Chaos analysis of effects of increased inertial load on quiet standing

Artigo Original

Artigo recebido em 19/12/2006 e aprovado em 27/01/2007

Werner J, Öhlander C-H, Ledin T.

Department of Otolaringology, Univerity Hospital, Linköping, Sweden.

Correspondence to: Torbjörn Ledin MSc MD PhD, Associate Professor Dept. of ENT University Hospital SE-581 85 Linköping ,Sweden phone +46-13-222000 beeper 2526, fax +46-13-222504, email torbjorn.ledin@inr.liu.se

ABSTRACT

Quiet standing is regulated by different sensory systems including vision, and the vestibular and somatosensory systems. Until recently, postural sway has predominantly been evaluated with rather non-specific tests like posturography where input data channels of the equilibrium are usually not disturbed. A way to understand characteristics of postural sway's regulation mechanisms is to study the sway's micromechanics. To accomplish this, the movement of the body centre of gravity has been modelled as a random walk using chaos theory and then characteristic parameters have been computed. Aim: In this study we investigated the effects of a 20% increased inertial load on the micromechanics of postural sway using the stabilogram-diffusion method. Material and Methods: 21 healthy non volunteers were tested with and without visual cues and with and without additional load. Postural stability was evaluated using the stabilogram-diffusion method. The parameters computed in the anteroposterior, mediolateral and radial terms were the critical time, the sway area at this critical time, the diffusion coefficient in the short term and the long term region and the scaling exponent in the short and long term region. We found that the critical time was not significantly affected by the extra load or the vision. Results: The critical areas were larger at additional load and with eyes closed, and the diffusion coefficient in the short term region was larger with the extraload and closed eyes. In the long term region the diffusion coefficient was unaffected by both factors. Scaling exponents were unaffected by extra load in both the long and the short term region, but greater in the short term region with eyes closed and significantly lower in the long term region with eyes closed. There was no interaction between visual and extraload effects in any of the parameters computed. Conclusion: We conclude that there is no regulatory strategy change of the sway's micromechanics in young healthy subjects when the body is affected by an acute 20% extra load.

Key words: postural control, inertial load influence, normal subjects, methods, chaos theory.

RESUMO

A posição parada de pé é regulada através de sistemas sensórios diferentes incluindo a visão e os sistemas vestibular e somatosensório. Até recentemente, o balanço postural era avaliado predominantemente com testes inespecíficos como a posturografia onde os dados dos canais de dados do equilíbrio normalmente não são perturbados. Um modo de compreender as características dos mecanismos de regulação do balanço postural é estudar a micromecânica do balanço. Para isto, o movimento do centro de gravidade corporal foi modelado como um caminhar aleatório usando a teoria do caos e computados parâmetros característicos. Assim foi possível ver se o equilíbrio tinha estratégias diferentes para controlar tipos diferentes de instabilidade. Objetivo: Neste estudo investigamos os efeitos do aumento de 20% na carga inercial na micromecânica do balanço postural usano o método de estabilograma de difusão. Material e Métodos: 21 voluntários foram testados com e sem sugestões visuais e com e sem carga adicional. Cada medida foi de 30 segundos repetida 10 vezes por agrupamento, quatro no total. Foi avaliada a estabilidade postural. Os parâmetros computados em termos anteroposterior, mediolateral e radiais foram o tempo crítico, a área de balanço neste momento crítico, o coeficiente de difusão no curto e longo prazo. Resultados: As áreas críticas foram maiores de acordo com a carga adicional e com olhos fechados, e o coeficiente de difusão na região a curto prazo foi maior com o excesso de carga e olhos fechados. O tempo crítico não foi afetado significativamente pela carga extra ou a visão. Na região longa o coeficiente de difusão não foi afetado por qualquer dos fatores. Não houve nenhuma interação entre visão e excesso de carga em quaisquers dos parâmetros computados. Conclusão: Nós concluímos que houve nenhuma mudança de estratégia regulatória de micromecânica do balanço em voluntários sãos jovens quando o corpo foi atinido por 20% de carga extra aguda.

