THE INFLUENCE OF DISCONTINUOUS LATERAL DISPLACEMENTS ON THE BEHAVIOUR OF IN VIVO LUMBAR COLUMN.

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ABSTRACT

The kinematical analysis of displacements of the vertebrae of an in vivo lumbar column during a movement of lateral inflexion allows one:

- to quantify the behavioural qualities of the spine,
- to obtain information about the way in which a vertebral column adapts to stresses
- to define the concept of standard column,
- to analyse the wear and tear produced by lateral impact on spinal columns and hence define the concept of standard column.

INTRODUCTION

The systematic analysis of the movements of the lumbar spine is a recent event. Three dimensional space studies were made by several teams (Rolander 1966, Kinzel et al 1972, White and Panjabi 1971). They were never in-vivo studies. Displacements were either measured directly with the help of displacement gauges or estimated by using X-Rays. In-vivo studies using biplane Roentgenography and subsequent computer analysis have been carried out by R.H. Brown et al. This technique involves the calculation of coordinates of points in three dimensional space, which are very hard to identify owing to certain peculiarities.

We defined a technique for analysing plane movements. When certains conditions are met, this technique allows one to use the coordinates which are directly measured on the films, without any data processing.

It was tempting to apply a well-tested technique to obtain partial but in themselves reliable results about the study of movements of a lumbar column during lateral inflexion.

The analysis of a movement of a lumbar column even if this movement is simplified yields a great amount of data. This very great amount of data dictates its interpretation ; we have been led to define parameters to characterize the curves of change, to synthesize tables of data ; we have been induced to propose a dynamica interpretation in order to explain kinematical characteristics. In this article we would like to present these techniques and the results we obtained from these tests.

MATERIALS

The subject is standing, his pelvis fixed in position. Seven plane radiographs, at regularly spaced intervals are taken. They allow one to follow the displacement of the vertebrae from L5 to T11 with respect to the sacrum during the whole range of movement for lateral inflexion.

Two series of X-Rays were taken :

- a series corresponding to a movement as continuous as possible,
- a series corresponding to a movement as discontinuous as possible.

In a three dimensional movement, the rotation vector of each vertebra with respect to the sacrum has three components : Ωx, Ωy, Ωz. The lateral inflexion movement can be likened to a plane movement if Ωx and Ωy are negligible with regard to Ωz during the whole movement.

The shadow technique allows one to calculate the component Ωz and to verify indirectly the size of Ωx and Ωy.

In this technique the shadow of each vertebra is traced on tracing paper. This shadow does not lose its shape during the whole movement. The displacements of the shadows are measured. The coordinates of the points and the errors due to bad coincidence are statistically evaluated.

METHODS

The coordinates of points measured from the shadow of each vertebra and for each position of the column are the data that allow one to obtain the kinematical characteristics of an elementary movement : rotation vector and point with zero displacement (Instant Center of Rotation I.C.R.).

Two sorts of movements are observed :

- the movement of each vertebra with respect to the sacrum : absolute movement,
- the movement of each vertebra with respect to the one next to it assumed to be fixed in position : relative movement.

For the whole lateral inflexion movement it is possible to draw :

- For the movement of each vertebra with respect to the sacrum :

. The curve of change in angles when the vertebra rotates during its displacement,

. The path of the absolute I.C.R. of the vertebra with respect to the sacrum assumed to be fixed in position.

- For the movement of each vertebra with respect to the one next to it :

. The curve of change in angles of the relative rotation,

. The path of the relative I.C.R.

The analysis of these numerous curves and paths involved two operations :

- the definition of the parameters capable of synthesizing a curve of change or path and to relate these parameters to the behavioural qualities of the lumbar spine in order to attempt an evaluation of these behavioural qualities.
- a mechanical study to relate the discontinuities and anomalies of displacement to the natural dynamic capacity of the column for sustaining and distributing these anomalies.

PARAMETERS OF SYNTHESIS : ABSOLUTE MOVEMENT

CURVE OF CHANGE IN ROTATION

The equation of the staightline nearest the rough curve (regression line) is :

$$\Theta = ax + \Theta_0$$

The coefficient a, can be used to define the absolute kinematic activity of the vertebra. The residual variance over an interval between the rough curve of change and its regression line is defined by :

$$V_A = \frac{\Sigma_i (\Theta_{curve} - \Theta_{line})^2}{n - 1}$$

V_A measures the fit between the dashed curve and the regression line ; V_A defines in a quantitative manner the smoothness of the movement of a single vertebra.

