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Male powerlifting performance described from the viewpoint of complex systems

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Abstract

This paper reflects on the factors that condition performance in powerlifting and proposes that the result-generating process is inadequately described by the allometric equations commonly used. We analysed the scores of 1812 lifters belonging to all body mass categories, and analysed the changes in the results achieved in each weight category and by each competitor. Current performance-predicting methods take into account biological variables, paying no heed to other competition features. Performance in male powerlifting (as in other strength sports) behaves as a self-organised system with non-linear interactions between its components. Thus, multiple internal and external elements must condition changes in a competitor's score, the most important being body mass, body size, the number of practitioners, and the concurrency of favourable factors in one individual. It was observed that each behaved in a specific form in the high level, according to the individuals' circumstances, which make up the main elements of the competitive system in every category. In powerlifting, official weight categories are generally organised in three different groups: light (<52.0 to <60 kg), medium (<67.5 to <90.0 kg) and heavy (<100 to >125 kg) lifter categories, each one of them with specific allometric exponents. The exponent should be revised periodically, especially with regard to the internal dynamics of the category, and adjusted according to possible changes affecting competition.

Keywords: Powerlifting; Performance; Complex systems; Power law

1. Introduction

At first sight, the largest and/or heaviest members of a species may seem stronger than their smaller, lighter counterparts. This, however, is not always true since some variables related to muscular strength (S_m) are not linked to body size. In sports, S_m is increased through specific training models that provoke adaptational responses. These models fall into two groups: (1) those geared towards achieving changes in body composition, especially muscular hypertrophy, and (2) those geared towards achieving neural adaptations of the central and/or peripheral nervous systems (e.g., improvements in the number of motor neurons and changes in their form of recruitment) that affect the level of tension generated during muscular contraction. The different strength sports are often characterised by the predominance of one of these training models. For example, weightlifting pays particular attention to the neuromuscular aspects of S_m while bodybuilding pays more attention to morphological aspects.

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Powerlifting, however, achieves more of a balance between these types of training.

This paper examines the factors governing performance (*Pf*) in powerlifting. This discipline was chosen since it evaluates the maximum S_m (the greatest mass lifted) of each competitor over three lifts—the squat (*SQ*), bench press (*BP*) and deadlift (*DL*) movements—none of which is of great technical difficulty. The *Pf* associated with the four scores generated by these movements (one for each movement and one for their sum (T_t)) in each regulation weight category was analysed.

To date, the analysis of *Pf* has mainly focused on the study of biological variables or their determinants. However, this approach appears insufficient when trying to understand how records and personal best scores come to change in powerlifting. This paper attempts to show that the results achieved in powerlifting depend not only on a competitor's characteristics but also on the internal structure of powerlifting competitions. The scores achieved will certainly depend on genetics, the number of years a competitor has practiced the sport, his/her level of training and experience, etc., but also on the training (trainers, ergogenic aids, nutrition, materials, etc.) and competition environment (the quality of competitions, the degree of professionalisation of the sport, rivals, incentives, organisations involved, etc.).

This work understands sporting *Pf* to be the result of a process that attempts to optimise numerous, non-linearly related factors that characterise it as a complex, self-organising system. Hopefully, this modern perspective based on the theory of complex, non-linear systems, will help us better understand the factors involved in powerlifting performance.

In recent decades, efforts have been made to understand systems with many interacting components whose collective result is not a simple combination of their individual behaviours (Zimmer, 1999). Complex systems show high levels of organisation (i.e., they show the emergence of coherent patterns) without the need for any external organising principle, and should be analysed holistically. A feature of most of these systems is their capacity to respond to external conditions, i.e., they can change in a self-adapting and self-organising fashion to produce new behaviours. Thus, complex systems cannot be studied independently of their surroundings.

Complex systems are ubiquitous in the natural world, and their scientific study has recently attracted disciplines such as engineering, economics, education, medicine, jurisprudence and the social sciences. Although no unified theory of complex systems exists (Vicsek, 2002), this area of thought provides the tools and techniques that could help improve our understanding of performance changes in powerlifting. In addition, it provides practical guidelines for analysing social organisations. In turn, the theoretical tools for studying complex systems are provided by non-linear dynamics, network theory, and the concepts of fractal geometry, power law distribution, scaling, clustering, and random processes, etc. (Anderson, 1972; Waldrop, 1992; Crutchfield 1994; Durlauf, 2001; Bar-Yam, 1997, 2000; Holland, 1995, 1998; Bouchaud, 2001; Sornette, 2004).

The tendency of some systems to organise themselves into scale-free systems has recently been discovered. This phenomenon, known as self-organised criticality (*SOC*) reflects a system's spontaneous attainment of a critical state without any fine-tuning of control variables. The two simplest (and probably most studied) systems that manifest this phenomenon are the sand pile and the forest fire (Binney et al., 1993; Bak, 1996; Jensen, 1998; Newman, 2005). In these scale-free models, a local perturbation can induce a chain reaction of events, or avalanche, which can eventually affect the whole system. These events are distributed according to power laws (*PLs*), i.e., they show scale invariance. *PLs* are mathematical expressions of the sort:

$$Y = cX^b, \tag{1}$$

where X and Y are variables, quantities or observables, c is a constant (it can also be understood as a normalisation constant) and b is the scale exponent.

An expression of this type has two key properties:

(a) Taking the logarithm in Eq. (1), we obtain

$$\log(Y) = \log(c) + b\,\log(X)$$

which is the equation of the curve b. In other words, if instead of plotting the values of X against those of Y on a graph, we plot $\log(X)$ against $\log(Y)$, we obtain a straight line.

(b) They are able to describe scale-free phenomena and have been used to analyse their distribution. However, *PLs* are also manifested in scaling or allometric relationships, which are used by biologists to describe how physiological and ecological attributes are related to body size. *PLs* are an important tool in the study of *SOCs*; given their relation to fractal geometry they are especially important in the study of living systems (Schroeder, 1991; Jensen, 1998; Solé and Goodwin, 2001).

Avalanche dynamics are indispensable to, and one of the clearest external manifestations of, the behaviour of this kind of complex system. Earthquakes, avalanches, forest fires, the Internet, and even extinctions, all obey *PL* distribution.

Many socioeconomic systems have been proposed as possible *SOC* phenomena; in these open systems, avalanches may serve as a means of dissipating market internal forces. However, even though many systems and phenomena are claimed to have self-organised critical behaviour, the underlying mechanisms of this phenomenon remain unknown; there is no clear set of criteria for identifying

SOC systems—obedience to a *PL* only indicates their possible existence.