Descritores: controle postural, influência, carga inercial, voluntários, teoria de caos.

INTRODUCTION

Quiet standing is regulated by different sensory systems - the vision, the vestibular and the somatosensory systems. Posturography, measured by e.g. EquiTest, is an important screening method where the vestibulospinal afferences during quiet standing can be studied (Voorhees, 1989; Nashner and Peters, 1990; Ledin et al 1991, a). The method can not decide the magnitude of influence of different inputs on the balance system, but the different components of the system may be provoked and differential effects may be studied.

To develop posturography to a clinically relevant testing method studies have most often been aimed, until recently, at disturbing the input data of the equilibrium (Ledin, 1991, b; Magnusson et al, 1993). It is also possible to use an alternative way, e.g. study the postural sway's micromechanics with ideas from the chaos theory to see if the equilibrium has different strategies to handle different degrees of instability (disturbances) (Collins & de Luca, 1993).

To estimate how instantaneous sway growth develops over just a few seconds, the movement of the body centre of gravity has been modelled as a random walk using chaos theory and then characteristic parameters have been computed. In a correlated random walk, old increments are correlated to new ones, i.e. the system has a sort of "memory". The term positive correlation means that an increasing/decreasing trend in the past will imply an increasing/decreasing trend in the future, a phenomenon known as persistence. If the process is negatively correlated an increasing/decreasing trend in the past will imply a decreasing/increasing trend in the future, something called anti-persistence.

J J Collins and C J De Luca of Boston University, USA, developed the stabilogram-diffusion method, which is based on the chaos theory, in the early 90's. The stabilogram is a diagram where the centre of pressure (COP) is plotted against a certain time. Collins and de Luca (1995) showed in their posturography studies of healthy subjects that the stabilogram-diffusion curves changed slope at a critical time (tc). The curve was for that reason divided into a short-term region (S, before tc) and a long-term region (L, after tc).

The results showed that the short term diffusion coefficient (i.e. sway growth) was larger in the short-term region than in the long-term region. In addition, the scaling exponents (H, i.e. sway feedback) in the short-term region were positively correlated, while negatively correlated in the long-term region. The correlation of the scaling exponents in the time series of COP depend on underlying dynamic processes.

These results were interpreted to show that the postural system uses open-loop control at short time periods, i.e. the system allows COP to float for some time without actual feedback control - a finding that challenged the notion that quiet standing is always regulated by feedback mechanisms. Closed loop control is used after longer time periods or larger displacements, i.e. after some time certain control mechanisms are activated and COP is brought back to an equilibrium position. The critical time indicates where the temporal transition between the short-term region and the long-term region takes place.

The stabilogram-diffusion method can therefore be used to formulate and test hypotheses concerning the contributions of different sensori-motor systems and strategies, i.e. open and closed loop functions, used in control of the human stance.

Recent studies (Grusell et al, 1998) have been aimed at investigating how the vision affects the parameters of the stabilogram-diffusion method. A study by Ledin and Ödkvist (1993) showed that increased inertial load deteriorates balance on a stable support surface. The present study was conducted to investigate the effects of a 20% increase of inertial load on the micromechanics of the sway analysed by using the model presented by Collins and De Luca.

CHAOS AND FRACTALS IN SHORT

Thoughts and theories concerning chaos have circulated in the scientific community for a long time, but it was not until the presence of advanced computer technology that scientists could start to understand how non-linear, dynamic systems work. The forerunner for this development is Mandelbrot, a polishborn French mathematician, that introduced the term fractal. He plotted millions of iterations (i.e. the solution to a previous equation is used as an input to the next) of a factor and saw a pattern that was very complicated even though it had an underlying structure.

This underlying structure, the variation pattern, exists even in such a chaotic system as the heart's beats. The explanation for this is that fractal geometry is the geometry of chaos (Jürgens et al, 1990).

FRACTALS

A fractal consists of geometric parts of varying size and orientation, but they all have similar shape. Idealised fractals have infinite parts (Goldberger et al, 1990).

