PROCESS OF MEASURES REPRESENTING SPINE CURVATURES IN A SAGITTAL PLANE FOR A SEATED SUBJECT, SUBMITTED TO ACCELERATION IN A HORIZONTAL PLANE.

F.X. LEPOUTRE

N. MALVACHE

CENTRE UNIVERSITAIRE DE VALENCIENNES ET DU HAINAUT CAMBRESIS

LE MONT HOUY

59326 VALENCIENNES CEDEX (FRANCE)

INTRODUCTION.

The study of a human operator's trunk-spine system dynamics is a difficult one, owing to the great number of degrees of freedom of the mechanical system (1) (2) (3) and the postural regulation mode complexity (reflex, proprioceptive, exteroceptives loops) (4) (5) (6). A good knowledge of these phenomena may be applied to the research on aviations and earthmover operator's spinal traumatisms. (8) (9).

In order to have a better knowledge of the postural regulation applied to the mechanical trunk-spine system - this paper presents theresults of a study concerning the spinal curvature variations in the sagittal plane of an operator submitted to acceleration in a horizontal plane.

After a brief survey of the material (10) and experimental setup characteristics (11) this paper present a statistical and frequential analysis applied to the recordings obtained concerning spine curvature variations. The results of this process lead to a simplified model of the trunk-spine system. The last paragraph refers to the simulation of this model on an analog computer and its validity.

I - MATERIAL AND EXPERIMENTAL SETUP FOR THE STUDY OF THE TRUNK-SPINE SYSTEM.

I.1 - THE "SPINE TRANSDUCER".

The "spine transducer" consists of a flexible fiberglass rod on which strain gauges - associated in pairs - are stuck ; the latter give an electric image of the rod curves. This rod is fixed on the subject's back by means of straps. The voltages obtained are proportionnal to the curves of the rod, i.e. the curvatures of the subject's spine detected at the T1, T6, T10, L3 vertebrae levels. The reference unit on the recording is m^{-1} (the inverse of meter).

I.2 - EXPERIMENTAL SETUP AND CHARACTERISTICS OF THE SUBJECTS STUDIED.

The subjects were seated on a mobile tractor seat (without a back) their hands on their legs and their task consisted in keeping their initial posture . They had to watch a visual signal which helped them to fulfill their task. The light spot was placed at the bottom of a horizontal tube which was 40 cm long and 2 cm^2 in cross section. The visual stimulus is adjustable in height and fixed in such a way as the subject might observe it in a resting posture.

The subjects, 20 to 27 years old, ranging in height from 1,70 m to 1,75m were all male and in good health. The experiment made consisted of a sequence of eight fast forward step displacement of the seat each followed by a slow return to the previous position. Each displacement of 2 cm was made in 50 mS with an acceleration of about + and - 2g (§ 1.3 fig. 1) spaced of about 1 S. The experiment were repeated on 20 subjects - all different.

I.3 - ANALYSIS OF THE DISTURBANCE-STEP POSITION DISPLACEMENT-AT THE LEVELS OF THE TRACTOR'S SEAT AND OF THE SUBJECT'S SACRUM.

Figure 1 represents the motion, the acceleration and the energy spectral density of the seat acceleration in the case of a perturbation in a step forward motion. A closer look to the figure 1a shows that the acceleration consists of 2 successive impulses with amplitude of about 2g of opposite sign separated of about 50 mS - and followed by vibrations of small amplitude during 200 mS.

On the one hand figure 1a shows that the acceleration spectrum at the seat level is greater than 25 Hz ; on the other hand figure 1b - illustrating the acceleration and its energy spectral density recorded at the sacrum level shows a spectrum limited to 18,7 Hz . This difference stresses on the influence first of the soft tissues existing between the seat and the sacrum position, second the pelvis rotation around the subject's fulcrum on the seat (ischia)

