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Editorial

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Dear readers,

Non-linear relations and interactions between variables are continuously observed in physical activity and sport and specifically in learning and training processes. Nevertheless, the theory, the strategies followed by teachers and coaches in practice, and the research methods commonly applied, are based almost exclusively upon a classical linear scientific thinking. Therefore the complex nature of human movement and especially sport is very poorly explained by traditional movement and sport sciences.
The fact that the linear approach is actually limiting the development of different manifestations of practice and research gives rise to a claim for changing the classical scientific paradigm.

The recent development of complex systems concepts that are already applied to diverse sciences offer a possibility of studying sport from a different perspective, that can capture more closely its nature.

Despite the interest and novelty of the approach, until now no European (or even international) event has intended to join scientists working in complex systems with the aim of applying their knowledge to movement sciences and sport.

Complex systems have been worked out intensively by non-linear scientists coming from physics (non-linear mechanics), mathematics (dynamical systems), etc. Their knowledge has traditionally been applied to physics, chemistry or engineering but more recently to other sciences as economy, biology, psychology, … Now is also time for sport science.

In order to face the complex nature of sport sciences for the development of a new approach and in order to develop new and suitable tools and concepts to study it the 1st Complex Systems and Sport Meeting has been organised together with the 4th International Conference of Computer Science in Sport giving rise to the COM&COM conference "Complex Systems and Computer Science in Sport".

The event has had the expressed interdisciplinary intention of bringing together professionals coming from different areas: physical activity and sport sciences, training, teaching, psychology, medicine, mathematics, computer science... Indeed, complex systems has not the same meaning for all of them. Anyway, far from trying to know who is right or not, the meeting has intended to serve as an interdisciplinary forum for the exchange of ideas regarding the development of an alternative paradigm.
Besides disseminating the main concepts and experiences related with complex systems, the meeting has also intended to generate interdisciplinary research projects. We are proud now to say that this objective has been accomplished and that some of the participants in the meeting are now working in some common research projects.

With the aim to open this forum to the readers of the IJCSS some full papers of the invited lecturers to the meeting and the abstracts of participants are published in this second issue of proceedings of the COM&COM. The readers will find in it contributions related to the following general topics:
- Applications of complex systems to sport,
- Applications of dynamical systems to learning and training
- Non linear dynamics in biomechanics, physiology and training

It is now expected that this contributions will lead to the enrichment of the readers with an emerging paradigm and to the improvement of the daily practice of professionals and researchers working in the field of physical activity and sport.

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Complex Systems insights to building effective teams

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Abstract

This lecture discusses the characterization of effective teams (their complexity / variety) and the role of competition and cooperation in the formation of effective teams. The context for the discussion, sports, provides examples that are also relevant to many other aspects of society and biology.

KEY WORDS: SPORTS, COMPLEX SYSTEMS, COMPLEXITY, COOPERATION, COMPETITION

Introduction

In this lecture I will be discussing some of the relevance of my research at the New England Complex Systems Institute to sports. I must state, however, that I find sports to provide important examples of complex systems that I often use to demonstrate the relevance of complex system research to many other areas of inquiry (Bar-Yam - http://necsi.org/guide) Sports provide a wide variety of semi-controlled (schematized) complex systems that can serve as a laboratory for testing and evaluating ideas from research on complex systems. I feel that there is a mutual benefit of the association of complex systems research and sports. This is an important reason for my enthusiastic embrace of this conference and my respect for the efforts of the organizers.

If you explore our website, at http://necsi.org you will find that I write there about the connection between complex systems and sports. I do so to illustrate that complex systems research and concepts are relevant and manifest in our daily lives. Please look at the Guide to Complex Systems that can be found linked from our home page.

Three approaches

To begin my discussion today, I have found that my research has revolved around three approaches to the study of complex systems. These approaches are not separate but form a kind of harmony. Still it is useful to identify them.

1. The first approach is the recognition of patterns of collective behavior and relating these patterns to the interactions between components. This approach, which is much of the study of complex systems in many research groups, also has a long history in sports. For example, consider the "play diagram" that is often used to illustrate the plan for what players are supposed to do. The idea of the diagram is to capture how the parts work together to make the action of the team as a whole.

2. The second approach is analyzing not a single play but rather the set of possible actions that a person or team can do. This topic is more difficult to talk about than the

first approach because it is more abstract. If we think about the effectiveness of a person or a team (or for that matter any complex system) it turns out that effectiveness is generally not related to a single possible action, but rather the set of all possible actions that one can do. This set of possible actions is therefore of great importance in all of complex systems research as well as in sports.

3. The third approach discusses how complex systems form. This approach is different from the first two. The first two are analytic. They describe how we can understand the structure and behavior of systems. The third approach is synthetic,describing synthesis. The only way that we know that very complex systems are created is by evolutionary processes. Thus, the study of evolution is central to our ability to understand complex systems in any context, and also of course in sports.

My plan today is to discuss the second and third aproaches as keys to the problem of understanding effective teams. The second approach (my first topic) will be analytic discussing what constitutes effective team play. The second topic will discuss the process by which effective teams are formed.

The Space of Possibilities; Complexity of Team Play

I will now turn to the topic of the set of possibilities as a way of characterizing the effectiveness of complex systems Complexity itself is a measure of the number of possibilities (Ashby 1957, Bar-Yam 1997, Bar-Yam 2003). In the context of sports, an effective defense has to meet the possible choices of the offense. Thus, the number of possible ways a player or team can create an offense is important. If a player or team has a more diverse set of offensive plays, the other side may not be able to defend against each play. The plays that it cannot defend against can be exploited. In basketball, this applies for two individuals playing one-on-one and for two teams playing against each other.

The 2000 NBA Finals between the Los Angeles Lakers and Indiana Pacers can serve to illustrate this principle both at the individual and at the team level [I note that I was a fan of the Pacers in this competition].

Shaquille (Shaq) O'Neil the 216 cm, 143 kg center of the Lakers is often called the most dominant player in basketball. When he has the ball near the basket, his opponents often send two or three rather than only one player to defend. He often scores anyway, averaging nearly 30 points per game during the 1999-2000 season, the best in the sport. Clearly his size had something to do with his success. However, when he talks about his abilities to defeat players in one-on-one play, he says that he can defeat his opponent because he has over thirty different moves.

The importance of having a variety of different team plays is generally recognized in the game of basketball. Teams practice passes to set up different shots, establishing first options and, if blocked by the defense, second or third options. However, the importance of having a variety of offenses extends to all aspects of the play in ways that are not always recognized. To illustrate this I will focus on the first game of the 2000 NBA Finals series which was won by the Lakers. Most of the commentators have emphasized how dominant Shaquille O'Neil was in this game where he scored 43 points. Once he had the ball, the Pacers almost never stopped him. While Shaquille's abilities are clearly important, I will argue that attributing the success to him is like saying that the head of the hammer is what pounds in a nail. To say that

Shaquille could not have done what he did without the rest of the team is not the point. There is something specific about the way the Lakers played in the first game of the playoffs that was significant.

To understand the key to the Lakers' play, we need to understand how the Pacers played their game. The 1999-2000 Pacers were a remarkably good team, but for someone who studies complex systems, and even for some who do not, they had one clear weakness. As is often the case this weakness is related to one of their great strengths. They had a pattern of play which, at one point, was simple. This simplicity arose because they were so good at what they did that they didn’t feel they had to vary it. Because they didn’t vary it, they were vulnerable to an opponent who recognizes this simplicity and attacked at that point.

Mark Jackson, the point guard of the Pacers in that year, was the player who, for most of the game, was responsible for bringing the ball from one end of the court to the other. The reason he did this was to set up the offensive play after the Pacers regained the ball from the Lakers. However, Mark did it essentially the same way every time he took the ball up court. This consistency reflected the incredible reliance of the Pacers on his ability to set up the play for the offense. The problem was that an opponent who recognized this could attack at this point, and the Pacers had almost no alternative.

If you watched the game, you would have seen that Kobe Bryant, who is generally one of the most successful scorers for the Lakers, was consistently trying to bother Mark on his way down the court. Kobe didn't stop him, because Mark is too good a ball handler to be diverted for very long. What Kobe achieved was a delay in time. There were two important consequences, the play that Mark eventually set up was more rushed and less likely to succeed, because there was not enough time to try for several possibilities. Second, and very importantly, Shaquille O'Neill had enough time to move up the court and take a position for defense. The importance of this is not to be underestimated. As the most massive player, Shaquille also has an important weakness, he has to expend a much larger effort to move quickly. Stated differently, he cannot move as fast for as long as other players, and changing direction is a major effort. This is a law of physics, which is well understood in basketball, smaller players are generally quicker (quicker does not only mean faster, quicker also means able to change direction). The extra time given to him by Kobe's defense, makes a difference each time he has to run up the court. Over the course of the entire game this is significant, especially since each player is expending their maximum possible effort.

One interesting question is: Are the Lakers consciously doing this or is it just a coincidence that they know what to do? There is one clear evidence for the consciousness of their effort. In 1998, two years previously, the Pacers faced the Chicago Bulls in the Eastern Conference Finals. At that time, in what was a hard fought series, the first two games were also lost by the Pacers. What was going on at that time? It wasn't Kobe Bryant, but it was Scotty Pippen who was pestering Mark Jackson mercilessly. Pippen was very intensively doing this and was very good at it. It was also clear what he was doing. Both Pippen and Kobe are very good offensive players scoring highly in most games. In these games, Pippen and Kobe both scored uncharacteristically little. Their energy was expended in this defense. There is another common factor between these two games. The coach of the Lakers in 2000 was the same coach as that of the Bulls in 1998, Phil Jackson.

This discussion illustrates the importance of complexity as a measure of the behavior of a system. Counting the number of ways one can act or react to environmental conditions is an important part of the study of complex systems in general.

Cooperation and Competition in Sports

I would like now to turn to the next topic, the evolutionary formation of complex systems. This topic centers on the interplay of competition and cooperation. There is an interesting attitude that one finds toward competition and cooperation that exists among many people. Often I find people either like competition or cooperation and find the other to be reprehensible. Some like competition, others cooperation. I would like to discuss their interplay, and particularly in sports. First I will explain the connection to evolution.

Since the beginning, Darwin's ideas and the study of evolution have focused on competition as the driving force of evolutionary change. As many of you know, evolution is a process by which populations of organisms change over time. The change occurs not because they change individually, but because of a change from one generation to the next. They change because some types reproduce more than others, and because traits are hereditary, the relative rates of reproduction cause the faster reproducing types to dominate the slower reproducing types over time. This description appears only to talk about competition Because of this, the idea that cooperation occurs among animals has seemed antithetical to evolutionary ideas. Indeed, many of you may be familiar with the book "The Selfish Gene" written by Dawkins (Dawkins 1989). This book popularizes the basic concepts of what is called NeoDarwinism. NeoDarwinism is the dominant theoretical framework in which evolution has been discussed since the early part of the last century, almost one hundred years ago. According to this theoretical framework, formulated by Fisher, Haldane and Wright, evolution can be understood as a competition between genes, and that's that. Any forms of cooperation arise merely through the hidden agendas of these Machiavellian genes.

For a number of years I have been unhappy with this formulation. In my textbook *Dynamics of Complex Systems* (Bar-Yam 1997) I discuss the reasons that it is both formally (mathematically) invalid and conceptually incorrect. Since then, I have published a number of papers on this subject that you can find on our website as well (Bar-Yam 2000; Bar-Yam &. Sayama 2000; Sayama, Kaufmann, Bar-Yam 2000a; Sayama, Kaufmann, Bar-Yam 2000b; Rauch, Sayama, Bar-Yam 2002; Rauch, Sayama, Y. Bar-Yam 2003)

I have found, however, that a discussion of cooperation and competition in sports provides a remarkably good way to explain this matter and to clarify the real relationship between competition and cooperation in all contexts.

We can start by simply listing some of the ways competition and cooperation might occur in sports. We might not characterize all of them as positive, but that value judgment is not what we are talking about..

For example:

Individuals compete among themselves to be players on a team.
Teams compete to win games
Teams cooperate to set times of events and to set the rules
Different sports compete to gain media attention and audiences. In this they also compete with other forms of entertainment.
Individual players cooperate as part of a team.
Teams might cooperate (this is a no-no in most sports) to fix games so that box office receipts are larger, for example. by extending a series.
Individual players might compete on a team to gain the best individual statistics, or individual salary.

When we think about these different kinds of competition and cooperation we recognize an important distinction. The type of relationship between competition and cooperation that we most often think about is the conflict between competition and cooperation of players on a team. We care deeply about their cooperation and we distinguish “team players” from non-team players. This relationship is the antagonism of cooperation and competition that disturbed Greek philosophers when they considered selfishness and altruism in social behavior and continues to be an issue till today: Why would anybody cooperate when they might benefit from selfish competition.

There is, however, a different relationship that is apparent, and is probably clear to many of you. That is the relationship that occurs when we consider competition between teams as opposed to cooperation between players. When players cooperate they can compete better as a team. When teams compete, this motivates the cooperation between players. We see that there is a positive or constructive relationship between cooperation and competition when they operate at different levels of organization: team competition and individual cooperation.

This is a quite general observation that can be illustrated by a figure. In the first figure we see that competition between teams enhances the collaboration between players. How does it do this? By the evolutionary process of selection. The better team is the team with the players who cooperate. If we select teams that are better at competition over time, we will find that the players on the team cooperate better. Also it is the cooperation between players that enables the teams to compete with each other. So this is a synergistic relationship. We might actually state something stronger, which is that cooperation occurs only when there is competition, and competition occurs only when there is cooperation.

The more usual relationship that people notice as a conflict between cooperation and competition occurs at the same level of organization. This is illustrated in the second figure, that shows the competition between players on a team at odds with cooperation between the players. The picture also shows that there can be ways in which players can compete and cooperate without conflict as long as these two behaviors are in some sense orthogonal, or independent of each other. For example, we can have players that are at different kinds of specialized positions. For example, “forward” and “point guard” in basketball. Players can compete for each of these positions separately without interfering with their cooperation as a team. The case of the LA Lakers is again interesting here, because over the past few years there have been periods of time when the two strongest players, Kobe Bryant and Shaquille O'Neil, competed with each other for attention, even though they are at different positions. This conflicted with their cooperation as teammates. When this occurred the team did not play well, and lost many games. When they cooperated the team was almost unbeatable.

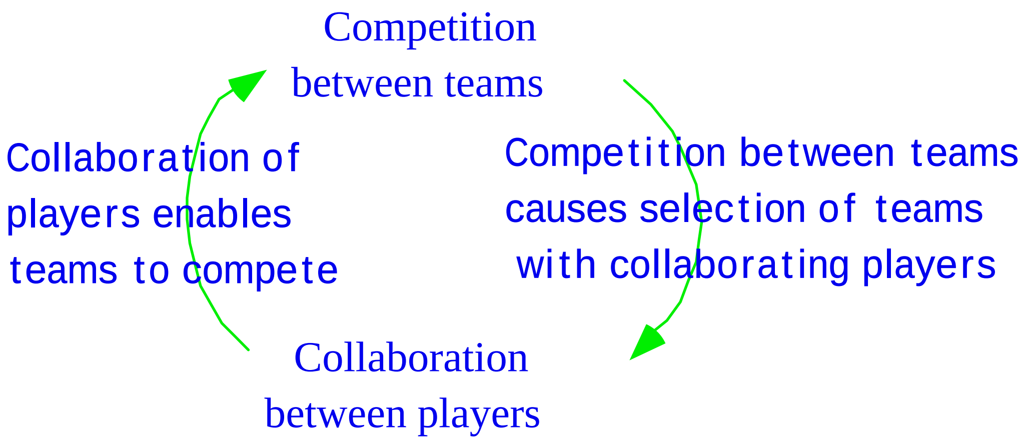

Figure 1.

