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ORIGINAL SCIENTIFIC PAPER

A mathematical modelling analysis of the response of blood pressure and heart rate to submaximal exercise

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ABSTRACT

Objective: According to Golden ratio (GR) and Fibonacci sequence, models of the organisation of various structures can be encountered in biology, medicine, architecture and engineering. Recent studies indicate that GR can be highlighted in the organisation and physiological functioning of the cardiovascular system. The aim of this study was to investigate the cardiovascular homeostasis during rest and exercise testing by determining the GR validity at the dynamic level of systolic and diastolic blood pressure (SBP, DBP) and heart rate (HR) values.

Methods and Results: We used data obtained from a cardiovascular testing of a group of 236 young healthy subjects (mean age of 19.35 ± 1.92 years). We realised a double assessment of subjects (HR and BP), at rest and immediately after a six minutes submaximal exercise test (Astrand and Rhyming protocol). The investigated group showed a normal cardiovascular reactivity in subjects. GR harmonic rhythm can be identified in the correlation of hemodynamic parameters of HR and SBP, respectively of SBP and DBP, at rest. The differences between means of the ratios (SBP/HR and SBP/DBP), at rest and after effort, were statistically significant ($p < .001$), with a large effect size.

Conclusions: We confirm that the rest state determines the harmonisation of SBP and HR, respectively, of SBP and DBP values, both ratios being very close to GR value. From the perspective of these cardiovascular parameters, the human body is designed to function in the harmonic regime at rest and to temporarily get out of synchronisation during exercise.

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Blood pressure; heart rate; exercise; Fibonacci series; Golden ratio

Introduction

The mathematical concept of consecutive Fibonacci numbers or sequence has led to Golden ratio (GR, represented by the Greek letter Phi or φ), which is an irrational number 1.61803398 …. [1], with important symmetric and harmonic properties [2].

GR represents, in fact, the limit of the ratio of consecutive terms of the Fibonacci sequence (proposed in twelfth century by Leonardo Fibonacci), with the following mathematical definition [3]:

$$F_0 = F_1 = 1, F_n = F_{n-1} + F_{n-2}, n>1; GR = F_n/F_{n-1}$$

Over different historical periods, even since Ancient Greece, GR and consecutive harmonic rhythm have been the subject of numerous scientific researches, which highlighted the fact that, in nature, there can be found a wide range of representations that seem to follow the mathematical model of organisation derived from the Fibonacci series.

Models of the organisation of various structures, in accordance with GR, can be encountered in biology, medicine, art, architecture and engineering [4]. Therefore, it has been proposed that the phi code could be strongly linked with the morphogenesis (development of forms of phyllotaxis) in biology, as well as the aesthetics and harmony of forms in various fields of design [5].

GR has very large applications, starting from the quantum mechanics, with the nanoscale symmetry hidden in solid state matter [6,7], up to fractal models or repeating patterns in biodiversity [8]. In medicine, it is discussed about anatomical, embryological, physiological and pathophysiological models of application of fractal geometry and harmonic rhythm in control of most systems functioning, with implications at molecular-genomic level, tissue and organ engineering [9–11].

Recent studies indicate that GR can be highlighted in the organisation and physiological functioning of

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the cardiovascular system at rest and can be used in cardiological clinical practice [12,13].

Various types of practical applications in terms of phi code can be mentioned, as follows: assessing of embryology development and correlating the size of the cavities of the heart [14], structure and kinetics of the heart valves [15,16], relationship between heart systole and diastole [17–19], distribution of coronary arteries branches at myocardial level according to a fractal pattern [20,21].

In a previous recent study, we proposed using a new electrocardiographic parameter, entitled synthetic fractal indicator (SFI), with dynamic nonlinear evolution during exercise, linked to the GR harmonic rhythm [22].

Several researches focussed on determining correlations between the variations in blood pressure induced by cardiac cycle and GR. Thus, there are cited mean values in the ratio of SBP and DBP of approximately 1.6 that is close to the golden proportion of φ [23,24]. Other authors consider that the existence of this harmonic report can be correlated with good health, while deviation from φ value would represent a higher risk of mortality at population level [25].

The application of the Fibonacci mathematical model in cardiovascular medicine is a subject in continuous development, based on the fact that the mainstream regulation of cardiovascular system seems to be associated with GR [26].