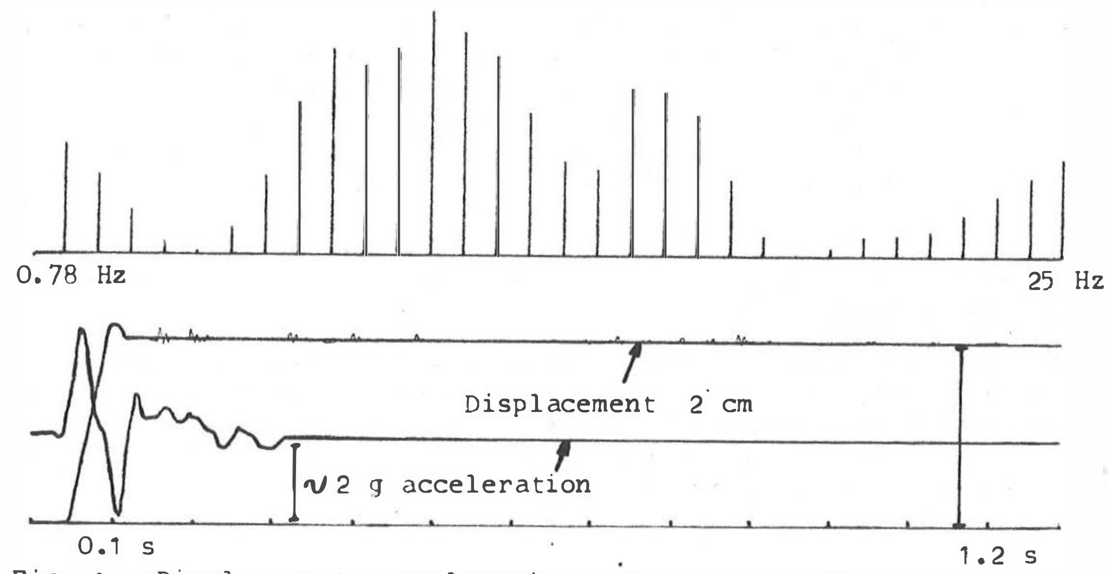

Fig. 1a :Displacement, acceleration and energy spectral density of acceleration at the level of seat. "Step position" disturbance.

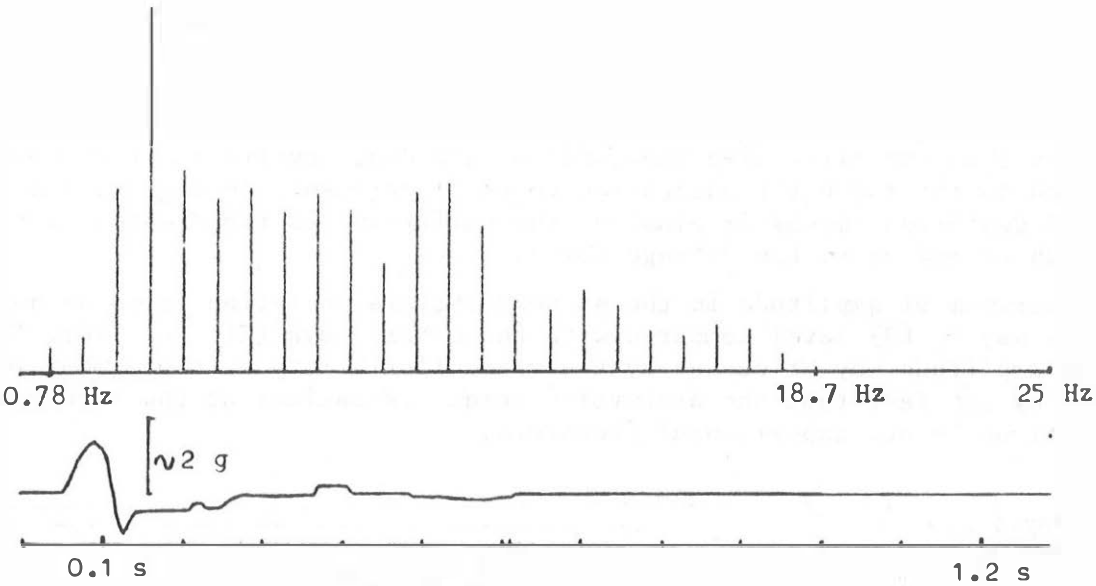

Fig. 1b : Acceleration and energy spectral density at the level of the subject's sacrum when submitted to a "step position" disturbance.

II - ANALYSIS OF THE SPINE CURVATURE VARIATIONS DUE TO THE PLATFORM STEP DISPLACEMENT AS A DISTURBANCE.

II.1 - STATISTICAL PROCESSING.

II.1.1 - CALCULATION OF THE AVERAGE SPINE CURVATURES VARIATIONS.

The study of the spine curvatures variations during a forward step displacement shows a great diversity of results. A criterion for classifying the "responses" to the disturbance is not easy to imagine. In order to make the parameters for one or severals subjects conspicuous the curves of the average and standard deviation of theses "responses" are displayed in fig. 2-3. This type of process eliminates noises and gives a general idea of the response. One of those noises, notably has for origin the slow variation of the subject's postural components.

II.1.2 - SUBJECT'S POSTURAL COMPONENT SPLITTING.

The continuous component of the signal recorded by the transducer, the subject being in a position of rest, corresponds to the static posture of the latter. It varies slowly with the subject breath (about 0.3 Hz) and fatigue. The amplitude of this evolution is low compared with the possible posture variations. The systematic study of this low postural variation may contribute to determine the influence of the subject's fatigue.

This "static posture" component was eliminated for each response so as to lay only the stress on the spine curvatures dynamic response variation to the disturbance due to platform motion.

II.2 - ANALYSIS OF THE SUBJECT'S AVERAGE SPINE CURVE VARIATIONS WHEN SUBMITTED TO DISTURBANCES DURING A FORWARD STEP POSITION DISPLACEMENT.

II.2.1 - ANALYSIS OF THE RESULTS.

The curves represented in figure 2 correspond to the average spine curvatures variations concerning the last three successive responses of 19 subjects disturbed by a forward step position displacement. The recordings made on the last volunteer had to be eliminated. The subject last three responses were chosen in the initial phase of research for they are apparently more homogeneous than the first five ones and for avoiding any transient phenomena connected to the subject's adaptation to the experiment. In figures 2,3 the standard deviation (minus or plus) of the variations is represented by the curves above and below the average curve.