We can generalize these figures to recognize that there is a multilevel picture that illustrates the interplay of competition and cooperation. As shown in the third figure the competition between sports is what gives rise to the collaboration between teams, the competition between teams gives rise to collaboration between players. Conversely cooperation at each level enables competition at the higher level of organization. At the same time competition and collaboration are antagonistic when they take place at the same of organization unless they are made `orthogonal' referring to different times or types of behavior.

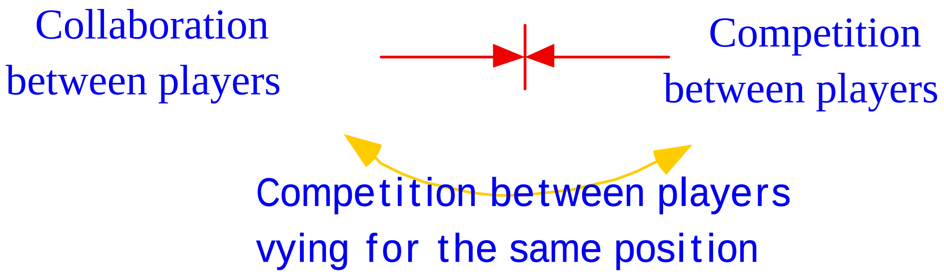

Figure 2.

The key point is that competition and cooperation always occur together at different levels of organization This topic might be so intuitive to some of you that you are wondering why I am talking about this at all. Surprisingly, it has not been clear to many in the context of scientific dialog about evolution. Even if understood intuitively in sports, and even if some scientists understand this intuitively as well, it is important to state clearly these basic relationships.

How does this help us make effective teams? The answer is, self-evident. Effective teams form naturally when there is a process of evolutionary selection of teams that perform well in competition. This may be a useful lesson for those who try hard to compel player behavior in one way or another. While I do not want to say that teaching is not important. Still, it is the role of competition itself to teach about cooperation. I would also say, that evolution teaches us something about the proper place of rewards for effective competition. The main reward is simply the right to stay together. This, after all, is what survival, survival of a collective, is all about.

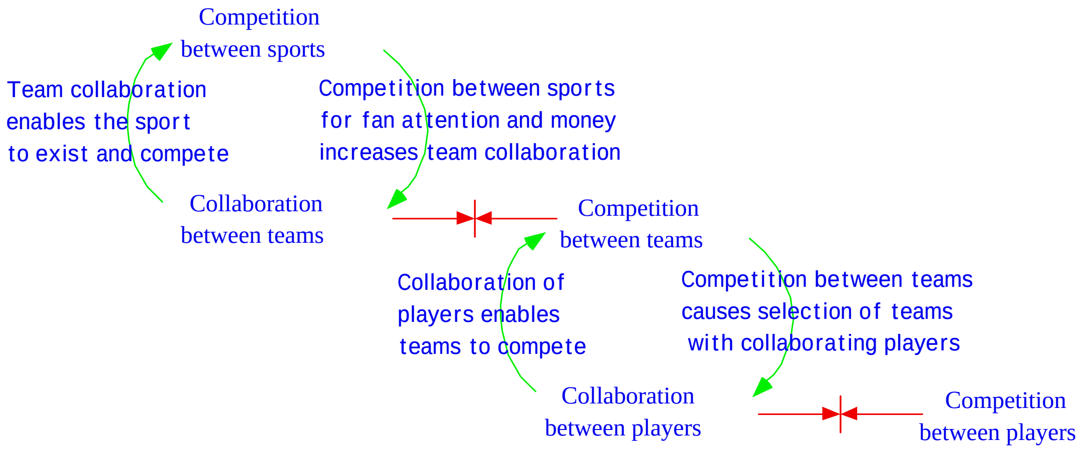

Figure 3.

Conclusions

I would like to summarize by emphasizing that to me sports provides a rich context for discussing complex systems ideas and application of complex systems theories. I also believe that complex systems research has a lot to contribute to the analysis of the effectiveness of teams, and the understanding of how they form. I have not discussed the more technical details of our research that can help in quantitative analysis of both the problems of analysis and the problem of creating an environment where effective teams will form. This will have to wait for more technical papers. My emphasis here has been on the power of concepts from complex systems to discuss teams in sports.

The specific conclusions have been as follows. First, that the complexity as a measure of the set of possibilities is a powerful tool for evaluating the effectiveness of a team and of its vulnerabilities. Second, that the main way that we create cooperative teams is through the competition and selection that is modeled by evolutionary process. This reflects the profound interplay of competition and cooperation wherever they occur.

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Fractal Analysis of Speed and Physiological Oscillations in Long- and Middle-Distance Running: Effect of Training

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Abstract

The fractal nature of the physiological signals: heart and respiratory frequencies and oxygen uptake was compared in long-distance runs performed at constant vs. free pace. Then we focused on the effect of training on this fractal behaviour. For that, we examined the scaling behaviour of heart rate (HR), oxygen uptake ($\dot{V}O_2$) and speed variation in exhaustive 10,000m runs performed at a free vs. constant average pace. The power law exponent α which characterizes scaling law behaviour and signal roughness was not affected by the type run. Furthermore the scaling law in HR signals did not disappear with fatigue in contrast to $\dot{V}O_2$ and speed. Then, we examined the training effect on the fractal behaviour of physiological signals in exhaustive run performed at the maximal lactate steady-state. In addition to the estimation of α as carried out in the first study, we approximated this exponent using continuous wavelet transform, the Veitch-Abry discrete wavelet and the Detrended-Fluctuation-Analysis estimators. These methods agreed to demonstrate that the heart rate signal showed a scaling behaviour which was not affected by training. These two studies together demonstrated that heart rate is the physiological signal showing a scaling behaviour whatever the exercise condition and the state of training.

KEY WORDS: FRACTAL, RUNNING, FATIGUE, HEART-RATE, WAVELETS

Introduction

Physiological rhythms are generated by nonlinear dynamic systems and in addition the physiological rhythms interact with one another as the increase of the heart frequency during inspiration (Gisiger, 2001; Glass, 2001). The fractal processes generate irregular fluctuations across multiple time scales, analogous to scale-invariant objects that have branching or wrinkly structure across multiple length scales. A qualitative appreciation for the self-similar nature of fractal processes can be obtained by plotting their fluctuations at different temporal resolutions. The irregularity seen on different scales is then, not readily distinguishable, suggesting statistical self similarity. A more rigorous representation of the temporal self-similarity of heartbeat has been reported to be provided by wavelet analysis [Arneodo, Bacry & Muzy, 1994; Braun et.al., 1998; Goldberger, 2001, 2002; Haussdorff, 1997, 2001; Huikuri, 2002; Jaffard, Meyer & Ryan, 2001; Pichot, 1999).

No studies have still focused on the scaling behaviour of heart rate and other physiological signals as the breathing frequency and the oxygen uptake in high-intensity exercise, especially when they are performed until exhaustion. The examination of the physiological signals in exhaustive exercise could be a new way to go further in the understanding of the limitation of exercise which remained unknown for exercise lasting between 3 and 30 minutes. The examination the lap time over middle distance running (800-10,000m) shows that world records are performed with variation of the speed of 5-10% depending on the distance run (Billat, 2001). In addition, two studies have reported that free speed middle-distance (3000m) run is felt more difficult than the one performed at the same average but constant speed [Billat, 2001; Cottin et.al., 2002). In a first study we examined the effect of constant vs. variable velocity 10,000m on physiological signals scaling behaviour. The fractal nature of the physiological signals: heart and respiratory frequencies and oxygen uptake was conjectured especially in free. constant speed at (same average) in all-out 10,000m runs. For that we examined the scaling behaviour of heart rate (HR), oxygen uptake ($\dot{V}O_2$) and speed variation (SV) in exhaustive 10,000m runs performed at a free vs. constant average pace. We studied also the effect of the fatigue analyzing each signal by peaces. Fast Fourier transform did not allow to distinguish modification of speed and physiological signals variations during a 3000m race (Cottin et.al., 2002). Therefore, we developed and validated a wavelet transform algorithm which computes log(wavelet transform energy) vs. log(scale). If this (log,log) representation can be approached by a line of slope α over a scale interval then we say that the signal obeys a scaling law with exponent α over this scale interval. This exponent measures the signal roughness (variability) which is maximal when the slope is zero. Scaling law is associated to the fact that a certain scale dependent quantity like wavelet transform energy behaves as a *power of the scale* cs^{α}, which means absence of any characteristic scale (and therefore absence of characteristic frequency), all scales (or frequencies) have equal importance. Thus, we have to estimate a *power law exponent* α which characterize scaling law behaviour and signal *roughness* [Audit et.al. 2002; Ivanov et.al., 1996; Peng et.al., 1998). Scaling exponents where computed for HR, $\dot{V}O_2$, SV.

In as second study we examined the influence of training on the scaling behaviour of heart rate, oxygen uptake and breathing frequency in a constant pace run at the maximal lactate steady state velocity performed until exhaustion (60 ± 10 min in average). These two studies were preliminary study to appreciate the effectiveness of such mathematical tools for training effect on physiological signal in exhaustive exercise analysis.
Methods: Experimental condition and protocols

Experimental conditions

All races were performed on a synthetic 400-m track at the same time on non windy days (< 2 m/s, anemometer, Windwatch, Alba, Silva, Sweden) at a temperature ranging from 19 to 22 °C. On the days between two tests, subjects were asked to undertake easy jogging at a very low pace (heart rate < 130 bpm). Prior to testing, they were asked to restrain from food or beverages containing caffeine. For the second test (see below), the runners followed a pacing cyclist traveling at the required velocity. The cyclist received audio beeps via a walkman, beep intervals determining the time required to cover the distance between visual marks set at 10-m stretch along the track (inside the first lane). For all the tests, measurement of $\dot{V}O_2$ was carried out throughout each test using a portable gas exchange analyzed (K4b^2, Cosmed, Roma, Italy) (Mc Laughlin et.al., 2001). Expired gases were measured breath by breath and averaged every 5 seconds. Before each test, the O_2 analysis system was calibrated using ambient air, whose O_2 percentage was assumed to be 20.9% and a gas of known CO_2 percentage (5%); calibration of the turbine flow-meter of the K4 b^2 was performed with a 3-L syringe (K4 b^2 instruction manual). Heart rate was measured beat-by-beat by Polar electrodes (Polar, Finland) and was transmitted and registered by the K4 b^2 to be coupled on the breath-by-breath data.

First study on the effect of type of run (imposed constant vs. free pace) on the physiological signals. Ten pairs of 10 km races composed of two all-out 10 km runs were compared: one performed at a free pace until exhaustion and the other at the same average but constant pace. Each run was separated by three days. The subjects who were endurance-trained subjects (age: 23 ± 3 yr, height: 174 ± 5 cm and weight: 74 ± 11 kg) provided voluntary written informed consent in accordance with the guidelines of the University of Evry. One week before the first 10 km, the subjects performed an incremental test to determine the maximal oxygen uptake ($\dot{V}O_2$ max), the velocity associated with $\dot{V}O_2$ max (v $\dot{V}O_2$ max) and the running velocity at the lactate threshold (vLT) (Billat & Koralsztein, 1996) During the 5 following weeks, the subjects performed one pair of 10,000m runs per week: one at a free speed all-out 10,000m run and the second was carried out three days later at the same average but constant speed. Therefore, in one month we succeeded to get ten pairs of free and constant pace runs performed by three subjects. Indeed, two subjects performed four pairs while one subject performed 2 pairs only of constant and free pace runs. Therefore, it was possible to compare velocity characteristics in ten constant vs. free pace runs.

The constant and free pace runs over 10,000m were performed after a 15 min warm-up at 50% v $\dot{V}O_2$ max and 5-min rest in order to reach oxygen uptake and blood lactate concentration baselines. For the free speed 10,000m race, the subject was instructed to run as fast as possible. During the free pace 10,000m runs, the subjects were asked to optimize their performance: they were neither informed of their own velocity, nor could they use any timing device. For each 10 meter stretch, the time was recorded by two moving time-keepers (chronometer Digisports Instruments, Seyssins, France) set exactly on the runner's side (in an electric car), so avoiding parallax error when crossing visual track marks. Thereafter, these data were downloaded into a microcomputer. As the two recordings were manually operated, they were checked that they were similar. This was indeed always the case. For the constant velocity runs, the subjects were instructed to follow a pacing cyclist moving at the average velocity of the 10,000m performed three days ago. Subjects were asked to maintain the pace as long as possible. In the constant 10-km run, as in the incremental run, the test was stopped when the subjects gave up or did not succeed in following the pace given by the cyclists i.e. when they had more than 5 meters behind the bicycle. In all cases they were exhausted.

Second study on the effect training on the physiological signals in exhaustive run performed at the maximal lactate-steady state (MLSSv).

We examined the training effect on the fractal behaviour of physiological signals in exhaustive run performed at the maximal lactate steady state i.e. in the apparent metabolic steady-state (Billat, 2003). According the same procedure and device that in the prior study, we analyzed heart rate, oxygen uptake and breathing frequency recorded before and after training in a constant pace run performed until exhaustion at the maximal lactate steady state velocity (exercise lasting one hour). We analyzed heart rate, oxygen uptake and breathing frequency recorded before and after training in a constant pace run performed until exhaustion at the maximal lactate steady state velocity (exercise lasting one hour). the purpose of this study was to determine whether the signal presents a particular structure (a scaling law). In addition we wanted to determine whether this structure was affected by training at this specific velocity and by the fatigue during the race. Then, the purpose of this study was to determine whether the signal presents a particular structure (a scaling law). In addition we wanted to determine whether this structure was affected by training at this specific velocities and by the fatigue during the race. The duration of exercise was 50% longer after training and was performed at 5% faster corresponding to the new (post training) maximal lactate steady-state velocity. The same duration of signal was analyzed.

Eleven highly experienced males veterans endurance-trained subjects aged 43-51 (48 ± 2.9 yrs) commenced the study but two withdrew during the study for job-related reasons (no longer any time for training). The subjects were specialized in long-distance running (best performance for the Half-Marathon = 83 ±5 min). After a warm-up lasting 15 minutes at 80% of MLSSv, subjects ran until exhaustion at MLSSv. Blood lactate concentration was measured at the end of the warm-up and every 10 minutes during the exhaustive run at MLSSv, stopping the subjects for only 10 s. Time to exhaustion at MLSSv was determined between the start and the time when the subject was not able to follow the pacemaker (cyclist) any more. As for the incremental test, each subject was encouraged to give their maximum effort. Distance run at MLSSv was the time limit at MLSSv multiplied by MLSSv. Between the two sets of three tests (pre and post tests) the runners carried out the following training procedure. The training was performed at this maximal lactate steady state-velocity during 6 weeks (2 times per week) in addition to two sessions of 1 hour of easy run (60% of the maximal heart rate).

The effect of fatigue

Since the subjects were instructed to run until exhaustion we considered that the fatigue of the runner increased along the races. Therefore, to appreciate the effect of fatigue, the recorded signals were split into two parts, each 50% of the distance run was analyzed with our algorithm and we checked whether or not physiological and speed signals still obeys a scaling law with fatigue according to the type of run (in the first study) and the state of training (in the second study).

Mathematical analysis of physiological and speed signals

During the free pace runs of the first study, the time (t_i) required to cover the distance between two boundary marks was precisely recorded. The boundary marks were all spaced 10 m (Δd) apart. The running speed (v_i) between 2 successive boundary marks was thus calculated as $v_i = \Delta d / \Delta t_i$. In order to obtain further information about speed variability throughout the running test, we performed a wavelet analysis on these specific signals (speed vs. time).

