STATISTICAL ANALYSIS OF FREQUENCY CONTENT OF SELECTED ANATOMICAL LANDMARKS IN TREADMILL RUNNING

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Quantitative kinematic analysis of sporting movements is particularly critical and stressing for the measuring devices and the processing algorithms. Fast movements and hardly detectable, slight differences among performances contribute to make this task more difficult. Moreover the speed of movement through the field of measurement, frequently allows to record only few samples on which werely for the analysis. The problems which arise from this condition include the choice of the device used to collect data together with a proper sampling rate and the design of procedures for data processing, such as filtering and derivate assessment.

Several equipments for kinematic studies have been developed relying on different physical principles (ultrasound, resistive electrogoniometers, accelerometers, cinematography and optoelectronic transducers). The less interfering measuring instruments are cinecameras and optoelectronic devices, but only these latter can guarantee the proper measurement accuracy. The systems based on optoelectronic sensors rely on the measurement of the displacement of a limited set of markers fixed to the body landmarks (Woltring,1984, Lanshammmar,1982). These latter must not interfere with the movements of the subject under analysis. For this reason systems employing passive small lightweight markers are preferable while those using LEDs (active markers) create problems due to wires and power supply packs.

The accuracy of the measurement and the sampling rate are strictly connected with the performances of the data processing algorithms. The evaluation of joint angles and linear and angular velocities and accelerations are heavily affected by acccuracy and sampling frequency (Gustaffson and Lanshammar, 1977).

A first attempt to establish the frequency content of some of sporting movements in order to state a correct sampling rate was made by these authors (D'Amico et al., 1989). The purpose of this paper is to concentrate the attention on a specific movement and to analyse its frequency content by a statistical point of view. Six trained runners of different sex and height have been analysed while running on a treadmill at 15 km per hour. This basic movement has been chosen because of its repeatability, necessary for the creation of a consistent statistical data base. The kinematic data collection has been performed with the ELITE system at the Bioengineering Centre of Milan.

The Power Spectrum Density (PSD) of the displacements of several landmarks has been estimated by a forward backward autoregressive (AR) model fitted to the data. This operation has been carried out or the X (advancing direction) and Y (vertical direction) co-ordinates of 8 markers placed on the main reference points of the subjects body. The chosen reference point are those necessary to identify the main joint angles and the centres of mass.

The frequency content has been estimated as the frequency bounding the 99.5% of the power in the frequency domain.

The study has been also used to evaluate the appropriateness of the choice of the cut-of frequency of the filtering technique proposed by D' Amico and Ferrigno, 1990.

The data were sampled at 100 Hz and successively undersampled at 50 Hz in order to test the sufficiency of this last sampling rate for the analysed motion, given the signal to noise ratio (SNR).

Finally some considerations are done on the possibility of using the frequency content of selected body landmark displacement to identify motor patterns related to different classes of athletes.

INSTRUMENTATION

The kinematics of the movements has been recorded with ELITE System (Ferrigno and Pedotti, 1985) a fully automatic motion analyser. The instrumentation measures the displacement of reflective hemispheric landmarks applied to the subject, the size and weight of the markers do not interfere with the execution of the movement.

The system configuration adopted was based on two CCD TV cameras placed 6 m far from the advancing plane of the subjects. This arrangement allows the computation of the three dimensional displacement of the markers. The optical axis of each TV camera was approximately horizontal and inclined of +\- 35° on the perpendicular to the advancing plane. The field of view was 4 m and the accuracy of the measurements equal to 1.42 mm, being the accuracy of the system 1\2800 of the field of view.

The cameras are electronically shuttered to be sensitive for 1 millisecond per frame, thus allowing a sharp sampling of the image. The sampling rate was 100 images per second and the subjects were lit up by infrared flashes, synchronised with the electronic shutter.

The three-dimensional coordinates of the markers were computed by using the stereophotogrammetric parameters of the cameras. The parameters, previously computed during the calibration procedure, are obtained by the acquisition of a control grid of landmarks of known geometry placed on different positions of the field of view.

All the data were acquired and stored on a personal computer Olivetti XP3, IBM compatible with a 80386 INTEL microprocesor and mathematical co-processor.

SUBJECTS

Subjects of the experiments were six trained runners (average body weight = 598 N, height = 1.71 m, age=24.1 years) all practising athletics at regional level. Three athletes usually run in competition 400m while the other three were devoted to 1500-5000 m.

PROTOCOL

On each athlete eight markers were placed on the following anatomical landmarks: temple, shoulder, elbow, wrist, hip, knee, ankle, 5th metatarsal head.

After 20 minutes of warming up, the subjects run on the treadmill at the fixed speed of 4.16 m\s. When the pace was reached, the acquisitions, consisting of 12 records of 3 sec., were performed.

Each record contained, at least 2, complete cycles of running.
The data so collected underwent a further software process: the tracking procedure and the three dimensional reconstruction.

The frequency analysis has been carried on the X (horizontal antero-posterior) and Y (vertical) co-ordinates of each marker by means of a proper computing program.