A maximum of amplitude in the spine curvature variation is to be noticed at the 4 way (L3) level compared with the others ways (T1, T6, T10). This greater amplitude may be caused by the spine flexibility at the lumbar level (2) and by the fact that the distorsion torque is maximal at the lower part of the trunk in our experimental procedure.

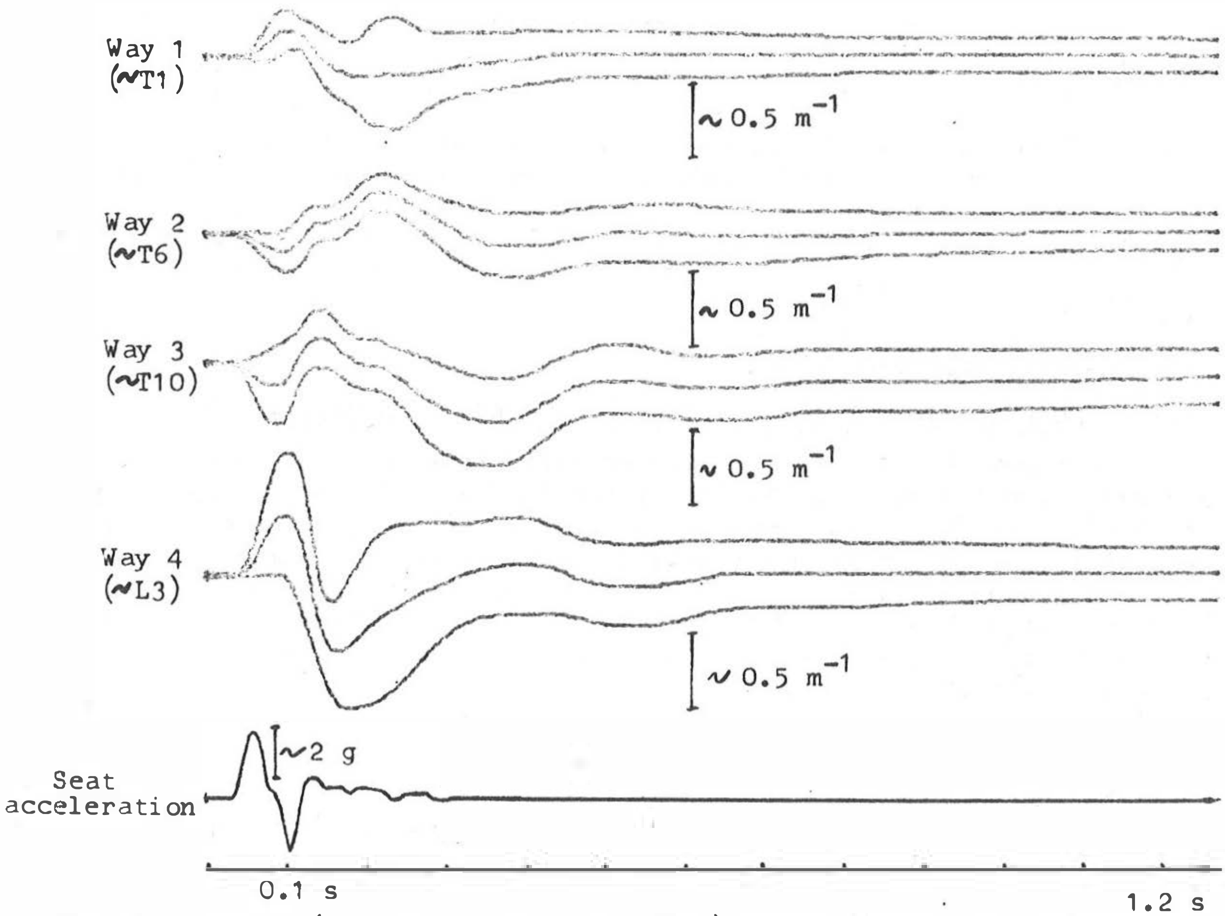

Fig. 2 :Average (+and- standard deviation) spine curvatures variations for 19 subjects submitted to 3 forward "step position" displacements.

A closer look at these curves makes a phase-shift between the signals from different ways very obvious. Particularly the 3 (D10) and 4(L3) ways are practically in opposition of phase. It would be of importance to cheek if there is a distorsion node between those 2 points. Similarly, the 2(D6) and 3(D10) ways seem to be in phase with each other and the 1(D1) and 4(L3) ways as well.

The curves in fig. 3a, 3b correspond to the spine curvatures average variations (+ and - standard deviation) of 2 different subjects taken among the

20 volunteers submitted to eight successive forward step position displacements. The remarks made about the 19 subjects (figure 2) are valid for these two subjects. Moreover the curves in fig. 3a, 3b show that these responses vary in amplitude and shape from one subject to the other. On the contrary the standard deviation which is small compared with the amplitude, shows that for one given subject the 8 successive responses may be approximately the same, figure 3a,b.