Continuous wavelet transform (CWT)

The wavelet which is being used determines the optics of the microscope; its magnification varies with the scale factor s. This property makes the continuous wavelet transform very useful in analyzing local regularity (scaling, roughness) properties of functions. In particular, such local scaling behavior is often characterized by a Hölder exponent “h”. It has been shown that the location of the singularity can be detected, and the related exponent can be recovered from the scaling properties of the wavelet transform, along the so-called “maxima line” converging towards the singularity. This is a line where the wavelet transform reaches a local maximum (with respect to the position coordinate). Connecting such local maxima within the continuous wavelet transform “landscape” gives rise to the entire tree of maxima lines.

In this paper, we chose the first derivative of the Gaussian θ (x) = exp($-x^2/2$) as the wavelet which is well localized in time and frequency. The scaling and translation actions are performed by two parameters: the scale parameter “s” which “adapts” the width of the wavelet to the resolution required and the position parameter u which locates the analyzing wavelet:

$$\Psi f(t) = \frac{1}{s}\Psi\left(\frac{t-u}{S}\right) \tag{1}$$

Nowadays scaling laws or self-similarities are playing an important role in signal processing.

Scaling and Roughness

For each scale s, the wavelet-transform energy:

$$energy_f(s) = \sum_{0<u\leq N} \left|W_f(u,s)\right|^2 \tag{2}$$

is the sum of the square of the values of a line in the time-scale *wavelet* transform representation (figure 1). *u* is an integer and is sampled as in Mallat (eg. Mallat, 1999).

If $energy_f(s) \approx cs^{\alpha}$ then, $\log_2(energy_f(s)) \approx \alpha\log_2(s) + \log_2(c)$ (3)

The $\log_2(energy_f(s))$ graph plotted vs. $\log_2(s)$, can therefore be approached by a line of slope α then the signal obeys a scaling law and exhibits a certain form of scale invariance. The slope α is the *scaling exponent* used to estimate signal *roughness* which quantifies the signal variation. We saw that the scaling law is associated to the fact that a certain scale dependent quantity, like wavelet transform energy, behaves as a *power of the scale*, cs^{α}. This means absence of any characteristic scale (and therefore absence of characteristic frequency), all scales (or frequencies) having equal importance. Thus, we have to estimate a *power law exponent* α which characterize scaling law behaviour and signal *roughness (figure 1 and figure 2)*. If f and g are two signals so that $\alpha < \beta$, $0 < s < 1$, $energy_f(s) \approx s^{\alpha}$ and $energy_g(s) \approx s^{\beta}$ then we obviously have $s^{\alpha} > s^{\beta}$. Therefore, $energy_f(s) > energy_g(s)$. This means that roughness (f) > roughness (g). This exponent α provides a measure of the “roughness” of the original time series: the larger the value of α, the smoother the time series. In this context, 1/*f*-like noise (α = 1) can be interpreted as a “compromise” between the complete unpredictability of white noise (α = 0.5) and the much smoother “landscape” of Brownian noise (α=1.5) [18, 31]. We illustrated *scale invariance* and *roughness* measure with two Weierstrass functions shown in figure 2 (at top). This figure shows the $\log_2(energy_f(s))$ graph plotted against $\log_2(s)$ for each Weierstrass functions (at bottom). Lines with a nearly constant slope show that both functions obey the scaling law. As the right Weierstrass function has less *roughness* (is smoother), the slope of the right line will be greater than the slope of left one.

Therefore, we developed and validated a wavelet transform algorithm which calculated log (wavelet transform energy) vs. log (scale). If this function can be approached by a line, then the signal obeys a scaling law and the slope, called scaling exponent, measures signal roughness (variability) which is maximal when the slope is zero. This means that lowest scales (highest frequencies) contain as much energy of signal as the largest ones. A class ζ of signals is self-similar if there exists a scaling exponent $\alpha > 0$ such that for any X (t) in ζ and any dilatation factor $\lambda > 0$, the dilated signal X (λ t) still belongs to ζ, once it is rescaled as $\lambda^{-\alpha}$ X (λ t). In other words X (λ t) = $\lambda^{-\alpha}$ ψ (λ t) where $\psi \in \zeta$. This is the statistical approach to self-similarity. It applies to the fractional Brownian motion $B_H(t)$. In this case $B_H(t + h)$-$B_H(t)$ is a stationary process for each increment h. Moreover, the structure functions E [$|B_H(t+h) - B_H(t)|^p$], where E is the expectation (or ensemble) average, satisfying the identity:

$$E\,[|B_H(t+\tau) - B_H(t)\,|^p] = c_p\,|\tau|^{pH} \tag{4}$$

Where $0 < p < \infty$ and c_p is a constant. Such structure functions are used as a classification tool. However, in many cases, such as turbulence, we do not have access to the expectation or ensemble average. We are then forced to make an ergodic assumption and to replace this expectation with an integral with respect to the time variable. These remarks lead us to replace (4) by

$$\int_{-\infty}^{\infty} \left| f(t+h) - f(t) \right|^p dt \approx |h|^{\tau(p)} \tag{5}$$

where $0 < p < \infty$, h is an increment and $\tau(p)$ is a characteristic exponent.

U. Frisch and G. Parisi used the function $p \rightarrow \tau(p)$ as a classification tool (Mallat, 1999). For the *f*Bm, $\tau(p)$ is a linear function of p while turbulent signals yield a more complicated behaviour. This is named multifractal signal processing. We now oversimplify our discussion and consider the special case p = 2 or (5). Then (5) is equivalent to:

$$\int_{2j}^{2j+1} \left| \hat{f}(\xi) \right|^2 d\xi \approx c2^{-2\pi t},\ j = 0,1,2,... \tag{6}$$

where $\tau = \tau(2)$ and $\hat{f}(\xi)$ is the Fourier transform of *f*. This is the case for "1/*f*" signals like the *f*Bm. Property (6) is a weak or average form of $\left| \hat{f}(\xi) \right| \approx |\xi|^{-(\tau+1/2)}$

The wavelet transformation can be used for checking (5). However, let us stress that a plain Fourier transformation does the same task. The wavelet formulation of (6) is:

$$\int |W(u,s)|^2 du \approx cs^{2\tau} \tag{7}$$

where $W(u,s) = W_f(u,s) = \frac{1}{s}\int f(t)\overline{\psi}(\frac{t-u}{s})dt$.

Using a wavelet transformation for checking (5) might be criticized. However, the wavelet transformation should be used when $p \neq 2$ since one cannot calculate L^p norms through a Fourier transformation. $\overline{\psi}$ conjugates ψ (figure 1). In other words, it is not clear that the wavelet transformation should be used if $p \neq 2$. Our next step will be the investigation of (5) for $p \neq 2$ in which case, the wavelet transform is needed. We used a filter-bank consisting of band-pass filters. More precisely the outputs of these band-pass filters are given by the convolution products $f * \psi_S$, $s \in S$, where f is the signal and $*\psi_S$ is the impulse response of the filter. The fundamental assumption concerning the family is the following $\psi_s(t) = \frac{1}{\sqrt{S}}\psi\left(\frac{t}{s}\right)$ where ψ is a localized function with a vanishing integral and s >0 is now playing the role of a scale. This specific role of the parameter s singles out the wavelet transform $W_f(u,s) = (f*\psi_S)(u)$ among the larger class of band-pass filter-banks. In this study, it will be convenient to assume that y is the derivative of the Gaussian function $y(t)=c\exp(-t^2/2)$

We used the *continuous wavelet* transform to analyse the recorded physiological signals. We calculated the *wavelet* transform *energy* over a time interval as a function of *scales s*. The $\log_2$ of this *energy* is plotted against $\log_2$ (scale). If this (log, log) representation is a line of slope α then the signal obeys a *scaling law* and the scale exponent α measures the *roughness* of the signal which quantifies its variation. A *wavelet transform* decomposes signals over dilated and translated *wavelets (figure 1).*

A *wavelet* ψ is a function of zero average: $\int_{-\infty}^{+\infty} \psi(t)\,dt = 0$.

The *wavelet* is translated by *u* and scaled by *s* : $\psi(t) = \psi[\,(t-u)/s)\,]$.

If the *wavelet* ψ is normalized: $|\psi| = \int_{-\infty}^{+\infty} |\psi(t)|^2 dt = 1$ then the wavelet $\Psi_{u,s}(t) = \frac{1}{\sqrt{s}} \Psi(\frac{t-u}{s})$ is also normalized: $\|\Psi_{u,s}\|^2 = \int_{-\infty}^{+\infty} |\Psi_{u,s}(t)|^2 dt = 1$. The *wavelet* transform $W_f(u,s)$ of a signal f at scale s and position u is the cross correlation between f and $\Psi_{u,s}$ which yields $\psi_{u,s}(t) = \frac{1}{\sqrt{s}} \int_{-\infty}^{+\infty} f(t)\overline{\psi}(\frac{t-u}{s})dt$ ($\overline{\psi}$ is the conjugate of Ψ). The normalization by 1/√S insures ψ ‖u,s‖2 = ‖ ψ ‖2. We used the first derivative of the Gaussian as a *wavelet*: $\psi(t) = -\frac{d}{dt}\Phi(t)$, $\Phi(t) = c\exp(-\frac{t^2}{2})$. Let us consider $\tilde{\Psi}_s(t) = \frac{1}{\sqrt{s}} \overline{\Psi}(-\frac{t}{s})$ and $\tilde{\Phi}_s(t) = \frac{1}{\sqrt{s}} \overline{\Phi}(-\frac{t}{s})$, the *wavelet* and the Gaussian function after scaling by $-\frac{1}{s}$ and normalizing by $\frac{1}{\sqrt{s}}$, which is a dilation when $0 < s < 1$ and a contraction when $s > 1$.

In figure 1, we plotted the Gaussian functions $\tilde{\Phi}_s(t) = \frac{1}{\sqrt{s}} \overline{\Phi}(-\frac{t}{s})$ with $s = 1$, $s = 1/3$, 2 at left and their associated *wavelets* $\tilde{\Psi}_s(t) = \frac{1}{\sqrt{s}} \overline{\Psi}(-\frac{t}{s})$ with $s = 1$, $s = 1/3$, 2, $s = 1/4$ at right.

The *wavelet* transform is the *convolution* of the signal f with the *wavelet*: $\tilde{\Psi}_s(t)$
$W_f(u,s) = (f * \tilde{\Psi}_s(t))(u)$.

Moreover, since $\tilde{\Psi}_s(t) = s\frac{d}{dt}\tilde{\Phi}_s(t)$ then the wavelet transform is given by:

$$W_f(u,s) = (f * s\frac{d}{dt}\tilde{\Phi}_s)(u) = s\frac{d}{du}(f * \tilde{\Phi}_s)(u).$$

The *convolution* of the signal f with the Gaussian $\tilde{\Phi}_s(t)$ function averages f proportionally to the scale *s*. Therefore, large values of $|W_f(u,t)|$ correspond to large variations of the analysed signal f.

In the second study, in addition to the estimation of a *power law exponent* α which characterize scaling law behavior and signal *roughness* (as done in the first study), we approximate this exponent using *continuous wavelet transform*, the Veitch-Abry *discrete wavelet estimator* and the *Detrended Fluctuation Analysis* (DFA) *estimator* which was proved to be among the best non wavelet based estimators. In the three cases, scaling law exponent is approximated by the slope of a linear fit. We used continuous and Daubechies wavelet transform and the detrended fluctuation analysis (DFA) algorithm [e.g. 27] to find scaling exponents which characterize the time-scaling behaviour of the physiological signals during a race.

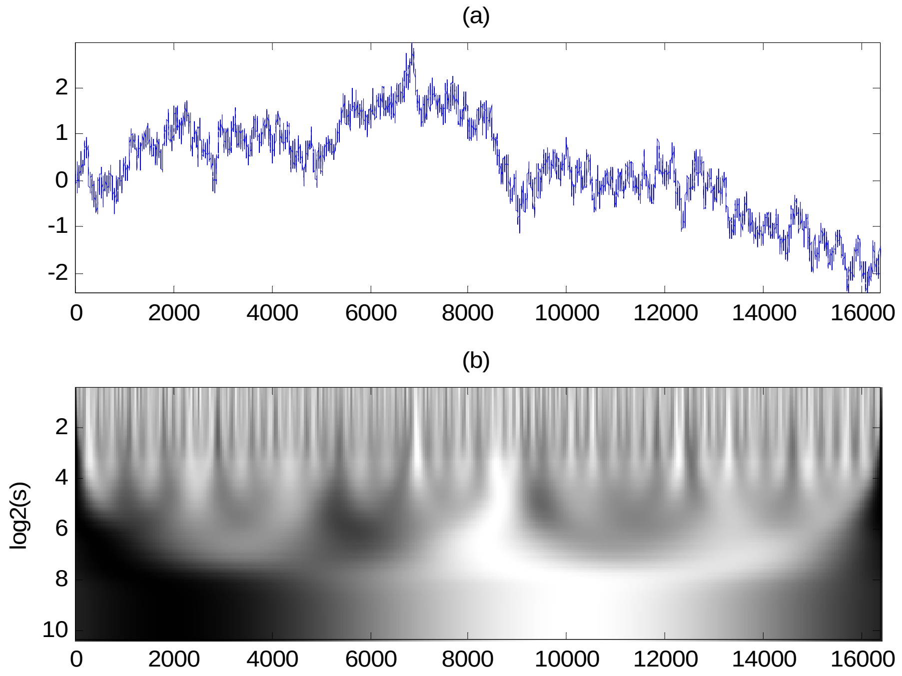

Figure 1. A fractional Brownian at top (a) and its *continuous wavelet transform* in a time-scale representation at bottom (b).

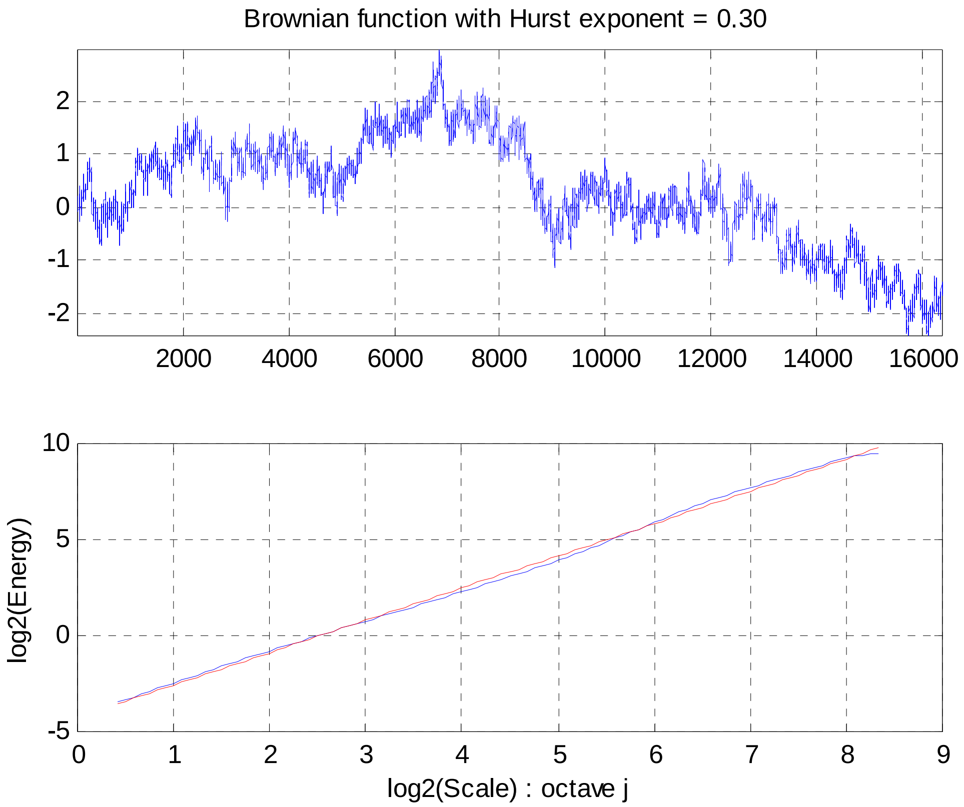

Figure 2. The *wavelet transform energy* of the last fractional Brownian and its linear approximation against the scale in a log-log representation. This graph shows the *scaling law* behavior of this fractional Brownian signal.

