# IN VITRO OPTO-ELECTRONIC ANALYSIS OF 3-D SEGMENTAL VERTEBRAL MOVEMENTS DURING GRADUAL RIB LENGTHENING IN THE PIG

B. SEVASTIK, B. XIONG, A. LUNDBERG, J. A. SEVASTIK

**The effects of gradual rib elongation on the 3-D position of neighboring vertebrae were studied *in vitro* in two pig specimens. The ends of one osteotomized rib were gradually distracted and the micromovements of the numerically corresponding vertebra with the osteotomized rib were studied in relation to the subjacent and suprajacent vertebrae with an opto-electronic motion analysis device. The study showed that gradual lengthening of the rib resulted in micromovements of the central vertebra in relation to the neighboring vertebrae registered as a) lateral translation in the coronal plane, b) rotation in the horizontal plane (both a and b were movements towards the opposite side of the lengthened rib), c) ventral translation in the sagittal plane and d) tilt in the coronal and sagittal planes. All movements were registered simultaneously. There was a significant linear correlation with the degree of rib elongation. From the results of this study it is concluded that gradual elongation of one rib affects the position of the numerically correspondig vertebra in relation to the suprajacent and subjacent vertebrae in the three cardinal planes in the same way as the apex vertebra is affected in idiopathic scoliosis. Moreover, the registered tilt, i.e., the rotational movement of the central vertebra in the coronal plane, could explain the wedging of the disc space, and the ventral translation in combination with the tilt in the sagittal plane could account for the lordotic tendency of the scoliotic segment.**

**Keywords** : vertebral micromovements ; gradual rib lengthening ; pig spine ; *in vitro*.

**Mots-clés** : micro-mouvements vertébraux ; élongation costale graduelle ; rachis de porc ; *in vitro*.

## INTRODUCTION

The pathogenesis of the spinal deformity in idiopathic scoliosis (IS) is still under dispute. Based on clinical and experimental observations it has been suggested that the 3-D malalignment of the spine in IS either originates from primarily disturbed vertebral growth or occurs secondary to neuromuscular dysfunction.

The following factors have been considered possible contributors to the development of the scoliotic deformity : a) unilateral growth disparity in the frontal plane resulting in lateral vertebral translation (13, 10, 5, 4, 11, 20), b) asymmetrical growth of the arch at the neurocentral plate leading to vertebral rotation (27, 16, 24, 14, 36) and c) growth disparity in the sagittal plane resulting in hypokyphosis or lordosis (33, 27, 29, 9, 7, 8, 17, 15, 26). On the other hand several reports have assigned the origin of the skeletal changes in IS to neuromuscular dysfunction arising from, for instance, abnormal subcortical structures (25, 12), structural changes of the thoracic roots or cord (21, 35, 17), muscular changes of varying origin (38, 44, 42, 43), disturbed postural equi-

Department of Orthopedic Surgery, Karolinska Institute, Huddinge University Hospital, S-141 86, Huddinge, Sweden.

Correspondence and reprints : B. Sevastik, Department of Orthopedic Surgery, Huddinge University Hospital, S-141 86 Huddinge Sweden.

librium (41, 28) or failure of control of spinal cyclical rotations (6).

Disturbed extravertebral skeletal growth as a pathogenetic factor in IS has not been taken into consideration earlier. However, an experimental scoliosis study in rabbits suggested that asymmetrical stimulation of longitudinal rib growth may be a pathogenetic factor of IS (30). A significant length difference of rib pairs between normal and scoliotic women has been reported ; in 5 of 6 scoliotic patients with right convex thoracic IS the left ribs were longer than the right ones (22). Length asymmetry of rib pairs was later reported in a mathematical study of scoliotic and normal women (34). In another study it was found that the left breast in girls with right convex adolescent idiopathic scoliosis was more vascularized than the right one, and it was suggested that increased vascularization of the left anterior thorax including the costosternal growth plates could be the cause of asymmetrical longitudinal rib growth (23). This assumption has later been supported by further experimental studies in rabbits (1-3).

Immediate unilateral elongation of one rib in rabbits has been reported to induce scoliosis with vertebral translation in the coronal plane, rotation in the horizontal plane and hypokyphosis (31). Also the redisposition of the vertebrae in the three cardinal planes has been shown to develop simultaneously (32).