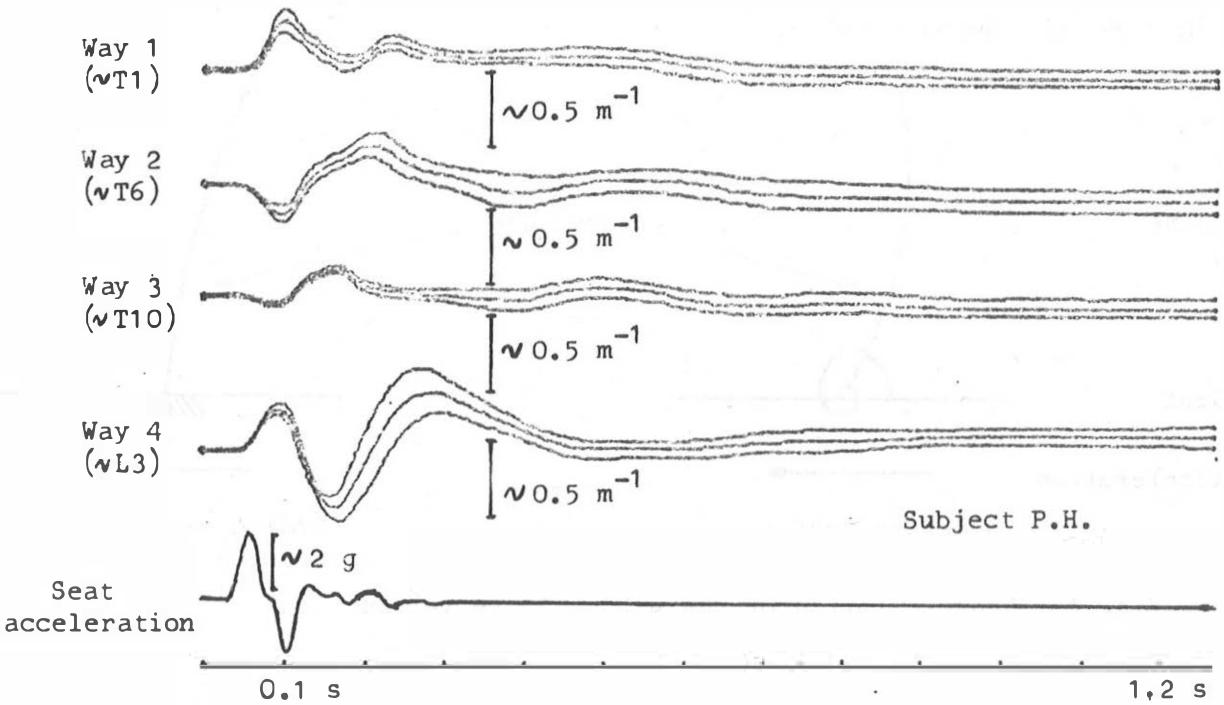

Fig. 3a : Average (+and- standard deviation) spine curvature variations for 1 subject submitted to 8 foward "step position" displacements

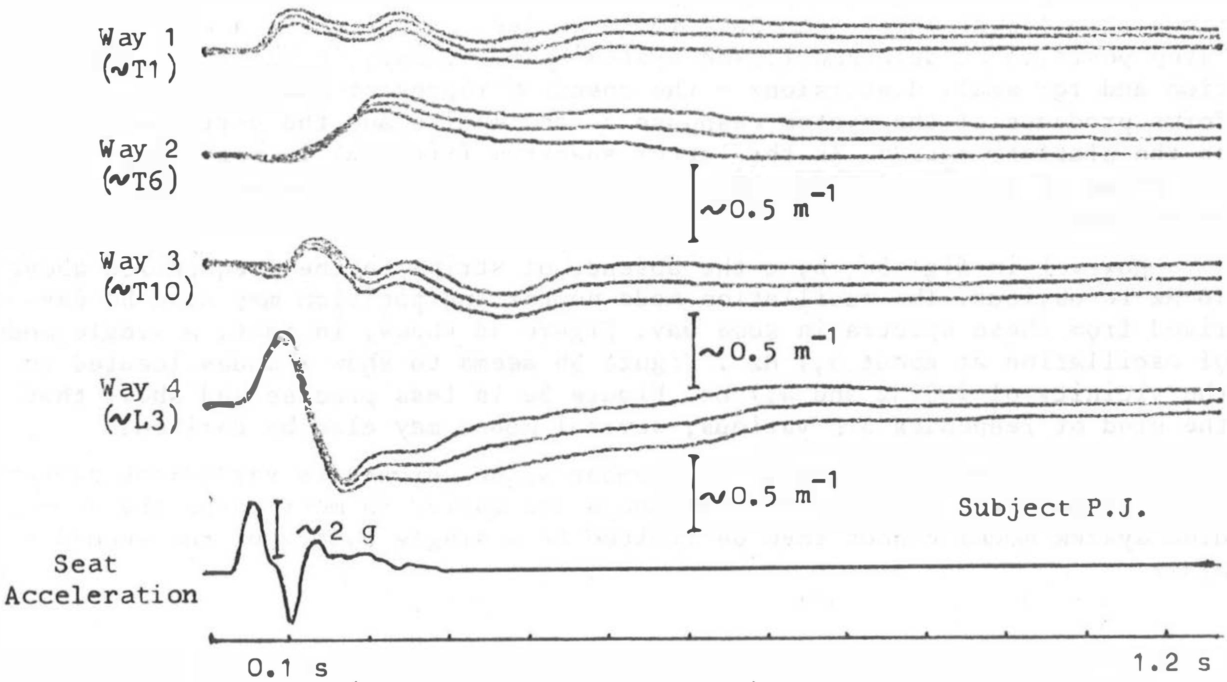

Fig. 3b : Average (+and- standard deviation) spine curvatures variations for 1 subject submitted to 8 forward "step position" displacements.