DFA-function and DFA-exponent

To compute this function [3], we first subtract the signal average from the given signal

$$\bar{f} = \frac{1}{N}\sum_{i=1}^{i=N} f[i], \quad \tilde{f}[i] = f[i] - \bar{f} \ , \ f = (f[n])_{1\le n\le N}$$

and we consider its indefinite integral (accumulated sums) :

$$F[n] = \sum_{i=1}^{n} \tilde{f}[i].$$

Next, we divide $(F[n])_{1\le n\le N}$ in pieces of equal length m. We call $\tilde{N}$ the larger multiple of m inferior or equal to N (in most cases m does not divide N exactly).

A line segment fit each piece of $(F[n])_{1\le n\le N}$ in the least square sense, its concatenation over $[1, \ N]$ is denoted by $(y_m[k])_{1\le k\le \tilde{N}}$. We detrended the integrated signal, $(F[n])_{1\le n\le N}$ locally, subtracting the trend segment of each peace of $(F[n])_{1\le n\le N}$ to obtain the DFA-function:

$$G[m] = \sqrt{\frac{1}{\tilde{N}}\sum_{k=1}^{\tilde{N}} (F[k] - y_m[k])^2} \ ,$$

which is the root mean square fluctuation of the detrended indefinite integrate signal $(F[n])_{1\le n\le N}$.

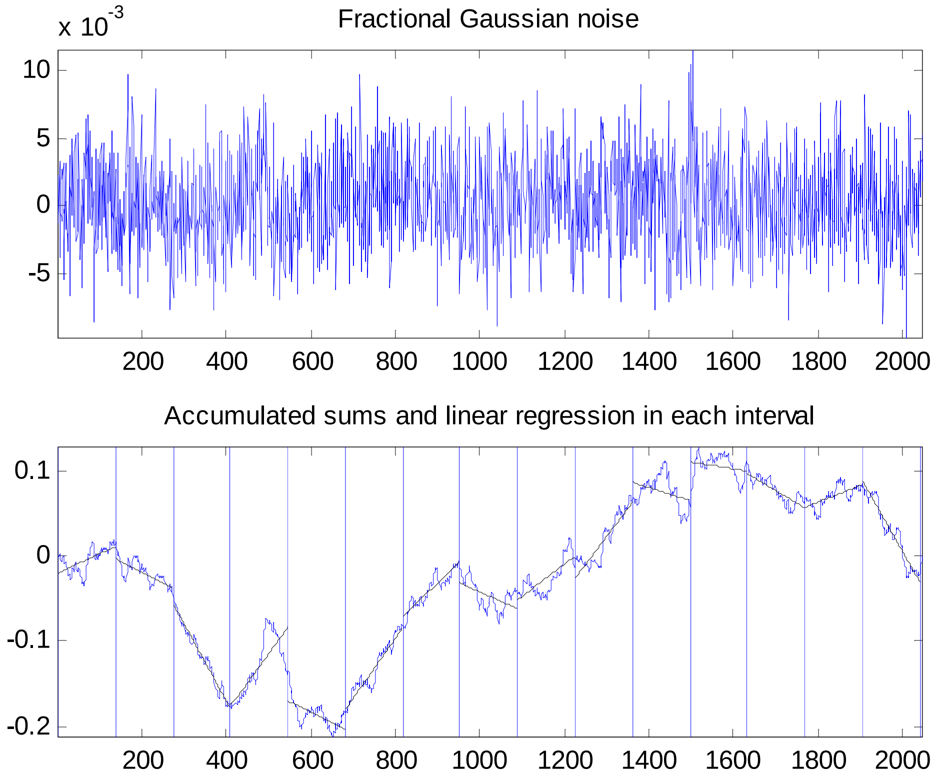

Figure 3. A *fractional Gaussian noise* obtained as a *fractional Brownian derivative* (at top), its indefinite integrate and linear regression over pieces (at bottom).

We approximate the graph of $\log(G[m])$ versus $\log(m)$ by a line in the *least square sense*, the slope α of this line approximates the DFA-function $G[m]$ to a power law, cn^{α}. The fitting quality can be measured using the residual standard deviation

$$residue = \sqrt{\sum_{k=1}^{\tilde{N}} (\log G[m] - \alpha \log m - \log c)^2}\,,$$

the smaller the residue, the better the approximation of $G[m]$ to a power law and the better the absence of a characteristic scale (frequency).

Veitch-Abry DWT estimator

Because the *continuous wavelet transform* is redundant, neighboring coefficients $W_f(k,a_j) = \left\langle f, \psi_{k,a_j} \right\rangle$ share a certain amount of information, Abry and Veitch [1,2,3,4], used *discrete Daubechies wavelet* ψ whose set of coefficients $W_f(k,j) = \left\langle f, \psi_{k,j} \right\rangle$ with $k \in Z$ and $1 \le j \le J_{\max}$, $J_{\max} = \log_2 N$, contains the total signal $f = f(n)_{1 \le n \le N}$ information without amount sharing. The *discrete wavelet transform* of a *process* or *signal* $f(t)$ is given by this set of scalar products $D_f(j,k) = \left\langle f, \Psi_{j,k} \right\rangle$ where $\Psi_{j,k} = 2^{-j/2}\Psi(2^{-j}t - k)$ is the translated and scaled wavelet function ψ, defined via a multiresolution framework.

A *stationary process* f display a *long-range dependence* if the spectral density verifies

$$\Gamma_f(\omega) \approx c_{\upsilon} |\omega|^{\alpha} \ ,\ \omega \to 0$$

with $0 < \alpha < 1$. The variance of the wavelets coefficients of a *long-range dependence* process verifies the following scaling law

$$E(D_f(j,k)^2) \approx 2^{j\alpha} c_{\upsilon} C(\alpha,\psi)$$

within a given rang of octaves, $j_1 < j < j_2$. The *scaling law* exponent α can be estimated using the graph of

$$\log_2(E\,(D_f(j,k)^2)) \approx j\alpha + \log_2(c_{\upsilon} C(\alpha,\psi))$$

against j, which can be approached by a line whose slope estimates the value of α.The random variable

$$\mu_j = \frac{1}{n_j} \sum_{k=1}^{n_j} \left| D_f(j,k) \right|^2$$

with n_j as number of coefficients at octave j is an unbiased estimator of the variance of the process $D_f(j,.)$. Because $E\lfloor \log_2(\mu_j) \rfloor \ne \log_2 E(\mu_j)$, D. Veitch and P. Abry [ ], introduced a small corrective factor $g(j)$ such that

$E\lfloor \log_2(\mu_j) \rfloor = j\alpha + \log_2(c_{\upsilon} C(\alpha,\psi)) + g(j)$.

Any kind of linear regression of $y_j = \log_2(\mu_j) - g(j)$ on j constitutes an estimator of α.

$E(y_j) = j\alpha + \log_2(c_{\upsilon} C(\alpha,\psi))$.

The *Veitch-Abry* estimator is used to characterize *long-range dependence phenomenon*, under well justified technical conditions, this estimator is *unbiased* and of *minimum variance*. In practice, even for small length signals, the *bias* and the *variance* seem to be very small.

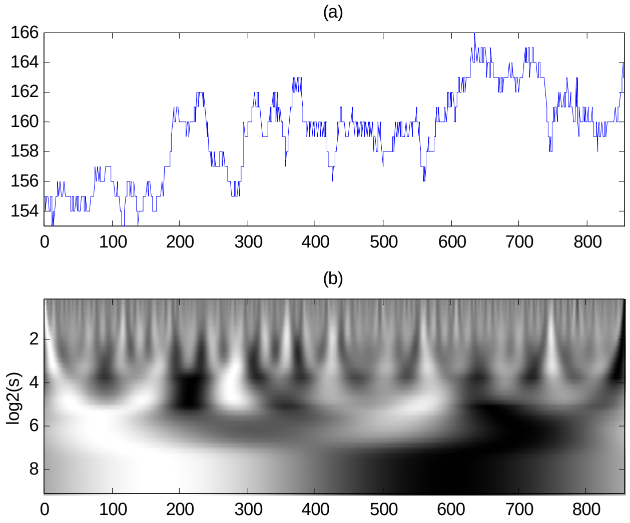

Figure 4 A heart rate signal recorded before training (at top) and its *continuous wavelet transform*, in a time-scale representation (at bottom). Its CWT energy with a linear regression against a scale in a (log-log) representation, the Veitch-Abry $y_j = \log(\mu_j) - g(j)$ against j (together with confidence intervals) and $\log(G[m])$ against $\log(m)$ are shown in figure 5.

Statistical analysis

Statistical analyses were performed with the software MATLAB® (MATHWORKS (Mathworks, Mathworks, Inc, Narick, MA) and Sigma stat® (SPSS, Inc, SAN RAFAEL CA). As the data were normally distributed, we used a student t-test for paired data to compare each data set in constant vs. free speed run. To test the effect of fatigue under each condition (constant vs. free speed runs) we compared using a one-way analysis of variance for repeated measurements. Correlations between two continuous variables (e.g. Heart rate roughness vs. speed in percentage of v$\dot{V}O_2$max) were measured using the Spearman or Pearson correlation coefficient r depending on the distribution of the data. Results are presented as mean ± SD. Coefficient of variation (CV) is the variability normalized to mean value (CV = 100 × SD/mean). Independent variables are subjects and distance run. Dependent variables are: roughness of the speed, heart rate and oxygen uptake time course. Significant differences are identified by Tukey's test. Statistical significance has been set at $P < 0.05$.

Experimental results

In the first study the scaling exponents where computed for HR, $\dot{V}O_2$, SV. Scaling exponents for SV were significantly higher in free vs. constant runs (0.78 ± 0.39 vs. 0.50 ± 0.25, P = 0.05) but not for HR and $\dot{V}O_2$ (1.17 ± 0.43 vs. 1.37 ± 0.33, P = 0.1 for HR; 0.93 ± 0.42 vs. 0.92 ± 0.37, P = 0.97 for $\dot{V}O_2$). Furthermore, the scaling law in HR signals did not disappear with fatigue in contrast to $\dot{V}O_2$ and speed. In conclusion of this first study, this suggests that in case where no speed was imposed, heart rate could be the driver for speed regulation. Further studies are needed to go deeper in this hypothesis.

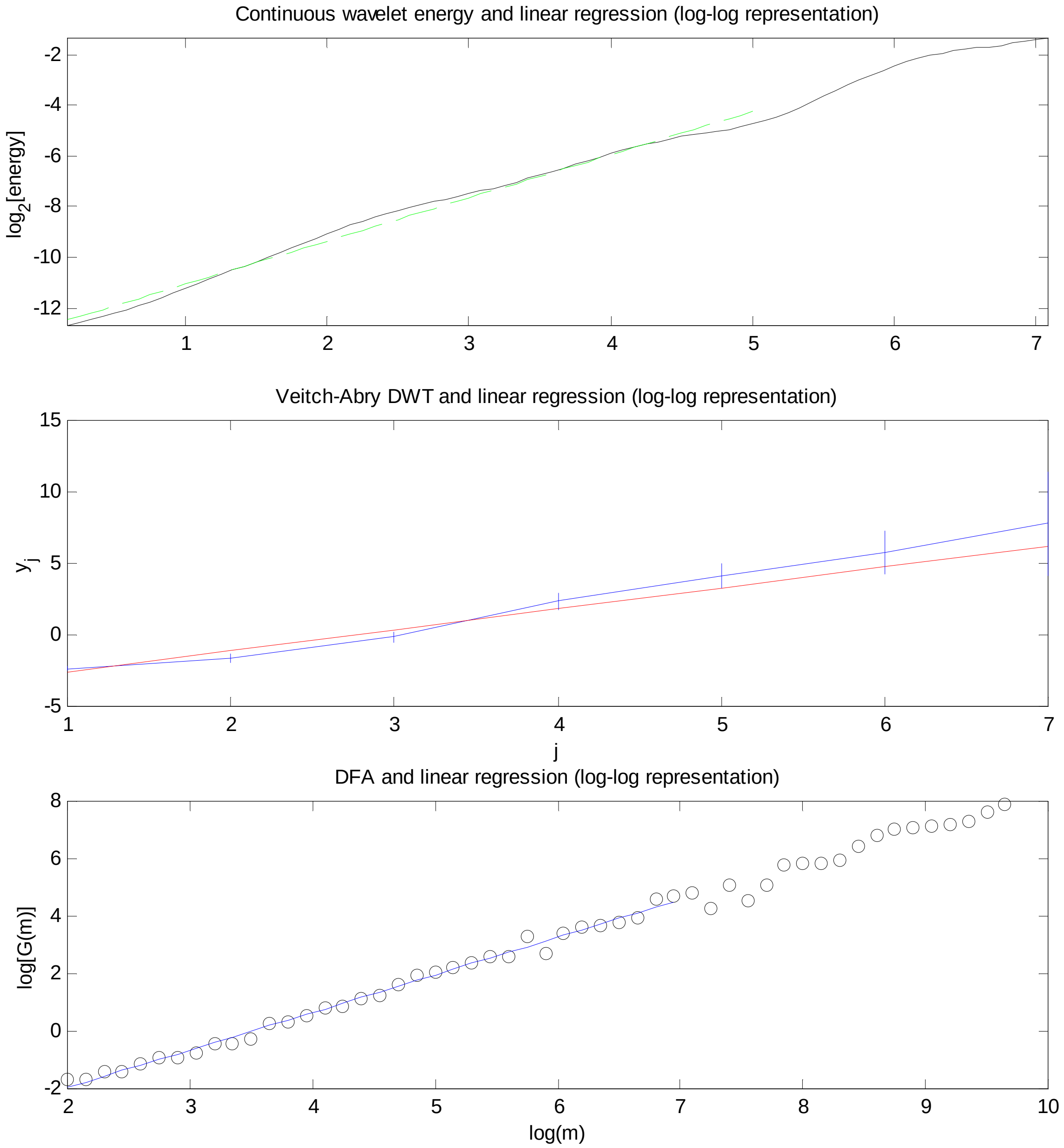

Figure 5 The CWT energy with a linear regression against a scale in a (log-log) representation, the Veitch-Abry $y_j = \log(\mu_j) - g(j)$ against j (together with confidence intervals) and $\log(G[m])$ against $\log(m)$

The results of *the second study* showed that training did not affect the structure of the physiological signals in an exhaustive race. In addition to the estimation of a *power law exponent* α which characterize scaling law behaviour and signal *roughness* (as done in the first study), we approximate this exponent using *continuous wavelet transform*, the Veitch-Abry *discrete wavelet estimator* and the *Detrended Fluctuation Analysis* (DFA) *estimator* which was proved to be among the best non wavelet based estimators. In the three cases, scaling law exponent is approximated by the slope of a linear fit. The three methods for estimating the scaling exponent α demonstrated that: i) the heart rate signal only showed a scaling behaviour (α = 0.66±0.20, 0.92±0.23 and 1.95±0.27; for VO_2, RF and HR with the CWT method; α = 0.24±0.31, 0.47±0.14 and 1.71±0.37; for VO_2, RF and HR with the DWT method; α = 0.25±0.39, 0.40±0.19 and 1.75±0.33; for VO_2, RF and HR with the DFA method) ii) the scaling exponent was not affected by training whatever the method used to estimate it which was not significantly affected by training (α = 1.89±0.2 vs. 2.00±0.33 before and after training with the CWT method; P = 0.48; α = 1.72±0.49 vs. 1.69±0.25, before and after training P = 0.92 with the DWT method; α = 1.73±0.38 vs. 1.77±0.31, before and after training P = 0.85 with the DFA method).