When the internal dynamics of competitive sport (number of competitions, number of people who practice the sport, the degree of professionalisation, the social importance of the discipline, etc.) are analysed, multiple interactions between very different external agents, tension and relaxation phenomena that affect the whole system, and avalanche-type record-breaking phenomena are all apparent. The system seems to change as a response to internal and external pressures manifested by modifications in personal best scores or *Pf*. In powerlifting there are many lifters whose personal best performance is considered low or normal, many fewer with good personal best scores, and very few with extraordinary results. However, an extraordinary result can affect the entire system, generating interest from the press, sponsors, the public, sports managers and teams. This kind of outcome bears a notable similarity to the natural and social phenomena described above (earthquakes, forest fires, etc.)—all of which are considered to be *SOC* systems, and all of which show the mark of *PLs* (Savaglio and Carbone, 2000; Katz and Katz, 1999; Malacarne and Mendes, 2000; Garcia-Manso et al., 2005; Aidt et al., 2006; Alvarez-Ramirez and Rodriguez, 2006).

The question therefore arises of whether powerlifting behaves as a complex non-linear system and whether it shows *SOC* behaviour. If either (or both) is the case, small changes in training methods or in competition strategy could lead to quantitative differences in *Pf*—making this variable difficult to predict. This unpredictability would be due to the appearance of emerging behaviours and/or responses, typical of complex adaptive systems.

The present study sought to show that competitive powerlifting shares a number of the characteristics of complex adaptive systems in which avalanche-type *PL* distributions occur, and that the sport possesses internal dynamics that resemble those of a *SOC* system. An attempt is also made to show how the use of models in which *Pf* is estimated from allometric or polynomic equations may be insufficient for describing the behaviour of the results obtained in this sport.

A database was created using the male powerlifting ratings published by the International Powerlifting Federation (*IPF*) for 2003, 2004, and 2005 (http://www.powerlifting-ipf.com). This provided a sample of 1812 lifters, including participants in all the weight categories contemplated under official competition rules (<52.0, <56.0, <60.0, <67.5, <75.0, <82.5, <90.0, <100, <110, <125 and >125 kg). Competitor rank was provided for each of the three lift types (*SQ*, *BP*, and *DL*) and for the sum of three movements (T_t). Only the atheletes' best scores for the above three seasons formed part of the study sample. In order to avoid the potential effect of organisation into weight categories, as regulations suggest, we always used the body mass (*BM*) of the powerlifter in the competition where the *Pf* result was recorded.

2. Analysis of competitor morphological characteristics

2.1. Basic biological principles

It is well known that the strength developed by a muscle depends largely on the creation of a large number of actomyosin bridges, and on the quality of these. Thus, S_m is directly related to the cross-sectional area (*CSA*) of the muscle, and therefore to the muscular mass (*MM*), the body mass (*BM*) and body size (Ikai and Fukunaga, 1968; Maughan et al., 1983; Schantz et al., 1983; Kawakami et al., 1993; Vanderburgh and Batterham, 1999; Ford et al., 2000).

The relationship between S_m and *BM* is therefore governed by the equation: $S_m = k \times BM^a$; or its equivalent logarithmic expression: $\log(S_m) = \log(k) + a\log(BM)$, where S_m is total mass lifted, k is a constant of proportionality related to the performance of the subject and the scaling exponent 'a' takes a value of close to 2/3.

However, these relationships of proportionality do not always remain stable or keep to the same range of values. The work of Ford et al. (2000) on weightlifters showed that, the relationship between the weight lifted and the *CSA* mean remained, more or less, constant up to a bodyweight of 83.0 kg in men and 64.0 kg in women, but that this relationship broke down in the higher regulation weight categories.

The *CSA* depends to a great extent on *MM*. Tall subjects on average have a larger *MM* than short subjects of comparable age. The *MM* of any individual is governed in large part by his or her size, and consequently height (*Ht*), and it remains practically invariable once the adult *Ht* is reached—unless the individual's level of physical activity, either the excess or lack of it, alters it (causing hypertrophy or dystrophy, respectively). Some authors believe $S_m \sim Ht^2$ (Vanderburgh and Batterham, 1999) or a value slightly higher the exponent $Ht^{2.16}$ (Ford et al., 2000). The latter authors indicate performance in weightlifting to be limited by the lifter's stature, and point out that it is difficult to find male specialists in this sport with an *Ht* of >180 cm or female specialists taller than 175 cm.

Ht is also a limiting factor in the amount of a competitor's fat-free muscle mass (*FFM*) (Behnke and Wilmore, 1974; Forbes, 1987b; Abe et al., 1999; Brechue and Abe, 2002), a variable habitually used in the estimation of the *MM* and muscular S_m. The relationship between *FFM* and *Ht* is not linear. Ford et al. (2000) indicate that *MM* is related to stature raised to the power of 3.16 ($\sim Ht^{3.16}$), slightly higher than the value of 3 normally assumed.

Biological limits therefore appear to exist with respect to the maximum *MM* that humans can acquire. Some authors (Behnke and Wilmore, 1974; Forbes, 1987a; Abe et al., 1999; Brechue and Abe, 2002) indicate that, for men, it is almost impossible to achieve more than 100–110 kg of *FFM*, while women reach a peak at 60–70 kg. Above these values, increases in *BM* are mainly due to increases in the fat mass and residual mass (the mass of the viscera). These values need to be checked, however, in samples of weightlifters, bodybuilders and powerlifters. These types of sportsmen probably show high values. Their very specialised and intense training schemes, and the use of anabolic hormones could determine *FFM* values higher than those mentioned. Although the *FFM* can be manipulated, it should be borne in mind that excessive muscular hypertrophy can modify the angle of pennation of the muscle fibres to the point that mechanical efficiency is compromised.

Another important factor in the determination of S_m is the quantity of body material that makes little contribution towards this variable (skeleton and fat). We should keep in mind that skeleton and fat contribute proportionately more of the total mass in larger mammals. Forbes (1992) indicated a direct relationship to exist between *FFM* and the amount of body fat (*BF*), which justifies why lifters with the greatest *BM* also have the greatest fat masses. In men, *BF* values usually lie somewhere between 6% and 12% of the *BM* in the lightest lifters, and can reach 20–30% or even more in the heaviest powerlifters. For female, these values are typically 5–10% percentage points higher. Forbes explains this increase in *BF* in terms of the greater energy requirements of the latter lifters (who need a greater energy reserve) and the double action of *IGF–Is* on protein synthesis and fat deposition. Changes in body composition, along with the effects of training, therefore, affect the strength developed by atheletes. Despite, percent fat tends to decrease with the increasing level of athlete.