II.2.2 - PRELIMINARY CONCLUSIONS.

The study of the 4(L3) way, in fig. 2 and 3 indicates that the spine curvature variation in response to a forward movement is at this level practically in phase with the platform acceleration (§ I.3 and fig. 1). This remark allows us to state that the seat trunk link through the pelvis is a visco-elastic one and not a housing (figure 4). This conclusion would not be valid in the case of a backed seat.

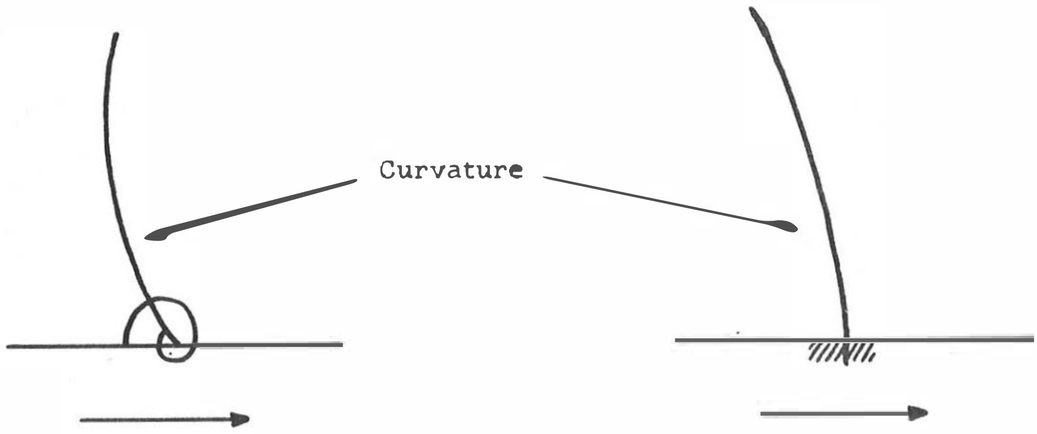

Fig. 4 : Representation of the subject's seat-trunk link.

II.3 - FREQUENTIAL ANALYSIS OF THE SPINE CURVATURE VARIATIONS OF A SUBJECT SUBMITTED TO A SINGLE "STEP POSITION" DISPLACEMENT.

The figures 5 a,b,c represent the energy spectral density of curve variations at a lumbar level (4th way) for a subject submitted to a single forward "step position" displacement. The system being linear, in the first approximation and for small distorsions - the spectra represent (12) the Fourier transforms products of the system response to an impulse and the perturbation due to the platform motion. As the latter spectrum (fig. 2a) is not constant within the range of the studied frequencies, one must take into account into the results analysis.

However in fig. 5a, b, c the absence of strips in the frequencies above 10 Hz is obvious. The oscillation mode number and position may also be derived from these spectra in some way. Figure 5a shows, in fact, a single mode of oscillation at about 3,1 Hz . Figure 5b seems to show 2 modes located in the vicinity of 2,3 Hz and 4,7 Hz. Figure 5c is less precise and shows that the kind of responses are various, several modes may also be derived.

This frequential study of the lumbar spine curvatures variations particularly shows that the oscillatory modes are varied in most cases the studied system model cannot then be limited to a single system of the second order.

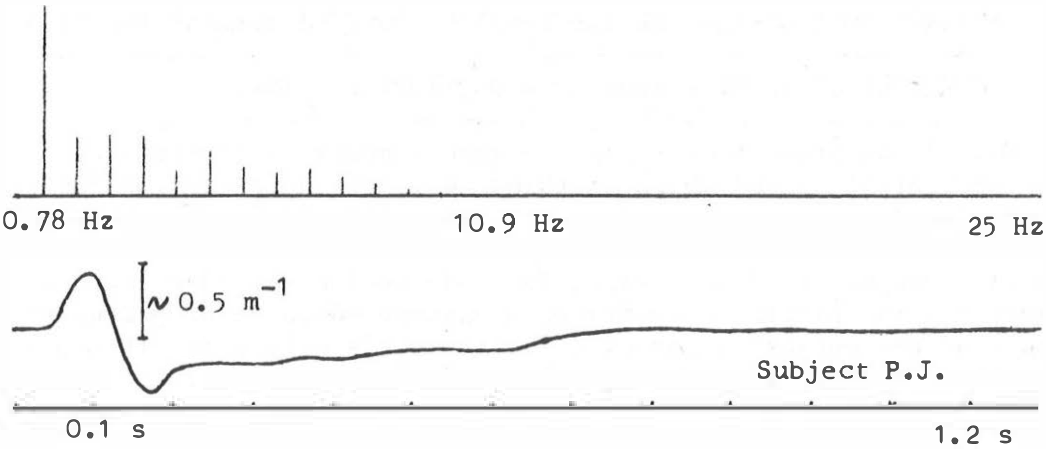

Fig. 5c :