Conclusion and perspectives

The healthy heartbeat is generally thought to be regulated according to the classical principle of homeostasis whereby physiological systems operate to reduce variability and achieve an equilibrium-like state. However, it has been previously demonstrated that under normal conditions, beat-to-beat fluctuations in heart rate display the kind of long-range correlations typically exhibited by physical dynamical systems far from equilibrium, such as those near a critical point (Amaral et al., 1998, 2001; Arai et al., 1989; Havlin et al., 1999; Ivanov et al. 1999; Wesfreid et al., 2002). Human heartbeat time series is the output of a complicated integrative control system and Peng et al. (Peng et al, 1995, 1999) showed the scale-invariant properties of the human heartbeat series in healthy subjects. The nonlinear interaction between the parasympathetic and sympathetic stimulations is the postulated mechanism for much of the erratic heart rate variability recorded in healthy subjects, although non-autonomic factors may also be important (Havlin et al., 1999). It seems that the resting heart rate variability is mediated by the parasympathetic neural activity rather than the sympathetic one and this could be similar for exercise (Ivanov et al., 1996). This is a preliminary study to appreciate the effectiveness of such mathematical tools for training effect on physiological signal in exhaustive exercise analysis. Multifractality in human heartbeat dynamics in exhaustive exercise remain to be addressed to examine if the change in shape of the D(h) curve for the heart rate in fatigue condition show a loose of cardiac control mechanism as already reported in heart-failure group of subjects (Bassingthwaighte et al., 1994; Bernaola-Galvan et al., 2001; Hausdorff & Peng, 1996; Ivanov et.al, 1999; Nakamura et al., 1993; Peng et al 1999).

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Acquiring Skill in Sport: A Constraints-Led Perspective

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Recently, sciences of complexity and chaos have been applied to the study of phenomena in sport with a view to enhancing understanding of approaches to performance, training and coaching (e.g., Mack et al., 2000; Mayer-Kress. 2001). For example, applications of nonlinear dynamics to the study of skilled performance and learning, have modelled athletes as dynamical movement systems (e.g., Davids, et al., 2000; Davids, et al., 2002). Movement coordination and control in sport performers involves two dimensions: (i) coordination between important limb segments over space and time to ensure appropriate temporal sequencing in the movements of joint segments when performing actions such as kicking or running; and (ii) coordination of effectors constrained by important objects, surfaces or events in the environment (Turvey, 1990). These applications are beginning to provide useful insights into processes of motor skill acquisition for players and coaches. The aims of this paper are to: (i) present a theoretical overview of complex, dynamical movement systems which are relevant for the study of coordination processes; (ii) review some of the key constraints on emergent coordination processes; and, (iii) draw some implications for coaching behaviours, such as the use of augmented feedback, from a constraints-led approach.

Coordinating Motor System Degrees of Freedom

The core problem for movement scientists over the past 30 years has been how the many interacting parts, or degrees of freedom, of the human movement system are coordinated and controlled during goal-directed activity (see Bernstein, 1967). Bernstein's (1967) seminal definition of movement coordination was "the process of mastering redundant degrees of freedom of the moving organ, in other words its conversion to a controllable system" (p.127). He highlighted the formation of specific functional muscle-joint linkages, later known as coordinative structures, as a method of constraining the large number of degrees of freedom to be regulated in the human movement system. Coordinative structures act as physical constraints, which specify how individual movement system degrees of freedom can become mutually dependent. The coordinative structures used to regulate biomechanical degrees of freedom during performance of functional actions can involve many or few motor system components (high or low dimensions), depending on the nature of the task constraints (Newell, Broderick, Deutsch & Slifkin, 2003). Typically, however, early in learning reduced dimensionality (i.e. complexity) of the motor system encourages the development of functionally preferred coordination states, or stable attractor states, to support goal-directed actions in sport (Turvey, 1990).

A Constraints-Led Perspective on Skill Acquisition

Despite the proliferation of degrees of freedom, dynamical movement systems show a surprising amount of order. Indeed, it has been known for some time that functional patterns of coordination emerge during self-organization in individual performers to satisfy competing and cooperating task, informational and environmental constraints (e.g., Newell, 1986).

Constraints have been defined as boundaries or features which influence the expression of the form achieved by the system or sub-system seeking a stable state of organisation (Kugler et al., 1980; Newell, 1986). Constraints operate in a Darwinian process by favouring some emergent features of behavior, rather than others. At the time scale of perception and action, selected coordination patterns in the human movement system emerge under constraint as less functional states of goal-directed behavior are disregarded. Within each attractor region, system dynamics become highly ordered and stable with practice under constraints, leading to the production of relatively reliable and functional movement patterns. Variability in attractor regions, exemplified by fluctuations in stability encourages the exploration of performance constraints in sport. For example, consider how an overarm throw possesses features of both consistency and adaptation in a sport such as baseball. This paradox between stability and variability explains why skilled athletes are capable of both persistence and change in motor output during sport performance. In other words, performers have the ability to actively exploit the environment to solve problems in a robust and flexible way.

Implications of a Constraints-Led Perspective for Understanding Skill Acquisition in Sport

Newell’s (1986) model of interacting constraints and self-organisation processes has important implications for the study of coordination and control of actions in sport (see Davids et al., 2004). The model has been taken to form the basis of a principled constraints-led approach to practice in sport, suggesting that the major role of the coach or teacher is to manipulate key constraints on the learner in order to facilitate discovery of functional movement behaviours (Davids, et al., 2004).

In a constraints-led approach there is a clear emphasis on discovery learning. Exploratory practice embraces problem-solving behaviours, because players must actively engage in learning rather than passively receiving information. Importantly, learners are encouraged to find and assemble their own unique solutions to motor problems during exploratory practice. Discovering various solutions to the task, whether successful or not, is essential in learning to experience varieties of task solutions (Davids, et al., 2004). Discovery learning occurs in a practice context similar to the performance context enabling the player to become more attuned to the available information sources. While a player actively participates in learning, they are able to concentrate on exploring potentially important sources of information as opposed to independently satisfying task demands prescribed by the coach. Exploratory practice is valuable at both the coordination and control stage of learning for different reasons (Davids et al., 2004). Initially, exploratory practice is useful for athletes to assemble functional and unique coordination structures to achieve a specific task goal such as intercepting a ball, whereas later in learning exploratory practice allows players to refine and adapt existing basic coordinative structures to enhance flexibility (e.g., control a ball in different ways and under different conditions). In sport, exploratory behaviour can be encouraged by manipulating key task constraints to direct the learners' search for effective coordination solutions. Therefore, an important issue concerns the nature of the constraints that learners have to satisfy during motor learning. Practice should provide opportunities for performers to learn how to *soft-assemble* adaptive behaviours in ways that robustly respond to local context and exploit the variability of intrinsic dynamics. In the remainder of this paper, we examine how three different task constraints can be manipulated during skill acquisition in sport: equipment, practice structure and augmented feedback.

Manipulation of Equipment Constraints

The design of sports equipment is an important factor that can influence the acquisition of skill, while satisfying health and safety requirements of practice conditions (Araújo et al., 2003). However, in the past, commercialised sports equipment has rarely been engineered to facilitate motor skill acquisition and the physical fitness of young children. The result is that, in sport, balls are typically too large or too heavy for children to grasp, throw or kick, and hitting implements are often too narrow, long or heavy for children's use (Herkowitz, 1984). This clearly increases the risk of injury, and could hamper skill acquisition. Current theoretical models of motor development across the lifespan recognise that children should not be viewed as 'mini-adults', but as coherent, developing complex systems (Savelsbergh, Davids, Van der Kamp & Bennett, 2003). For example, there have been many claims about the use of smaller footballs with lower coefficients of restitution, such as the Futebol de Salão (FDS), to enhance the acquisition of ball skills. Araújo et al.'s (2003) review revealed that there appear to be some benefits to using the FDS to improve ball skills, particularly at the control stage of learning, but not necessarily at the coordination stage (Newell, 1985). One study reviewed examined whether use of the FDS by groups of 11-year-old beginners at soccer would enhance ball skill acquisition relative to a conventional size 5 football. After a pre-test to equate basic skill level, one group practised dribbling and juggling skills with the FDS, while a control group practised with the regulation size 5 soccer ball. Results showed that both groups significantly improved juggling and dribbling performance during acquisition. In the juggling test, results indicated that the FDS experimental group juggled the conventional ball more successfully than the control group in the post-test (see Figure 1). Araújo et al. (2003) suggested that children using a smaller, heavier ball could be guided towards relevant information (such as haptic and proprioceptive sources) for establishing functional coordination structures, enabling effective transfer to other task constraints.

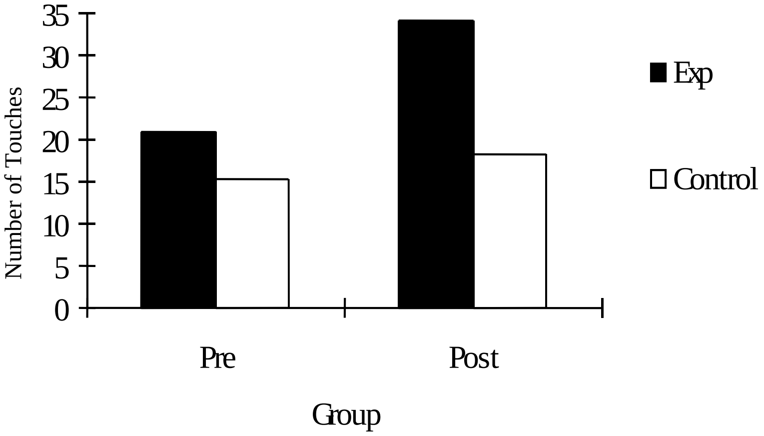

Figure 1. Pre- and Post-Test data on performance on a ball-juggling test for groups using an FDS (Exp) and a size 5 (Control) soccer ball. Data reported in Araújo et al. (2003).

Practice Structure: Task Simplification vs. Task Decomposition

A common belief in sports coaching is that there are benefits for learners in the strategy of breaking down complex tasks, such as the long jump or volleyball serve, into smaller components which are more manageable (Magill, 2001). A fundamental objective of task decomposition techniques, including part-task training programmes and adaptive instruction, in sports coaching is the reduction of attentional demands on the learner during skill acquisition. Part-task training involves practising some subset of task components as a precursor to practice or performance of the whole task, for example when a volleyball player practises throwing the ball to a consistent height separately and before practising the throw-up to serve the ball. Adaptive training is a technique in which task difficulty is progressively increased as its performance is mastered, for example jumping off two feet into the long jump pit before practising running to jump from the take-off board. This coaching strategy, where practice routines start at an easy level and then increase in movement demands and time pressure, is used in teaching many complex skills in sport.

However, this approach to practice organization is being questioned by research on the informational constraints on specific tasks in sport (e.g., Davids, Kingsbury, Bennett, & Handford, 2001). Furthermore, neuroscientific support is emerging for employing the principle of information-movement coupling to constrain the way that sports actions are decomposed for subsequent practice (e.g., Milner and Goodale, 1995). They argued that there are two separate pathways connecting visual and motor centers in the cortex. A ventral stream running from the striate cortex to the inferotemporal region is critical to the visual perception and identification of objects, whilst a dorsal root which runs from the striate cortex to the posterior parietal cortex mediates the required sensorimotor transformations for visually guided actions directed at those objects. This dedicated visuomotor pathway could provide a neurological basis for the concept of information-movement coupling and its implications for practice.

The implication from the theoretical and empirical findings in dynamical systems theory and neuroscience is that practice structure should emphasize ‘task simplification’ rather than the more traditional technique of task decomposition. In the case of the volleyball serve, practice of the ball toss component without the strike component, prevents learners from strengthening the relationships between perceptual information from the ball’s trajectory and the functional muscle synergies of the striking system. A decoupling of the demands on the perceptual and motor-systems during practice prevents learners from developing the cortical neural pathways underlying perception-for-action. In the case of the long jump, the run-up phase should not be practiced without the jump component of the task. Both tasks should be practiced as ‘wholes’ with initial reductions in the amplitude of ball toss in volleyball and the run-up in the long jump to manage the complexity of the coordination processes involved for learners (Araújo et al., 2003).

Instructional Constraints on Skill Acquisition

Delivery of augmented information to the learner has been a primary concern for motor learning theorists for many years (Newell, Morris, & Scully, 1985). From a constraints-led perspective, the transmission of verbal instructions and visual demonstrations during practice

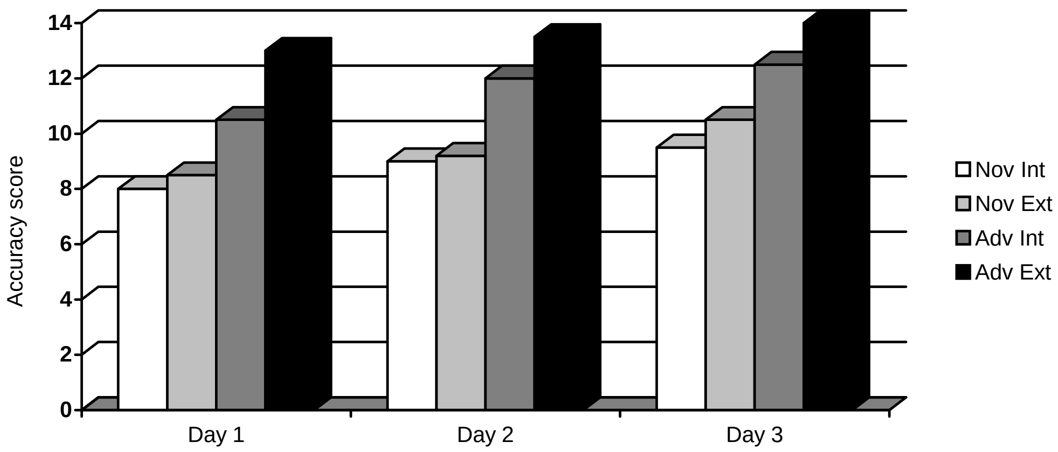

Figure 2. Accuracy scores of the Nov-Ext, Nov-Int, Adv-Ext, and Adv-Int groups during 2 days acquisition and retention. Nov, Adv, Ext, and Int = novices, advanced, external and internal. (Graph adapted from Wulf et al., 2002).

are seen as instructional constraints to channel the learner's continually evolving search for functional movement solutions (Newell, 1986). Consequently, attention has been focused on the quality and nature of instructional constraints to direct learners' attention during skill acquisition. Based on Bernstein's (1967) insights, Whiting and Den Brinker (1982) proposed that learners are concerned with information about the *image of the act* (focus on movement dynamics or topological form) and the *image of achievement* (focus on the movement effects to be achieved). The image of achievement is not a prescriptive internal plan of action, but rather an intended functional solution, which emerges from the task constraints. More recently, such proposals have been supported by data showing beneficial effects of instructions and feedback as a function of an external focus of attention (emphasis on movement effects on the environment) compared to an internal focus (focus on movement of specific body parts) (e.g., Wulf et al., 2001).