Methods

Aim of the study and premise

If the organism's adaptation to effort from a hemodynamic perspective represents today a more in-depth domain, however, the applicability of mathematical models in this case, as it is the GR harmonic rhythm, still remains a subject less approached by researchers. As most surveys focussed typically on cardiovascular investigations at rest, consequently the relationship between effort parameters and the mathematical models presented above is less known.

The objective of this research was to investigate the cardiovascular homeostasis during rest and exercise testing, with the determination of the GR validity at the dynamic level of blood pressure and heart rate (HR) values.

Participants and data acquisition

Our study used data obtained from a cardiovascular testing of a group of young healthy subjects. The tests were carried out on a sample of 236 young subjects, with the mean age of 19.35 ± 1.92 years (sex ratio 0.45, 73 men/163 women) and the range of variation of the age of 18–22 years.

Selected subjects are students in physical therapy, clinically healthy, with no history of cardiovascular pathology and declared fit for exercise after passing a medical consultation. Subjects with significant cardiovascular medical history were excluded from the study group.

We took into account the most cited paradigms in the literature of specialty that can generate experimental variables in the cardiovascular field and the possibility to be correlated with GR and Fibonacci sequence. Under these circumstances, we designed a double assessment of subjects, at rest (r) and immediately after effort (e). Hence, systolic blood pressure (SBP), diastolic blood pressure (DBP) and HR were registered for each subject in both circumstances, in standardised conditions.

The evaluations were performed in the morning, between 8 and 11 am, according to the same type of protocol (sitting position, left arm supine at right atrium level), with the following sequence of the evaluation: at rest (after a five minute rest) and after a six minute exercise test, during the first 15 seconds after completing the exercise. Exercise testing was realised after the protocol of the Astrand and Rhyming Submaximal Bicycle Test, an accurate and largely used standardised tool to estimate maximal oxygen consumption [27,28].

Thus, each subject performed a six minute exercise Ergometer test, using an Ergoline Ergometer exercise bike, cycling with a load of 150 W for men and 100 W for women. The settled speed was of 60 rotations per minute, according to the specifications of Astrand and Rhyming test application [29].

The HR was continuously monitored for each subject during the exercise test by a Polar Team2 recording system. This sort of equipment is very appreciated in terms of good validity and reliability for clinical research and has a higher accuracy compared to ECG measurements for both HR and HR variability [30].

For blood pressure measurement, we used the Omron M7 Blood Pressure Automatic Monitor (HEM-780-E) for upper arm, with good references for clinical use [31,32].

Outcomes and statistical analysis

After finalising the mentioned tests for the group of subjects, we obtained a number of data series that were statistically analysed through descriptive statistics (univariate analysis) by determining of mean, standard deviation, coefficient of variation (relative standard

Table 1. Statistic indicators for heart rate (HR), systolic blood pressure (SBP), diastolic blood pressure (DBP), at rest (r) and after effort (e) for the experimental group.

Variable	HRr	SBPr	DBPr	HRe	SBPe	DBPe
Mean	73.86	117.86	73.21	139.02	148.58	79.49
SD	7.46	11.62	8.25	11.45	9.27	7.60
CV	10.10	9.86	11.27	8.24	6.24	9.57
Minimum	56	80	56	120	116	61
Maximum	91	143	92	168	172	102
95% CI	72.91–74.81	116.36–119.36	72.11–74.30	137.52–140.52	147.38–149.78	78.52–80.46

SD: standard deviation; CV: coefficient of variation; CI: confidence interval.

Table 2. Statistic indicators for the rates between investigated parameters, at rest (r) and after effort (e) for the experimental group.

Variable	SBPr/HRr	SBPr/DBPr	SBPe/HRe	SBPe/DBPe
Mean	1.61	1.62	1.08	1.88
SD	0.23	0.13	0.10	0.17
CV	14.57	7.83	9.58	8.86
Minimum	1.16	1.26	0.83	1.33
Maximum	2.39	1.98	1.35	2.33
95% CI	1.58–1.64	1.60–1.64	1.07–1.09	1.86–1.90

SD: standard deviation; CV: coefficient of variation; CI: confidence interval.

deviation), of maximum and minimum registered values and 95% confidence intervals for the means (CI). Then we calculated mean rates between certain parameters, respectively, at rest (SBPr/DBPr, SBPr/HRr) and after effort (SBPe/DBPe, SBPe/HRe).

