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USING DIMENSION QUANTITIES TO CHARACTERIZE THE STANDING BALANCE

by

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The theme of the study was the description of the standing balance by a nonlinear dynamic approach. On the assumption that the motor ability of equilibrium is based on a chaotic process, we used the model of a strange attractor. The special problem of our investigations was to examine if the dimensionality of the postural control system decreases when the conditions of the standing balance are reduced.

The tests were carried out on a force plate with 5 male sports students and a male child at an age of 6 years. By means of the COP-trajectories a substitute phase space was created and the fractal and correlation dimensions were calculated. The results obtained for the dimension quantities show statistically significant differences between the tests under various conditions. So we can conclude that by means of nonlinear techniques it is possible to estimate the postural control system.

Keywords: Dynamic approach, Posture, Dynamic systems, Phase-space reconstruction, Chaos

PsycINFO classification: 2221, 2260, 2330, 3700, 3720

Introduction

The motor ability of equilibrium is an ability of coordination and can be subdivided into a static and a dynamic equilibrium (Hirtz et al., 1985; Meinel and Schnabel, 1987). The static equilibrium is defined as a sway of the centre of gravity of the body with small amplitudes around a fixed point. The standing balance is a special form of the static equilibrium. We can consider the standing balance as a result of continual movements of compensation. Therefore, a certain variability of the coordinates of position of the centre of gravity is typical of the standing balance. Mester (1987) regards the regulating torques, which can be recorded by A KISTLER force plate, as a criterion of the ability of equilibrium of athletes. On this basis the question is: Which quantity is correct for

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the characterization of these variations or, in other words, which quantity can be used as a unit of measurement of the stability of the standing balance ? Many tests of equilibrium have been developed for the solution of this problem (Nigg, 1977). Prieto et al. (1993) carried out further classification of the methods. Thus the human standing sway, which is a reaction to conscious and unconscious disturbations, can be described by quantifying the motion of the single body segments or joints, the torques of the joints, the EMG activities or the change of position of the COP (centre of pressure). A large section of the techniques based on the assumption that the COP reflects the internal dynamics as a whole is founded on measurement of the coordinates of the COP by means of a force plate. For quantifying of the COP-trajectories there exist many different methods (for instance: Schumann et al., 1995; Black et al., 1982; Collins and Deluca, 1995a,b; Maki and Whitelow,1993; Hasan et al., 1990; Wade et al., 1995; Parys and Njihikjen,1976; Spaepen et al. 1979a,b; Tokumasu et al.1983). But only the ground reaction forces were also investigated (Goldi et al., 1989, 1992,1994; Gu et al., 1996; Nigg, 1977). For special applications, for example in medicine, it is helpful to combine the several dynamometric, kinematic und electromyographic methods (Gu et al., 1996; Spaepen et al., 1979a,b; Horak and Nashner, 1986; Boissel and Zattara, 1981; Allum and Büdingen, 1979; Diener et al., 1983; Dietz et al., 1989,1992; Gollhofer et al., 1989).

Most methods of describing the postural sway assume irregular motions, which can be characterized by statistical techniques. But it is not convincing that the course of the COP-trajectory is stochastic.

On this reason Newell (1993) proved that centre of pressure variability is not a sufficient measure of postural stability. The central theme in his study was that the assessment of postural stability can only be made when taking the dynamic structure. With nonlinear techniques it is possible to distinguish different attractor dynamics underlying postural control. So Newell et al. (1993) propose that postural stability can only be assessed by considering the attractor dynamics of the postural control system.

Similar nonlinear approaches are used by Prieto et al. (1993), Riccio (1993) and Yamada (1995). The nonlinear concept including the estimation of "dimension" is taken as an indication of the complexity of the system (Prieto et al., 1993). Conventional statistical techniques do not realize the complex nature of the postural control system (Newell et al., 1993, Witte et al., 1999). Riccio (1993) describes the functional role for movement variability. He assumes that the basic "observable" in movement science are the qualitative dynamics of the interaction between an animal and its surroundings. The qualitative dynamics can be described by means of attractors. Also Yamada (1995) takes the view that it is useful to apply the nonlinear approach to characterize the static balance. In his study, posture was considered to be dynamic stability of a continuously moving body. The results suggest that chaotic swaying of the body is a dynamically stable state of the body while receiving information from many segments within the body and its external environment.

On the assumption that the collaboration of all muscles participating in the posture are coordinated and not used hephazardly, in our following researches we also agree that the postural sway has chaotic characteristics.

According to Newell and Corcos (1993) variability is an important component for many mechanisms in biology. So following the upright stance as a form of the static equilibrium is considered as a coordinated phenomen of stability of the organism in relation to the environment and the task. Do to the coupling of many deterministic processes it can be concluded that the time course of only one parameter of state contains the most important information on the dynamics the overall system. This quantity of state has the function of a so-called key term which as a rule influences the microscopic properties of the system organism/environment. On the other hand, the microscopic properties influence the order parameter. For the task of preservation of the upright stance the COP can be considered to be the order parameter. The dynamic behaviour will be described by means of the conception of the attractor. In particular it will be assumed that the static equilibrium can be characterized by the model of the chaotic or strange attractor. Two essential reasons exist for the use of the strange attractor:

- The preservation of the static balance is not understood as a stochastic process, it is founded on a coordinated acting of a multitude of compensation movements which organize the total system in a complex way.
- The COP-trajectories used in the substitute phase space are not identical, they are characterized by anpredictable course.