However, the exact sequence of how the 3-D movements of the vertebrae within a spine segment during gradual lengthening of a rib is brought into action has not been studied earlier. Therefore, the present investigation was undertaken in order to study the very first movements of vertebrae subjected to such forces using opto-electronic motion analysis, which permits the study of the micromovements in the three cardinal planes simultaneously.

## MATERIALS AND METHODS

*Experimental set-up* : The torso from two recently killed growing pigs was skinned and the subcutaneous fat was removed. The specimen including the whole thorax with its contents, the diaphragm and the spine from the 5th cervical to the 2nd lumbar vertebra was stabilized in the upright position in a specially constructed frame with slight pressure along the axis of the spine (fig. 1). Four 10-mm spherical reflecting markers, placed on each of three holders, which were fixed to the spinous process of the vertebra corresponding to the numerical level of the osteostomized rib, on the suprajacent and on the subjacent spinal process (fig. 1) were used.

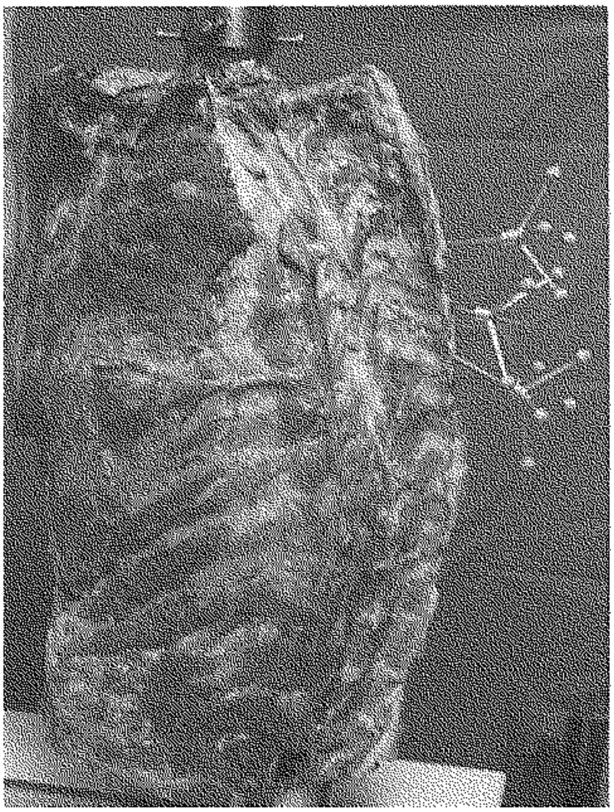

*Fig. 1.* — The experimental set-up. The torso of the pig is placed in the erect position on the frame. Reflecting markers are placed on the tip of the spinal process of the central vertebra (corresponding to that of the lengthened rib) and of the vertebrae suprajacent and subjacent to it.

The left 8th or 9th rib was dissected free from soft tissues and periosteum. An osteotomy of the rib was performed close to the costotransverse joint of the vertebra corresponding numerically to the osteotomized rib. A mini-Wagner's distraction instrument was applied over the ends of the osteotomized rib. The distance between the fragments was gradually increased by 1 to 2 mm at intervals of 1 to 2 min up to 30 mm, during a total period of approximately 60 min.

All movements were recorded using an opto-electronic motion analysis device (Qualysis, Göteborg).

With the calibration procedure used the equipment has been shown to be accurate to approximately 0.2° of rotation (19).

*Parameters studied*: the movements of the central vertebra in relation to the suprajacent and subjacent vertebrae were registered in the three cardinal planes i.e., translation in the coronal and the sagittal plane and rotation in the horizontal plane. The tilt in the coronal and sagittal planes of the central vertebra in relation to the other two vertebrae was also registered.

*Statistics*: Linear regression analysis was used for the correlation between the degree of the vertebral movements and the gradual increase in the rib length.

The time elapsed between killing the animals and the end of each test did not exceed 10 hours. There were no signs of rigor in the specimens at the end of each test.

## RESULTS

### *Vertebral translation in the coronal plane*

The translation of the central vertebra in relation to the suprajacent vertebra was not significantly correlated with the degree of rib lengthening ($r = 0.09$, $p = 0.5686$) (fig. 2); in relation to the subjacent vertebra it was positively correlated with the lengthening of the rib, i.e., it moved towards the opposite side of the elongated rib ($r = 0.882$, $p = 0.0001$) (fig. 3).