Fig. 1 shows the sum of the three powerlift movement scores (T_t) plotted against the *BM* of the atheletes in the present sample. As expected, the mean *Pf* tends to increase with *BM*. High level sportspersons always try to produce the maximum performance for their morphological and functional capacities. The subjects with the best results in each category are those approaching the theoretical limits of the S_m for a person of a determined constitution and functional profile.

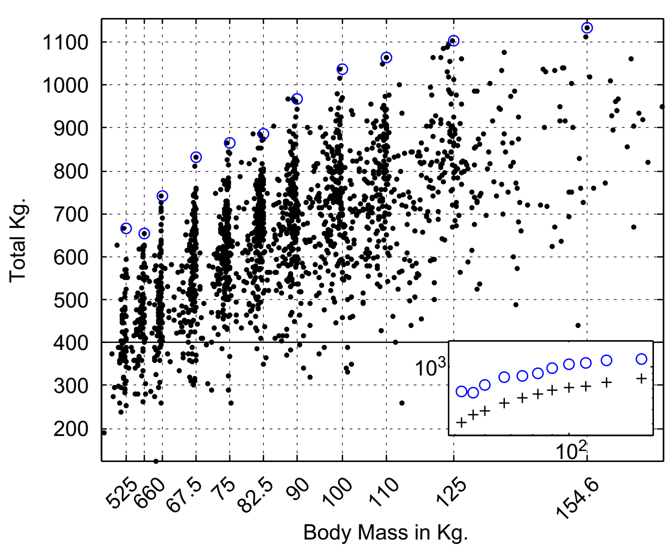

Fig. 1. The sum of the three powerlift movement scores plotted against body mass: distribution shown by the studied sample of powerlifters. The circles represent maximum values. The inset is a log–log plot of the mean scores for each regulation weight category.

2.2. Organisation of powerlifters into bodyweight categories

Over the years, different proposals have been made regarding the assessment and comparison of lifters with different *BMs*. All seek to relate *Pf* with *BM* via the use of different regression models (allometric equations, different order polynomial equations, multi-exponential functions, etc.). The underlying idea of these proposals is simple: to find a coefficient that depends on body muscle weight that is sufficiently simple to use, and that corrects the effect of *BM* on personal best scores. However, Fig. 1 shows that *Pf* does not always follow a single allometric model.

To confirm this affirmation, care must be taken when selecting the data to be examined. The use of only the best results seems reasonable at first glance, but this is not possible because of their irregularity. This may be due to the competitive immaturity of this sport, and to the possibility that exceptional atheletes may exist whose *Pfs* are not the consequence of their potential and their level of training, but to biological manipulation (doping). In the present work the mean personal best scores in the 25th–75th interquartile range for each regulation weight category are examined. This choice was made in order to eliminate extremes in each *BM* category included in the sample. Further discussion of the reasons for this decision is included below.

Analysis of sporting *Pf* often uses for reference purposes one or more functional parameters (including VO_2, *BM* and *Ht*). A number of studies also seek the best mathematical fit between *Pf* and other variables, such as distance, test timing, or weight category. In fact, the relationship between body size and yield, or other physiological variables, is a curvilinear relationship, so an *allometric* equation is generally applied for such relationships. This type of model is widely accepted in the strength-sport world, using a scale exponent of 0.67 (i.e., 2/3). Several studies have shown that the exponent value is no more than a simple approximation; it would be more appropriate to determine the value on the basis of certain parameters, including population characteristics, mechanical characteristics of movement, age and sex (Croucher, 1984; Bancroft et al., 1987; Hui et al., 1995; Kauhanen et al., 2002).

For powerlifting, a number of published studies relate *BM* with *Pf* (Batterham and George, 1997; Vanderburgh and Batterham, 1999; Dooman and Vanderburgh (2000); Cleather, 2006); Wilks equation is used by the *IPF* to evaluate powerlifters' yield regardless of *BM*. However, in all cases the mathematical fit is more precise than when a single *PL* is applied.

The present paper did not seek to study the relationship between strength and *BM*, nor to relate best scores to a given parameter, but rather to analyse sporting activity in general through a specific sport (powerlifting) from, the standpoint of adaptative complex systems.

Fig. 2 shows the log–log plot of *BM* against the scores achieved for the *SQ*, *BP* and *DL* and T_t scores for each regulation weight category. The circles show the mean *Pf* of the lifters with personal bests within the mentioned interquartile range.

The values that show linear behaviour in a log–log plot are those which correspond to a *PL* or allometric law, the exponents of which give the slope of the straight line to which they fit. Note that overall the data do not follow a linear pattern; therefore, they do not all obey same *PL*.

However, nearly all the graphs in Fig. 2 show three areas with linear behaviour that can be regarded as grouping the light (<52.0 to <60 kg), medium (<67.5 to <90.0 kg), and heavy (<100 to >125 kg) lifter categories; these are clearly separated by cut-off points provided by the intersections of the *PL* lines.

The fact that a system can be characterised with three *PLs* appears to conflict with the prevailing notion of a single law of scale. In fact, it suggests that different dynamics may exist within these sporting activities, which imply different training and competition strategies. Most of these differences may be ascribed to the morphological profile of the sportsman.

Further statistical analysis is thus required to discriminate between significantly different groups, when results are not due simply to noise or the use of very few data points. The Chow test generally used to test for a structural break, or structural change, uses an *F*-test to determine whether a single regression is more efficient than two separate regressions involving splitting the data into two sub-samples Chow (1960).

The data shown in Table 1 indicate statistically significant differences between the three regression lines for *PT*, *SQ* and *BP* ($p<0.05$). By contrast, differences between lightweight and middleweight for *DL* are not statistically significant.

Table 2 shows the data for the regression lines for the three detected weight categories and for *SQ*, *BP*, *DL* and T_t. The values for the slopes *a* of the regression lines are also presented, along with the values of the ordinate at the origin log *b*.

Table 3 shows data regarding the intersections of the regression lines for each detected weight category for the movements *SQ*, *BP* and *DL* and T_t.