The results so obtained were (see below for details):

-frequency neglecting 0.5 % of the signal power;

- cut-off frequency at which the signal to noise ratio falls under 50 (at 50 and 100 Hz).

SPECTRAL ESTIMATION

Makhoul, 1975 and Kay and Marple, 1981, made exhaustive reviews on the techniques which can be used for the estimation of the PSD of a deterministic signal or of a stationary stochastic process.

Among these techniques, the use of AR models guarantees good PSD estimates and a lot of well proven algorithms. The advantages of these are the availability of continuous PSDs and the posibility to work with short data recordings, not unusual condition in sporting movement data collection.

Among the available algorithms, our choice has been oriented to the forward backward least square technique (also called modified covariance0 which allows to obtain very sharp PSD estimates (Ulrych and Clayton, 1976, Nuttall, 1976) without showing spectral line splitting or biases (Kay and Marple, 1981, Marple, 1987).

A description of how this algorithm has been implemented and used for our purposes can be found in D'Amico and Ferrigno, 1990 and D'Amico et al., 1989.

SIGNAL BANDWIDTH ESTIMATION

Three bandwidth values have been determined for the purposes of this paper. The first one represents the frequency content of the signal. The second and third are the cut-off frequencies of the above cited filter with sample rate of 100 and 50 Hz respectively.

FREQUENCY CONTENT OF THE SIGNAL

A theoretical bandlimit to the biomechanical data does not exist (Slepian, 1976). The bandwidth of the displacement data extend up to very high frequencies, although with negligible power. However it is reasonable to bound the PSD of a signal where the SNR falls under a given value (Lanshammar, 1982). The frequency content has thus been approximated at the frequency by which the 99.5% of the total power in the frequency domain is bounded. The 0 Hz component has been removed before the computation because it depends on the absolute position of the landmark in the space. Once this dominant component has been removed, the left 0.5% of the PSD can be reasonably thought to be mainly noise.

In a previous work (D'Amico et al., 1989), we took into acount also the frequency bounding the 99% of the PSD power. We found, by examining the differences between the 99% and the 99.5% frequencies, that the power of the PSD of our signals rolls off smoothly in those regions. The study showed that the 99.5% frequency gives a better approximation than the 99%, without suffering for the typical oscillations that PSDs of noisy signals estimated with high order (15) AR models show at high frequencies. The 99.5% frequency was in fact consistently correlated with and not randomly different from the 99% one. Beyond the 99.5% of the total power the above cited problems arise. It is difficult to set a further threshold (let say 99.7% for example) over which the bounding frequency increases without random oscillations.

FILTER CUT-OFF FREQUENCIES

The filter cut off frequencies at 50 and 100 Hz respectively are set (D'Amico and Ferrigno, 1990) at the frequency for which the SNR falls below 50 (-34 dB). The noise power is estimated as the mean power in the last 20% of the Nyquist frequency, where, practically, the noise is predominant (D'Amico and Ferrigno, 1990). Since the data have been sampled at 100 Hz, the 50 Hz cut-off frequencies have been obtained from the same data, by simple undersampling: i.e. the data record have been reduced to one half discarding one sample every two.

RESULTS

The 99.5% frequencies for X and Y co-ordinates of all the markers (mean and standard deviations) averaged on all the subjects and trials are reported in Figure 1. The mean values ranged between 2.48 and 6.28 Hz with low standard deviations (4 to 31% of the mean value). With exception of 1X and 5X, that as we will see hereafter suffer from inter-individual differencies, the scattering of the 99.5% of all the other markers is extremely small.This means that the obtained statistics are reliable and can be taken for reference in deciding the bandwidth of each landmark displacement data set.

The 100 Hz cut-off frequencies of the filter are bounded between 4.6 and 11.6 Hz with standard deviations ranging between 7 and 23% of the mean value (Fig2). Comparing these values with those of Figure 1 we can see that the filter cut-off frequencies always exceed the 99.5% power boundary. This means that the cut-off frequency practically extracts all the possible information from the signal, although maintaining an high SNR which allows to obtain good quality derivatives.

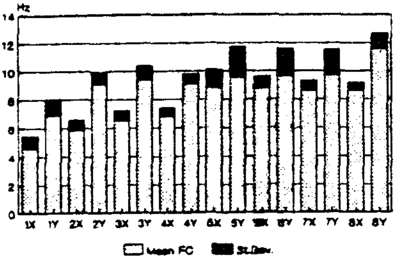

Figure 1: Mean standart deviation of 99.5% frequency of X and Y coordinates of all markers

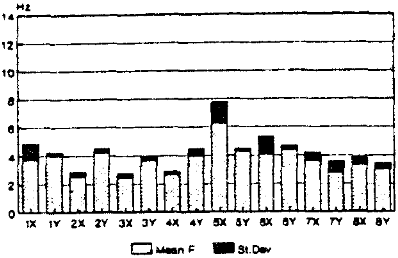

Figure 2: Mean and standard deviations of the filter cut-off frequency at 100 Hz of X and Y coordinates of all markers