### *Vertebral translation in the sagittal plane*

The translation of the examined vertebra in relation to the suprajacent vertebra in the sagittal plane was not significant ($r = 0.253$, $p = 1148$) (fig. 4); in relation to the subjacent vertebra it was significant and positive indicating a ventral direction of movement ($r = 0.853$, $p = 0.0001$) (fig. 5).

### *Vertebral rotation in the horizontal plane*

With increasing length of the rib both the central and the suprajacent vertebrae rotated towards the opposite side of the lengthened rib. However, since the suprajacent vertebra rotated more than the central vertebra, the latter seemed to rotate to the same side as the lengthened rib, compared to the suprajacent ($r = -0.496$,

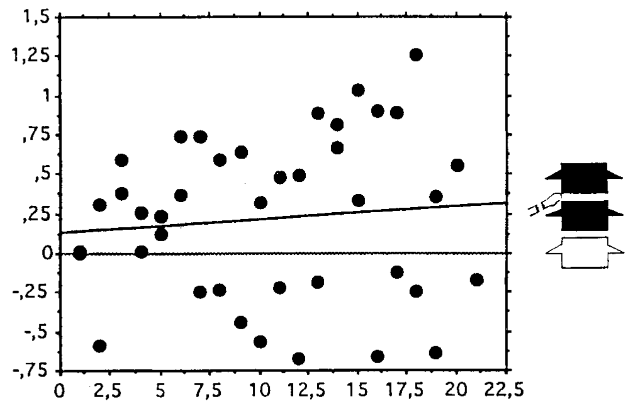


*Fig. 2.* — Translation of the central vertebra in the coronal plane, in relation to the suprajacent vertebra. $Y$ = vertebral movement mm $X$ = rib elongation mm ($r = 0.09, p = 0.5686$).

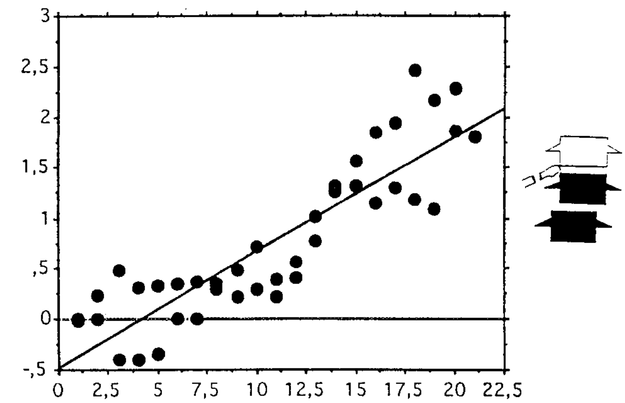


*Fig. 3.* — Translation of the central vertebra in the coronal plane to the opposite side of rib lengthening, in relation to the subjacent vertebra. $Y$ = vertebral movement mm $X$ = rib elongation mm ($r = 0.882, p = 0.0001$).

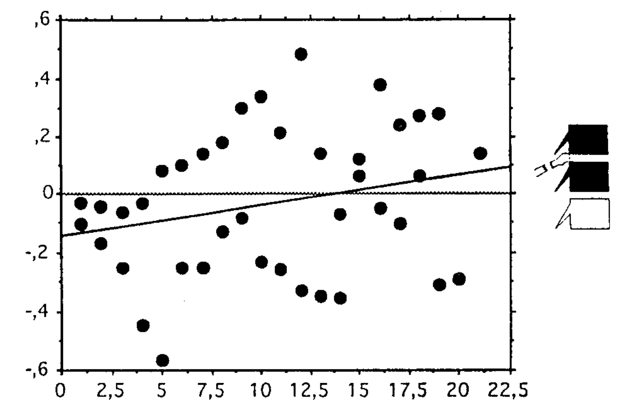


*Fig. 4.* — Translation of the central vertebra in the sagittal plane, in relation to the suprajacent vertebra. $Y$ = vertebral movement mm $X$ = rib elongation mm ($r = 0.253$, $p = 0.1148$).

