factors that could deteriorate their performance elite athletes exhibit a surprisingly high degree of precision and very fine control.

Experimental data proved that the adopted by athletes posture is mechanically unstable as consequence of interactions among the body segments (Gianikellis et al. 1999). Therefore the *"fine tuning"* of the movements at different joints is required in order to balance their posture eliminating degrees of freedom at the joints. As far as it is known the most original scientific endeavour to improve postural stability in shooting is described in the book *"On the center of gravity of human body as related to the equipment of the German infantry soldier"* (Braune and Fischer, 1895). However, up to now, there is no answer to the question *"How the vertical posture is maintained and how it is related to voluntary limb movements"*. In the research studies on the control of the vertical posture the human body is sometimes modelled as an inverted pendulum (Gurfinkel and Osovets, 1972; Hayes, 1982) that is not easy to equilibrate, especially in the presence of external perturbations (Fig.1). However the problem is much more complex due to the presence of a great number of joints and the direction of body segments oscillations. However the *"fine tuning"* that makes sure that the projection of the centre of gravity falls within the area of support is very close to the concept of *"synergy"*. Bernstein established some theoretical bases defining synergy as built-in co-ordinated sequences of motor commands to a number of joints leading to a desired common goal. The presence of synergies could be considered that simplify the control of vertical posture and of the aiming process, solving (at least partially) the problem of mechanical redundancy. Postural synergies are frequently described as combinations of muscle activation patterns for a given perturbation and modulated by local sensory information.

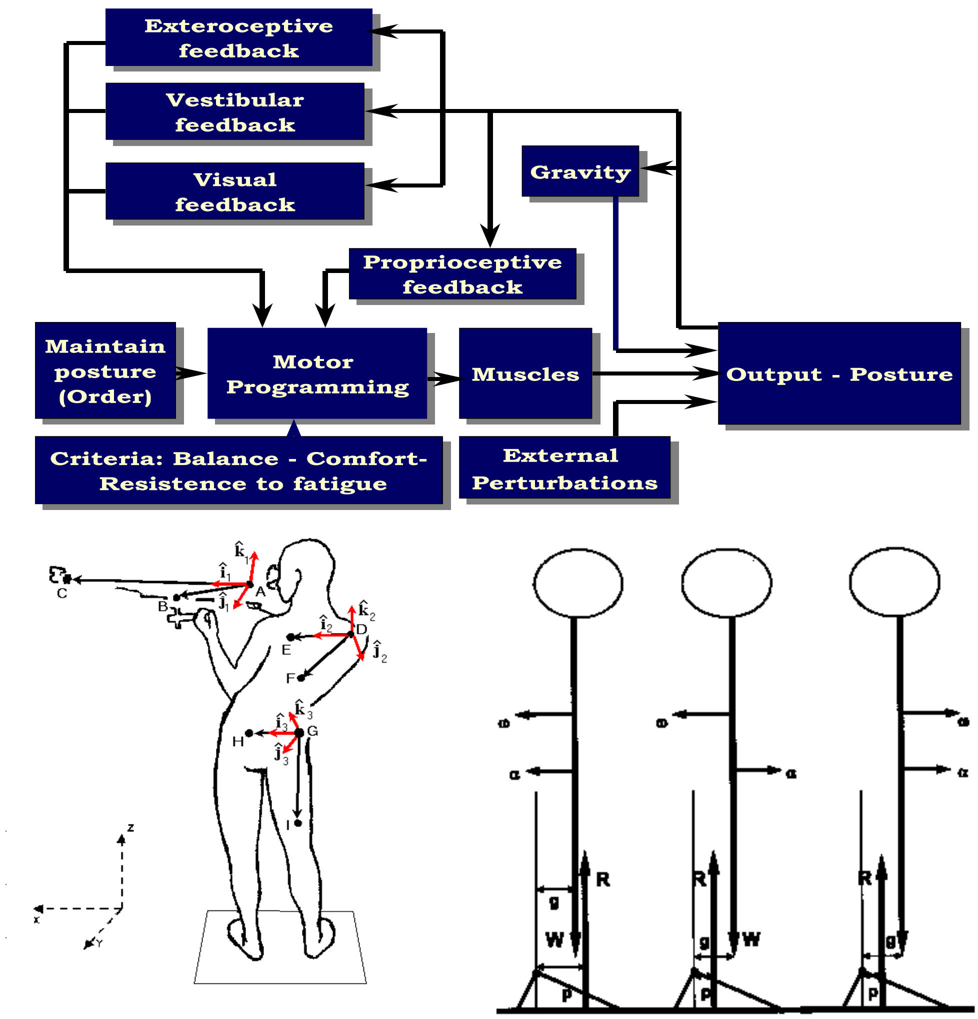

Figure 1 - Control mechanisms and mechanical models of the vertical posture in rifle - shooting.