The technique of time delay after Takens (1981) can be used for the reconstruction of the substitute phase space by means of the time courses of the x- and z-components of the COP. This attractor created can be characterized by the maximal Lyapunov-exponent and several dimensions. The maximal Lyapunov-exponent is a measure for exponential convergence or divergence of neighbouring trajectories (Argyris et al., 1994). The number of the degrees of freedom can be determined with help of this dimension.

Calculations of dimensions were carried out also for the quantification of the postural equlibrium. Prieto et al. (1993) computed fractal dimensions of stabilograms on the basis of the x-z-curve of the COP and found out that the dimension reacts very sensitively to small changes in the external conditions. This method can be used for the determination of bilateral asymmetries by using two separate force plates. In the clinical field this method provides good results for the qualification of the upright stance of patients with Alzheimer' disease (Antuono et al., 1990; Myklebust and Myklebust, 1989; Myklebust et al., 1990). It was found that the fractal dimensions of Alzheimer patients are significantly smaller (1.53 ± 0.09) than the fractal dimensions of healthy persons (1.73 ± 0.06).

Yamada (1995) proposes another procedure. He reconstructed a time course on the foundation of the distance between the actual position of the COP and its starting position. Tests were carried out for the two-footed stance with fixed arms and with oscillating movements of the arms. But no significant differences exist.

Newell et al (1993) researched normal and tardive dyskinetic adult subjects. They compared statistical variability of certain centre of pressure parameters with dimension estimates of the centre of pressure time series. It could be shown that "(1) there is more structure in the centre of pressure pattern of normal subjects than is traditionally interpreted; (2) the dimension of the centre of pressure in tardive dyskinetic individuals is systematically lower than in normals" (Newell et al ,1993). On the basis of these results and the results by Myklebust and Myklebust, 1989 and Myklebust et al., 1990 Newell et al ,1993 concluded that the dimension decreases with abnormal function in a variety in physiological systems and the dimension increases with information processing activities.

The aim of the following investigations with normal subjects is to examine how the dimensionality changes when the control mechanisms of the equilibrium are varied.

Corresponding to the definition of the dimension we expect that a reduction of control mechanisms leads to a decrease of degrees of freedom and so also to a decrease of dimension.

The reduction of control mechanisms of the static balance we realized by means of the following experimental conditions:

- elimination of the visual system (comparison of the results when the eyes are open or closed)
- restriction of the somatosensorical system (comparison between the results for the bipedal and the monopedal stance).

Methods

For the treatment of the problem it was necessary to apply the methods of the nonlinear dynamics to the static balance under different conditions. We want to note that the topic of our researches is not the development of a general technique for the quantification of the static equilibrium, but the purpose of this study is the comparison of the results which are obtained by means of calculations of dimensions for the standing balance under following conditions:

- monopedal and bipedal stance
- stance with open or closed eyes.

Importance was attached to procedure of the reconstruction of substitute phase space. In contrast to the studies up to now separate analyses of the x(lateral) - and z(anteroposterior) - course of the COP-trajectories were carried out.

Experimental Methods

Five normal male subjects (M, G, Ni, K and B) were studied whose ages ranged from 18 to 27 years. In addition a male child (W) at an age of 6 years was investigated. Subjects stood barefoot with arms behind their backs on a force platform (by KISTLER-company). The signals were recorded with 300 Hz. The lateral sway was registered by the x-component of the COP-trajectory and the anteroposterior sway by the z-component. The tests were carried out under the following different conditions

- bipedal stance, eyes open
- bipedal stance, eyes closed
- monopedal stance, eyes open
- monopedal stance, eyes closed.

The duration of one test was 65 s, but the first 5 s were not used so as to make the state of stability possible. Every test was divided into 6 intervals with equal duration. The reason was to produce stationary signals in these intervals.

Nonlinear analysis of data

A substantial property of the strange attractor is its sensitive dependence on the starting conditions. It is possible to examine this quality by means of the Lyapunov exponents. It is sufficient to determine the maximal Lyapunov exponent. When its value is positive, the trajectories with nearly identical initial coordinates in the phase space diverge from each other. The maximal Lyapunov exponent can be calculated with a method by Loistl and Betz (1994). We used the technique after Kantz (1994) to compute the maximal Lyapunov exponent, which was developed for short experimental time series.

Two substitute phase spaces were created on the basis of the time series of the x-component and the z-component of the COP-trajectory. There is a possibility to investigate the two swinging directions. One important piece of preliminary work for the reconstruction of the substitute phase space is the determination of the embedding parameters. The embedding procedure can be interpreted as a topological picture of the attractor in the functional area without change to the relations between the measuring points or the trajectories in the phase space. The embedding parameters can be determined with the help by the Waberproduct-analysis by Liebert (1991). The Waberproduct is, on the one hand, a topological criterion for the decision on the right embedding and, on the other hand, the Waberproduct-analysis supplies the optimal values of the embedding dimension m and the delay τ from a relative short time series simultaneously. This technique was developed for the analysis of the heart dynamics and was tested on the Lorenz-system by Liebert (1991) and applied to the EEG-time series by Pawelzik (1991).