Table 1
Results obtained by applying the Chow test to the regression lines obtained from average scores obtained for *PT*, *SQ*, *BP* and *DL* by powerlifters in the interquartile range of each weight class included in the sample

Movement	Lights vs. medium		Medium vs. heavy	
	F-value	*p*	*F*-value	*p*
PT	14.37	0.03	63.08	0.00
SQ	34.17	0.01	21.88	0.01
BP	96.83	0.01	44.55	0.01
DL	6.17	0.09	187.16	0.00

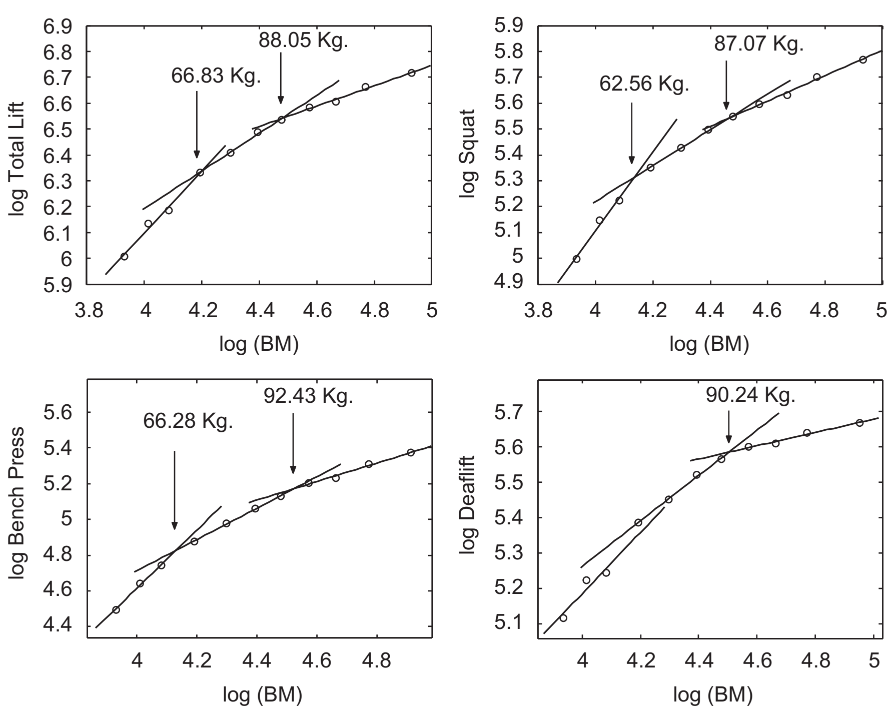

Fig. 2. Log–log plot for the *SQ*, *BP*, *DL* and T_t scores for each regulation weight category, and the regression lines for each detected weight category (light, medium and heavy). The circles show the mean *Pf* of the lifters with personal bests within the 25th–75th interquartile range.

Table 2
Values of a, b, r^2 and p for SQ, BP and DL and T_t for the three detected weight categories

Categories	a	b	r^2	p
Movement—*PT*				
Light	1.19	3.76	0.957	0.13
Medium	0.73	26.29	0.997	0.00
Heavy	0.39	119.70	0.989	0.00
Movement—*SQ*				
Light	1.52	0.37	0.973	0.10
Medium	0.69	11.66	0.999	0.00
Heavy	0.48	28.66	0.989	0.00
Movement—*BP*				
Light	1.64	0.14	0.995	0.05
Medium	0.88	3.33	0.998	0.00
Heavy	0.52	16.74	0.986	0.00
Movement—*DL*				
Light	0.86	5.70	0.893	0.21
Medium	0.64	15.01	0.996	0.00
Heavy	0.19	114.97	0.981	0.00

Table 3
Cut-off points for the log–log values of Pf and BM corresponding to the regression lines for the mean personal best SQ, BP, DL and T_t scores in the three detected weight categories

Lift	Cut-off 1 (kg)	Cut-off 2 (kg)
Squat (SQ)	62.56	87.07
Bench press (BP)	66.28	92.43
Deadlift (DL)	–	90.24
Total (T_t)	66.83	88.05

Agreeing with Cleather (2006), we verified that SQ and BP results show very similar behaviour. However, with respect to the DL movement (lower left), anomalous behaviour can be seen for the lifters in the lowest regulation weight categories (<60.0 kg). This might be explained by the current lack of interest in this lifting movement (especially notable in terms of the detected low weight category), or by the low Pf associated with it. However, the strong linearity shown by the middleweight competitors with respect to DL reflects the overall more rational behaviour of their results. The anomalous behaviour of DL has also been highlighted by Dooman and Vanderburgh (2000), who consider inappropriate the application of an allometric model for stuyding this powerlifting movement (allometric exponents: $DL = 0.46$; $PB = 0.57$; $SQ = 0.60$).

The Pf obtained by adding the three movement scores (Fig. 2d) reinforces the idea that different PLs define the three detected weight categories. This information might be important to trainers since it might affect the Pf training strategies adopted.

The values of the exponents of a for lifters in the medium detected weight category were the only ones to show any relationship with the value of the theoretical allometric exponent of 2/3. For the light lifters the slope is very steep

Table 4
Results obtained by applying the Chow test to the regression lines obtained from average scores obtained for PT by the top 20 powerlifters in each weight class sampled

Movement	Lights vs. medium		Medium vs. heavy	
	F-value	p	F-value	p
PT	74.78	0.01	20.31	0.01

(>1.0), indicating a greater dependence of Pf on BM, and in particular MM. The opposite is seen, however, for the heaviest lifters; the slope for the DL movement was particularly gentle ($a = 0.19$). This indicates that, currently, lifters are not significantly increasing their Pf with increases in BM in this movement. This reinforces the idea that the DL movement is poorly trained for and that its associated Pf is different to that seen for the SQ and BP movements.

The sample data reveal the existence of three scales that separate the detected weight categories from one another (defined by the competitors' BM values). This multi-scale process seems to indicate that each detected weight category shows a different behaviour defined by the allometric relationship between Pf and BM.

In order to confirm this result, other possibilities were tested. The following table provides the results of the Chow test applied to the Pf of the top 20 powerlifters in each category (Table 4).

The results appear to confirm the existence of three regions. However, the test failed when applied only to the top-ranked powerlifters (best performance), as was to be expected due to the considerable irregularity of the scores. The behaviour of the lighter categories was particularly poor; the specific characteristics of some of the more interesting outliers are addressed below.

3. Effect of competition variables on *Pf*

When studying Pf a number of circumstances that commonly arise during competitions should be taken into account since these can affect the results competitors obtain. The rules of the competition, competitive strategies, the internal dynamics of each regulation weight category, the number of competitors, or the appearance of elites with exceptional results, can all influence individual performance.