ABSOLUTE PATH OF I.C.R.

The movements studied in biomechanics have their I.C.R. paths concentrated within specific zones. The paths vary from one live subject to another, but the zones of concentration are comparable. The absolute path of I.C.R. is characterized by a scattering circle. The center of this circle is I_{AM} defined as the barycenter of the set of absolute I.C.R. along the path. The radius of this circle is denoted R_A. R_A is defined as the average of the distance between the barycenter I_{AM} and each I.C.R.

$$R_A{}^2 = \frac{\Sigma \; (x_i - x_{IA})^2 + (y_i - y_{iA})^2}{n}$$

I_{AM} can be considered to be the point at which displacement is zero on an average.
R_A serves to measure the dispersion of the path with regard to its center.

RELATIVE MOVEMENT

CURVE OF CHANGE IN RELATIVE ROTATIONS

The equation of the regression line is :

$$\Psi = bx + \Psi_0$$

The coefficient b defines the kinematic activity of the intervertebral disc ;

$$V_R = \frac{\Sigma_i (\Psi_{curve} - \Psi_{line})^2}{n - 1}$$

the residual variance over an interval, measures the regularity of the strains sustained by a disc during a complete movement.

RELATIVE PATH OF I.C.R.

There is a relationship between the positions of the relative I.C.R. and the stresses sustained by an interverterbral disc.

In healthy subjects any path of the relative I.C.R. is always progressive and concentrated within a zone. In order to take these facts into account we have replaced the path by a circle of disparity of stresses. The center of the circle is I_{RM} barycenter of the relative I.C.R., the radius is the average distance between two successive I.C.R. on the trajectory.

$$R_R = \frac{\Sigma_i (x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}{n - 1}$$

R_R measures the disparity between the different stresses sustained by a disc.

ABSOLUTE TOTAL MOVEMENT

One can draw :
- the curve of change in average kinematic activity in terms of the positions of the vertebrae in the lumbar column,
- the curve of regularity in functioning along the column,
- the path of scattering circles which serves as a model for the mechanics of the joints of the whole column.

RELATIVE TOTAL MOVEMENT

One can draw :
- the curve of change in average activity of the discs in terms of the position of each disc,
- the curve of regularity in functioning of the disc in terms of its position along the column,
- the path of circles of disparity of stresses. Some circles can be divided into two, in order to make the dyssymetry of functioning caused by stresses, become apparent (as in scoliosis).

MECHANICAL STUDY OF DISCONTINUITIES

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LOCAL STUDY

For a given position, the curve of change of absolute rotation for a given vertebra is assumed to have a discontinuity. This discontinuity is most frequently accompanied by a discontinuity in the path of the absolute I.C.R. for the corresponding position. In some cases this discontinuity can be observed in the change of relative rotation of the vertebra in question with respect to the adjacent ones.

As we do not know anything about the motion of the subject between two successive stes of X-Rays, we assumed that :

- the motion is continuous between the i-1th and the ith X-Rays, between the ith and the i+1th X-Ray ;
- the kinematical discontinuties are produced at the time of the ith X-Rays therefore impact forces are acting at this level.

THe rotational momentum $I\omega_{i-1}$ of a given vertebra may be changed to $I\omega_{i+1}$ by the action of impulsive torque M_{ex} and M_i from t_{i-1} to t_{i+1}

$$\int_{i-1}^{i+1} M_{ex}dt + \int_{i-1}^{i+1} M_i dt = I_G(\omega_{i+1} - \omega_{i-1})$$

Denoting :

M_{ex}, M_i the impulsives torques about the center of mass of external forces (muscular forces) and internal forces due to discs respectively.

I_G the mass moment of inertia about the center of mass,

ω_{i-1}, ω_{i+1} the average angular velocity before and after the discontinuity respectively ;

$$\omega_{i+1} = \frac{\theta_{i+1} - \theta_i}{dt} \qquad \omega_{i-1} = \frac{\theta_i - \theta_{i-1}}{dt}$$

Assuming that the duration dt is the same between two successive X-Rays.