A fractal is characterised by:

1) Noninteger dimensions (as opposed to the one dimension of a line, the two dimensions of an area and the three dimensions of a sphere), e.g. a coast line that has a dimension between one and two.

2) Self similarity, i.e. the geometric structure of fractals is basically the same independent on the scale used. The

structure is not equal, but has the same properties. Physically there is a limit for this branching, e.g. the human bronchial tree that is a fractal structure, but not in theory (Aasen, 1993).

Fractals are expressed in algorithms, that are composed of mathematical procedures. These algorithms are then translated to geometric figures by the computer. There are two main groups of fractals:

1) Random fractals: assembled by incorporating controlled randomness.

2) Linear fractals: composed of algorithms with the same form as those defining lines in a plane (i.e. they incorporate only first-order terms) (Jürgens et al, 1990).

CHAOS

To define what chaos is, we need to understand the concept of non-linear dynamics. A dynamic system includes all processes that develops with time, e.g. a heart's beats and the pulmonary ventilation. In non-linear systems a y-value can be related to two or more x-values. Under certain circumstances the system becomes unorganised and results in chaos. Non-linear dynamics is actually the same thing as deterministic chaos (Hauge, 1993).

Chaos means instability in a deterministic system. All chaotic systems exhibit sensitive dependence on initial conditions, which means that the system can change direction after a slight perturbation. Other systems, both periodic and chaotic, can affect the development of the system and keep it from returning to its normal state. Because of its sensitivity, the system can not be predicted in practice.

Another characteristic of chaotic dynamics is that the underlying structure, the complex geometrical shape in the so called phase space, has an inner regularity that can be calculated and the measure is called the fractal dimension.

Phase space is an abstract mathematical space in which a dynamic behaviour of a system can be described. It has the shape of a curve that is supposed to reflect the system's behaviour over a certain period of time. The axes may consist of different variables that decide the development of the system over a given time. In phase space there may be a point to which the curves are attracted, the so called attractor (Aasen, 1993).

The attractor is the boundary that the system is attracted to, but never exceeds. It may have a complex structure and is often a fractal. Deterministic and stochastic systems do not have attractors. The attractor is constructed by determining the active variables that influence the system's dynamics at (infinite) points in time. By combining the points, a trajectory of the system's development in phase space is created. The simplest attractor may be an individual point, but it may also be a so called limit cycle, i.e. a system that develops to a periodic cycle. Close to the limit cycle the trajectories then follow a regular pattern, e.g. a circle (Aasen et al, 1997).

In this context the notion "strange attractor" should be introduced. A strange attractor describes systems that are neither static nor periodic, i.e. they are chaotic. In a phase space near a strange attractor two curves that started under the same conditions will now differ, in a short perspective modestly, but in a longer markedly (Goldberger et al, 1990).

The geometrical structure in a phase space can, somewhat simplified, be described as the system's dynamic fingerprint.

The knowledge of non-linear dynamic systems have been put together to what today is called chaos theory. One can define this as "the mathematical understanding of mechanisms involved in regulation of non-linear dynamic systems" (Aasen et al, 1997).

So why is the different physiological systems chaotic? The human body is known to have an exceptional ability to solve the challenges from our environment and in most cases there are important advantages to these bodily solutions. This is most probably the case also concerning the chaotic physiological systems. The greatest advantage is that, as described above, a chaotic system functions under many different circumstances. Thereby a tremendous adaptability and flexibility is created that the body can use to solve different challenges. This is also seen in many diseases when the periodic, regular behaviour increases while the adaptability decreases. To simplify, one could argue that a normal biological system is irregular, while a pathological biological system shows regularity (Hauge, 1993).

It is this fact that is the corner stone in the recent use of chaostheoretical models to diagnose different pathological states in the human body.

MATERIAL AND METHODS

Material: 21 healthy non-paid volunteers with a mean age of 23+/-3 years, mean height of 175+/-10 cm and mean weight 69+/-8 kg were studied. 10 were men and 11 were women.