Dimensions are used for analysis of the reconstructed attractor. Various notions of dimension allow one to quantify the number of generalized degrees of freedom that are relevant to the dynamics. The dimension of a chaotic or strange attractor is a fractured number. The fractal dimension or Kolmogorov-capacity characterized the fractal geometry of the attractor. This quantity was calculated with the method by Leven et al. (1989). In the practical implementation it is necessary to note that the smallest value of the length of the elemenry elements is limited by the measuring error. But then the correlation dimen*sion considers the density of distribution of attractor points.* A popular numerical method to calculate this dimension is given by Grassberger and Procaccia (1983).

For the special application of this nonlinear method on kinematic and dynamic characteristic curves, Witte and Kagerl (1998) developed a PC-software package with which it is possible to convert the experimental data and to compute the embedding parameters by means of Waberproduct-analysis, the maximal Lyapunov exponents, the fractal and the correlation dimensions. This software was tested with surrogate data. Table 1 shows the results of these tests.

Table 1. Calculation of Surrogate Data with the software package

Surrogate Data (Function)	Fractal Dimension	Correlation Dimension	Max. Lyapunov exponent
sin-function with different arguments	0,94 ... 1,01	0,995 ... 1,005	0,04 ... 0,05
random data (5 series)	14,1 ... 14,5	4,24 ... 4,77	0,00
horicontal hip velocity (breasstroke with equal cycles)	0,95 ... 1,05	1,10 ... 1,05	0,05

The quantities from a biomechanical time series were calculated in the last row. The horizontal hip velocity was used which was recorded during a breaststroke test in a swimming flume (Blaser et al., 1996). One cycle was separated from the total time series. These data were attached to each other and so we obtained a new periodic time series data but with normal variations of movement inside a cycle. The length of each data series amounts to 3.000. We can conclude that the dimensions of the synthetic created breaststroke time series are only a bit greater than the dimensions of the sin-functions. The cause of this is that the breaststroke data represent a cyclic limit attractor.

Maximal Lyapunov exponent

At first we reconstructed the substitute phase spaces for the x- and the z-component of the COP-trajectories seperately. With the help of the Waberproduct-analysis we obtained the pairs of the embedding parameters. For the reason that the value of the fractal dimension is smaller than the value of the correlation dimension, we chose the embedding dimension of m = 5 for the fractal dimension and m = 7 for the corralation dimension. The Waberproduct-analysis provided for each test interval the accompanying delay τ.

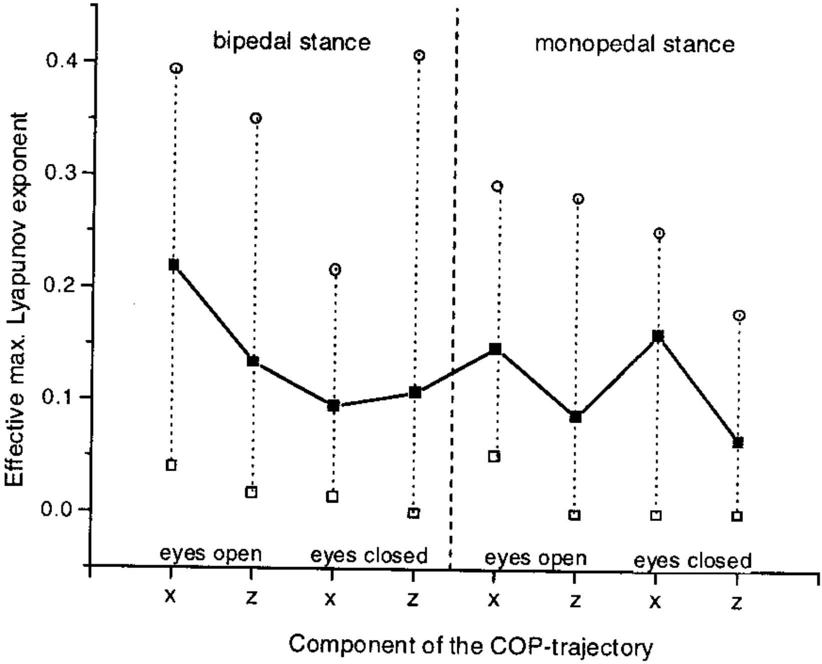

Figure 1. Effective maximal Lyapunov exponent for the subject M (average, maximal and minimal values for each test)