Denoting by $\Delta\theta_m$ the average increment over an interval : $\Delta\theta_m = a\,\Delta t$

$$\omega_{i+1} = \frac{\Delta\theta_i}{\Delta t} = \frac{\Delta\varepsilon_i}{\Delta t} + a \;; \quad \omega_{i-1} = \frac{\Delta\theta_{i-1}}{\Delta t} = \frac{\Delta\varepsilon_{i-1}}{\Delta t} + a$$

This yields :

$$\int_{i-1}^{i+1} M_{ex}dt + \int_{i-1}^{i+1} M_i dt = I_G\frac{(\Delta\varepsilon_i - \Delta\varepsilon_{i-1})}{\Delta t} = I\frac{\Delta\varepsilon}{\Delta t}$$

When the curve of change in absolute angle deviates sharply from the regression line, for a given position, $\Delta\varepsilon$ no longer equals zero. This would suggest an impact for this position. The impulse of the impact torque is a finite quantity, but we have no way of knowing if the impact is due to an external or an internal torque.

The momentum counterpart of the previous equation uses the mass of the vertebra :

$$\int_{i-1}^{i+1} F_{ex}dt + \int_{i-1}^{i+1} F_{in}dt = M\left[V_{i+1}(G) - V_{i-1}(G)\right] \qquad (4)$$

Denoting by G the center of mass ; F_{ex}, F_{in} are respectively the external and internal forces acting upon the body from t_{i-1} to t_{i+1} ; $V_{i-1}(G)$, $V_{i+1}(G)$ the average velocity of the center of mass before and after the discontinuity respectively.

$$V_{i-1}(G) = \frac{G_{i-1}\,G_i}{\Delta t} \quad ; \quad V_{i+1}(G) = \frac{G_iG_{i+1}}{\Delta t}$$

using the properties of the I.C.R. :

$$\frac{G_{i-1}G_i}{\Delta t} = Z\ x\ \frac{\Delta\theta\ _{i-1}}{\Delta t} I_{i-1}G_{i-1} \qquad \frac{G_iG_{i+1}}{\Delta t} = Z\ x\ \frac{\Delta\theta_{i+1}}{\Delta t} I_{i+1}G_{i+1}$$

Equation (4) becomes :

$$\int_{i-1}^{i+1} F_{ex}dt + \int_{i-1}^{i+1} F_{in}dt = M\ Z\ x\left[\frac{\Delta\theta\ _{i+1}}{\Delta t} I_{i+1}\ G_{i+1} - \frac{\Delta\theta_{i-1}}{\Delta t} I_{i-1}G_{i-1}\right]$$

G_{i+1} is always near to G_{i-1} ; $\Delta\theta_{i+1}$, $\Delta\theta_{i-1}$ being finite quantities it is possible to define an average angular velocity $_m$ and write in vector notation :

$$\int_{i-1}^{i+1} F_{ex}dt + \int_{i-1}^{i+1} F_{in}dt = M\ \omega_m Zx\ I_{i-1}I_{i+1}$$

The kinematical discontinuity takes the form of a sudden change in the path of absolute I.C.R. for a given position. This corresponds with either external or internal forces, it is impossible to say which.

In relative movement, the same vertebra is subject to the same forces (external and internal forces which become constraint forces). The impact analysis states that a phenomenon can be analyzed both in absolute axis (movement with respect to the sacrum) as well as in relative axis (with respect to the previous vertebra).

Let us assume we have a shock. We can state :

$$\int_{i-1}^{i+1} M_{ex}dt + \int_{i-1}^{i+1} M_L dt = I_G\left[\frac{\Delta\psi_{i+1}}{\Delta t} - \frac{\Delta\psi_{i-1}}{\Delta t}\right]$$

$\Delta\psi_{i+1}, \Delta\psi_{i-1}$ denoting the change in relative rotation.

If the curve of change in relative angle deviates from the regression line and if the variation in relative movement is the same as in absolute movement we can state that the phenomenon is a shock.

