A MECHANICAL MODEL FOR MEASURING IN THREE DIMENSIONS THE SMALL AMPLITUDE COUPLED MOTION THAT CHARACTERIZES MOTOR PATTERNS IN SHOOTING ACTIVITIES

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INTRODUCTION: During the aiming process in air rifle shooting from the standing position, shooters adopt a posture characterized by a pronounced extension with simultaneous lateral bend and slight twist of the trunk (coupled joint motion) with respect to the pelvic girdle, in order to align their eye with the rifle and the target. As consequence of the dynamic interactions of the parts of the shooter-rifle system, this posture is mechanically unstable and the system sways with respect to an equilibrium position. On the other hand, shooters try to maintain their posture stable, passing the mechanical loads across the passive structures and elements of the locomotor system. However, the viscoelastic properties of the muscles introduce oscillations of small amplitudes that divert the aiming line from the target. Despite the variety of methodological approximations intended to analyze and evaluate sport technique in shooting sports, there is no information about the geometry of the shooter-rifle system and the variation in the orientation of its parts (Zatsiorsky and Aktov, 1990). However, up to now, several 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, directly, using triaxial electrogoniometry (Chao, 1980), or, indirectly, by means of the helical axis method (Spoor and Veldpaus, 1980), Cardan-Euler angles (Panjabi et al., 1981), Joint Coordinate System (Grood and Suntay, 1983), and the Attitude vector method (Woltring, 1991, 1992). The study of 3-D motion requires both a sufficiently accurate method for measuring that motion, as well as a data reduction method which can provide a convenient and accurate description of that motion. In this way the main purpose of this work is to describe the development of a theoretical model as the basis of non-invasive procedures for obtaining, with accuracy, low cost and time efficiency, information about the small amplitude rotational coupled movements related to the anatomical frame of reference and the application of these procedures to the study of the kinematics of the shooter-rifle system during aiming, where precision and postural stability strongly determine performance.

METHODS: The 3-D rotations of the parts of the shooter-rifle system, namely rifle, upper trunk and pelvic girdle with respect to the anatomical reference position are derived from the measured positions of three non-collinear markers (ultrasound emitters) fixed on every segment between two positions in the space recorded at two consecutive instants (t_i, t_{i+1}) (Fig. 1). From the position vectors of the markers local orthogonal frames are assigned to the three segments and then the orientation of each segment with respect to the global system of reference is expressed by means of the Cardan angles. The rotation matrix is parameterized in terms of three independent angles resulting from an ordered sequence of rotations with respect to the three axes of the global system of reference following the next steps:

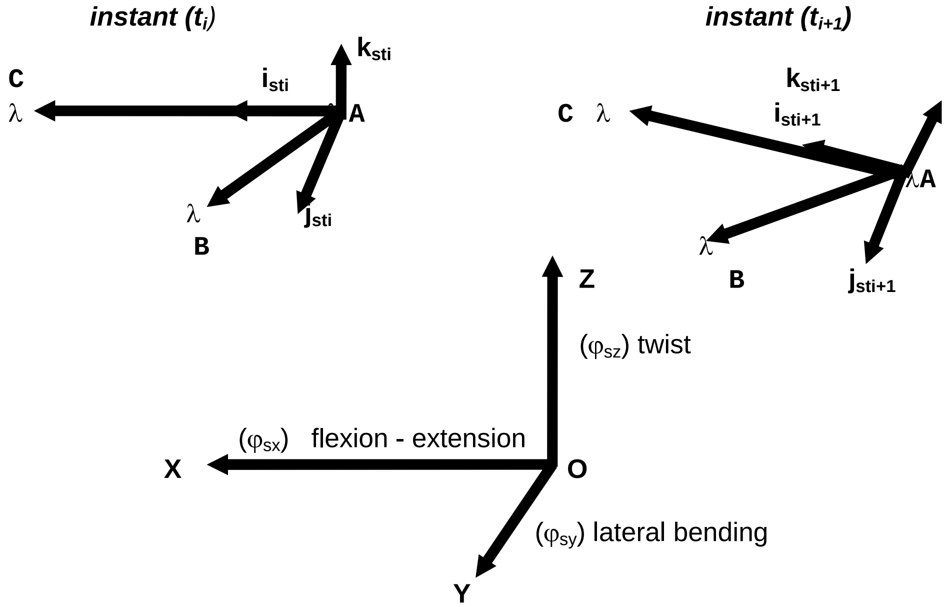

Fig.1. Variation of the orientation of a local frame fixed on the segment S defined by the markers A,B,C with respect to the global system of reference.

i) The unit vectors of the local systems of reference are calculated from the reconstructed smoothed 3-D coordinates of the markers in two consecutive instants (t_i, t_{i+1}) determining the orientation and the variation of the orientation of every local system of reference with respect to the absolute one. ii) Then the matrices **$[T_{sti}]_{3x3}$** and **$[T_{sti+1}]_{3x3}$** are calculated, where columns vectors express the orientation of the local system of reference with respect to the global system of reference. iii) Next, the rotation matrix **$[R_s]_{3x3} = [T_{sti+1}]_{3x3}$ x $[T^T_{sti}]_{3x3}$** is calculated expressing the rotation of the segment (s) in the time interval (t_i, t_{i+1}) with respect to the axes of the global system of reference. iv) Finally the Cardan angles are calculated according a standard sequence of rotations.