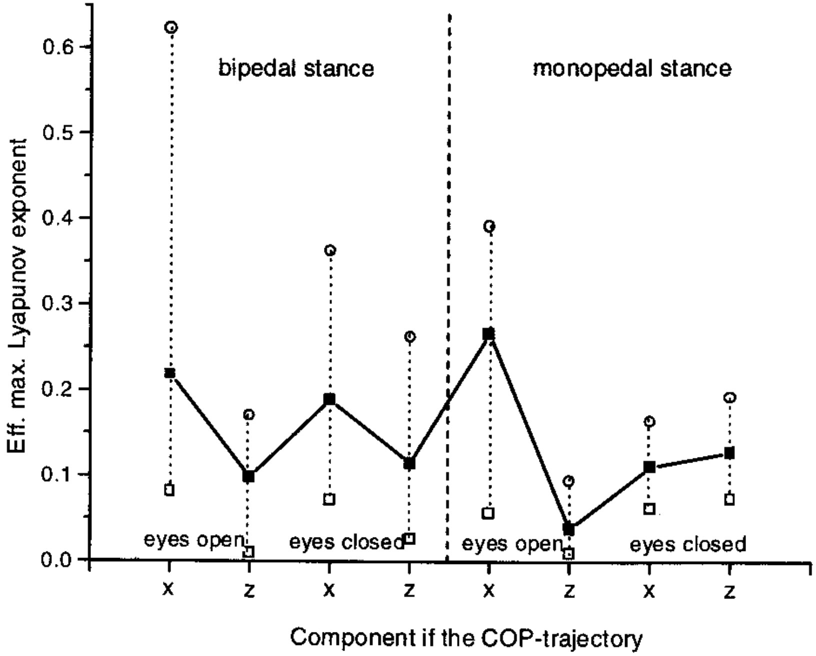

Figure 2. Effective maximal Lyapunov exponent for the subject G (average, maximal and minimal values for each test)

The results for the subjects M and G are represented as being examplary for the determination of the maximal Lyapunov exponent. Figures 1 and 2 show the mean, maximal and minimal values of the maximal Lyapunov exponent for every test. A high variability is recognizable. One possible reason is the small number of individual data. But an increase of the time of the test could lead to stationarity ceasing to exist or the subject not being able to keep his balance.

On the basis of all investigations the effective maximum Lyapunov exponent lies in the range between 0.05 and 0.62. These positive values are evidence of the chaotic characteristic of the attractor in the substitute phase space.

Dimensions

The fractal and the correlation dimensions were computed for the individual test intervals. As a trend of the dimensions could not found for the duration of a test. Therefore we used mean, maximal and minimal values. Figures 3 – 6 demonstrate, for instance, the results of the subjects B and K. At first it is evident that there exist differences between both parameters of dimensions for one subject in quantity. We explain this with the different subject matter of the definitions. Allowing for tab. 1, we have to interpret the values of the correlation dimension carefully. In addition as can be seen from our research there exist individual variations of the dimension values. But when we compare the tests under different conditions we discover that the fractal dimension and the correlation dimension show similar characteristics. Both dimensions show the following trends (see figs. 3 – 6):

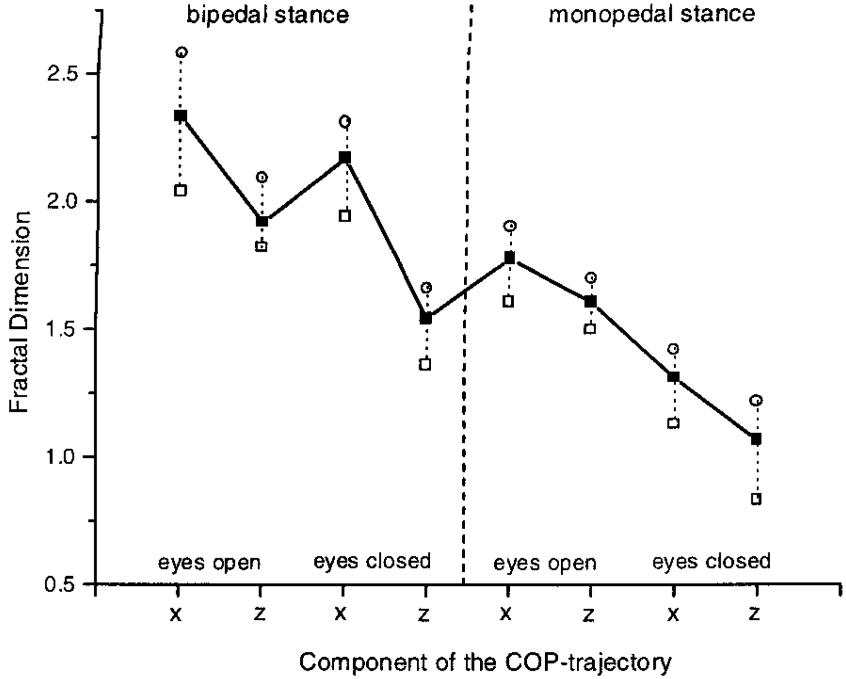

Figure 3. Fractal dimension with m = 5 for the subject B (average, maximal and minimal values for each test)

- The dimensions on the basis of the x-component of the COP-trajectory are greater than the dimensions on the base of the z-component.
- The monopedal stance shows smaller dimensions than the bipedal stance.
- If the eyes are open the dimensions are greater than if the eyes are closed.