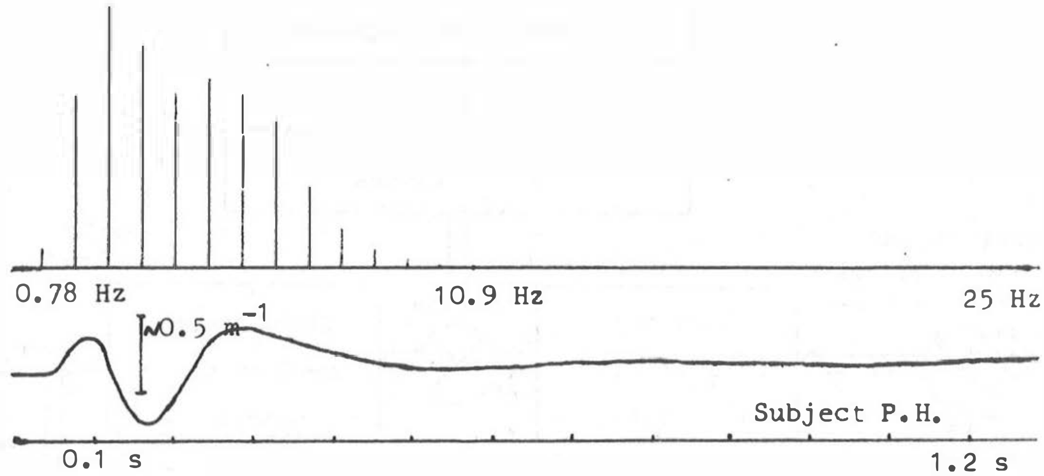

Fig. 5b :

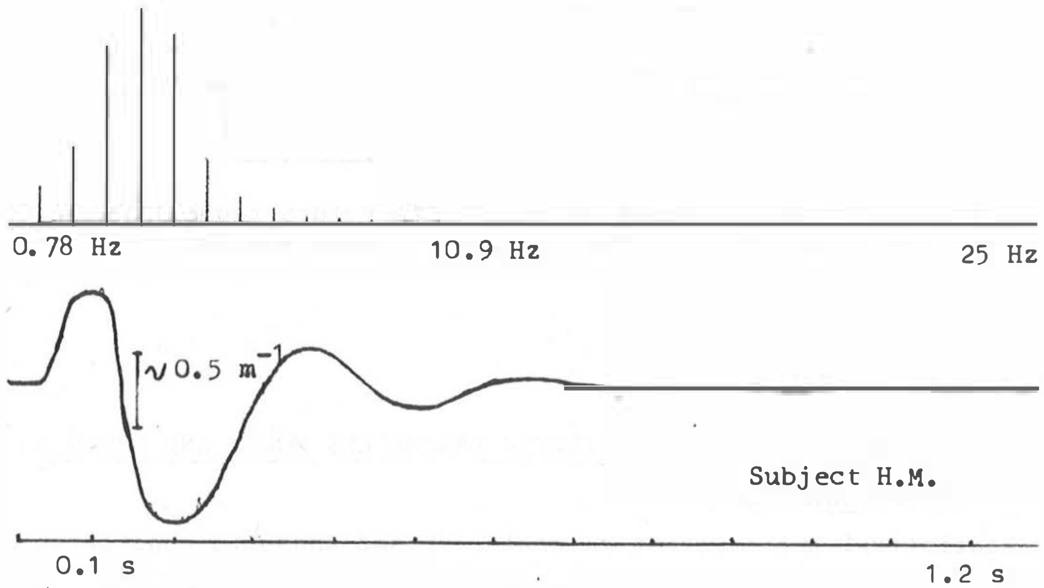

Fig. 5a : Lumbar curvature variation and corresponding energy spectral density.

III - ATTEMPT TO MODELING THE TRUNK-SPINE BIOMECHANICAL SYSTEM OF A SUBJECT SUBMITTED TO ACCELERATION IN A HORIZONTAL PLANE.

In a first stage the attempt to make a model is limited to the trunk spine mechanical system whose disturbance is the acceleration imparted by the platform and the spine curvature output (figure 6). The kind of acceleration used for the simulation consist of a set of 2 impulses whose signs are opposed - spaced of 50 mS - which is close to the recorded acceleration (figure 1). The platform vibrations are supposed to be damped by the soft tissues of the subject . Moreover the subject's will acts-after a time to determine - for modifying his purely mechanical response.