Finally, the Pearson correlation coefficients *R* between HR, SBP, DBP, SBP/HR and SBP/DBP for all data and for each patient, at rest and postexercise were calculated. For the same data series, we applied the methods of inferential statistics, by determining the statistical significance of the differences between means (*t*-test, paired two sample for means), with 95% confidence intervals for the means (CI) and effect size measures (Cohen's *d*).

Results

The calculated statistical indicators of the data series are presented in Tables 1 and 2, for the investigated parameters, at rest and after effort.

Results are presented as mean ± standard deviation. Analysis of investigated cardiovascular parameters revealed mean values at rest and during exercise that confirms the status of normality in studying subjects, the series of data having a high homogeneity (coefficients of variation (CV) of less than 20% for all parameters). This aspect supports the idea of the validity of the study group in terms of the good level of health considered in the selection of subjects.

It should be noted that the ranges of variability of the HR of the subjects were respectively 56–91 beats/minute at rest and 120–168 beats/minute during exercise and the subjects' group mean of the HR 73.86 ± 7.46 beats/minute at rest and 139.02 ± 11.45 beats/minute during exercise.

Regarding the values of blood pressure, the obtained mean values at rest were 117.86 ± 11.62 mm Hg for SBP and 73.21 ± 8.25 mm Hg for DBP, while after exercise mean values of the same parameters increased to 139.02 ± 11.45 mm Hg and respectively to 79.49 ± 7.60 mm Hg.

After determining the mean rates of SBP and HR SBP/HR in the group of subjects, we obtained a value of 1.61 ± 0.23 at rest and 1.08 ± 0.10 after effort. Our results suggest that the mean value of the SBP/HR ratio at rest is very close to the value of the GR (1.618), while during effort there is a trend towards reduction of its mean value. The decreased value of this rate is easy to be understood if we take into account the modification of parameters in terms of size order, the value of exercise HR increasing much more than SBP during effort.

Also, the recorded mean values of the SBP/DBP ratio (1.62 ± 0.13 at rest and 1.88 ± 0.17 after exercise) were very close to GR, and again the distancing from the GR reference value was higher after exercise.

Regarding the correlation analysis, the calculated *R* coefficients are presented in Table 3.

The observed correlation coefficients for the six first parameters can be interpreted as having a very weak intensity, a fact also confirmed by other studies on the relationship between HR and blood pressure [33]. In other words, the linear association of these investigated parameters is limited. The results are in line with the view of other researchers who presented the random and unpredictable character of HR variation according to SBP and DBP in effort testing [34,35].

Some authors demonstrated a relationship only between elevated resting HR and increased SBP and DBP, in adolescents, regardless of gender [36].

However, in our case, the correlation coefficients between HR and the ratios SBP/HR and SBP/DBP, at rest and respectively after effort (Table 3 and Figures 1–4) recorded important values: strong negative linear relationship between HRr and SBPr/HRr, HRe and

Table 3. The correlation coefficients *R* for the series of data – heart rate (HR), systolic blood pressure (SBP), diastolic blood pressure (DBP), at rest (r) and after effort (e) for the experimental group.

	HRr and SBPr	HRr and DBPr	HRr and SBPr/DBPr	Hre and SBPe	HRre and DBPe	Hre and SBPe/DBPe
R	−0.02	0.04	0	0.11	0.03	0.04
	HRr and SBPr/HRr	HRe and SBPe/HRe		SBPr/HRr and SBPe/HRe		SBPr/DBPr and SBPe/DBPe
R	−0.71	−0.75		0.37		0.77