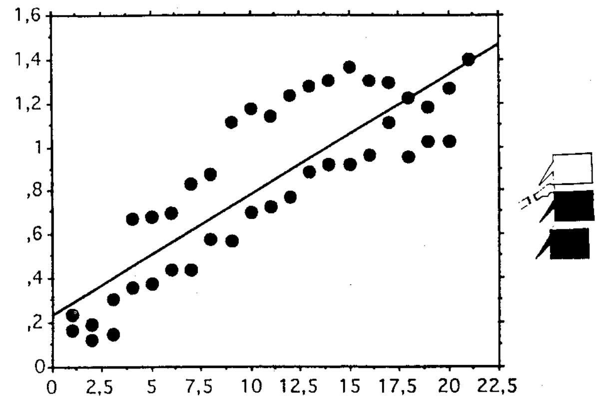


*Fig. 5.* — Translation of the central vertebra in the sagittal plane, in relation to the subjacent vertebra. $Y$ = vertebral movement mm $X$ = rib elongation mm ($r = 0.853$, $p = 0.0001$).

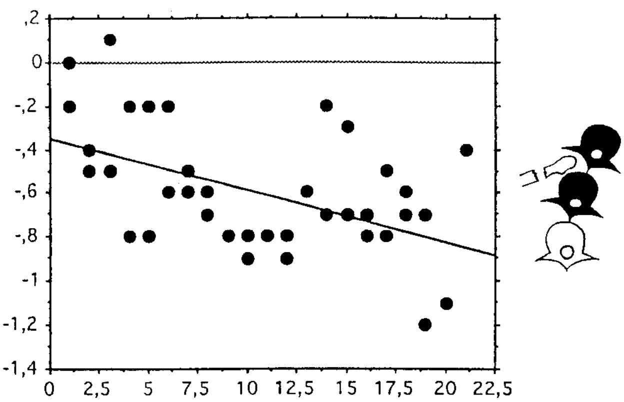


*Fig. 6.* — Rotation of the central vertebra in the horizontal plane to the direction of rib lengthening, in relation to the suprajacent vertebra, which is more rotated to the opposite side of the lengthened rib. $Y$ = rotation degrees $X$ = rib elongation mm ($r = -0.496$, $p = 0.0001$).

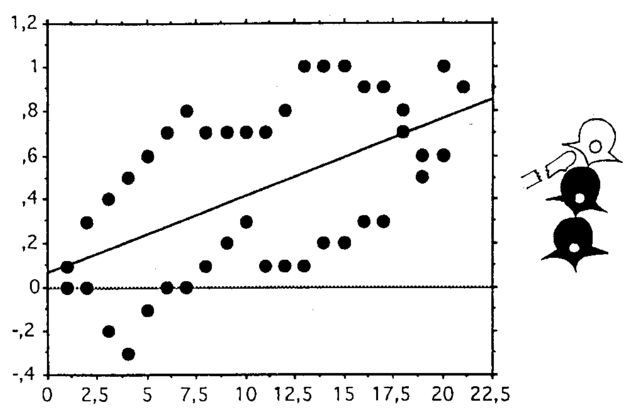


*Fig. 7.* — Rotation of the central vertebra in the horizontal plane to the opposite direction of rib lengthening, in relation to the subjacent vertebra. $Y$ = rotation degrees $X$ = rib elongation mm ($r = 0.559$, $p = 0.0001$).

$p = 0.001$) (fig. 6). The rotation of the central vertebra in relation to the subjacent vertebra was significant i.e., it rotated towards the opposite side of the elongated rib ($r = 0.559$, $p = 0.0001$) (fig. 7).

*Vertebral tilt in the coronal plane*

The central vertebra was positively tilted in relation to either the suprajacent or subjacent vertebra during increasing rib lengthening ($r = 0.743$, $p = 0.0001$ and $r = 0.919$, $p = 0.0001$ respectively) (figs. 8, 9). This implies that the central vertebra, besides its translation in the coronal plane, also rotated clockwise in relation to both the suprajacent and subjacent vertebra.