TOTAL STUDY

The conditions under which the X-Rays were taken, did not permit us to follow the diffusion of the disturbance in time. On the other hand we had the means to understand the way in which a disturbance was distributed along the column at a given time.

If for a given position we observe a disturbance in the change of relative rotation acting on the vertebra, we can write :

$$P_K = \frac{I_K}{\Delta t} (\Delta\theta_{Ki} - \Delta\theta_{Ki-1})$$

Denoting by P_K the sum of the impulse of imact torque (external and constraint forces) acting on the vertebra.

For the adjacent vertebrae we can state :

$$P_{K+1} = \frac{I_{K+1}}{\Delta t}(\Delta\theta_{K+1,i} - \Delta\theta_{K+1,i-1})$$

$$P_{K-1} = \frac{I_{K-1}}{\Delta t}(\Delta\theta_{K-1,i} - \Delta\theta_{K-1,i-1})$$

Assuming that the mass moments of inertia I_{K-1}, I_{K+1} , I_K are equal, the comparison of the change $\Delta\theta_{K,i}$ $\Delta\theta_{K,i-1}$ with those of the adjacent vertebrae allows us to compare the way in which impulse P_K can be distributed along the column for a given position.

The analysis of the distribution of disturbances by the whole column for each position gives too great an amount of data for practical purposes.

We have defined a method for determining the average way in which a column distributes a disturbance during the whole movement of lateral inflexion.

We have calculated the residual variance over an interval to quantify the harmonious character of the movement of a vertebra with respect to the sacrum and to the adjacent vertebra.

In the case of shock : $V_A=V_R = \frac{\Sigma (\theta_{i,K} - \theta_{miK})^2}{n} = \Sigma \frac{(\psi_{iK} - \psi_{miK})^2}{n}$

If we assume that there is an average state of impact forces during the whole movement of a vertebra, this average state can be quantified by the change of variance for the given vertebra.

The curve of change in absolute variances with respect to their position along the column is an illustration of the way in which the impulses are distributed on average along the column during a whole movement of lateral inflexion.

RESULTS

Two series of tests were carried out (healthy subjects bending laterally with both a continuous and a discontinuous movement) The aim of these tests was :

- to define the criteria of normality for columns subjected to continuous movements,
- to study the way in which a healthy subject distributes impulses which ressemble lateral shocks as far as possible.

After tests tne continuous movement of a healthy column can be defined as having the following characteristics :

ABSOLUTE MOVEMENT

A linear curve of kinematic activity, each vertebra plays an equal part in the mobility of the whole column. The movements are harmonious, the variances are slight and distributed uniformly along the column. The scattering circles are specified, they are centered along the axis of the column, their radii vary progressively.

RELATIVE MOVEMENT

The discs have a comparable kinematical activity, the variance are slight, the scattering circles are centered on the zone of the discs along the axis of the vertebra, their radii are small.

The behaviour of a healthy column subjected to a discontinuous lateral movement can be described as follows :

ABSOLUTE MOVEMENT

The curve of change of kinematical activity is linear. The gradient of the line of change of a discontinuous movement is nearly the same as for a continuous movement.

As a result of the discontinuity provoked during the movement, there are irregularities in the curve of change of rotation for each vertebra and hence considerable variances are caused.

A standard subject distributes a shock uniformly along the whole column, spreading the variances over all the discs.

The scattering circles have practically the same position with respect to the axis of the column during the previous test and the radii are considerably larger. Normality can be recognized by the fact that the radii of scattering circles of an individual vary progressively along the length of the column.

RELATIVE MOVEMENT

All the discs of a standard subject act in a manner similar to the previous test (continuous movement).

The impulses are distributed regu larly along the length of the column. There is no sudden change in the radii of the progressiveness circles.

Some clinically healthy subjects may show evidence of scoliosis They are able to sustain considerable forces during discontinuous movement but these forces are not evenly distributed along the whole column. Some discs are under great stress. The scattering circles allow us to throw light on some disturbing assymetries.

CONCLUSION

The techniques presented in this paper are also used for clinical purposes in the view to being a diagnostic aid. However it is important to state that clinically healthy subjects without any radiological anomalies can have a lumbar column whose dynamica behaviour is such that they are much more likely to have low-back pain than subjects who are dynamically normal.

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