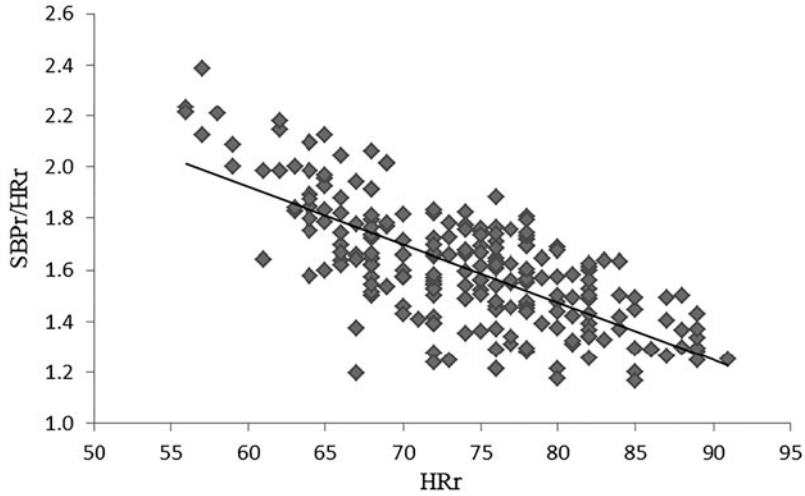

Figure 1. The correlation between HRr and SBPr/HRr (HR: heart rate; SBP: systolic blood pressure; r: rest).

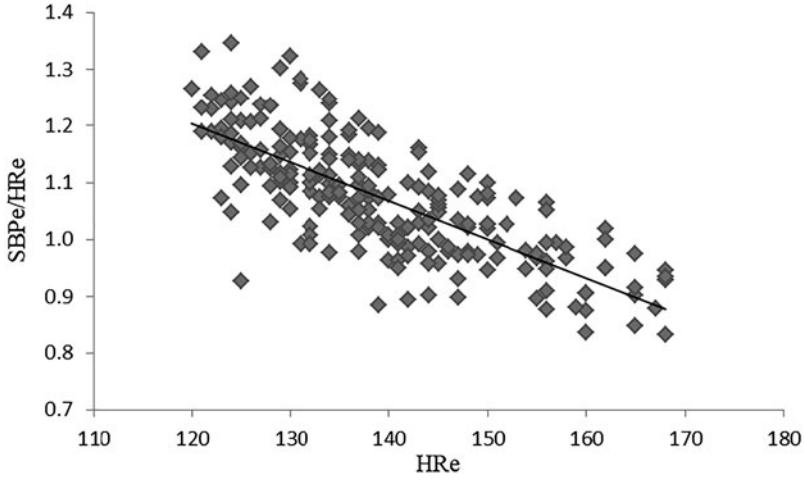

Figure 2. The correlation between HRe and SBPe/HRe (HR: heart rate; SBP: systolic blood pressure; e: after effort).

SBPe/HRe; moderate positive relationship between SBPr/HRr and SBPe/HRe; strong positive relationship between SBPr/DBPr and SBPe/DBPe.

In addition, the differences between means of the ratios SBPr/HRr and SBPe/HRe, respectively, SBPr/DBPr and SBPe/DBPe (Table 4) were statistically significant ($p < .001$), with a large effect size for both situations (Cohen's $d > 0.80$).

Discussion

The results obtained in this study have revealed that GR harmonic rhythm can be identified in the correlation of hemodynamic parameters of HR, SBP and DBP, only at rest (Figure 5).

This situation has also been confirmed by other authors who have highlighted the fact that SBP/HR and SBP/DBP ratios are closer to the GR especially during night time. The explanation given by the authors relies on the existence of growing parasympathetic autonomic tone overnight, while the diurnal variations, conditioned by daily activities, are directly influenced by sympathetic predominant tone [24]. Continuing this idea, the more plausible it seems that acute body adaptation to physical exercise, mediated by the autonomic sympathetic system [37], would further modify

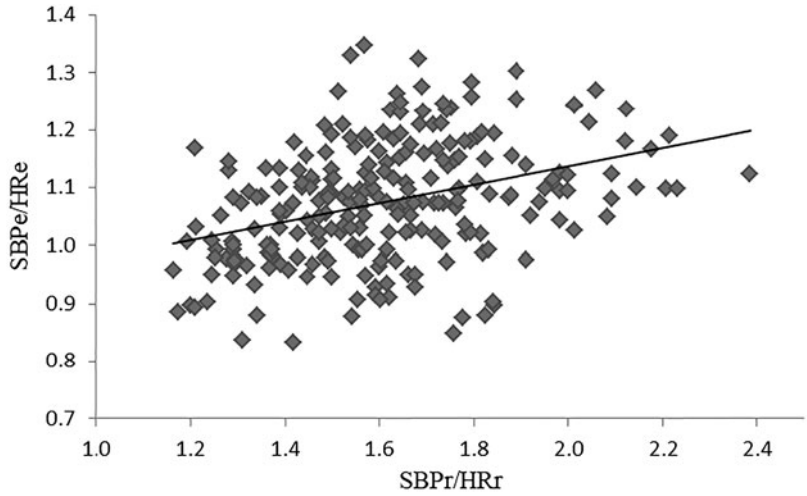

Figure 3. The correlation between SBPr/HRr and SBPe/HRe (HR: heart rate; SBP: systolic blood pressure; r: rest; e: after effort).