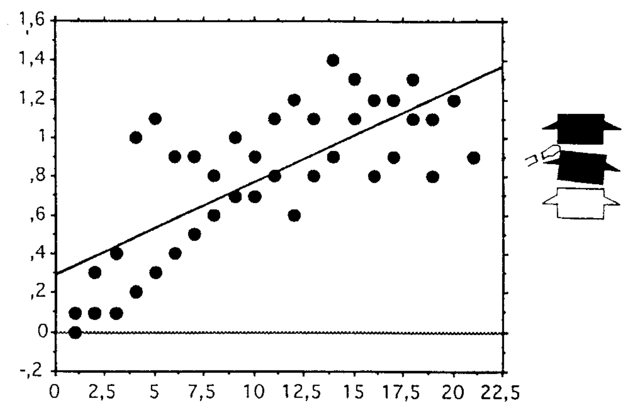


*Fig. 8.* — Tilt of the central vertebra in the coronal plane, rotating clockwise to the opposite direction of rib lengthening, in relation to the suprajacent vertebra. $Y$ = vertebral movement degrees, $X$ = rib elongation mm ($r = 0.743$, $p = 0.0001$).

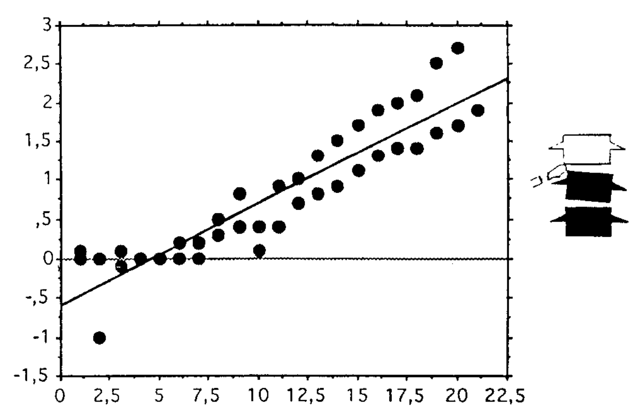


*Fig. 9.* — Tilt of the central vertebra in the coronal plane, rotating clockwise to the opposite direction of rib lengthening, in relation to the subjacent vertebra. $Y$ = vertebral movement degrees, $X$ = rib elongation mm ($r = 0.919$, $p = 0.0001$).

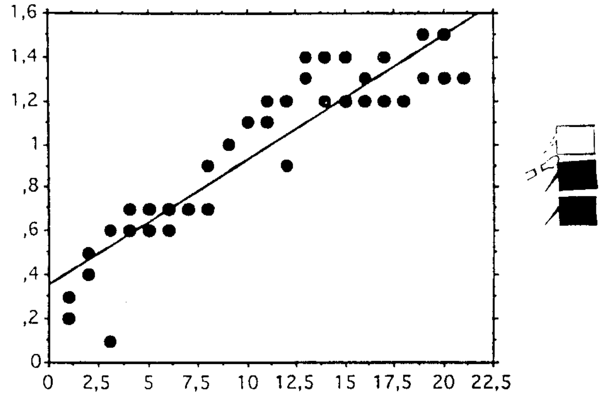


*Fig. 10.* — Tilt of the central vertebra in the sagittal plane, rotating counterclockwise in relation to the suprajacent vertebra. $Y$ = degrees, $X$ = rib elongation mm ($r = -0.509$, $p = 0.008$).

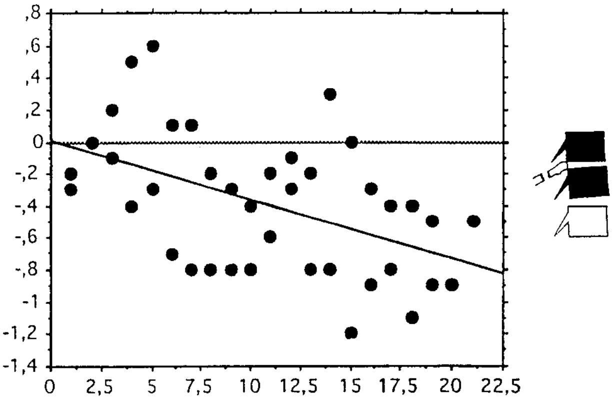


*Fig. 11.* — Tilt of the central vertebra in the sagittal plane, rotating counterclockwise in relation to the subjacent vertebra. $Y$ = degrees, $X$ = rib elongation mm ($r = 0.912$, $p = 0.0001$).

*Vertebral tilt in the sagittal plane*

The tilt of the central vertebra in relation to the suprajacent vertebra was negatively correlated with the extent of rib elongation ($r = -0.509$, $p = 0.0089$) (fig. 10). In relation to the subjacent vertebra, the central vertebra was positively correlated with the extent of the lengthening ($r = 0.912$, $p = 0.0001$) (fig. 11). In other words, the central vertebra, besides its ventral translation, also rotated countercklockwise in relation to both the suprajacent and subjacent vertebrae.