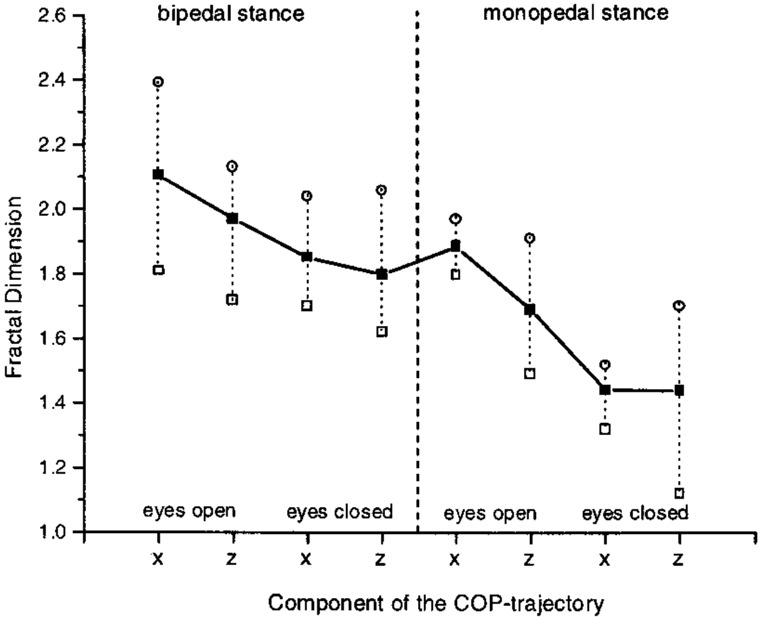

Figure 4. Fractal dimension with m = 5 for the subject K (average, maximal and minimal values for each test)

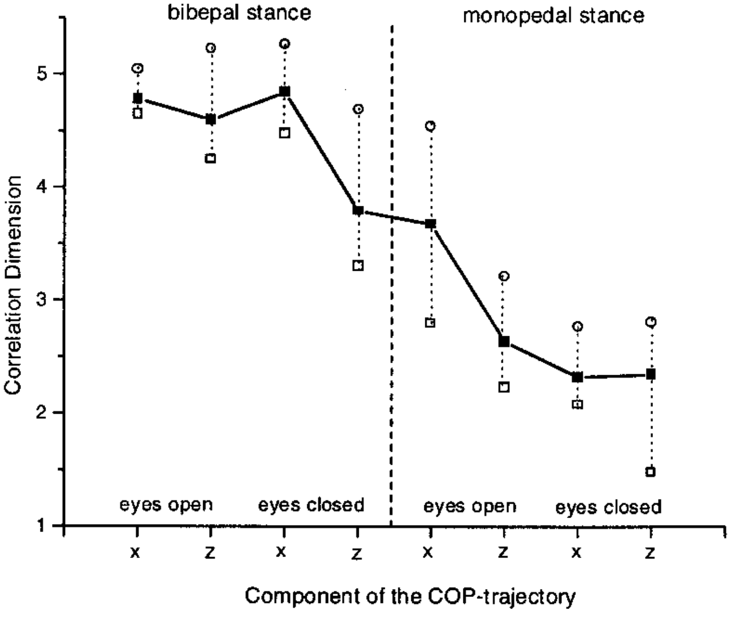

Figure 5. Correlation dimension with m = 7 for the subject B (average, maximal and minimal values for each test)

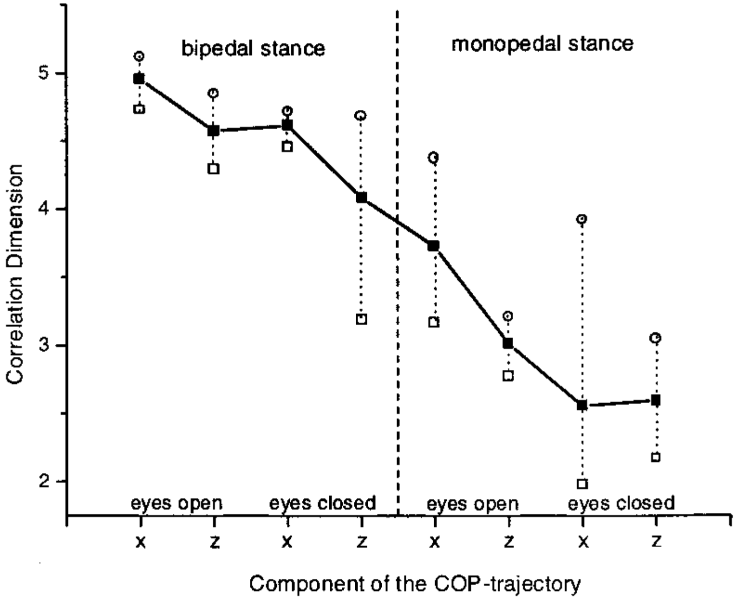

Figure 6. Correlation dimension with m = 7 for the subject K (average, maximal and minimal values for each test)

Table 2. Statistical analysis of the tests under different conditions by means of Wilcoxon test

	Monopedal stance - bipedal stance		**x-component - z-component**		**Open eyes – closed eyes**	
	x-component	**z-component**	**Monopedal stance**	**Bipedal stance**	**x-component**	**z-component.**
Fdim-M	n.s.	*	n.s.	n.s.	**	*
Cdim-M	**	*	n.s.	*	**	*
Fdim-G	*	**	n.s.	n.s.	*	*
Cdim-G	**	**	n.s.	**	*	n.s.
Fdim-B	**	**	**	**	**	n.s.
Cdim-B	**	**	n.s.	*	n.s.	*
Fdim-K	**	*	n.s.	n.s.	**	*
Cdim-K	**	**	n.s.	**	*	**
Fdim-N	**	*	*	n.s.	**	**
Cdim-N	**	**	n.s.	n.s.	**	*
Fdim-W	*	**	n.s.	n.s.	*	*
Cdim-W	**	**	**	n.s.	*	**