3.1. Competition rules

Powerlifting events involve competition between lifters within the same weight range as determined by the sport's regulations. Fig. 3a and b show the distribution of the weights of the competitors studied (normalised histograms divided by the area under the curve). The lighter lifters tend to cluster around the maximum weight permitted for their category. With increasing weight, however, bodyweights

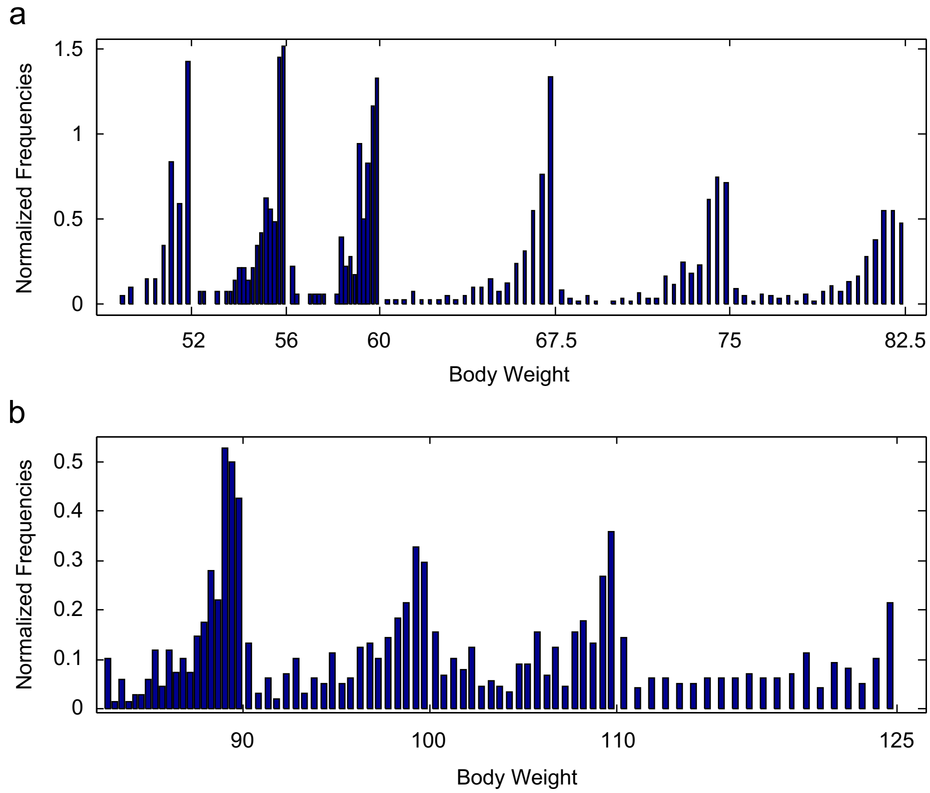

Fig. 3. Distribution of lifters by *BM* in each regulation weight category. The *X*-axis represents the *BM* and the *Y*-axis the number of lifters expressed in terms of normalised values.

become more uniformly distributed over the permitted range. In other words, the tendency to reach the weight limit is more evident among lighter lifters. Figs. 1 and 3 show that in the heavier weight categories there is a relatively large number of lifters who, without being on the weight limit allowed, achieve important results.

Over the years a number of methods have been developed for relating strength to bodyweight in weightlifting and powerlifting, in order to compare results achieved in different weight categories. With respect to powerlifting, proposals have been made by Schwartz (men) and Malone (women) (www.aausports.org), Siff (1988), McCulloch (http://tsampa.org), Reshel (www.irondawg.com), Wilks (www.preparation-physique.net), Dooman and Vanderburgh (2000), American Powerlifting Association—Glossbrenner Bodyweight Coefficient (www.AmericanPowerlifting.com), Natural Athlete Strength Association (NASA Powerlifting Rule Book), and Cleather (2006). However, none of these sufficiently takes into account the complexity of the process, i.e., they do not take into account the triple *PL* shown by the *Pf* with respect to bodyweight.

3.2. Competition strategies

A competitive strategy commonly used in disciplines organised by *BM* is that of the 'category change', i.e., to go up or down in the bodyweight category in which a lifter competes. Thus, a lifter with a certain *Pf* might prefer to lose weight in order to drop a weight category and thus achieve relatively better results; the risk is that a loss of *MM* could significantly affect his/her *Pf*. A recent example of the consequences of a major increase in *BM* is furnished by Woszla, 2006-winner in the <52 kg category (*BM*: 51.55 kg) with a score of 582.5 kg. In 2007, this category was discontinued and he was obliged to compete in the <56 kg category (*BM*: 55.45 kg), where he also won with a score of 620 kg (Δ6.44%).

The strategy of reducing *BM* for competition purposes is more complex and risky. The trick is to lose *BF* and residual weight without altering the other components making up the *BM*. Although reducing the *BM* is generally associated with greater risks and difficulties than increasing weight, experience shows that this is a commonly followed strategy, especially among lighter lifters (e.g., losses of 1–3 kg in the <52 and <56 kg categories close to competition dates). Among the heaviest lifters, a loss of *BM* could be useful if fat is lost without *MM* (which is needed for building *FFM*) being affected.

However, the *BM* limits between which these lifters move (for light lifters the range is 4 kg, for medium lifters it is 7.5 kg, and for heavy lifters 10 kg) hinder this kind of strategy, even though the actual percentage bodyweight change is similar in all cases (about 10–12%). When it is advisable to lose weight, especially if this is to be done artificially (e.g., using diuretics), problems such as possible dehydration, the loss of energy reserves, result-related factors (potential scores) and competition tactics (depending on the rivals to be faced) need to be taken into account. If sufficient care is not taken, a situation could arise with a negative outcome for the lifter, e.g., not taking enough nutrients on the day of the competition or not having taken any food in the hours prior to weighing in. This behaviour may partly explain the distribution seen in Fig. 3, and be responsible for the observed separation of the three detected weight categories.

3.3. Internal dynamics of the different movements

It is likely that each lifter will have had a fairly large number of not particularly important results, fewer good results, a small number of very good results, and the odd excellent result. In any perfectly configured sporting discipline, decay in the results histogram should be seen given the falling number of individuals capable of obtaining the highest scores. Mathematically, this histogram ought to behave with decreasing monotony, and a great many mathematical functions could represent this process. When trying to identify a possible *SOC* phenomenon, the mathematical form adopted by the distribution should be checked to see whether it obeys a *PL*. This is the only function with the property of scale invariance. In addition, a straight line is achieved in a log plot. Alvarez-Ramirez and Rodriguez (2006) and Garcia-Manso et al. (2005) show how the result behaviour described appears to be normal in sports with a large number of practitioners and strong social interest (e.g., mid and long distance running). This is not exactly the case in powerlifting.