## DISCUSSION

The results of the present investigation show that the forces generated by gradual lengthening of one rib result in simultaneous micromovements of the vertebra corresponding numerically to the lengthened rib. The results further indicate that there is an immediate translation of the central vertebra in the coronal and sagittal planes and rotation in the horizontal plane increasing linearly with the rib lengthening. The central vertebra also rotates significantly in relation to the suprajacent and subjacent vertebra in the coronal and sagittal planes.

The gross anatomy of the vertebrae and the ribs as well as the shape of the thoracic cage of the pig are similar to those in humans. This in combination with the appropriate size of the pig specimen for the purpose of the experiment was the reason for the choice of animal in this study. There are, however, essential biomechanical differences between the pig and the human spine, and they are related to the bipedal and quadrupedal gait, respectively. These differences were not considered to be important for the outcome of this experiment because the instantaneous micromovements registered were not influenced by muscular factors or long-term effects of gravity on the spine.

The study was designed to determine the micromovements between two vertebrae caused by gradual elongation of one rib *in vitro*, and the results can, therefore, not be considered to reflect the conditions of the living spine. Hence the impact of muscular forces on the outcome of the study was assumed to be negligible. For the same reason, and given the short experimentation window for recently killed animals, viscoelastic factors affecting intervertebral discs and ligaments also were considered marginal for the outcome.

The results of the current investigation are based on two experiments only, since the aim of the study was to examine the qualitative rather than the quantitative effects of gradual rib lengthening on the corresponding vertebrae. Stronger statistical support would certainly have been provided if a larger number of animals had been used, but considering the objectives of the study the results were found to be satisfactory.

The opto-electronic method used in this experiment has been proved to measure accurately extremely small movements between two skeletal segments, fractions of one degree, in good accordance with Roentgen-stereophotogrammetic measurements (19). Therefore, the results of the study are considered reliable.

The registered micromovements in the present study increased proportionally with the gradual increase of the forces generated by the elongated rib up to 20 mm. In two earlier studies in rabbits, rib lengthening by 7 or 10 mm resulted in 3-D changes of the position of the vertebra as well, but the movements were more accentuated (31, 32). The difference between the degree of the vertebral movement in the three planes in the present and earlier studies is probably due to the difference of the vertebral anatomy between the two species and hence different degrees of stability and rigidity in the spines.

Due to the anatomical connection of the elongated rib to the vertebra corresponding numerically to the lengthened rib and the suprajacent vertebra by a common articulation, these two vertebrae behaved as a single segment during the experiment. This explains why there is no significant relative change of position between the two in the coronal and sagittal planes. In the horizontal plane the suprajacent vertebra was more rotated in relation to the central vertebra, which is in accordance with the findings of a cross-sectional study on IS, where a significant rotation in the horizontal plane was registered first at the vertebra above the apical one (39). In relation to the subjacent vertebra, the central vertebra was significantly repositioned in the three cardinal planes, the positional changes of the vertebrae corresponding to the known vertebral displacement in IS.

The lateral and ventral tilt of the central vertebra, i.e., its rotation in the coronal and the sagittal planes in relation to the other two vertebrae has not been documented earlier. It seems, though, that the clockwise rotation of the central vertebra in the coronal plane registered in this study could explain the wedging of the disk space towards the concavity observed in early IS (37). Likewise the vertebral translation together with the counterclockwise rotation of the central vertebra in relation to the subjacent vertebra in the sagittal plane could explain the lordotic tendency of the scoliotic segment observed in early IS (38). However, the registered wedging of the disk space towards the opposite side of the elongated rib, between the central and the suprajacent vertebrae in the sagittal plane, does not correspond to the findings in the earlier study (38). This could partly be due to the spreading of the registered values but also to the common anatomical relation of the two vertebrae to the elongated rib.

The present results show that the registered vertebral micromovements in the coronal, sagittal and horizontal planes occur simultaneously. This observation is in agreement with the results of earlier experiments in rabbits (32). In a clinical cross-sectional radiographic study in patients with early IS it was also found that structural vertebral changes in the coronal and the sagittal planes and rotation in the horizontal plane occurred simultaneously (40). The reported simultaneous repositioning of the vertebrae within a spine segment in these clinical and experimental scoliosis studies contradicts earlier hypotheses that the 3-D scoliotic deformity is initiated by vertebral translation in only one plane.