Fdim – Fractal dimension, Cdim – Correlation dimension
* $p < 0.05$
** $p < 0.01$

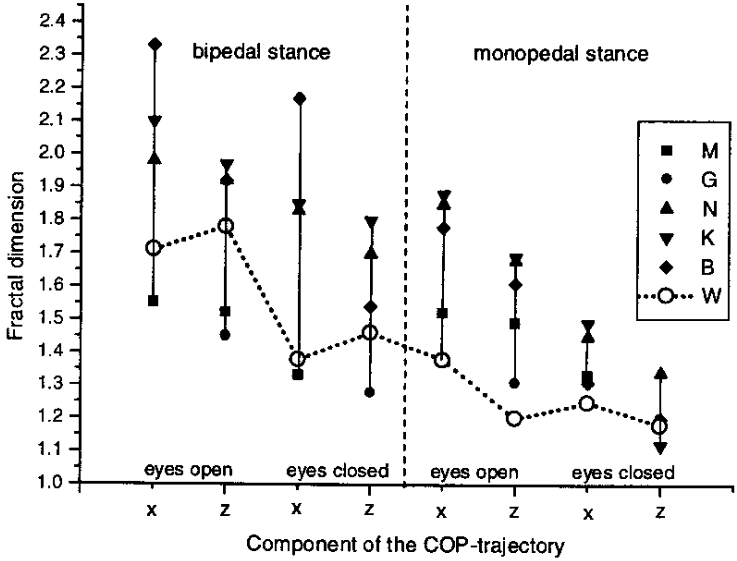

Figure 7. Mean values of fractal dimension for all subjects included child W

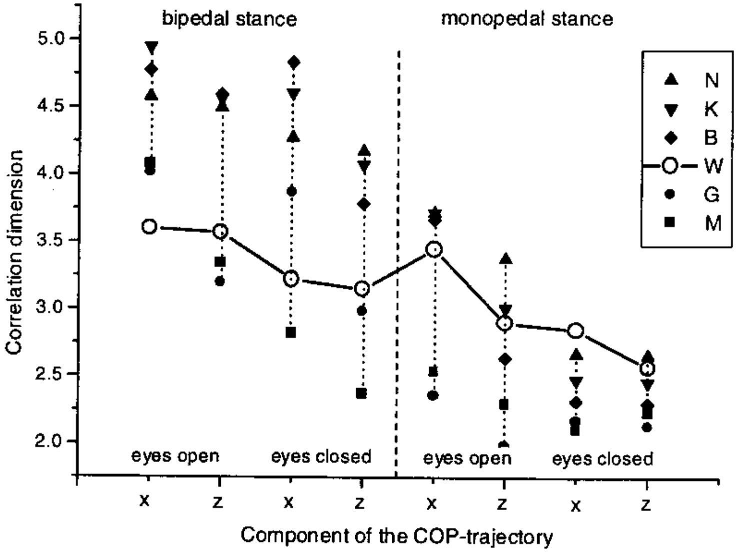

Figure 8. Mean values of correlation dimension for all subjects included child W

To examine these visual impressions by statistical means, we integrated the test series into the following groups: bipedal and monopedal stance, x- and z-component of the COP-trajectories, stance with open and with closed eyes. With help of the Wilcoxon-test we obtained the results from tab. 2. Tab. 2 shows not only the statistical significances of the adult subjects, it also shows the results of the child W. One may conclude from this that significant differences between monopedal and bipedal stance for both components of the COP-trajectories exist. The same results are there for the child W at an age of 6 years. Variations between the x-component and the z-component of the COP-trajectory are not evident. But we could find significant differences in the comparison between the stance with open eyes and with closed eyes both in the adults and the child. If we consider only the mean values (see figs. 7 and 8) we can see that the dimensions of the child are situated within the range of the dimensions of the adults. It follows that the ability of static equilibrium of a child is the same as the adult.

Discussion

On the basis of the results of the Waberproduct-analysis and the positive maximal Lyapunov exponents we can conclude that the upright stance can be described by the model of the strange attractor. By means of the COP-trajectories it is possible to create a substitute phase space. The attractor formed was characterized by the fractal and the correlation dimension. We interpret the quantities of dimension as the number of the degrees of freedom. We found out that this number is individually different. Yamada, 1995 and Newell et al., 1993 computed also different dimensions for various subjects. This indicates that single subjects are provided with an individual number of mechanisms to keep the equilibrium. Momentary a sufficient explanation does not exist.

But we obtained interesting results in the comparison between the tests under various conditions (see tab. 2). The statistical analysis shows that the dimensions of the bipedal stance are higher than those of the monopedal stance. One plausible explanation is that in the bipedal stance the subject has more possibilities of control mechanisms by activation and deactivation of a greater number of muscles than in the monopedal stance. Also other authors (see for instance Slobounov et al., 1997 and Goldie et al., 1989) obtained different results in the investigations of bipedal and monopedal stance. But we have to note that these researches are based on statistical analysis of the force signal or of the COP-trajectories.