Given that the number of degrees of freedom in a motor system is always excessive, the process of control can be regarded as overcoming the indetermination caused by redundant degrees of freedom (*Bernstein's problem*). The equilibrium – point hypothesis, for example, is an essentially single-joint model and can not be directly generalised to multi-joint movements (e.g. postural synergies). In fact seemingly different markers trajectories that perturbate systems consistency do not necessarily imply an unsuccessful solution of the aiming task, fixing the aiming line on the centre of the target up to triggering or triggering at the moment that the aiming line intercepts the centre of the target. The main problem of sport technique in precision sports consists in maintaining the relative orientation of the body segments as stable as possible. On the other hand, shooters and archers try to make their posture more consistent and reproducible reducing the variability in the aiming procedure. They align their eye with the rifle or bow and the target adopting a characteristic posture that depends on the modality. In order to avoid or to limit the intervention of muscles that control the involved joints shooters try to pass all mechanical loads across the passive structures and elements of the locomotor system. In the rifle shooting (standing position), for example, shooters adopt an uncomfortable posture characterised by a pronounced extension with simultaneous lateral bend and slight twist of the trunk respect to the pelvis (Fig.1). Their capacity to control the quasi-static motor patterns during the aiming has been proved to be fundamental to obtain good results. However muscular activity in order to maintain a desired posture is not a continuous process but short duration contractions of a number of motor units contribute to produce a desired level of muscular tension. It is known that the temporal inconsistency of the electrical impulses that arrive to the motor units cause considerable fluctuations in the resultant muscular force level (Kuznecov, 1985). This fact joined to the muscles viscoelastic properties bring about oscillations in the extremities of the S–G/B system and deviations of the aiming line from the target. Many researchers have set up instrumentation chains and measurement systems in order to study shooting technique. Thus, optoelectronic systems based on TV–camaras, position-sensitive devices or mechano-optical scanners, photogrametric techniques, sonic digitizing, accelerometry, ELG, laser beams, LVDT, Force Plates, EMG etc. have been used to obtain biomechanical parameters related with performance (Zipp et al., 1978; Nickel, 1981; Niinimaa, 1983; Dal Monte, 1983; Myllyla and Ky, 1986; Gajewski et al. 1986; Gallozi et al.; 1986; Leroyer et al.; 1988; Iskra et al. 1988; Larue et al. 1989; Mason et al., 1990; Stuart and Atha, 1990; Pekalski, 1990; Zatsiorsky and Aktov, 1990;Squadrone and Rodano, 1994; Gianikellis et al.; 1992; 1994). However and in spite of the importance of the postural consistency most biomechanical studies have contributed in obtaining information merely respect to the kinematics of the rifle or the bow neglecting the importance of the variability respect to the geometry of the S–G/B system. The second point to mention is respect to the lack of relevant information about the technical characteristics of the measurement systems and the quality of the obtained signals and signals processing. Thus there is lack of information respect to the sampling rate, the range of measurement, resolution, precision, accuracy, linearity, spatio–temporal resolution, the maximum amplitude error caused by a the time skew in the time-multiplexed sampling systems, the maximum marker shift for a given aperture time, and the calibration procedures.