Method: The subjects were placed on a stable dual forceplate (EquiTest Neurocom Int. Inc. Clackamas, Oregon, USA.) and were asked to stand still during the measuring period of 30 sec. These measuring periods were registered and repeated 10 times per measuring set. Every subject were exposed to four different sets V, nV, L, nL (V=vison, nV=no vision, L=load, nL=no load.) The sequence of the sets were randomly organised according to a latin square. Sufficient time to relax between the tests were given and no subject considered the test stressing.

The dual forceplates were enclosed by a shielding screen at a distance of approximately 60 cm from the person, to reduce outer disturbing visual input. The force plates were equiped with marks allowing the positioning of the feet to be similar throughout the measuring periods and sets, if rest were needed. The subjects were standing without shoes on the platform that samples data from the forcetransducers at 25 Hz placed in the outer corners of the plates. Feet were at an angle of approximately 10 degrees and heels 6 cm apart, not allowing the calves to touch each other. Arms were folded on the chest and a relaxed posture ensued. When adding weights (20% of total body weight) the subjects were equipped with an especially sewn vest applying the weight to the upper thorax equally divided in an anterior-posterior and lateral-view.

The output of the transducers were collected using customised software and stored on hard disc for subsequent processing in Matlab. (The MathWorks Inc., USA) the Stabilogram-diffusion method presented by Collins and de Luca (1993) was employed. Stabilogram-diffusion analysis starts by computing the square in x, y and radial directions between all possible pairs of time data separated as a defined time delta-t. This delta-t can be any value up to 10 sec in the present analysis. Thus a curve is constructed having on one axis the time difference delta-t (from 0-10 sec) and on the other axis the average squared distance connected to that time interval. The growth of sway has two distinct sections; a short time zone with rapid growth of sway (up to approximately 1 sec) and thereafter a long time zone with a very low growth of sway (above 1 sec).

The transition between the two zones yields two important parameters; the critical time (tc) and its associated area. The sway growth is termed the diffusion coefficient (D, mm2/sec.) and has very different values in the short and long term zones. The control behaviour of the postural system in each of the-zones is computed as the scaling exponent (termed H) using theory from random walks. A positively scaling coefficient above 0.5 is always at hand in the short term zone (termed HS) and this implies a positively correlated sway growth, i.e. an equilibrium disturbance is amplified during approximately 1 sec. On the other hand, the scaling exponent in the long term zone (HL) is always far below 0.5, indicating that a postural disturbance is counteracted after approximately 1 sec.

Statistics: Two way ANOVA with repeated measures evaluated the effects of vision and weights in the investigated group of subjects. P less than 0.05 was considered significant.