Another result is that the closing of the eyes decreases the dimension. Many authors could detected differences between the studies of balance with open and with closed eyes by means of the determination of the variability of the COP trajectory. In these cases the variability under the condition of closed eyes is higher than under the condition of open eyes (examplary Parys and Njihikjion, 1976, Goldie et al., 1989). But the reason for the other relation by using of the dimension could be the elimination of the visual control mechanism. This leads to the reduction in the number of degrees of freedom of the total system.

The differences between the dimensions of x- and z-component of the COP-trajectory are not significant. Even though it is possible that this trend exists if we note the relatively small number of tests and test subjects. This would not correspond with the results by Mester (1987). He found out that the regulation torques in the frontal plane are higher than in the sagittal plane. But Day et al., 1993 reported about analogous results. They found out greater angular fluctuations between adjacent body segments in the sagittal plane than in the frontal plane. As reasons for this we can see that the functional anatomy of the hip, knee and ankle and the locations of the muscles allow a better coordination of synergists and antagonists in the sagittal plane than in the frontal plane.

We also found all these results for the child. This is evidence of the same control mechanisms for the equilibrium for a child at an age of 6 years as the adults.

Conclusions

We assume that a nonlinear dynamical approach is just right to describe the static equilibrium. A decisive advantage to this approach is the comprehensive phenomenological view. It could be proven that the continued compensation movements are not stochastic the regulating mechanisms are a deterministic-chaotic process. The model of the strange attractor is useful on this foundation. Using the theorem of Takens and the Waberproduct-analysis, we created the attractor by means of the COP-trajectories. It can be quantified by dimensions which are a measure of the number of control mechanisms to keep the balance. This could be demonstrated by tests under different conditions. So the bipedal stance shows a higher value of dimension than the monopedal stance and the stance with closed eyes has a smaller dimension than the stance with open eyes.

We can conclude that the decrease of the number of the control mechanisms of the standing balance leads to a reduction of the dimension. So it is possible to confirm the studies by Newell et al., 1993 that it is useful to describe the postural stability and variability by means of nonlinear techniques.

REFERENCES

Allum, J. H. J. & Büdingen, H. J. 1979. *Coupled stretch reflexes in ankle muscles: an evaluation of the contribution of active muscle mechanisms to human posture stability*. Progress in brain research, 50, 185–195.

Antuono, P. G., Myklebust, B. M., Myklebust, J. B. & Hu, Q.-T. 1990. *Standing balance measures in alzheimers disease*, Abstract of 2nd Int. Conference Alzheimers Disease & Relative Disorders, Toronto, Neurobiology of Aging, 11, 258.

Argyris, J., Faust, G. & Haase, M. 1994. *Die Erforschung des Chaos*. Braunschweig/Wiesbaden: Friedrich Vieweg & Sohn Verlagsgesellschaft mbH.

Black, F. O., Wall, C., Rockette, H. E. & Kitch, R. 1982. *Normal subject postural sway during the Romberg test*. American Journal of otolaryngology: head and neck medicine and surgery, 2, 5, 309–318.

Blaser, P., Witte, K., Stucke, Ch. 1996. *Die Freiheitsgrade der Bewegungskoordination – eine Reflexion über neue Erklärungstendenzen des BERNSTEIN´schen Ansatzes*. 2. Bernstein-Konferenz, Zinnowitz/Usedom.

Boissel, S. & Zattara, M. 1981. *A sequence of postural movements precedes voluntary movement*. Neuroscience Letters, 22, 263–270.

Collins, J. J. & De Luca, C. J. 1995 a. *The effects of visual input on open-loop and closed-loop postural control mechanisms*. Exp. Brain Research 105, 151–163.

Collins, J. J. & De Luca, C. J. 1995 b. *Upright, correlated random walks: A statistical biomechanics approach to the human postural control system*. CHAOS, 5, 1.

Day, B. L., Steiger, M. J., Thompson, P. D., Marsden, C. D. 1993. *Effect of vision and stance width on human body motion when standing : implications for afferent control and lateral sway.* Journal of Physiology, 469, 479–499.

Diener, H. C., Bootz, F., Dichgans, J. & Bruzek, W. 1983. *Variability of postural "reflexes" in humans.* Experimental Brain Research, 52, 423 - 428.

Dietz, V., Gollhofer, A., Klieber, M. & Trippel, M. 1992. *Regulation of bipedal stance, dependency of "load" receptors.* Experimental Brain Research, 89, 229–231.

Dietz, V., Hartmann, A. & Berger, W. 1989. *Interlimb coordination of leg - leg activation during perturbation of stance in humans.* Journal of Neurophysiology, 62, 3.

Goldie, P. A., Bach, T. M. & Evans, O. M. 1989. *Force platform measures for evaluation postural control: reliability and validity.* Archives of physical medicine and rehabilitation. 70, July.

Goldie, P. A., Evans, O. M. & Bach, T. M. 1992. *Steadiness in one-legged stance: development of a reliable force-platform testing procedure.* Archives of physical medicine and rehabilitation ,73, 4.

Goldie, P. A., Evans, O. M. & Bach, T. M. 1994. *Postural control following inversion injuries of the ankle*, Archives of physical medicine and rehabilitation. 75, 9.

Gollhofer, A., Hartmann, G. A., Berger, W. & Dietz, V. 1989. *Compensation of translational and rotational perturbations in human posture stabilization of the center of gravity.* Neuroscience Letters, 105, 73–78.