A METHODOLOGY APPLIED TO THE BIOMECHANICAL ANALYSIS OF POSTURAL STABILITY: Elite shooters and archers display high levels of precision. For example, in air - rifle shooting the angular error to obtain a hit of "ten" must be no worse than 0.016º (Zatsiorsky and Aktov, 1990). The same respect to the torsion angle of the bow, from the distance of 30 m in archery, should not exceed the value of 0.2º (Pekalski, 1990). These values give an idea respect to the order of magnitude of the movements in shooting sports. As already has been mentioned shooters adopt a posture, characterised by an extension with simultaneous lateral bend and twist of the trunk (coupled joint motion) respect to the pelvic girdle. This mechanically unstable posture is consequence of the shooters' adjustments to align their eye with the rifle or the bow and the target. These dynamic actions introduce oscillatory rotations of very small amplitude of the S-G/B system's parts. Therefore a very interesting question in the analysis of motor patterns in shooting could be the description in three dimensions of the geometry of the S-G/B system. This kind of study requires a very precise measurement chain for data acquisition, a valid theoretical model and adequate data treatment procedures.

The theoretical model. As far as it is known different methods have been used to determine the instantaneous orientation or 3-D rotational movement of a segment with respect to a global or local system of reference. This is directly possible, using triaxial ELGoniometry (Chao, 1980), or, indirectly, by means of the helical axis method (Spoor and Veldpaus, 1980), Cardan-Euler angles (Panjabi et al., 1981), Joint Co-ordinate System (Grood and Suntay, 1983), and the attitude vector method (Woltring, 1991, 1992). For this particular case of the coupled motions that take place in shooting sports the system of Cardan-Euler angles could be very useful for the next reasons (Fig. 2). First, because rotations respect to the global system of reference can be anatomically defined, second, because mathematical singularities (gimbal lock) are avoided, and, third, because rotations are small (< 10º) and the established sequence of rotations do not affect the obtained results. In any case, it is possible to standardize this sequence.

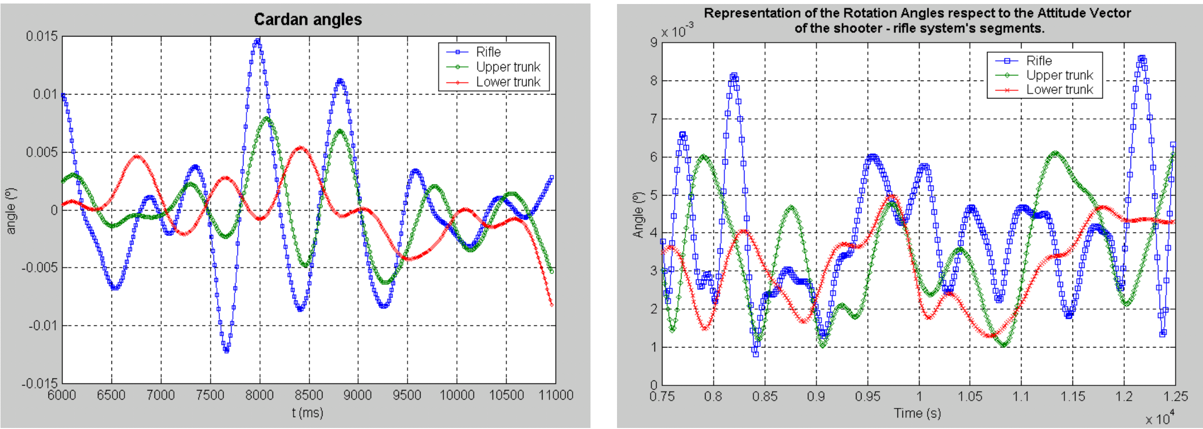

Figure 2 - Representation of the Cardan angles and attitude vector of the shooter-rifle system segments.

Three dimensional rotations of the S-G/B system's parts respect to the anatomical reference position are derived from the measured 3-D co-ordinates of three non-collinear markers fixed on every segment between their position registered at two consecutive instants (t_i) and (t_{i+1}). Local orthogonal frames are assigned to the segments and then the orientation of each segment with respect to the global system of reference is expressed by means of Cardan angles (Fig.1). The rotation matrix is parameterised in terms of three independent angles resulting from an ordered sequence of rotations with respect to the three axes of the global systems of reference. Thus if the elements of the constructed orthogonal matrices $[T_{sti}]_{3x3}$ and $[T_{sti+1}]_{3x3}$ express the orientation of the local system of reference with respect to the global system of reference, at two consecutive instants, then the rotation matrix $[R_s]_{3x3} = [T_{sti+1}]_{3x3} \times [T^T_{sti}]_{3x3}$ is calculated expressing the rotation of the segment (s) in the time interval $\Delta t = (t_{i+1} - t_i)$ with respect to the axes of the global systems of reference. Finally the Cardan angles are calculated according a standard sequence of rotations following the next steps:

Given that $\left[T_{st_i}\right]_{3x3} = \begin{vmatrix} i_{st_i x} & j_{st_i x} & k_{st_i x} \\ i_{st_i y} & j_{st_i y} & k_{st_i y} \\ i_{st_i z} & j_{st_i z} & k_{st_i z} \end{vmatrix}$ and $\left[T_{st_{i+1}}\right]_{3x3} = \begin{vmatrix} i_{st_{i+1} x} & j_{st_{i+1} x} & k_{st_{i+1} x} \\ i_{st_{i+1} y} & j_{st_{i+1} y} & k_{st_{i+1} y} \\ i_{st_{i+1} z} & j_{st_{i+1} z} & k_{st_{i+1} z} \end{vmatrix}$

$$\left[R_s\right]_{3x3} = \left[T_{st_{i+1}}\right]_{3x3} \left[T^T_{st_i}\right]_{3x3} =$$

$$\begin{bmatrix} (c\varphi_{sz} c\varphi_{sy}) & (c\varphi_{sz} s\varphi_{sy} s\varphi_{sx} - s\varphi_{sz} c\varphi_{sx}) & (c\varphi_{sz} s\varphi_{sy} c\varphi_{sx} + s\varphi_{sz} s\varphi_{sx}) \\ (s\varphi_{sz} c\varphi_{sy}) & (s\varphi_{sz} s\varphi_{sy} s\varphi_{sx} + c\varphi_{sz} c\varphi_{sx}) & (s\varphi_{sz} s\varphi_{sy} c\varphi_{sx} - c\varphi_{sz} s\varphi_{sx}) \\ (-s\varphi_{sy}) & (c\varphi_{sy} s\varphi_{sx}) & (c\varphi_{sy} c\varphi_{sx}) \end{bmatrix}$$

where

$$\text{sen}\,\varphi_{sy} = -R_{31}, \quad \text{sen}\,\varphi_{sx} = \frac{R_{32}}{c\varphi_{sy}}, \quad \text{sen}\,\varphi_{sz} = \frac{R_{21}}{c\varphi_{sy}}$$

$$\cos\varphi_{sy} = \sqrt{1 - \text{sen}^2\varphi_{sy}}, \quad \cos\varphi_{sx} = \frac{R_{33}}{\cos\varphi_{sy}}, \quad \cos\varphi_{sz} = \frac{R_{11}}{\cos\varphi_{sy}}$$

In the case that this procedure is taking place to describe coupled motions in shooting sports it is very important the validation of the model because rotational movements are very small and the propagated errors could be harmful for the obtained results. In rifle-shooting, an analysis of errors of the computed values of the Cardan angles, based on simulation procedures, yielded random relative errors ($p<.01$) that not exceed the 5% of the mean values of the range of the real rotations (Gianikellis et al., 1998). The second point that is important in this process is to establish conveniently the absolute system of reference during the calibration procedure. In this way rotational movements are clinically described (flexion – extension, lateral bending and twisting movement).

The measurement chain. The measurement of the 3-D co-ordinates of a sufficient number of superficial landmarks that define the segments of the S-G/B is necessary to describe the postural consistency. Furthermore postural stability can be evaluated on the basis of Stabilometric measurements, like the displacement of the Centre of Pressure (CoP) on the horizontal plane as an integrator of the postural sway, using force plates (Fig.3). The Centre of Pressure is defined as the point of application of the resultant of the external forces applied to the support area. Its variability respect to the time expresses the neuromuscular answer to the instantaneous position of the Body's Centre of Gravity in order to maintain the equilibrium.