Table 1 – Results obtained on the stabilogram-diffusion method

Variables	No vision				Vision				P load	P vision	P interaction
	No load		Load		No load		Load				
	m	SD	m	SD	m	SD	m	SD			
Radial axis											
Critical time, tc (s)	1,13	0,30	1,10	0,38	1,09	0,28	1,21	0,37	0,58	0,58	0,20
Area r2 (mm2)	60,18	41,85	87,31	65,63	32,19	19,85	62,12	52,48	0,006	0,005	0,85
Diffusion coefficient, short term (mm2/s)	39,30	28,84	52,35	42,85	20,13	12,15	29,30	16,85	0,015	0,001	0,57
Scaling exponent, short term (-)	0,87	0,04	60,87	0,031	0,84	0,03	0,83	0,041	0,70	0,001	0,76
Diffusion coefficient, long term (mm2/s)	2,12	2,55	2,54	2,05	2,30	1,96	3,88	3,92	0,13	0,10	0,30
Scaling exponent, long term (-)	0,11	0,081	0,093	0,05	60,19	0,072	0,17	0,11	0,23	0,001	0,98
Antero-posterior axis											
Critical time, tc (s)	1,08	0,32	1,11	0,46	1,03	0,30	1,24	0,47	0,089	0,66	0,21
Area r2 (mm2)	35,25	25,81	53,70	41,48	17,76	11,61	36,88	37,82	0,002	0,023	0,95
Diffusion coefficient, short term (mm2/s)	23,45	16,85	32,48	24,53	11,78	6,98	17,32	10,29	0,009	0,001	0,40
Scaling exponent, short term (-)	0,87	0,045	0,86	0,036	0,83	0,036	0,82	0,047	0,59	0,001	0,79
Diffusion coefficient, long term (mm2/s)	1,38	1,64	1,89	1,77	1,74	1,76	2,74	3,06	0,20	0,13	0,53
Scaling exponent, long term (-)	0,12	0,08	70,10	0,07	40,21	0,08	40,19	0,12	0,43	0,001	0,94
Lateral axis											
Critical time, tc (s)	1,32	0,42	1,44	0,52	1,26	0,32	1,45	0,45	0,16	0,61	0,65
Area r2 (mm2)	26,79	19,72	38,39	28,68	14,94	19,91	28,70	22,91	0,005	0,001	0,70
Diffusion coefficient, short term (mm2/s)	15,88	12,81	19,99	19,3	68,39	5,64	12,08	7,51	0,047	0,003	0,90
Scaling exponent, short term (-)	0,87	0,05	70,87	0,03	30,8	50,03	80,85	0,039	0,67	0,007	0,56
Diffusion coefficient, long term (mm2/s)	0,76	0,87	0,61	0,69	0,65	0,52	1,09	1,65	0,25	0,28	0,21
Scaling exponent, long term (-)	0,11	0,081	0,073	0,065	0,16	0,09	10,12	0,10	0,011	0,002	1,00

RESULTS

The numerical results are outlined in table 1 and are briefly described below. The findings in the x- and y-directions are essentially the same as in the radial direction (see Table) and are not presented further.
critical time (tc) for the young healthy persons was not significantly affected neither by the 20% extra load nor the vision, as shown in figure 1. The critical areas, depicted in figure 2, were larger at additional load and with closed eyes (without interaction). The diffusion coefficients in the short term region (DS) were larger with the extra load and closed eyes respec-

tively (no interaction), while unaffected by both factors in the long term region (figure 4). The scaling exponents, outlined in figure 3, in the short term region (HS) were greater with closed eyes, but were not affected by the extra load. In the long term region the scaling exponents (HL) were significantly

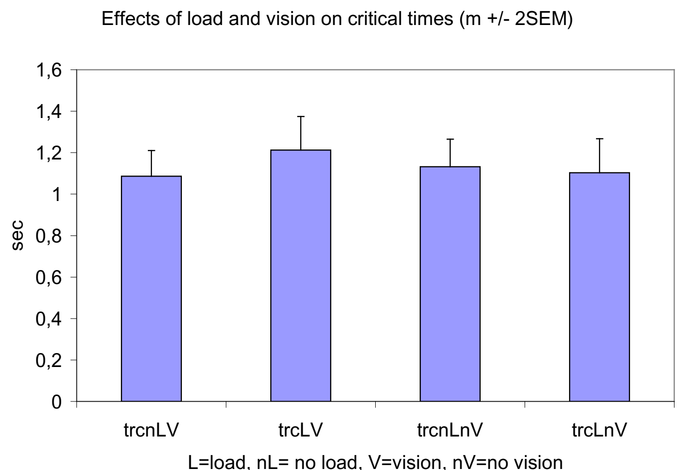

Figure 1
Tc shows were the stabilogram-diffusion curve change slope. Tc was not significantly affected, neither by load nor vision as shown here by tc for the radial axis.

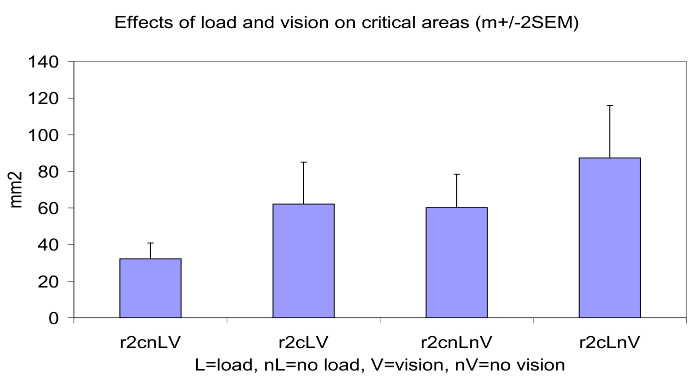

Figure 2
The sway areas (critical areas) were larger at both additional load and without sight (without interaction), shown here by the critical areas in the radial axis.