It is believed that an external focus on the "image of achievement" (i.e. an emphasis on task outcomes) provides better opportunities for learners' search of the task during practice and constrains the emergence of movement behaviour (e.g., see Wulf et al., 2000). For example, Vereijken and Whiting (1990) studied the role of instruction and feedback in learning to ski and found few meaningful differences between the groups of directed and undirected learners. Vereijken and Whiting (1990) proposed that an external focus allowed discovery learners to focus on an image of achievement alone. It is possible that augmented information, in the form of verbal instruction, may have directed the learners' search to the dynamics of the movement instead of information on the effects on the environment (ski-simulator). In contrast, the undirected (discovery) group performed a far wider search of the perceptual-motor workspace encompassing the pick-up of behavioral information on movement dynamics coupled with perceptual information on movement-related effects on the environment, to support movement behaviour. It has been argued that an external focus of attention does not interfere with self-organisation processes of the movement dynamics as performers explore the task (Davids et al., 2004). Interestingly, Wulf et al. (2000) found that an external focus that directed performer's attention towards the movement effects, rather than to other external sources of information, yielded better learning and performance of a tennis forehand drive. That is, the effects of instructions towards an external focus of attention were not due to distracting performers from an explicit focus on their movement dynamics, but were influential in allowing self-organisation processes to implicitly regulate task performance and learning. Other empirical findings from several studies have added to a growing body of data highlighting the benefits of a self-regulated feedback system with an emphasis on discovery learning (e.g., Janelle, et al., 1997; Chiviacowsky & Wulf, 2002).

These findings are in line with the idea that augmented information (i.e., instruction and feedback) directs search toward perceptual information relating to the ‘image of achievement’ (effects of the movement pattern on the environment) and will enable self-organising processes to occur leading to more effective learning. This idea was exemplified in recent work by Wulf et al. (2002, Experiment 1.), using a volleyball-serving task to examine the effects on learning of frequency (20% of trials) and direction of feedback. Feedback provided groups with identical task goals but differed by directing the search to either the movement dynamics or the effects of the movement pattern on the environment in both novice and advanced level players. As shown in Figure 2, accuracy of the tennis serve was significantly enhanced in both novice and advanced pattern-effect feedback groups in the acquisition and retention phases. It appears that the learners search for appropriate movement solutions is enhanced by directing the search to the effects of the movement pattern on the environment and thus developing an ‘image of achievement’. In contrast, the movement-dynamic group was narrowly constrained by the informational constraints and provided with limited opportunity to explore the wider landscape for possible movement solutions to the task demands. Advanced learners in the pattern-effect group also demonstrated improved performance and learning effects, more so than the novice group. These performers may have already attained a skill level that characterised them at a ‘control stage’ of learning (Newell, 1985). The less restrictive form of feedback and instruction, afforded to the advanced learners in the pattern-effect group in the study by Wulf and colleagues (2002, Experiment 1.) may have provided sufficient opportunity for external control strategies to develop and performance consequences to be realized, leading to the relatively successful adaptation of movement behaviour to meet task requirements.

These findings have been replicated in other studies involving the learning of complex skills in laboratory and field-based tests (e.g., Wulf, Höß, & Prinz, 1998 Experiment 2.; Wulf, Lauterbach, & Toole, 1999; Maddox, Wulf, & Wright, 1999). Further evidence of the positive effects of directing search to movement effects rather than to the movement dynamics has been seen in tennis and golf (e.g., Wulf, Lauterbach, & Toole, 1999; Maddox, Wulf, & Wright, 1999).

Frequency of Feedback

Another important instructional constraint concerns the frequency of feedback to be provided for effective skill learning. Wulf and colleagues (2002, Experiment 2.) examined the effects of frequency of feedback as a function of directed search on the learning of a lofted pass in football. Feedback statements were manipulated to direct the search of the learner to either their movement dynamics or movement effects. The movement dynamic feedback comprised such statements as ‘Position your foot below the ball’s midline to lift the ball’ and ‘Position your body weight and the non-kicking foot behind the ball’ and pattern-effect feedback comprised statements such as ‘Strike the ball below it’s midline to lift it; that is, kick underneath it’ and ‘To strike the ball, create a pendulum-like motion with as long a duration as possible’.

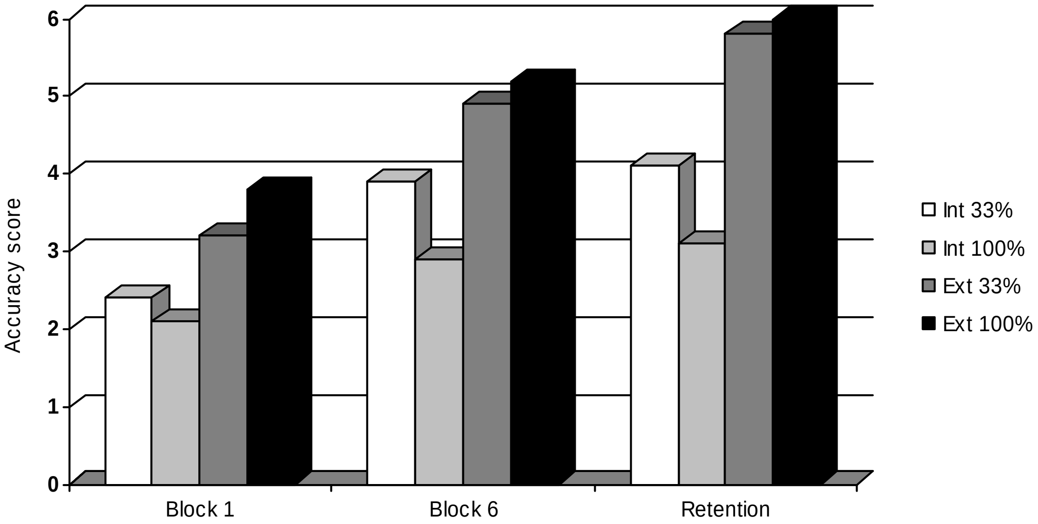

Figure 3. Accuracy scores of the Int - 33, Int - 100, Ext – 33 and Ext - 100 groups (Graph adapted from Wulf et al., 2002).

In Figure 3 immediate effects on performance outcome and learning can be seen in both external-focus (movement-effect) feedback groups. Furthermore, the interaction between feedback frequency and directed search resulted in more effective performance during both practice and retention in the group receiving reduced feedback (33% of trials) relative to the constant feedback group (100% of trials). These data indicated that receiving external focus feedback once in every three trials is as functional for learning as receiving external focus feedback on every trial. The findings highlight the detrimental effect that directing search to movement dynamics and body parts has on learning and performance in complex skills.

Instructional constraints that direct a learners search to movement dynamics may deprive them of the opportunity to discover and satisfy the multiple task constraints unique to each individual. Instructional constraints relating to the task goal early in practice should attempt to direct the search toward relevant feedback sources that take into account their movement effects on the environment. It appears that movement effects are an ideal interface between the performer and environment and that directed search should aim to exploit the information sources it affords in support of action. In this way performance consequences are realized and used in the development of an image of achievement to support further action. Less prescriptive, learner-regulated feedback, which complements discovery learning and encourages the player to explore the task environment, seems to be a more appropriate instructional technique.

Conclusion

The empirical data from these ongoing programs of work have revealed the potential of adopting a constraints-led viewpoint on skill acquisition in sport. From this constraints-led perspective' the major issues of concern for researchers include: (i) getting a better understanding of the term discovery learning and what it means to search, discover and exploit functional movement solutions; (ii) understanding how to break down sport tasks for the purposes of practice; (iii) exploring the validity of principles such as information-movement coupling for the design of practice conditions and learning environments (see Handford et al., 1997); and (iv), focusing on the nature and type of instructional constraints used during practice. Data reviewed in this paper suggest the importance of providing feedback to athletes in a self-regulated manner, directing search to movement-effects (i.e. an emphasis on developing an image of achievement) have the potential to provide better opportunities to constrain learners' search for emergent task solutions during discovery learning. These are particularly interesting issues as technological advances in equipment and programming (such as on-line motion analysis systems, biofeedback, and virtual environments) could become increasingly common tools in support work with elite athletes. An important challenge for practitioners will be to harness burgeoning new technology to effectively constrain activity during practice and training time. For example, recent advances in the use of information technology in the study of sport performance have highlighted the importance of enhancing intrinsic feedback mechanisms for athletes. High performance coaches in gymnastics and pistol shooting are now able to access augmented feedback technologies that sensitize performers to proprioceptive information in order to enhance balance and stability (Lieberman et al., 2002). A considered approach is necessary to understand how such augmented feedback devices might be employed within the practice environment. These, and many other issues, could form the basis of a theoretico-practical program of work on a constraints-led approach to skill acquisition in the coming years. From a constraints-led perspective, the major issue for researchers involves understanding the nature of the key constraints on performance and learning of skills.

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Coordination Dynamics and its Consequences on Sports

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The coordination or systems dynamics approach is very often reproached for the usage of fairly sophisticated instruments of analysis, which are only applicable on cyclic movements of single body limbs. In this article the possibility of transferring the coordination dynamics approach on ballistic and whole body movements will be explained by deriving commonalities from rather abstract levels of description. Within the methodological consequences the process oriented approach leads to the identification of highly individual movement patterns. As a rather practical consequence a new movement learning approach is derived which rather puts the focus on the adaptational part of a movement than on the movement itself. A major influence on this approach is given by a change. Several experiments verify the success of this differencial learning approach.

Introduction

Traditionally, methods of training in sports are strongly confirmed with models (Leitbilder) or idealized movements which are derived from top athletes in the respective sports discipline. In this context differences taken from such aims are most often considered as movement errors that have to be kept as small as possible until the desired form is achieved. Here, variability means uncontrollability and consequently, traditional methods of training adhere to the principle of avoidance of movement errors. On the analogy of behavioural conditioning, "correct" movements should be repeated several times. Concerning this, one assumes that the quality of a movement correlates to the number of repetitions. So far, biomechanical variables derived from the top athletes helped to detect those measures to be aimed at in performing the optimal technique. Epistemologically, this product oriented approach leads to numerous success in world class athletes as long as no-one else has ever tried another approach to achieve master ship.

In contrast to the question how to treat variability of movement outcome has become a core element in the study of movement coordination (Riley & Turvey, 2002). The acceptance of variances in movements lead to new concepts of motor learning that deal with and utilize those variabilities instead of avoiding them. It is shown how these ideas lead to a new approach of training, called differencial learning.

Two phenomena of special interest in coordination dynamics

At first glance it seems to be difficult to find connections between with various problems in sports and the finger experiment (Haken, Kelso, & Bunz, 1985), which can be considered as a milestone in the coordination dynamic approach. Considering this more precisely, the coordination dynamics approach *opened up new vistas*, which were formerly locked or overseen by self-determined too narrow boundary conditions, but in an unlocked situation provide deeper insight into movement coordination and movement learning in general. Introducing new perspectives, the coordination dynamic approach requires an assignment to another level of abstraction leading to new presuppositions and special terminology.

Only two characteristic phenomena of the coordination dynamic approach and its consequences on sports will be discussed in more detail in this article, and will be connected with some practical demonstrations. The first phenomenon, the phase, is closely related to the type of applied analysis and often emphasized in the experiments of Kelso and coworkers. The second phenomenon is related to a key element in the coordination dynamic approach and is used as a model for the explanation of the changes in variance of movements over time (Schöner & Kelso, 1988) and utilized for the sensation of torques of geometric objects (Turvey, Burton, Pagano, Solomon, & Runeson, 1992): fluctuations and intermittencies.

First phenomenon

According to physics the term “**phase”** in coordination dynamics is applied with two meanings or interpretations. On the one hand the term “phase” describes different states or modes of a system, like water, ice or steam. On the other hand the term “phase” describes the angular displacement of two sinusoidal functions. In both cases the term “phase” is closely related to different qualitative states of a system, which are taken under certain situations. If a shows system contains different states, it is most probably that each of the states will be traversed in the course of time and therefore both usages of the term phase are connected with processes. In the current approach the relative phase is an indicator for the description of the behaviour of at least two cyclic moving body segments. Besides mathematical reasons, another advantage of this measure is the possibility of describing a time continuous process by time discrete variables. Typicalof the relative phase is that the time delay of two equal events on two different waves within a cyclic movement is described. In the HKB-experiment the relative phase describes the relative shift of two fingers by passing e.g. a maximum flexion angle. By providing the relative phase of a movement cycle at a certain instant, the whole information about the interaction of two time courses is given. On a more abstract level the relative phase of two sinusoidal curves can be considered as a measure of similarity of their time courses. By extending the time discrete measure of a relative phase to a continuous measure of similarity a first door to sport science opens and transfers this approach to ballistic and complex types of movements. Hereby, similarity is a statistical measure for the proximity of two objects and can easily be transferred into distance measures by strong linear maps and vice versa (Everitt, 1993).

Second Phenomenon

The terms “**fluctuations and intermittencies**” Kelso’s and coworkers fingerexperiments(Kelso, 1995) occur in the context of multiple repetitions of the “same“ movement with an adequat precision of measurement. Actually, these terms repeat the phenomenon that was formulated by Bernstein’s statement ”repeating without repetition” (Bernstein, 1967), or, expressed by Heraklitus’ famous dictum: “You never step into the same river twice”. Although the intended finger or hand movements seem to be simple in comparison to complex sport movements like pole vaulting or football playing, it seems to be impossible to move the fingers exactly in a given relative phase. We always observe more or less deviations from the given value. Most intriguing, by traditional sports or movement theories these ubiquitous phenomena had either to be avoided during learning processes or to be patient under compulsion when the deviations were very small, which depends on the size of deviation from a target value (soll-value). In the theory of coordination dynamics ‘fluctuations and intermittencies’ prepossess core roles by describing several phenomena. Besides the stability dependent size of fluctuations, the transition from one stable state to another is only achieved by a dramatic increase of the fluctuations. Due to the numerous analogies in statistical physics and thermo dynamics a further ‘door’ to a large field of already existing research results opens. In another branch of coordination dynamics fluctuations were utilized in order to find sensationally the main momentums of inertia of geometric objects (Solomon, Burton, & Turvey, 1989). By means of a dynamic touch subjects were able to sense the ‘Eigenvectors’ of rods with different shapes.

Consequences on the analysis of movements

As a consequence of the transition from the relative phase to the process oriented proximity measure, the analysis of sports movement has altered. Whereas traditional time discrete quantitative analyses of sports movements were mostly limited on comparisons within the same types of movement. The new process oriented approach allowed to compare quantitatively new movement qualities like classes of movements (e.g. running, jumping, throwing), modes of movements (e.g. springy, creepy running) and styles of movements (individual expressions of classes and modes) (Schöllhorn, 1998). Therefore, different timescales have to be distinguished. Considering each movement execution as a process, the analysis requires a time scale of milliseconds. In contrast changes of movement patterns due to learning or developmental processes are analysed with a measurement frequency that typically amounts at least a time between two movement executions. Both time scales were taken into consideration during a training experiment in discus throwing (Schöllhorn 1998). For this double process oriented analysis of a discus learning process two top level athletes were accompanied with biomechanical feedback training during several training sessions and competitions. The kinematic data were acquired by means of two high speed cameras (200Hz). 20 body landmarks were digitised in each frame of the final throwing phase which starts when the left foot touches down and ends when the discus releases the hand. From the discus specialist 8 throws in competition were analysed during one year and from the decathlete 45 throws during training sessions and competitions.

The process-oriented comparison reveals clearly individual throwing patterns of both athletes and the identification of a qualitative change in the throwing pattern by the discus specialist and certain strategies during each training session. All results could only be achieved by analysing the throwing pattern in a process oriented way. By investigating the same discus throwing processes on the basis of time discrete parameters, continuous fluctuations could only be identified, although the athletes already performed several thousand throwing repetitions. According to former theoretical derivations, e.g. (Bernstein, 1967) and (Hatze, 1986), these fluctuations provide further strong evidence for an extremely low probability of finding two identical movements.