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

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

$$\begin{bmatrix} (c\varphi_{sz} c\varphi_{sy}) & (c\varphi_{sz} s\varphi_{sy} s\varphi_{sx} - s\varphi_{sz} c\varphi_{sx}) & (c\varphi_{sz} s\varphi_{sy} c\varphi_{sx} + s\varphi_{sz} s\varphi_{sx}) \\ (s\varphi_{sz} c\varphi_{sy}) & (s\varphi_{sz} s\varphi_{sy} s\varphi_{sx} + c\varphi_{sz} c\varphi_{sx}) & (s\varphi_{1z} s\varphi_{sy} c\varphi_{sx} - c\varphi_{sz} s\varphi_{sx}) \\ (-s\varphi_{sy}) & (c\varphi_{sy} s\varphi_{sx}) & (c\varphi_{sy} c\varphi_{sx}) \end{bmatrix}$$

with $sin\varphi_{sy} = -R_{31}$, $sin\varphi_{sx} = \frac{R_{32}}{c\varphi_{sy}}$, $sin\varphi_{sz} = \frac{R_{21}}{c\varphi_{sy}}$

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

During the calibration procedure the absolute system of reference has been established with the axis OX indicating the direction of the aiming line, the axis OY indicating the medio-lateral direction and finally the axis OZ indicating the direction of the longitudinal axis of the subject in the anatomical frame of reference. In this way rotations of the local systems of reference with respect to the OX axis indicate flexion-extension, to the OY lateral bending and to the OZ axis twist movement.
The spatial coordinates of the nine superficial landmarks that define the three segments of the shooter-rifle system are obtained using sonic digitizing techniques. Data acquisition apparatus consists of a Sonic Digitizer (SAC GP8-3D) with sampling rate 66.6 Hz (7.4 Hz per emitter), accuracy 0.054, precision (calculated standard deviation for stationary emitters) of the reconstructed coordinates .115 mm (P_x= 0.064 mm, P_y= 0.050 mm and P_z= 0.082mm) and spatio-temporal resolution 70.7 √Hz mm^{-1} (Gianikellis et al., 1994,1996). All technical and performance characteristics of the Sonic Digitizer have been evaluated according to a standard protocol (Stüssi and Müller, 1990). Position-time "data smoothing" carried out by quintic splines using the package *"Generalized Cross-Validatory Spline"* (Woltring,1986), according to the *"true predicted mean-squared error"* criterion, given the automatic identification of the markers (w_i = 1) and the known precision of the spatial coordinates (σ^2).
Since it was not possible to reproduce rotational movements of the same order of magnitude using instruments with more precision capability, the validation of the model, knowing the precision in the coordinates data, carried out by means of simulations with stable markers distributed in the same active volume as in the practice of shooting. So the random errors (p<.01) that "contaminate" the computed values of the Cardan angles and the relative error (in brackets) with respect to the average values of the range of the real rotational movement were calculated.

	rifle	**upper trunk**	**pelvic girdle**
flexion - extension	0.021º (< 1.5 %)	0.010º (< 4.5 %)	0.035º (< 2.0 %)
Lateral bending	0.012º (< 0.5 %)	0.068º (< 0.5 %)	0.042º (< 1.0 %)
twist	0.010º (< 2.0 %)	0.060º (< 2.0 %)	0.046º (< 3.0 %)

RESULTS: By means of this method it is possible to measure with precision the small rotations that take place in such particular motor activity (Fig. 2). In the table the average values of the range of angular movement of the three segments are represented for the concrete case of 60 trials that we studied. Also, in this particular case, the rotations with respect to the global system of reference are anatomically defined. Given that rotations are small (< 10º), the obtained results are not affected by the established sequence of rotations. In any case, it is possible to standardize this sequence. With this method mathematical singularities (gimbal lock) are avoided. Finally, the model facilitated the study of the coupled motion that takes place in shooting. The obtained results confirm the interactions between the parts of the shooter-rifle system and the continuous regulation of the shooter's posture during aiming. Also, the range of variation of the orientation of the pelvic girdle with respect to the global system of reference is correlated with performance in shooting ($p < 0.0037$, $r = -0.37$).

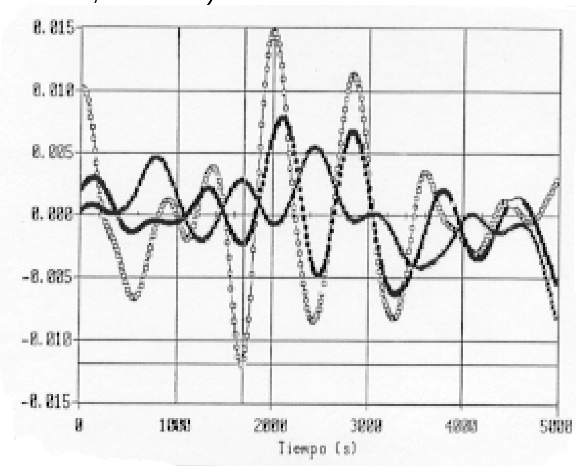

Fig. 2. Flexion-extension movement of the upper trunk (v) and pelvic girdle (T) and yaw of the rifle (□).

CONCLUSIONS: Given that in shooting sports the rotations are very small, the use of the here-presented validated model could contribute to the description of coupled motion and the improvement of knowledge about the motor patterns in sport shooting activities, as well as in other similar motor patterns.

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