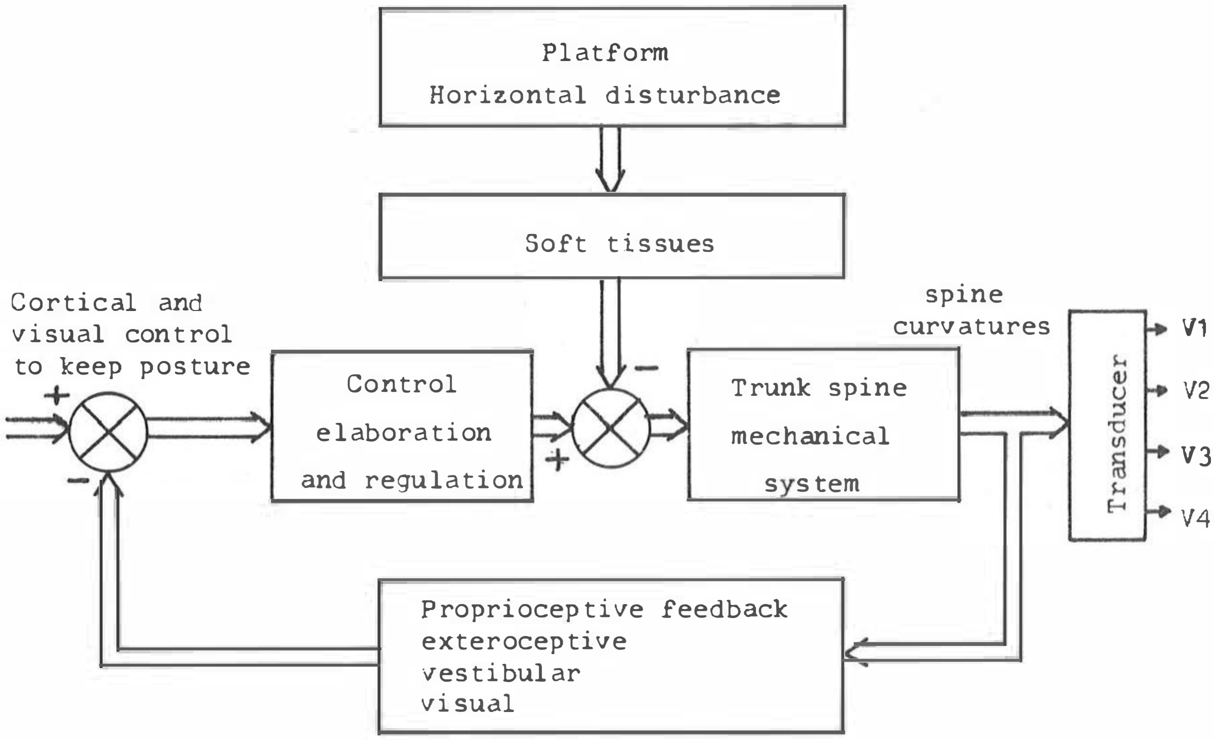

Fig. 6 : Functionnal diagram of a spine curvature regulation system of a subject disturbed by a horizontal motion.

III.1 - INTRODUCTION OF A DISTRIBUTED PARAMETERS MODEL AND PROPOSAL OF A SIMPLIFIED MODEL.

Statistical and frequential analyses and anatomic consideration as well show that the spine-trunk mechanical system has a great number of degrees of freedom. An approach to the problem may then consist in modelling this system by using equations with partial derivatives and refers to the theory of systems with distributed parameters. The latter lead to complex equations which

can hardly be exploited with respect to the aim pursued. The principal difficulties come from non linear phenomena and from an irregular parameter distribution, chiefly those referring to mass and intervertebral link elasticity.
The following model is a compromise : it limits the theoretical and simulation problem and remains actual. It is limited to 5 degrees of freedom and consists of 5 segments linked by articulations having a visco elastic reaction (figure 7) . This choice is guided by the use of a transducer which measures the spine distortion in 4 points. However, we believe that the model quoted above may allow us to increase our knowledge of the reaction and shock transmission along the human spine.

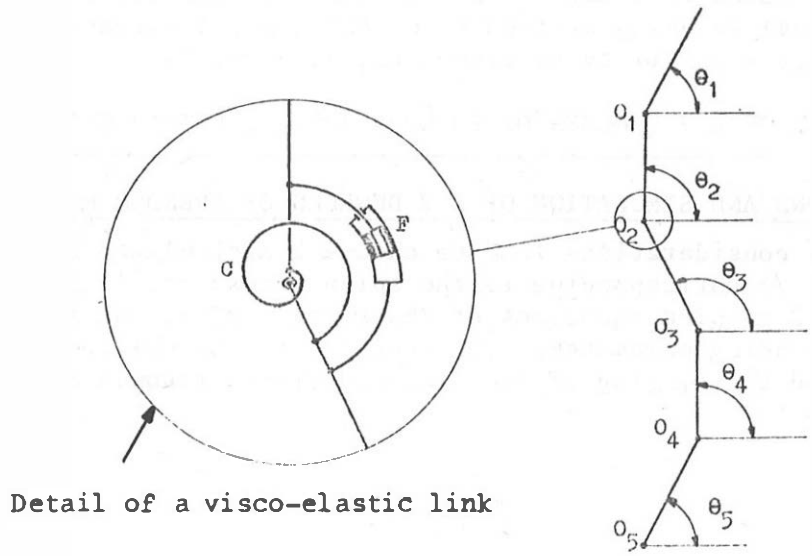

Fig. 7 : Structure of a trunk-spine system model with 5 degrees of freedom. Visco-elastic articulation.