Meanwhile several studies have verified the individuality of movement patterns in running (Schöllhorn & Bauer, 1998a), walking (Schöllhorn, Nigg, Stefanyshyn, & Liu, 2002), javelin throwing (Schöllhorn & Bauer, 1998b) and other sport movements independent of age and performance level.

Furthermore, the process-oriented idea was transferred to several areas of research. Mainly two areas of research can be distinguished. The first area covers methodological questions about which variable and how many variables are necessary to detect the best recognition rate. Until now the pressure distribution below the foot provides the best recognition rates of bare foot gait patterns (Schöllhorn, Schaper, Kimmeskamp, & Milani, 2002).

The second field of research concentrates primarily on the application in different types and modes of movements. The application of the time continuous approach in a most recent study about gait patterns allowed to recognize the ability to express emotional states in an individual gait pattern. Hereby the individuality seems to be stronger than the emotional involvement (Bühner, 2003). The question about similarities within gait patterns of family members was of central interest in the study of (Lubinietzki, 2002). Gait patterns of two families, consisting of parents and two female siblings, were compared with each other on the basis of kinematic and dynamic variables during ground contact phases. The similarity and classification analysis provided differentiated results. Dependent on the partitioning of the variables both families could not be separated completely and displayed quite different similarities with respect to the lower and upper body or with respect to the left and right body side. Even the variations within the siblings excelled the variations between the siblings.

A transfer of the process-oriented approach to team sports leads to the recognition of team characteristic defence patterns in women's volleyball (Westphal & Schöllhorn, 2001). If the time discrete approach is assigned to a rather reductionistic character, the time continuous approach corresponds to a more holistic character. Whereas the reductionistic time discrete approach typically is applied by scouting approaches in team sports (Bremer, 1980), where each event is considered as a single independent situation, a specific time continuous approach with rather holistic character is followed by investigations with probabilistic objectives ((Lames, 1991),(Perl, 1997)) where series of single events are analysed by Markoff-chains or transition probabilities. Transferring the part-whole problem from time to space dimension, an analogous structure can be defined in space. In a rather reductionistic glance only spatial positions of single players are analysed separately, whereas in a more holistic view information about relative positions of all players as well as information about "holistic" team qualities are central objectives of investigation. Holistic measures for describing the behaviour of a team in space and time as a whole are (Figure 1):

a) time courses of movements of several or all players,
b) covered area of several or all players,
c) common centre of gravity of several or all team members
d) geometric shape which is formed by several or all team members.

In connection with the dimension of time all changes of the spatial parameters b)-d) over time provide fruitful information about the behaviour of a team as a whole.

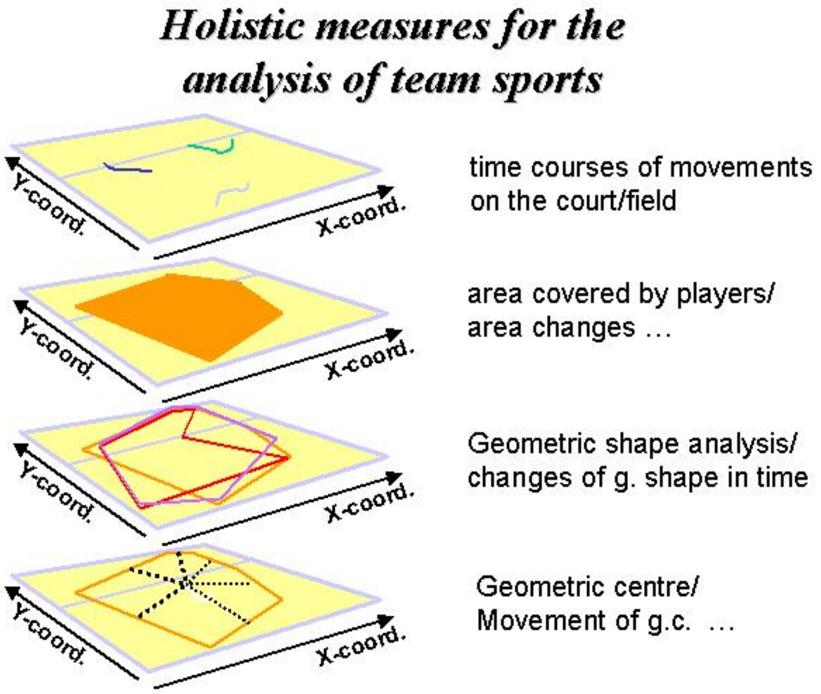

Figure 1: Holistic measures a)-d) for the quantification of tactical movements in team sports

Consequences on Sports practice

In comparison to the traditional training philosophy in most kinds of sports, in which an ideal solution of a movement problem is demonstrated by the momentary world's best athletes, the identification of individuality in movement patterns, independent of performance level and age, leads to contradictions. A further problem within the traditional training philosophy of sports is present by the fact that an extremely low probability of performing in an identical way twice exists. Furthermore, individual ideal techniques change continuously and it is very unlikely to reproduce exactly the same movement during competition and training In consequence, an alternative approach is suggested: the differencial learning approach (Schöllhorn, 2000). A theoretical support for the differencial learning approach is provided by the epistemiological qualitative step in the coordination dynamics approach that considers the observable fluctuations and intermittencies not as a disturbance or measurement error, but rather as a necessity for adaptive systems. Hereby, a new question arises. If fluctuations seem to be core elements or variables of major influence in adaptive systems, does a change in the expression of this variable lead to a change in the adaptive process automatically? Utilizing fluctuations in form of wielding rods for the recognition of momentums of inertia of hand held objects has been shown by Turvey and coworkers quite innovatively (Solomon et al., 1989). However, the differencial learning approach puts major focus on the increase of fluctuations. Besides continuously changing individual movement patterns the differencial learning approach emphasises the human ability of interpolation. If no movement repetition is identical, every movement repetition logically contains new elements to which the athletes have to adapt to. Therefore, the major aim of the differencial training approach is to confront the athlete with new movement tasks all the time in order to improve his ability to adapt to new situations rapidly. Instead of intending to improve stability in the first place, the differencial learning approach focuses on the adaptability to new situations. Both abilities are characteristic for top-level athletes with one major difference. If some one is able to adapt to new situations instantaneously he is able to move stable but not vice versa. The stability of a movement becomes a by-product of the ability to adapt to new situations quickly.

Meanwhile, in several pre-post-test designed experiments the differencial learning approach was compared to traditional training approaches. Exemplarily, one experiment on training shot putting is displayed in more detail. Two groups of sport student, in each group 10 subjects participated in the experiment. After the pre-test all subjects were assigned to each group randomly. The pre-, post- and two retention tests were a shot put with out approach. In the 4 weeks training period 8 training sessions were completed. The retention tests controlled the performance after 2 and after 4 weeks of no special shot put training. The traditional training group trained according to an increase of the difficulty in the exercises beginning with the easiest exercises and repeated each exercise until the basic technique coincided with an ideal execution. The differencial training group performed over 260 different exercises during the 8 training sessions by avoiding any repetition.

Whereas in the pre-test both groups shot put 6.51m and 6.52m with no significant difference, in the post-test the traditional group improved significantly up to 6.75m. Moreover the differencial group increased the average performance highly significant up to 7.07m. In the first retention test the traditional group dropped back to the starting level of 6.50m and remained there for the second retention test too. Most intriguingly the differencial group showed a further improvement of their performance in the first retention test with 7.19m and with 7.36m in the second retention test, too. Obviously, the differencial training group improved almost by the same distance in the retention phases like the group did during the training period. Because an ongoing improvement in performance after the post-test could be diagnosed in one training group a real learning process seemed to be initiated by the

differencial learning approach in which the athletes learned how to learn. These phenomena of better improvement during the training process and continuing increase in performance after differencial training could be verified in technical training in soccer, basketball, tennis and several other kinds of sports.
Without knowing the process of adaptation in detail, similar improvements in balance control were achieved by applying subconsciously mechanical noise to the feet demonstrated in an investigation about stochastic resonance (Priplata et al., 2002). With respect to this phenomenon further potential is expected.

Overall the coordination dynamics approach provides various innovative ideas with which numerous ideas of the gestalt psychologists and Bernstein were proceeded. The presented scientific and practical consequences on sports just highlight a small extraction of a huge spectrum. Nevertheless, the practical consequences as demonstrated in the differencial learning approach seem to contain a large potential for alternative ways on improving individuals and team performances.

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Dynamic Systems and Performance in Team Sports

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Abstract

In order to create an appropriate training process for team sports, it is relevant to define a differential paradigm of sport performance. Traditionally, the sport training science has been developed through the study of the needs of several individual sports and, in contrast, its results are applied to team sports. We strongly believe that the analysis of the dynamic complex systems theories will provide us the best theoretical basis to construct a specific training science for team sports. Accordingly, it is necessary to modify the systematical Cartesian paradigm in such a way that can provide more adequate solutions to explain the complexity. Our proposal is to build channels of access between these theories and the different levels of the training process of team sports.

KEY WORDS: STRUCTURAL TRAINING, TEAM SPORTS, DYNAMIC COMPLEX SYSTEMS.

Sport in the 20th Century

Sport in the 20th century is developed by means of its teaching and its training. The teaching-learning processes are based on behaviorists theories ("what is observable") such as psychology, pedagogy, didactics and methodology. The training-performance processes are based on mechanistic theories ("what is measurable") such as physiology, physics, medicine and biomechanics. These sciences –through its contributions- have been useful to construct an atomist and multidisciplinary sport model; in other words, a model based on the dualism "mind-body" that has been an ongoing debate since the beginning of the human knowledge.

Classical Paradigm

In the classical paradigm there exists a reproduction of models by ... "contrasted evolution". The model is reproduced depending on:

The evolution of the rules.
The evolution of the competition demands.
The evolution of the knowledge of the coach.
The evolution of the social and economical valuation of sport.
The evolution of technology and research applied to sport.

All of them are external, alien to the athlete. The model is made up from the sport and from society.

Fundamentals to Practice

Behaviorist and mechanistic theories have developed certain practices to achieve these models.

Practices of global tendency (during the first stages of sport learning): global training and small games.

Practices of analytical tendency (during stages of sport performance): technique, tactic and physical conditioning.

Both of them, are developed by quantitative practices of lineal and progressive sequences of analytical exercises.

The player is built in order to fulfill the demands of a certain model that at this moment "dominates" a concrete sport.

This paradigm, now in recession, has dominated our culture for several hundreds of years, during which it has been constituted our occidental society and considerably influenced the rest of the world.

Such paradigm consist of an entrenched set of ideas and values among which we can mention the following: the vision of the universe as a mechanical system that is compound of pieces, the vision of the human body as a machine, the vision of living in a society as a competitive struggle for survival, the belief in the unlimited material progress by the economical and technological growth, ...(Capra, 1998).

Sport in the 21st Century

Sport in the 21st century is developed by means of an integral development of the athlete ("mind-body" as a whole). Its teaching and training are an unique optimization process of the athlete. Cognitivism and structuralism _supported by organizational biology, neural-sciences, theory of the systems, theory of the information and ecological theories_ achieve the auto-modeling or auto-structuring of the athlete.

Consequences: New Paradigm

The aim is to achieve the auto-structuring by "differential optimization" and this is obtained by means of:

The establishment of technical-tactical skills in which the player shows a certain competence.

The observation of the impact that competition causes to the player.

The constant acquisition of new knowledge of the player about the game, training and himself.

The formation of the own social image.

The achievement of the knowledge of the player during practice by means of technology and adequate research tools.

All of them are related to the athlete. The proposals are taken from the athlete.

If proposals are taken from the athlete, it is necessary to modify our thought, ideas and values about the sport-person as a living being that seeks the constant dynamic interaction between what is rational, analytical, reductionist, lineal, competitive, quantitative (for individual sports) and what is intuitive, synthetic, holistic, non-lineal, cooperative, qualitative (for team sports).

The Athlete According to These Theories

Based on the new paradigm, we are nowadays able to interpret the sport-person as a hyper-complex structure that is made up by interactions and retroactive actions between the following structures:

- Conditioning structure
- Coordination structure.
- Social-Affective structure.
- Emotional-Volitive structure.
- Creative-Expressive structure.
- Mental structure ... ?

Each structure must be considered as the expression of underlying processes.

This means that the processes _a complete net of dynamic connections among systems_ become apparent through what we call structures.

Also, what we traditionally call capacities are just forms of sectorial evaluation of part of the processes that occur in some systems which makes up a determined structure.

1st Contribution of the Systems Theory to the Development of Training

This systematic and holistic conception of the player will provide clues about the conditions under which the athlete must develop his training activity in order to obtain his differential auto-structuring. As a result, the own contents of the structural training appear; understanding that despite it can also provides new elements to “individual” sports, it is much more adequate for “team” sports in which the continue interaction among objects-partners-opponents requires high levels of auto-structuring of all their components.

Therefore, high variation contents and high variability practices are relevant.

As pointed out in the new paradigm, teaching and training are a single fact of optimization of processes which will become apparent as properties of each aforementioned structure, because these properties can only be considered from two standpoints:

- The dynamic inter-activity of all the systems.
- The global consistency of their interactions ...

We must construct specific exercises of structural training that provide such dynamic inter-activity and consistency; in contrast to the repetitive and analytical training exercises typically used by individual sports and based on other theories.

Practical Conditions

These practice requirements are offered by Preferential Simulation Situations. It must be defined such determined conditions of work that fix a “preferential” performance on some of the functional systems of the athlete. Thus, we will make up the building of the conditioning substratum of the training system. It is applied by certain movement forms that the athlete performs during his practice. These movement forms must include basic coordination elements that support the sport technique _execution of coordinate simulation_. (Stable levels that assure the consistency of the interactions). They are practiced under concrete situations which contain relevant information that must be processed so as to perform consequently. The cognitive structure must be involved. Connections with the partners-opponents-object must be established to feed the social-affective structure. Episodes of specific personal challenge must be experienced so as to commit the emotional-volitive structure. (Levels for the variability that provides dynamic inter-activity).

2nd Contribution of the Systems Theory to the Development of Training

One of the essential properties of any life manifestation is the irreducible tendency to construct multi-level structures of systems inside of systems. These structures are consequence of varied inter-active processes among systems of differential complexity that take shape as a net in which nothing is the most important.

This triggers the need to modify the laws of the traditional training, inasmuch as synergy relations are more used than progressive training loads and sequential planning is substituted by differential priority. Many other principles based on the hierarchical and lineal conception must be substituted by inter-connected multi-level guidelines.

Practical Consequences

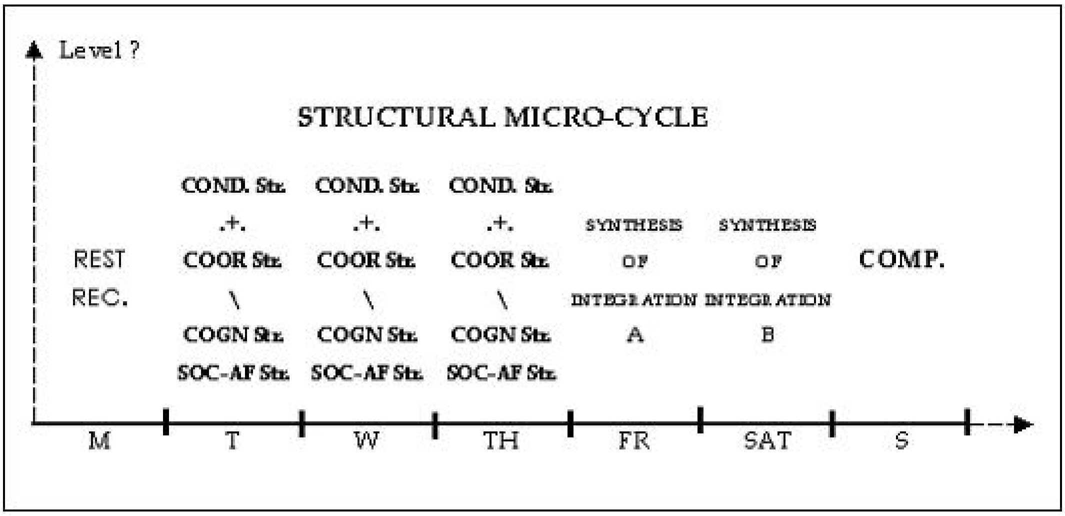

Figure 1. Model of a Structural Micro-cycle.