Fig. 4 shows the histogram for lifters in the regulation <90 kg category, the accumulated sum (line of points)

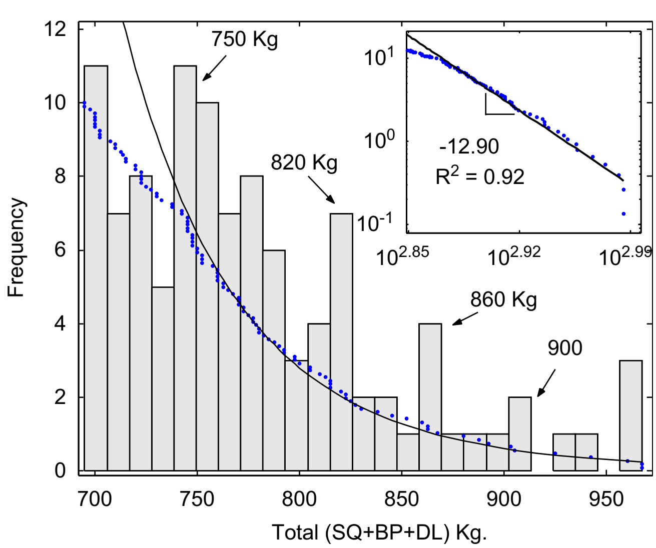

Fig. 4. Distribution of lifters in the regulation <90 kg category with respect to T_t results. Numbers represent the weights lifted. Each blue dot represents the number of lifters who have achieved a particular cumulative result with respect to their *Pf*. The *PL* line is fitted to the points. The inset shows a log–log plot for the values shown (T_t vs. frequency).

representing the lifters' performance, and the *PL* line (continuous line). Newman (2005) indicates that on many occasions it is better to study the data as a cumulative distribution than as a histogram when trying to determine the *PL*. The inset shows the log–log plot for the cumulative result and the line fitted to the data. The construction of the graph required the use of the best 100 results of the sums of the *Pf* for the three lifting movements. This typical behaviour is also seen in the other regulation weight categories. Note how, except at the left and at the end of the tail of the distribution, the line reflects a *PL*. At the left, where the worst results lie, the distribution is practically uniform. This is a consequence of the nature of these competitions—particularly high scores do not seem necessary for one to take part in the competitions that provide the rank list from which the sample was obtained. However, in the tail of the distribution (where the real competition lies) the distribution appears to reflect a strong decay in the *PL* (although with a final upturn). This is also seen for the other categories of lifter, especially for those with a more stable internal behaviour (regulation medium weight categories).

The upturn at the end of the distribution indicates that, over the sampled years, the number of lifters who achieved excellent results increased moderately. This does not correspond to the normal competitive logic followed by other sports. This small concentration of lifters at the end of the distribution tail may reveal the immaturity of this sport with respect to potential *Pfs*. The popularisation of this discipline and an increase in the number of people participating in it could drastically modify current competitive levels and change the internal dynamics of each weight category. This supports the proposal that the best scores achieved by lifters should not be used to study the allometric relationship between *Pf* and *BM*. The importance of the universe of potential participants is shown in the latest category restructuring by the international federation. The <52 kg was eliminated for the 2007 season, among other things because of the lower number of participants good enough for top-level competition in that category.

This type of histogram also manifests the barriers to *Pf* (Garcia-Manso et al., 2005). These barriers, found in all sports aimed at improving on a given score, are represented by concentrations of lifters around certain scores—the most important achieved by lifters achieved during competitions. The appearance of new records represents new competitive horizons that introduce changes in strategy and validate certain training methodologies, etc. These barriers could be used to qualitatively organise lifters and to establish minimum scores for participation in competitions. For the <90 kg category represented in the histogram in Fig. 4, the upper limits for national, international, elite, super elite, and champion levels would be 750, 820, 860, 900 and 960 kg. These values would need to be revised periodically to keep pace with the development of the sport. The form in which the barriers are constructed is similar in all the sports and they have certain analogy with a *Devil Staircase* (Garcia-Manso et al., 2005). It is a well-known fact that this type of multiplicative process generates multi-fractal structures (Feder, 1988; Halsey et al., 1986).

Barriers generated by world records have sometimes become a factor compromising the progress of the sport as a whole. In athletics, weightlifting and possibly powerlifting, records of doubtful validity appear from time to time which modify, and even slow down, the natural progress of the discipline, leading in some cases to radical changes in the structure of the sport. One example is the change in weight classes in the international weightlifting federation. In 1993 the classes were rearranged (<54, 59, 64, 70, 76, 83, 91, 99, 108 and >108 kg) and all the records were set at zero. The aim was to make a new, doping-free start and to show the world that the fight against doping was taken very seriously. Later, in 1998 new classes were officially introduced, and the total number reduced to 8.

3.4. Number of participants

The number of people who undertake physical exercise beyond that demanded by their work is reduced; this is particularly true of people living in poorer countries. Only a very limited number are involved in competitive sport, and even fewer in strength sports. Thus, the number of people who practice powerlifting, which is not an Olympic discipline, is very small. The number of participants in each regulation weight category is conditioned by the number of inhabitants, the mean morphological characteristics of the population, and the number of sports practitioners (all of which conditions the potential of any sporting discipline). The use of small samples sizes reduces the probability of exploring the true relationship between *Pf* and *BM*.

Since the *BM* and *Ht* of the general population follow a normal distribution, light and heavy lifters belong to the opposite tails of the distribution. This further conditions the potential of powerlifters and, consequently, the internal dynamics of the sport and its development. In the light categories, the chances of staying under a weight threshold are conditioned by the lifter's height: tall lifters are hardly ever seen in these categories. In addition, tall lifters would be unable to acquire sufficient *MM* to be any good at lifting weights. It should be remembered that S_m is related to *MM*—and more correctly with the *CSA* of the muscular structres directly involved. If we add to this the low interest shown by the general population towards weightlifting and powerlifting, etc., it is easy to see how the number of people who practice these sports can be low.