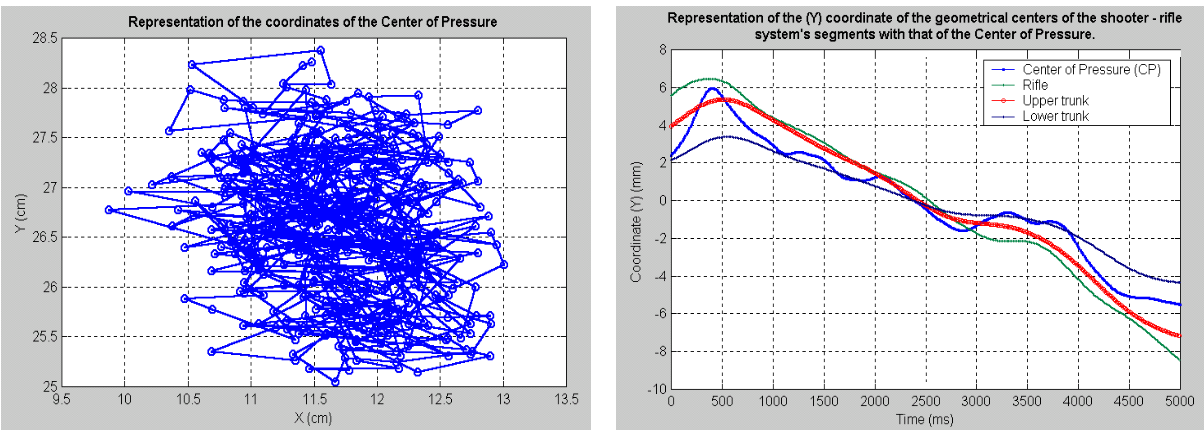

Figure 3 - Representation of the CoP trajectory and of its (Y) co-ordinate.

Finally, the analysis of the muscular activity in shooting sports is a very interesting question for two reasons. First, because in shooting modalities postural stability is the unique technical objective, whereas in archery an intensive neuromuscular activity is necessary to draw the string and to withstand temporally the *"bow weight"* during the aiming. In that phase known as *"push – pull"* the bow's tension is balanced with the muscular force of the archer. Furthermore Electromyography (EMG) enables the detection of the local muscular fatigue (Fig.4). Because of all these considerations the measurement chain consists of a Sonic Digitizer, a strain-gauge Force Plate, a microphone sensor to detect the instant of triggering and an EMG system with surface electrodes.

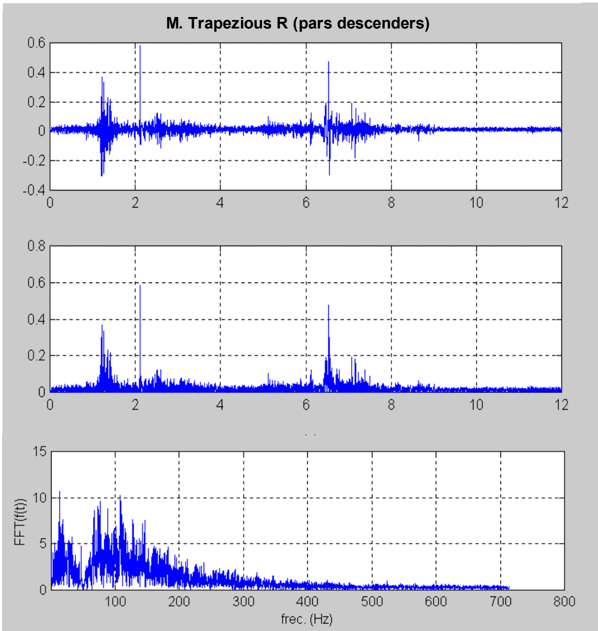

Figure 4 - Row and rectified EMG signal and its spectrum.