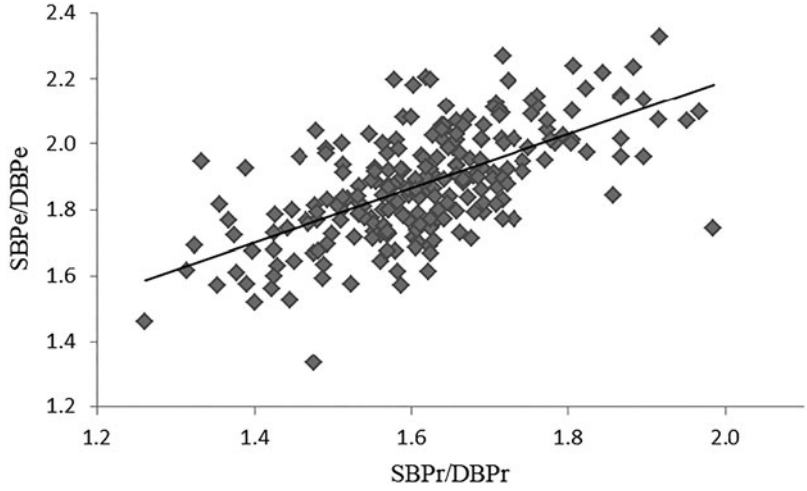

Figure 4. The correlation between SBPr/DBPr and SBPe/DBPe (SBP: systolic blood pressure; DBP: diastolic blood pressure; r: rest; e: after effort).

Table 4. The *t* test values, the thresholds of statistical significance (*p*) for differences between means of the ratios and the effect size measures (Cohen's *d*).

Ratios	*t*	*p*	Cohen's *d*
SBPr/HRr/SBPe/HRe	37.60	<.001	−2.05
SBPr/DBPr/SBPe/DBPe	−30.73	<.001	2.95

HR: heart rate; SBP: systolic blood pressure; DBP: diastolic blood pressure; r: rest; e: effort.

the values of these rates, towards distancing from the ideal value, assumed to be the GR.

It is known that dynamic exercise produces a large increase in SBP, without much change in DBP [38]. Therefore, in agreement with this idea, after effort the SBP/DBP ratio must necessarily increase. If we consider that an increase in DBP more than 10–15 mm Hg during effort means a pathologic condition [39] or at least a high sympathetic reactivity [40], we can admit that lack of increased SBP/DBP ratio during exercise becomes a negative indicator of the subject's physiological status.

In this context, the results obtained in the group of subjects, which revealed that the SBP/DBP ratio during effort is getting further from the GR reference value, show a normal reactivity in subjects, placed within the cardiovascular homeostasis.

If we consider the rest cardiovascular haemodynamic status as harmonically, designed according to predefined mathematical models that respect the principles of maximum functional efficiency, then the organism adaptation to exercise can be understood from the perspective of the concept of synchronisation/desynchronisation/resynchronisation.

Thus, during exercise, the vagal activity is covered by the sympathetic one [41], both mechanisms having a synchronous activity with each cardiac cycle, but influenced by the central nervous system [42].