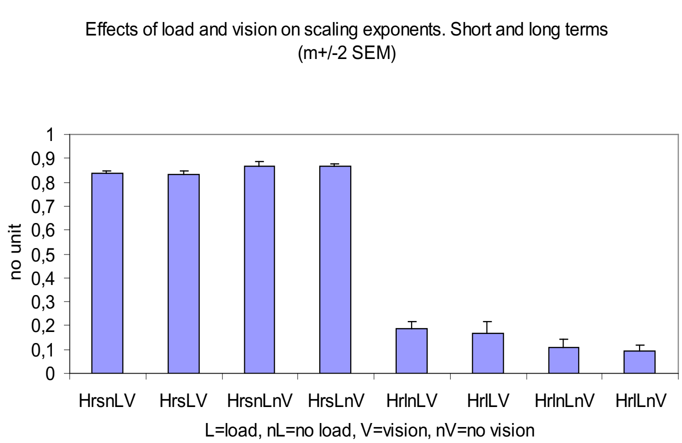

Figure 3
The scaling exponents in the radial direction (H) reflect sway feedback. They were unaffected in both the short and long term region by additional load. HS were greater with closed eyes and HL were lower without sight.

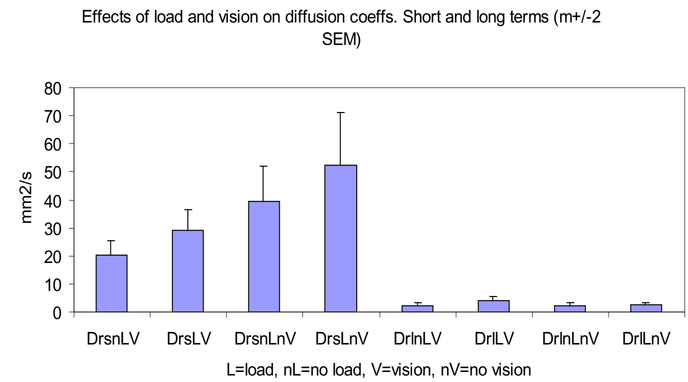

Figure 4
The diffusion coefficient in the radial direction (D) represent sway growth. DS were larger with additional load and closed eyes (without interaction), while unaffected by both in the long term region.

lower with no visual cues, but were also unaffected by the additional load. No interactions of vision and added weight could be interpreted. The same results were achieved when using the two-way ANOVA and the univariate Student's t-test.

DISCUSSION

In the study, by Collins and de Luca (1993), the results showed two subgroupings, between which no coherence was found, within the studied group. Therefore they suggested that different ways of handling reflexbased feedback mechanisms of the open loop system exists. In the present study and in concordance with Grusell et al (2000), the results were homogenous, showed coherence, within the group of subjects and found nothing else indicating such differences.

There were no significant interactions of increased body weight and vision on the postural control mechanisms. Thus, one can conclude these factors to be independent of each other. They will therefore be separately considered in the following discussion.

The area and all short time values, excluding tc, increases when a subject closes his/her eyes. This has been explained by Grusell et al, as a state where the body is "free floating", only influenced by the laws of chaos. The afferent feedback factors controlling balance are not yet engaged (Grusell et al 2000) and subsequently the sway increases over time. Concerning tc, our study does not agree with Grusell et al. (2000) when not allowing the subject to see. This is most likely explained by a minor numerical difference giving a significant increase for tc in the study made by Grusell et al (2000) but not in the present one. Thus the actual difference is practically negligible.