Grassberger, P. & Procaccia, I.,1983. *Characterization of Strange Attractors*, Physical Review Letters, 50, 346–349.

Gu, M.-J., Schultz, A. B., Shepard, N. T. & Alexander, N. B. 1996. *Postural control in young and elderly adults when stance is perturbed: dynamics.* J.of Biomechanics, 29, 3.

Hasan, S. S., Lichtenstein, M. J. & Shjavi, R. G. 1990. *Effect of loss of balance on biomechanics platform measures of sway: influence of stance and a method for adjustment.* J. of Biomechanics, 23, 8, 783–789.

Horak, F. B. & Nashner, L. M. 1986. *Central programming of postural movements: adaptation to altered support - surface configuration.* Journal of Neurophysiology, 55, 6..

Kantz, H.1994. *A robust method to estimate the Lyapunov exponent of a time series*. Physics Letters, A 185, 77–87.

Leven, R. W., Koch, B. P. & Pompe, B.1989. *Chaos in dissipativen Systemen.* Berlin: Wissenschaftliche Taschenbücher Mathematik / Physik, Bd. 304.

Liebert, W. 1991. *Rekonstruktion und Charakterisierung seltsamer Attraktoren aus skalaren chaotischen Zeitreihen.* Frankfurt am Main - Thun: Verlag Harri Deutsch.

Loistl, O. & Betz, I. 1994. *Chaostheorie.* München - Wien: R.Oldenborg Verlag.

Maki, B. E. & Whitelow, R. S.1993. *Influence of expectation and arousal on center of pressure responses to transient postural perturbations.* Journal of vestibular research, 3, 25–39.

Mester, J.,1987. *Sinnesphysiologische Aspekte der Motorikforschung.* (In:) Daugs, R. (Red.): *Neuere Aspekte der Motorikforschung.* Academia-Verlag: Sankt Augustin.

Myklebust, J. B. & Myklebust, B. M. 1989. *Fractals in Kinesiology,* Abstract of 19th Annals Meeting of the Society of Neuroscience, 15, 604.

Myklebust, J. B., Prieto, T. B., Myklebust, B. M. & Lang, D. G. 1990. *Dimensionality of postural steadiness.* Abstract of 20th Annal Meeting of the Society of Neuroscience, 16, 1315.

Newell, K.M., van Emmerik, R.E.A., Lee, D., Sprague, R.L. 1993. *On Postural Stability and Variability.* Gait & Posture, 4, 225 - 230

Nigg, B. M. 1977. *Menschliche Mikrovibrationen.* Basel: Barkhäuser Verlag.

Parys, J. A. P. & Ch.-J. Njihikjien. 1976. *Romberg´s sign expressed in a quotient.* Agressologie, 17, 95–100.

Prieto, Th. E., Myklebust, J. B. & Myklebust, B. M. 1993. *Characterization and modeling of postural steadiness in the elderly: a review.* IEEE Transactions on rehabilitation engineering, 1, 1.

Riccio, G.E. 1993. *Information in Movement Variability about the Qualitative Dynamics of Posture and Orientation.* (In:) Newell, K.M.; Corcos, D.M.. *Variability and Motor Control.* Human Kinetics Publishers, Champaign.

Schumann, T.; Redfern, M.S.; Furman, J.M.; El-Jaroudi, A.; Chaparro, L.F. 1995. *Time-frequency analysis of postural sway.* J. Biomechanics, 28, 5, 603–607.

Slobounov, S.M., Slobounova, E.S., Newell, K.M. 1997. *Virtual time-to-collision and human postural control.* Journal of Motor Behavior, 29, 3, 263–281

Spaepen, A. J., Fortuin, J. M. & Willems, E. J. 1979 a. *Comparison of the movements of the center of gravity and of the center of pressure in stabilometric studies - Comparison with Fourier analysis.* Agressologie 20, 6B, 115–116.

Spaepen, A. J., Peerear, L. & Willems, E. J. 1979 b. *Center of gravity and center of pressure in stabilometric studies. A comparison with film analysis.* Agressology, 20, 6 B, 117–118.

Takens, F. 1981. *Detecting strange attractors in turbulence.* (In:) Warwick, D. Rand, I. Young (1980): *Dynamical systems and turbulence.* Springer, Berlin, 366–382

Tokumasu, K., Ihegami, A., Tashiro, A., Bre, M. & Yoneda, Y. 1983. *Frequency analysis of the body sway in different standing postures.* Agressology, 24, 2, 89–90.

Wade, M. G., Lindquist, R., Taylor, J. R. & Treat-Jacobson, D. 1995. *Optical flow, spatial orientation, and the control of posture in the elderly.* The Journals of Gerontology, 50, 1.

Witte, K., Kagerl, Th,, Stucke, Ch., Blaser, P.1999. *The Determination of the Fractal Dimension for Estimation of the Standing Balance.* (In:) Blaser, P. (ed.*) Proceedings: Kinetics'97,* Academia-Verlag: Sankt Augustin.

Witte, K., Kagerl, Th. 1998. *Software package „Applications of Nonlinear methods on biomechanical and biological time series*". Magdeburg.

Yamada, N. 1995. *Chaotic swaying of the upright posture.* Human Movement Science, 14, 711–726