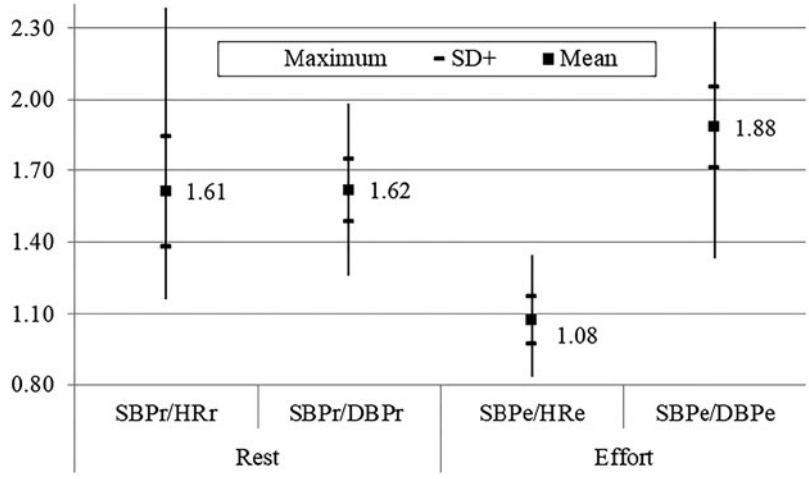

Figure 5. The evolution of the SBP/HR and SBP/DBP ratios for the group of subjects during the exercise testing (SD: standard deviation; HR: heart rate; SBP: systolic blood pressure; DBP: diastolic blood pressure).

This activity is modulated by the intervention of central control mechanisms (bulbar cardioacceleratory and cardioinhibitory centres, vasomotor and respiratory centres) and peripheral control mechanisms (oscillations in blood pressure and respiratory movements) [43,44].

At the end of the submaximal exercise testing, the body reaches the steady state, as a biologic system. At this point, the adaptation to effort can be expressed in terms of ventilatory, circulatory and metabolic changes and the flow of oxygen become constant at all levels [45].

After effort, the harmonic rhythm of correlation of HR and BP values (especially through the systolic component), according to mathematical modelling of GR, is gradually restored. Thus, after the rest state is achieved, hemodynamic parameters will become again synchronous. This evolution ensures the possibility of energy recovery after effort and preparedness to deal with any other future metabolic requests.

Overall, the results provide new lights on the possibility of applying of the GR harmonic rhythm for cardiovascular parameters of HR and blood pressure in terms of adaptability of the body to a common form of stress, such as exercise. According to physiological principles, we cannot speak about homeostatic absolute values, but instead, we use homeostatic intervals of variation. That is why it seems reasonable to consider that, at least numerically, we can frame the analysed ratios in a mathematical model derived from the existence of the Fibonacci series.

In the same idea, several authors have concluded that the validity of GR harmonic rhythm in nature can be accepted and understood in an extrapolated form. For example, the GR ($\varphi = 1.618$) becomes applicable to common shapes with length/height ratios close to 3/2, which give the impression that they are being 'designed' to match the GR criterion [46].

From this perspective, the relationship between SBP and HR, respectively, between SBP and DBP, at rest, fit into this hypothetical ideal model. Our study confirms the new concept that the mainstream regulation of cardiovascular system seems to be associated with GR [26].

Limitations

In analysing the above data, we did not take into account the particularities of subjects by gender, given that recent studies indicate that there are no differences between men and women (healthy subjects) regarding the appropriate response to the effort testing, by cycloergometer or treadmill [47]. Other authors reported the existence of a possible little different response in women regarding the hemodynamic adaptation to effort, according to the menstrual cycle phase [48].

We also did not consider important the subjects' stress determined by the process of testing itself, even some authors reported possible little interferences with the cardiovascular parameters [49].

Conclusions

We confirm that the rest state, in which predominates the parasympathetic autonomic tone, at least in the studied parameters, determines the harmonisation of SBP and HR, respectively, of SBP and DBP values, both ratios being very close to GR value. Adaptation to exercise, without being considered as a mechanism of

destruction of harmony, involves the prominent intervention of the sympathetic autonomic system, which changes the correlation pattern of hemodynamic parameters towards another form of manifestation.

From the perspective of these cardiovascular parameters, the human body is designed to function in the harmonic regime at rest and to temporarily get out of synchronisation during exercise, and then to revert to a synchronous system, open to interaction with the external environment.

It becomes obvious that the promptness wherewith the body reaches the rest state again after the effort and regains the harmonic rhythm between the hemodynamic parameters may become a quantifiable parameter of its adaptive capacity, with possible implications for interpretation of health status, performance level or potential pathological conditions.

This theme requires further research in an area that can combine knowledge of the Chaos theory, biological theories of self-organisation, mathematical modelling theory and the theory of evolution of open systems.

Disclosure statement

No potential conflict of interest was reported by the authors.

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