Although no conclusions can be drawn from the results of this study with regard to the pathogenesis of IS in man, comparable results of earlier experimental (1-3, 31, 32), clinical (22) and cross-sectional (37-40) investigations of IS indicate that it is the same mechanism that underlies the development of the spinal deformity in all these cases.

*Acknowledgement*

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## SAMENVATTING

*B. SEVASTIK, B. XIONG, A. LUNDBERG, J. A. SEVASTIK. Electronische analyse in vitro van de wervelbewegingen, in drie-dimensioneel, tijdens progressieve ribverlenging bij het varken.*

Op twee anatomische varkenstukken hebben de auteurs in vitro het effect van een progressieve ribverlenging op de positie van de drie belendende wervels, bestudeerd. De uiteinden van een geosteotomiseerde rib werd gradueel van elkaar verwijderd en de micro-bewegingen van de wervel met hetzelfde nummer als de rib, tov. boven- en onderliggende wervels, werden nagegaan. Deze studie gebeurde d.m.v. opto-electronisch analysemateriaal. De studie toonde aan dat de geleidelijke verlenging van de rib aanleiding gaf tot microbewegingen van de corresponderende wervel t.o.v. de belendende wervels, onder vorm van een laterale verplaatsing in het frontaal vlak en van een rotatie in het horizontaal vlak (deze twee bewegingen gebeuren in de tegenovergestelde richting van de verlengde rib). Er werd ook een ventrale translatie in het sagitaal vlak en een kanteling in frontaal en sagitaal vlak gezien. Al de bewegingen werden simultaan geregisteerd. Er bestond een relevante lineaire correlatie met de graad van ribverlenging. Aan de hand van de resultaten van deze studie wordt er gekonkludeerd dat een graduele ribverlenging de stand van de corresponderende wervel t.o.v. boven- en onderliggende wervels in de drie vlakken beïnvloedt, zoals het gebeurt voor een apexwervel bij idiopatische scoliotische curve. Bovendien kan de kanteling, m.a.w. de rotatiebeweging van de centrale wervel in het frontaal vlak, de wigvormige misvorming van de discusruimte uitleggen ; de ventrale verplaatsing gecombineerd met een kanteling in het sagitaal vlak kan de oorzaak zijn van het lordoseren van het skoliotisch segment.

## RÉSUMÉ

*B. SEVASTIK, B. XIONG, A. LUNDBERG, J. A. SEVASTIK. Analyse opto-électronique in vitro des mouvements vertébraux, pendant l'allongement progressif des côtes chez le porc.*

Les auteurs ont étudié in vitro sur deux pièces anatomiques de porc les effets d'une élongation costale graduelle sur la position dans l'espace des vertèbres voisines. Les extrémités osseuses d'une côte ostéotomisée ont été graduellement écartées et on a étudié les micro-mouvements de la vertèbre de même numéro par rapport aux vertèbres sus- et sous-jacentes ; cette étude a été faite au moyen d'un matériel d'analyse opto-électronique de mouvement. Cette étude a montré que l'allongement progressif de la côte avait pour résultat des micro-mouvements de la vertèbre correspondante par rapport à ses voisines, sous forme d'une translation latérale dans le plan frontal et d'une rotation dans le plan horizontal (ces deux mouvements se produisant vers le côté opposé à la côté allongée). On notait aussi une translation ventrale dans le plan sagittal et une bascule dans les plans frontal et sagittal. Tous les mouvements ont été enregistrés simultanément. Il existait une corrélation linéaire significative avec le degré d'élongation costale. Les résultats de cette étude permettent de conclure que l'élongation graduelle d'une côte affecte la position de la vertèbre correspondante par rapport aux vertèbres sus- et sous-jacentes dans les trois plans cardinaux, comme c'est le cas pour la vertèbre au sommet de la courbure dans la scoliose idiopathique. De plus, la bascule enregistrée, c'est-à-dire le mouvement de rotation de la vertèbre centrale dans le plan frontal, pourrait expliquer la cunéiformisation de l'espace discal ; la translation ventrale combinée à la bascule dans le plan sagittal pourrait expliquer la tendance à la lordose du segment scoliotique.