Sonic Digitising consists in converting information respect to the body landmarks co-ordinates to digital values, using the properties of the sound propagation (Engin and Peindl, 1984; Hsiao and Keyserling, 1990; Worringham, 1991; Steffny and Schumpe, 1991; Charteris et al., 1994; Herriots and Barret, 1994; Gianikellis et al., 1994). It is a very efficient solution not only to quantify kinematics of the S-G/B but also to establish an on-line feedback loop providing to shooter information respect to his aiming quality. The sonic digitizer (SAC, GP8-3D) consists of sixteen sequentially activated ultrasound emitters (60 KHz) connected to a multiplexer unit that are automatically identified. Four microphones fixed on a rigid frame receive the sonic waves of the sequentially fired emitters. The control unit connected to a PC by means of Parallel Interface Card (PIO12) for high data rate throughput in ASCII packed binary format. The system works counting the time that require the emitted sound waves to reach the microphones. Knowing the speed of the sound in still air, the time is converted in distances of the emitter to the four microphones and later in the 3-D co-ordinates of the emitters. All technical and performance characteristics of the Sonic Digitizer have been exhaustively evaluated according to a standard protocol (Stüssi and Müller, 1990) and the following have been obtained: *sampling rate* of the whole system 66.6 Hz for an *active volume* of 1800mm x 1300mm x 1400mm. We have calculated that in rifle-shooting more than a 95% of the cumulative periodogram is contained up to 2.5 Hz of the spectrum frequency. *Range of measurement* 2625 mm; *accuracy* 0.054 (A_x= .22, A_y= .038 y A_z = .032); *precision of the reconstructed 3-D co-ordinates* of the emitters .115 mm (p_x=1:28125, p_y =1:26000, p_z=1:17073); *spatio-temporal resolution* of the system (70.7 Hz)$^{1/2}$ mm^{-1}. The calibration is carried out knowing the position of at least three points (emitters) into the working volume to calculate the position of the four microphones by means of an iterative process of optimisation (Newton-Raphson) (Gianikellis et al., 1994,1996). Given that the Sonic Digitizer is a multiplexing system there is a need of a data interpolation algorithm to obtain the co-ordinates at the same instant, and, a “smoothing” process to eliminate part of the contaminating high frequency "noise" before differentiation. Position-time "data smoothing” is carried out by quintic splines using the package "Generalized Cross-Validatory Spline" (Woltring, 1986), according to the “True Predicted Mean-squared Error" criterion (Craven and Wahnba, 1979), given the automatic identification of the markers (w_i = 1) and the known precision of the spatial co-ordinates (σ^2). This subroutine for smoothing and differentiation is based on the natural B-Spline functions. The strain-gauged Force Plate (DINASCAN-Ibv) is synchronised with the Sonic Digitizer. In this way stabilometric analysis, of the system's sway can be carried out. Strain gauges are highly linear sensors and their application to shooting sports measurements is particularly appropriate due to their good behaviour at low frequencies. The sampling rate is up to 1 KHz for single force-plate. The precision respect to the position of the (CoP) is 2 mm. The EMG system uses active surface electrodes (Ag/AgCl) to transmit myoelectrical signals to a differential amplifier (input impedance 100 Mohm) of variable gain (10 – 10000). CMRR is 90 dB, and the frequency response 10 to 2000 Hz. Data “filtering” is accomplished by “high pass filters” (10 or 100 Hz), “low pass filter” (300, 1000 and 2000 Hz) and “notch filter” to filter out the 50 Hz power line noise. The resulting EMG signal is recorded and stored for further digital processing in a PC using a 12-bit acquisition card (DI-200/PGH). The sampling rate of the system is 50 KHz allowing the use of 16 channels. The processing of EMG signals and the calculation and graphical representation of all parameters take place in the MATLAB environment where data are exported in ASCII files. Thus, after the rectification and envelope detection of raw EMG signals (Fig. 4) the mean rectified value (MRV) and other parameters in time domain are calculated, namely, RMSEMG, moving average (MA), and integrated EMG (iEMG). To compare EMG signals normalisation can be achieved normalising the MRV or RMS with respect to some maximal measurable value for the particular experimental procedure (maximal voluntary contraction or the “weight of the bow”). Processing EMG in the frequency domain involves determining the frequency spectrum via FFT and then obtaining the power density spectrum (PDS) which may be affected by recruitment, firing rate, fatigue, and filtering. However, the calculated median frequency (AF), mean frequency (MF) and bandwidth of the signal can be very useful parameters for EMG evaluation. The measurement chain that is completed with a detector of the triggering instant enables to carry out biomechanical analysis of technique in shooting sports. This is possible recording the 3-D co-ordinates of superficial landmarks that define the body segments, the displacements of the Centre of Pressure (CP) and the electrical activity of the involved muscular groups.

CONCLUSION: The here presented methodology could provide relevant and objective information respect to the motor patterns in the precision sports identifying the nature of the postural instability and its influence on the performance. Given that scoring is consequence of the dynamic interactions of the system’s parts the shooter and his trainer have to look for aiming techniques reducing all undesired oscillations and making possible the stabilization of the body segments.

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