The mean *Ht* of a population changes from country to country (e.g., the Danes, Swedes, Germans, Lithuanians, and Canadians have a mean height of >180–183 cm, while the average Vietnamese, Cambodian or North Korean barely reaches 165 cm) and between the different races that inhabit a country. In the database used for the present study, the majority of lifters were European (1294 out of 1812, or 71.4%). The second most numerous group was North Americans. Only 35% lifters in categories <52 kg came from Europe; those of Asian origin predominated in this group. In contrast, 202 out of the 357 lifters (56.6%) in the >110 kg categories were European, while Asian lifters were very rare. It should be pointed out that, in the heaviest weight category, there are lifters with a *BM* of >160 kg. The fact that the composition of each regulation weight category largely corresponds to lifters of different ethnic or ethnogeographic origin (and therefore of different morphology) may be among the factors that explain the existence of more then one *PL* regulating the *BM*/*Pf* relationship. Certainly, the *BM*/*Ht* relationship differs depending on the biotype of the competitor, and his/her body composition and body size. The different *BM*/*Ht* relationships (weight/height, weight/height^2, weight/height^3, weight$^{0.33}$/height, weight$^{1.2}$/height$^{3.3}$, etc.) show that after a certain bodyweight, the increase in *BM* in an average size subject is usually due to gains in fat, liquid and residual mass. This, however, is not the case in the smallest and lightest people. Together, this explains why the majority of lightweight category competitors are significantly shorter than members of the normal population; they can be defined as having a particularly hypertrophied biotype dominated by the mesomorphic component. Trained, smaller subjects show a body structure particularly favourable to the development of strength, allowing them to lift relatively heavier loads than larger people. It should be remembered that sportspersons in the lighter categories are those who develop the greatest strength (*Pf*/*BM*) of all powerlifters.

3.5. Lifters attracting people to the sport (outliers or freaks)

Without doubt, the scores of the most outstanding sportsmen, especially record holders, act as powerful motivations for their competitors. Although this does not mean that many will beat a current record, attempts to do so surely change the dynamics of the category.

Among the best of each category, someone will arise from time to time who stands out significantly from those who traditionally show the *Pf* profile of a specialist in that sport and category. This leads to an irregular development of best scores (asynchrony) and would not appear to be suitable for analysis of powerlifting. This was particularly evident in the <52 kg class during the last few seasons prior to its elimination in 2007. Analysis of the particular circumstances in that class over the last few seasons may help to understand the competition and the performance achieved from the standpoint of complex systems.

The Polish powerlifter Stanaszek and the Russian Fedosienko obtained scores far superior to those of their competitors (T_t of 627.5 and 680.0 kg (non-official), respectively). The Polish lifter dominated the world championships between 1993 and 1999 and obtained spectacular *SQ* and *BP* scores (300 and 182.5 kg,

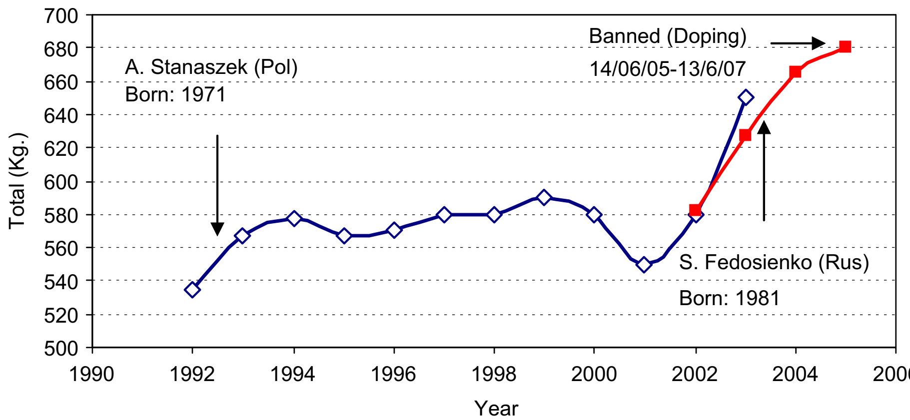

Fig. 5. Best performance scores for Stanaszek and Fedosienko from 1992 to 2005. Note the age each season, and the banning of the Russian powerlifter.

respectively)—results that would have allowed him to beat opponents (or at least strongly compete) with lifters in heavier categories (56–90 kg). Stanaszek improved his score in T_t by 10.28% between 1993 and 2002; in his last season, at the age of 32, he improved his score 12.07% (see Fig. 5).

The Russian lifter broke the T_t world record nine times, and the sum of his best scores for each movement was actually 13 times his own bodyweight—making him the greatest lifter of all time, kilo for kilo. However, his record of 680 kg in T_t was not included, since it was not recognised by the *IPF* (due to doping).

As well as dominating their own categories, these competitors became a world focus for the sport, so that other competitors take their records as the score to beat. This may have a positive or negative effect on the development of the sport. The stagnation sometimes caused by very high scores has also been reported in other events (e.g. Beamon (8.90; 1968) in long jump and Sotomayor (2.45; 1993) in high jump).

4. Conclusions

As in any other sport, powerlifting results are influenced by a number of important factors (biological, competitive, statistical, etc.). The *Pf* of this sport, at least for men, appears to behave as an *SOC* (as in other strength sports), which requires we accept that there are both internal and external elements that condition its development. *BM*, *Ht*, the sport's regulations, competition strategies, and the confluence of favourable factors in a single competitor should all be considered important aspects of this sport. Other factors also exert some influence, including sport-related strain, arousal, population characteristics and others, which appear to induce score avalanches or various types of power-law behaviour.

Current methods for the overall comparison of lifters are based on allometric laws or other mathematical functions that only take into account biological variables; no other competition features that might configure the internal dynamics of each weight category are considered.

Rules are an important factor in characterising a sport and distinguishing it from primitive play. Here, the rules themselves govern to a significant extent the progress of *Pf*, by setting body weight limits for each class. Participants are therefore concentrated around those limits, which also influences competition strategy.

With respect to lifter *BM*, *Pf* appears to follow a triple *PL*, so that the speciality can be divided into three different subgroups or structures, each with its own peculiarities and internal dynamics. This should allow us to organise lifters into different weight classes—light, medium, and heavy—that take into account common morphological characteristics. The limits of each group are determined from the intersections of the log–log plots for each *PL*. The proposed light category would include the regulation <52, 56 and 60 kg categories, the medium proposed category would cover the regulation <67.5, <75.0, <82.5, and <90.0 kg categories, and the proposed heavy category would cover the <100.0, <110.0, <125.0 and >125 kg regulation categories. The dynamics of the results for each regulation category should be reviewed periodically (perhaps after each world championship) in order to make adjustments to the way evaluations are made.

References

Abe, T., Brown, J.B., Brechue, W.F., 1999. Architectural characteristics of muscle in black and white college football players. Med. Sci. Sports Exerc. 31 (10), 1448–1452.

Aidt, T.S., Leong, B., Saslaw, W.C., Sgroi, D., 2006. A power-law distribution for tenure lengths of sports managers. Physica A: Stat. Theor. Phys. 370 (2), 697–703.

Alvarez-Ramirez, J., Rodriguez, E., 2006. Scaling properties of marathon races. Physica A: Stat. Mech. Appl. 365 (2), 509–520.