III.2 - STRUCTURE OF A 5 DEGREES OF FREEDOM MODEL.

The transducer outputs are proportionnal to $\phi_i = \theta_{i+1} - \theta_i$ if it is assume that the spine curvatures vary slightly which is the case in our study. Solving the problem by using the Lagrange method without previous approximation leeds to differential equations with non linear coefficients (sinus and cosinus). This can partly explain the response asymetry and show that the results will be differents according to the subject's position of rest.

III.3 - EQUATIONS.

The approximation based on small angles provides equations which are more easily used and eliminate the gravity influence. A system of 5 differential equations of the second order is obtained, they are coupled and of the following type :

$$J_i \ddot{\theta}_i + F_i(\dot{\theta}_i - \dot{\theta}_{i+1}) - F_{i-1}(\dot{\theta}_{i-1} - \dot{\theta}_i) + C_i(\theta_i - \theta_{i+1}) - C_{i-1}(\theta_{i-1} - \theta_i) = \sum_{\substack{j=1 \\ j \neq i}}^{5} A_{ij} \ddot{\theta}_j + B_i \ddot{x}$$

These couplings of equation may represent the anatomic coupling of ligaments and muscles connecting the vertebrae.

A model reduced to 2 degrees of freedom representative of the lumbar curvature (4 L3 way) is being studied below this spinal curvature was chosen for it has a greater sensibility to trauma (2, 7, 8, 9, 13).

IV - SIMULATION OF A 2 DEGREES OF FREEDOM MODEL : LUMBAR CURVATURE VARIATION.

IV.1 - EQUATIONS AND SIMULATION OF A 2 DEGREES OF FREEDOM MODEL.

The above considerations lead to choose 2 articulated segments (segments 4 and 5 figure 7) corresponding to the spine transducer 4(L3) way. The system is reduced to 2 coupled equations of the second order. The simulation makes uses of 10 depending parameters, the most significant of them being the proper frequencies and the damping of the 2 second orders assumed to be independant.

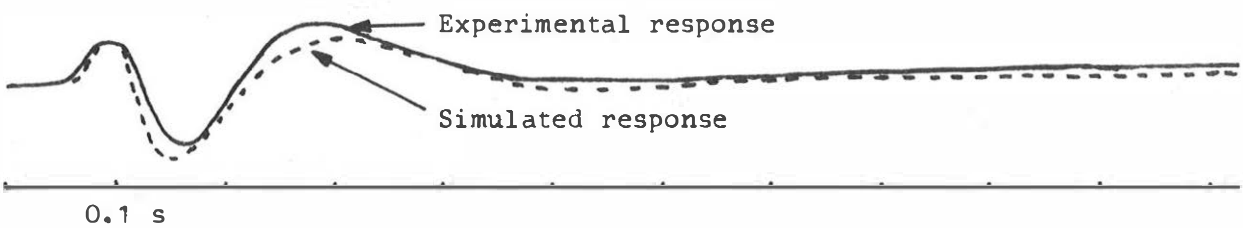

Fig. 8 : Experimental and simulated responses of the lumbar curve variation

IV.2 - VALIDITY OF THE SPINE CURVATURES VARIATIONS MODEL. REMARKS AND CONCLUSIONS.

This model, with 2 degrees of freedom, can oscillate but in 2 modes on different frequencies. It will not then be complex enough to simulate the responses whose spectra seem to show more than 2 modes (figure 5c). Moreover, the influence of the soft tissue between the subject's seat and the pelvis is not taken into account. At last the part played by the subject's reflexe and voluntary control which is to be determined may modify the actual response (closed loop system fig. 6) as compared with the purely mechanical one (open loop system).

The simulation of this model on an analog computer allow us to derive responses whose shape is analogous to the experimental recordings obtained. Figure 8 shows experimental and simulated responses for one subject. We can think that a better knowledge of the acceleration which is really transmitted to the subject would permit to ameliorate the simulated response during the first 100 mS. It is also probable that the model with 5 degrees of freedom would allow to simulate the dorsal and lumbar spine behaviour - measured by the transducer 1 to 4 ways.

CONCLUSION

Those few remarks may allow us to get an aspect of the dynamic behaviour of the complex trunk-spine system. A systematic identification of the model with 5 degrees of freedom would be interesting but the number of parameters (20) needs to elaborate a more original method. First it seems that the number of proper frequencies for the trunk spine set unit in sagittal plane is not limited to one. The frequential study shows in fact, different modes whose frequencies may very from a subject to another. The second conclusion is about the use of a backed seat. It seems that the latter may block part of the trunk (one or several segments of the model) and transmit the disturbance almost unchanged to a level where the trunk characteristics will not allow sufficient damping any longer.

The developpement of our research is directed on the one hand to making a better model at the level of the disturbance transmission by soft tissue and on the other hand to studying the contribution of the subject's reflex and voluntary controls on his spine curvature variations.

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