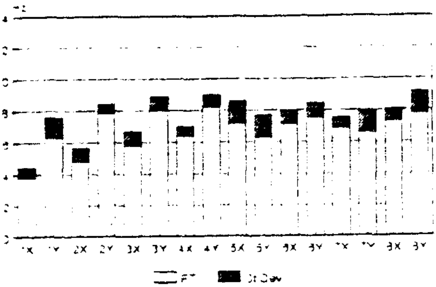

Figure 3: Mean and standart deviation of the filter cut-off frequency at 50Hx of X and Y coordinates od all markers

Figure 3 shows the filter cut-off frequency values on the same data undersampled at 50Hz. Also in this case the filter saves more than 99.5% of the signal power.

The high homogeneity of the population, evidentiated by the low standard deviations of the data in Figures 1, 2 and 3, shows the existence of similar motor co-ordination patterns in the examined subjects. This fact is related to the good motor strategy achieved by the athletes in order to optimise the efficiency of the motion.

Figure 4a and b reports the mean values and standard deviations of the 99.5% frequency averaged, for each subject, on all the markers and trials. No inter-individual differencies among the athletes seem to arise from these data, but while on the Y co-ordinate the standard deviations are small, these become more important on the X co-ordinate. This fact seems to indicate that, being the progression the task of the run, the vertical movements of each marker are kept as low and smooth as possible, while in the advancing direction bigger variability is tolerated.

Figure 5a and b report the behaviour of selected markers (those presenting the maximum variability in Figure 1). Considering the antero-posterior movement (X) of the head marker, we can see that the three athletes marked with a star, show a lower 99.5% frequency than the others. This three athletes are long distance runners, while the others are 400 m runners.

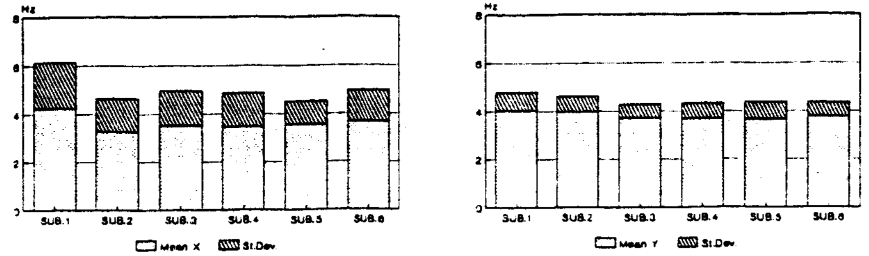

Figure 4: Mean and standard deviation of the 99.5% frequency for all the markers of each subject
X coordinate (a) and Y coordinate (b)

Figure 5b reports the 99.5% frequency of the horizontal movement of hip marker. In this case the subjects are ordered by height (from 1 to 6, 6 is the taller). The correlation of the frequency with height is evident with a linear correlation coefficient of -0.87 and with a probability of 0.024.

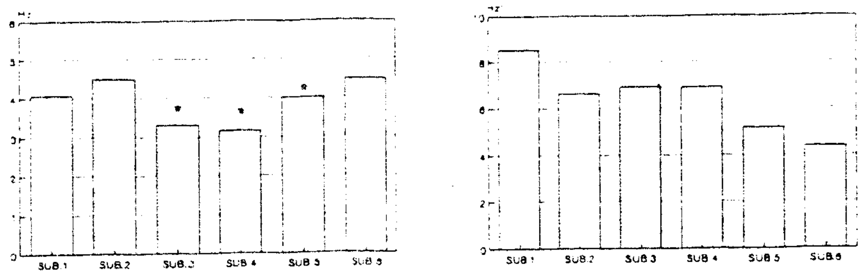

Figure 5: Mean value of the 99.5% frequencies of X coordinate of marker 1 (a) and 5 (b).
Stars indicate the long distance runners.

CONCLUSIONS

The frequency content analysis performed shows the necessity to process each co-ordinate of each marker with a proper cut-off frequency. Using an unique cut-off value should cause oversmoothing of some co-ordinates and undesirable noise effects on others. The proposed 99.5% frequency, for each marker co-ordinate, represents a good approximation when only angles and displacements must be assessed and is valid for a wide range of measurement systems.

In the case in which first and second derivatives must be computed, the problem requires more attention. The cut-off frequency presented depends, in fact, on the SNR and sampling rate of the measuring systems, as stated by Gustaffson and Lanshammar, 1977. An assessment of the measuring system is thus mandatory before starting the data processing. Furthermore one must be sure to extract the maximum allowable information from the data, because small differencies in displacements can cause effective deviations in the final performance. For example, differencies between velocities and accelerations can easily be masked by the choice of an erroneous cut-off frequency.

Although this paper was not oriented to the interpretation of the frequency content as characterising the individual motor pattern, the observations made about the data reported stimulate a deeper analysis on inter-individual differentiations.

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