Anderson, P.W., 1972. More is different': broken symmetry and the nature of the hierarchical structure of science. Science 177, 393–396.

Bak, P., 1996. How Nature Works: The Science of Self-Organized Criticality. Copernicus, New York, USA.

Bancroft, G.A., Biddle, S.J., Brown, S.C., 1987. Handicapping formulae in Olympic weightlifting: a reappraisal for schoolboy weightlifters. Res. Q. Exerc. Sport 58, 388–391.

Bar-Yam, Y., 1997. Dynamics of Complex Systems. Perseus Books.

Bar-Yam, Y., 2000. Applications of complex system: sport and complaxity. NECSI. Website publication: ⟨http://necsi.org/guide/examples/basketballcomplexity⟩.
Batterham, A.M., George, K.P., 1997. Allometric modeling does not determine a dimensionless power function ratio for maximal muscular function. J. Appl. Physiol. 83, 2158–2166.
Behnke, A., Wilmore, J., 1974. Evaluation and Regulation of Body Build and Composition. Prentice-Hall, Englewood Cliffs, NJ.
Binney, J.J., Dowrick, N.W., Fisher, A.J., Newman, M.E.J., 1993. The Theory of Critical Phenomena. Clarendon Press, Oxford.
Bouchaud, J.P., 2001. Power-laws in economy and finance: some ideas from physics. Quant. Finance 1 (1), 105–112.
Brechue, W.F., Abe, T., 2002. The role of FFM accumulation and skeletal muscle architecture in powerlifting performance. Eur. J. Appl. Physiol. 86 (4), 327–336.
Chow, G.C., 1960. Tests of equality between sets of coefficients in two linear regressions. Econometrica 28 (3), 591–605.
Cleather, DJ., 2006. Adjusting powerlifting performances for differences in body mass. J. Strength Cond. Res. 20 (2), 412–421.
Croucher, J.S., 1984. An analysis of world weightlifting records. Res. Q. Exerc. Sport 55, 285–288.
Crutchfield, J., 1994. Is anything ever new? Considering emergence. In: Cowan, G., Pines, D., Meltzer, D. (Eds.), Complexity: Metaphors, Models, and Reality, pp. 479–497.
Dooman, C.S., Vanderburgh, P.M., 2000. Allometric modeling of the bench press and squat: who is the strongest regardless of body mass? J. Strength Cond. Res. 14 (1), 32–36.
Durlauf, S., 2001. A framework for the study of individual behavior and social interactions. Social Methodol. 31, 47–87.
Feder, J., 1988. Fractals. Plenum, New York.
Forbes, G.B., 1987a. Human Body Composition: Growth, Aging, Nutrition and Activity. Springer, New York, pp. 1–350.
Forbes, G.B., 1987b. Lean body mass-body fat interrelationships in humans. Nutr. Rev. 45, 225–231.
Forbes, G.B., 1992. Exercise and lean weight: the influence of body weight. Nutr. Rev. 50 (6), 157–161.
Ford, L.E., Detterline, A.J., Ho, K.K., Cao, W., 2000. Gender- and height-related limits of muscle strength in world weightlifting champions. J. Appl. Physiol. 89, 1061–1064.
Garcia-Manso, J.M., Martin-Gonzalez, J.M., Davila, N., Arriaza, E., 2005. Middle and long distance athletics races viewed from the perspective of complexity. J. Theor. Biol. 233 (2), 191–198.
Halsey, T.C., Jensen, M.H., Kadanoff, L.P., Procaccia, I., Shraiman, B.I., 1986. Fractal measures and their singularities: The characterization of strange sets. Phys. Rev. A 33 (2), 1141–1151.
Holland, J.H., 1995. Hidden Order: How Adaptation Builds Complexity. Addison-Wesley.
Holland, J.H., 1998. Emergence: From Chaos to Order. OUP.
Hui, S.C., Mahar, M.T., Jackson, A.S., 1995. Adjusting upper body strength by body mass using allometric scaling. Med. Sci. Sports Exerc. 27, S211.
Ikai, M., Fukunaga, T., 1968. Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. Eur. J. Appl. Physiol. 26 (1), 26–32.
Jensen, H.J., 1998. Self-Organized Criticality. Emergent Complex Behaviour in Physical and Biological Systems. Cambridge University Press, Cambridge, UK.
Kauhanen, H., Komi, P.V., Häkkinen, K., 2002. Standardization and validation of the body weight adjustment regression equations in Olympic weightlifting. J. Strength Cond. Res. 16 (1), 58–74.
Katz, J.S., Katz, L., 1999. Power laws and athletic performance. J. Sport Sci. 17 (6), 467–476.
Kawakami, Y., Abe, T., Fukunaga, T., 1993. Muscle-fiber pennation angles are greater in hypertrophied than in normal muscles. J. Appl. Physiol. 74, 2740–2744.
Malacarne, L.C., Mendes, R.S., 2000. Regularities in football goal distributions. Physica A: Stat. Mech. Appl. 286 (1–2), 391–395.
Maughan, R.J., Watson, J.S., Weir, J., 1983. Relationships between muscle strength and muscle cross-sectional area in male sprinters and endurance runners. Eur. J. Appl. Physiol. 50 (3), 309–318.
Newman, M.E.J., 2005. Power laws, Pareto distributions and Zipf's law. Contemp. Phys. 46, 323–351.
Savaglio, S., Carbone, V., 2000. Scaling in athletic worlds records. Nature 404, 244.
Schantz, P., Randall-Fox, E., Hutchison, W., 1983. Muscle fibre type distribution, muscle cross-sectional area and maximal voluntary strength in humans. Acta Physiol. Scand. 117, 219–226.
Schroeder, M., 1991. Fractals, Chaos and Power Laws. Freeman, New York.
Siff, M.C., 1988. Biomathematical relationship between strength and body mass. J. Res. Sport Phys. Educ. Recr. 11, 81–92.
Solé, R.V., Goodwin, B.C., 2001. Signs of Life: How Complexity Pervades Biology. Basic Books.
Sornette, D., 2004. Critical Phenomena in Natural Sciences: Chaos, Fractals, Self-Organization and Disorder: Concepts and Tools. Springer, Heidelberg.
Vanderburgh, P.M., Batterham, A.M., 1999. Validation of the Wilks powerlifting formula. Med. Sci. Sports Exerc. 31, 1869–1875.
Vicsek, T., 2002. The bigger picture. Nature 418, 131.
Waldrop, M.M., 1992. Complexity: The Emerging Science at the Edge of Order and Chaos. Viking, London.
Zimmer, C., 1999. Complex systems: life after chaos. Science 284 (5411), 83–86.