The long term diffusion coefficient (DL) is unaffected by vision and the scaling exponent in the long time region (HL) reads a lesser value when the subject's eyes are closed. Thus the sway feedback (H) is established when initiating the long term period (closed loop) preventing the sway growth (D) more firmly than in the visually aided state (Grusell et al 2000). This is also true for DL when increasing the body weight by 20 %.

We conclude that during the short time period (when the system works in open loop) the sway growth increases partly due to the laws of mechanics, augmented by the mechanisms of chaos, as well as because of poor inhibition of the feedback system. Therefore it can be expected that the area increases significantly when adding weight. This is partly explained by the mechanical principles of the inverted pendulum. The centre of gravity (CG) is approximated to be at a height of 55% of the total body height (Ledin 1991b) which is equal to 110 cm at body height of 180 cm. The weights were placed at a height of approximately 140 cm, thus raising the CG to a height of 115 cm, or by about 4.5%, which would increase all area measures by about 9%. As seen from data, area measures increase by more than these 9%, in accordance with the above arguments.

This explains the increase in the short term diffusion coefficient (DS) when adding weight, as this factor is related to the sway growth. On the other hand, adding 20% of BW, aiming to influence proprioception and lower the muscle force relatively to the mechanical demands, seems not to have had crucial influence on the sway feedback mechanism in the short term region (HS), nor in the long term feedback mechanisms (HL).

We conclude that there is no regulatory strategy change of the sway's micromechanics in young healthy subjects when the body is affected by an acute 20% extra load. The critical areas should be interpreted conservatively, since the mechanical characteristics of the body is somewhat changed. This is explained by the principle of the inverted pendulum giving an increase in area by 9% and also affecting the diffusion coefficient in the short term, though this can not explain the full extent of the changes seen.

REFERÊNCIAS BIBLIOGRÁFICAS

1. Voorhees RL. "The role of dynamic posturography in neurootologic diagnosis". Laryngoscope 1989: 99: 995-1001.
2. Nashner LM, Peters JF. "Dynamic posturography in the diagnosis and management of dizziness and balance disorders". Neurology Clinics 1990: 8: 331-49.
3. Ledin T, Ödkvist LM, Vrethem M, Möller C. "Dynamic posturography in assessment of polyneuropathic disease". J Vest Res 1991: 1: 123-8.
4. Ledin T. "Dynamic Posturography in Evaluating Human Equlibrium". Linköping University, Medical Dissertation No 329, 1991.
5. Magnusson M, Enbom H, Johansson R, Wiklund J. "Significance of pressor input from the human feet in lateral postural control". Acta Otolaryngol (Stockh) 1990: 110: 321-7.
6. Collins J J, de Luca C J. "Open-loop and closed-loop control of posture: A random-walk analysis of center-of-pressure trajectories" Exp Brain Res 1993; 95: 308-18.
7. Grusell M, Osbeck M, Schulin M, Ledin T. Evaluating postural control using chaos theory - A preliminary report. Annales Medicinae Militaris Fenniae 2000: 75 (1): 102-6.
8. Ödkvist LM.Ledin T, "Effects of increased inertial load in dynamic and randomized perturbed posturography". Acta Otolaryngol (Stockh) 1993: 113: 249-52.
9. Jürgens H, Peitgen H-O, Saupe D. "The Language of Fractals". Scientific American, 1990:8:40-47.
10. Goldberger A, Rigney D, West B. "Chaos and Fractals in Human Physiology". Scientific American, 1990:2:35-41.
11. Aasen T. "Chaos Theory Applied to the Caloric Response of the Vestibular System". Computers and Biomedical Research, 1993, 26:556-67 .
12. Hauge A. "Om kaos och fraktaler". Tidssk. Nor. Laegeforen., 1993, 30:3678-86.
13. Aasen T, Nordahl S, Molvaer O, Olofsson J. "Kaosteori i otonevrologisk diagnostikk". Norsk medicin, 1997, 10:352-5.
14. Collins J J, de Luca C J. "Upright, correlated random walks: A statistical-biomechanics approach to the human postural control system". Chaos, 1995, 5 (1):57-63.