Every training day, there exists a differential priority adjusted to the needs of the athlete. All priorities are integrated in the synthesis pre-competition.

The total of contents of each micro-cycle are related with the consecutive and next micro-cycles. This is based on different inter-connection guidelines so as to obtain a high level of structural optimization.

3rd Contribution of the Systems Theory to the Development of Training

We know that the function of the components of such nets is to participate in the production or transformation of other components of the net. Consequently, all the net is built by itself. This provokes that the product of processes is the own organization, the differential auto-organization based on processes of qualitative production which bring about each unique human being.

On the whole, the called improvement of performance can not be evaluated by quantitative criteria that are alien to the person; on the contrary, they should be evaluated by qualitative proposals which are based on the interpretation that the own athlete is able to complete at any episode and from any perspective of the practice that performs.

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Models of Ventilatory Control During Exercise: Peripheral Chemoreflex Considerations

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Abstract

Models of ventilatory ($\dot{V}_E$) control during exercise have classically incorporated both proportional humoral feedback (carotid and central chemoreflex) and neurogenic feedforward (central command, muscle, cardio-circulatory) control. During moderate exercise (below the lactate threshold, θ_L), $\dot{V}_E$ manifests first-order kinetics ($\phi 2$), increasing mono-exponentially to the new steady state; the close correlation of $\dot{V}_E$ with pulmonary CO_2 output ($\dot{V}_{CO_2}$) ensuring stability of arterial PCO_2 and pH (and PO_2). Above θ_L, $\dot{V}_E$ kinetics become nonlinear, and steady states are either delayed or not attained. This reflects the influence of the developing metabolic acidemia on $\dot{V}_E$ (a) indirectly via body CO_2 stores washout which augments $\dot{V}_{CO_2}$ and (b) directly to effect respiratory compensation (the hypocapnia resulting from $\dot{V}_E$ increasing out of proportion to $\dot{V}_{CO_2}$ constrains the fall of pH). The carotid bodies (CBs) are widely regarded to fine-tune arterial blood-gas and acid-base regulation, by speeding $\phi 2$ $\dot{V}_E$ kinetics and increasing the steady-state $\dot{V}_E$ response amplitude; events which might be expected to lead to a loss of first-order behavior, but do not. The CBs are also important in mediating the respiratory compensation above θ_L, which has surprisingly slow kinetics (i.e. inconsistent with the rapidity of CB responses to infused acid loads in animals). These issues are explored in the context of recent advances in both ventilatory control and CB chemotransduction.

KEY WORDS: CAROTID BODIES, CHEMOTRANSDUCTION, KINETICS, DEJOURS TEST, RESPIRATORY COMPENSATION

INTRODUCTION

Models of ventilatory ($\dot{V}_E$) control during muscular exercise have classically incorporated elements of proportional chemosensory feedback (peripheral-carotid, central-medullary) and neurogenic feedforward (central command, intramuscular, cardio-circulatory) (Dejours, 1964; Whipp, 1981; Whipp & Ward, 1991; Ward, 1994a; Dempsey, Forster, Ainsworth, 1995; Waldrop, Eldridge, Iwamoto, & Mitchell, 1996; Ward, 2000), although cardio-circulatory pathways responsive to changes in central circulatory pressures and peripheral vascular conductance and/or tissue pressure within the exercising muscles have also been proposed (Wasserman, Whipp, & Castagna, 1974; Haouzi, Hill, Lewis, & Kaufman, 1999). However, despite there being general agreement regarding the overall characteristics of the $\dot{V}_E$ response to exercise, the precise details of the control process(es) remain unresolved. This is the consequences of several factors, such as: technical and interpretational limitations inherent in isolating putative control mechanisms in the intact human, species differences in animal species, and the limitations of conventional linear control theory in accommodating multiple-input integration, especially with regard to the ventilatory and gas-exchange complexities encountered at work rates engendering a metabolic acidosis. What many investigators now recognize is that the peripheral chemoreceptors (the carotid bodies, in humans (Holton & Wood, 1965; Wade, Larson, Hickey, Ehrenfeld, & Severinghaus, 1970; Lugliani, Whipp, Seard, & Wasserman, 1971; Swanson, Whipp, Kaufman, Aqleh, Winter, & Bellville, 1978; Honda, Watanabe, Hashizume, Satomura, Hata, Sakakibara, et al., 1979b)) exert significant, and often obligate, modulating roles both in moderate exercise (below the lactate threshold, θL) and also at higher work rates. This article interprets relevant aspects of the evidence base relating to carotid body (CB) control of the exercise hyperpnea in humans, in the light of recent advances in both ventilatory control and CB chemotransduction. Based on both in situ and in vitro investigations on a range of different species (e.g. rat, rabbit, cat), it is now generally agreed that the sensing of hypoxia, hypercapnia and metabolic H+ occurs at the "presynaptic" glomus (or Type I) cell, involving membrane depolarization, activation of high-threshold voltage-gated calcium (Ca2+) channels, elevation of cytoplasmic [Ca2+] and neurotransmitter release for post-synaptic stimulation of afferent nerve endings (Buckler & Vaughan-Jones, 1994; Gonzalez, Dinger, & Fidone, 1995; Waldmann, Champigny, Bassilana, Heurteaux, & Lazdunski, 1997; López-Barneo, Pardal, Montoro, Smani, Garcia-Hirschfeld, & Ureña, 1999; Buckler, Williams, & Honorre, 2000; Petheö, Molnár, Róka, Makara, & Spät, 2001; Peers, 2002).

MODERATE-INTENSITY EXERCISE

The fundamental challenge to conventional humoral control of $\dot{V}_E$ by CB (and central chemoreceptor (CCR)) mechanisms in moderate exercise is the lack of demonstrable sustained error signals in arterial PCO_2 ($PaCO_2$), PaO_2 (PaO_2) and pH (pHa). Clues to the identity and operation of alternative humorally-mediated control models emerge from considerations of the $\dot{V}_E$ response kinetics.

Transient Responses

In response to a range of classical dynamic work-rate forcing functions (e.g. square-wave, ramp, impulse, sinusoidal), the predominant phase 2 ($\phi 2$) $\dot{V}_E$ component responds as a linear first-order process, as do O_2 uptake ($\dot{V}O_2$) and CO_2 output ($\dot{V}CO_2$) (e.g. Linnarsson, 1974; Hughson & Morrissey, 1982; Whipp, Ward, Lamarra, Davis, & Wasserman, 1982; Whipp & Ward, 1991; Miyamoto, 1992; Ward, 2000):[1]

$$H(s) = Ae^{-s\delta}/(1 + s\tau) \qquad (1)$$

where s is the Laplace notation of the complex frequency variable, A is the steady-state (zero-frequency) amplitude of the $\dot{V}_E$ response (also $\Delta\dot{V}_{Ess}$), τ is the $\dot{V}_E$ time constant, and δ is a delay term that reflects the limb-to-lung vascular transit time and any delays associated with signal transmission from the lungs, chemotransduction and reflex transmission (Whipp et al., 1982). Implicit in the assumption of linearity is that A, τ and δ are independent of both the baseline work-rate and the imposed work-rate forcing function (i.e. satisfying the principle of superposition).

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[1] i.e. neglecting the initial phase 1 ($\phi 1$) component that is expressed over the first 15-20 s of exercise where $\dot{V}O_2$ and $\dot{V}CO_2$ are essentially determined only by the increases in venous return and therefore pulmonary perfusion.

Thus, for square-wave work-rate forcings, this yields:

$$\Delta \dot{V}_E(t) = \Delta \dot{V}_{Ess} \cdot (1 - e^{-(t-\delta)/\tau}) \qquad (2)$$

where $\Delta \dot{V}_E(t)$ is the $\dot{V}_E$ increment at time t.

As $\phi2$ $\tau \dot{V}_E$ is normally ~55-65s, $\dot{V}_E$ cannot correlate temporally with work rate, or with muscle O_2 consumption ($\dot{Q}O_2$), muscle CO_2 production ($\dot{Q}CO_2$) or $\dot{V}O_2$ - all of which have appreciably faster kinetics (i.e. ~30-40s) (Whipp et al., 1982; Barstow, Lamarra, & Whipp, 1990; Whipp & Ward, 1990 & 1991; Grassi, Poole, Richardson, Knight, Kipp Erickson, & Wagner, 1996). Interestingly, the $\phi2$ τ for $\dot{V}CO_2$ (~50-60s) is very similar to, but slightly shorter than, that for $\dot{V}_E$. This close "matching" of $\dot{V}_E$ to $\dot{V}CO_2$ in $\phi2$ (e.g. Linnarsson, 1974; Whipp et al., 1982; Miyamoto, 1992; Whipp & Ward, 1990 & 1991) (Fig. 1) is preserved even when $\tau \dot{V}CO_2$ is experimentally manipulated (reviewed in Whipp & Ward, 1990 & 1991). Thus, it seems as if the ventilatory control system is somehow "aware" of the component of metabolic CO_2 production that is not expressed at the lungs but rather is stored in the high-capacitance (predominantly exercising muscle) CO_2 stores. This stored component therefore does not constitute any demand for a hyperpneic component to effect regulation of $PaCO_2$.

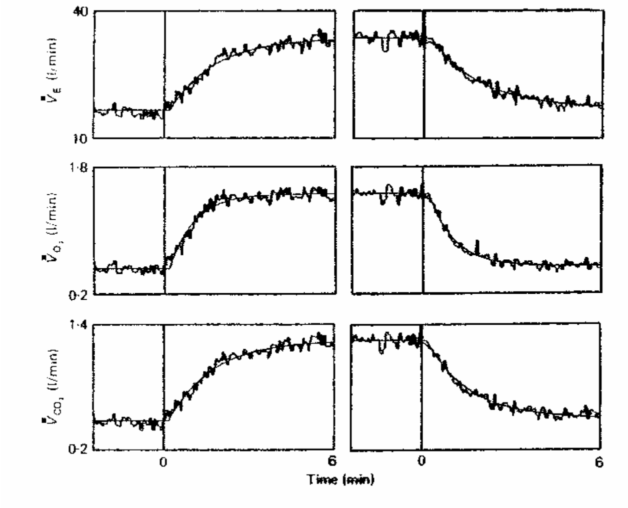

Figure 1. $\dot{V}_E$, $\dot{V}CO_2$ and $\dot{V}O_2$ responses to square-wave cycle-ergometer exercise from a background of unloaded pedaling. Taken from Griffiths et al. (1986), with permission.

These observations are not readily compatible with simple neurogenic models, unless in the seemingly unlikely event that the feedforward drive(s) manifest kinetics similar to those of $\dot{V}CO_2$. It is perhaps not unreasonable, however, to view the CBs as the first "temporal" line of defense against the impact of an increased metabolic rate on arterial blood-gas and acid-base status (Dejours, 1962 & 1964). Indeed, the limited available evidence suggests that the CBs initiate the $\phi2$ hyperpnea; i.e. the duration of the $\phi1$ hyperpnea is prolonged during hyperoxia, relative to normoxia (Cunningham, Spurr, & Lloyd, 1968; Ward & Bellville, 1983) (The more stringent requirement to demonstrate that the $\phi1$-$\phi2$ transition for $\dot{V}_E$ is delayed, relative to that for $\dot{V}O_2$ and $\dot{V}CO_2$, by the lung-to-CB transit delay has yet to be reported.) In addition, the CBs exert a significant modulating effect on the $\phi2$ $\dot{V}_E$ kinetics: increasing CB chemoreflex sensitivity (e.g. by inhalational hypoxia or NH_4Cl-induced metabolic acidemia) shortens the $\phi2$ $\tau \dot{V}_E$, both in absolute terms and relative to $\dot{V}CO_2$ (Oren, Whipp, & Wasserman, 1982;

Griffiths, Henson, & Whipp, 1986; Ward, Blesovsky, Russack, Ashjian, & Whipp, 1987b); suppression of CB responsiveness (e.g. by inhalational hyperoxia, NaHCO$_3$-induced metabolic alkalemia, dopamine infusion[2], and bilateral carotid body resection (CBR)) lengthens the $\phi 2$ $\tau \dot{V}_E$ (Wasserman, Whipp, Koyal, & Cleary, 1975; Oren et al., 1982; Boetger & Ward, 1986; Griffiths et al., 1986; Ward et al., 1987b; Whipp, Baum, Winter, & Ward, 1993) (Fig. 2).

Meaningful model structures of the exercise hyperpnea require a precise knowledge of the exact magnitude of the CB contribution to both the $\phi 2$ (and $\phi 3$) $\dot{V}_E$ responses. There is some uncertainty in this regard, even for $\phi 3$. Thus, perhaps the most widely-used tool to effect a functional "silencing" of the CB chemoreflex in humans is the inhalation of 100% O$_2$, at least for rest and moderate exercise (Miller, Cunningham, Lloyd, & Young, 1974; Ward & Bellville, 1983). However, sustained hyperoxia of even only a few minutes' duration also predisposes towards to secondary CCR stimulation consequent to a lowered brain pH caused by a reduced cerebral vascular buffering power and cerebral vasoconstriction (reviewed in Dejours, 1962; Ward, 1994b) and to the hypercapnia resulting from the initial hypoventilation. This complicates identification of that component of the ensuing "steady-state" hyperoxic $\dot{V}_E$ response that can confidently be attributable to CB inactivation.

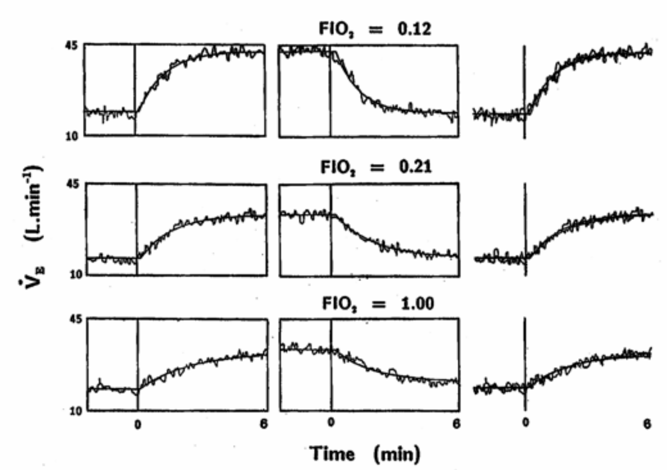

Figure 2. $\dot{V}_E$ responses to square-wave cycle-ergometer exercise from a background of unloaded pedaling, against hypoxic, normoxic and hyperoxic backgrounds (inspired [O2] fraction = 0.12, 0.21 and 1.00). Left: on-transient responses, with the best-fit exponential superimposed. Center: off-transient responses, with the best-fit exponential superimposed. Right: off-transient responses (reversed) superimposed on the corresponding on-transient responses (note "on-off" symmetry). Taken from Whipp & Ward (1991), with permission.

The transient O2-switching technique that Dejours pioneered at rest and in the steady-state ($\phi 3$) of exercise is not prey to such concerns, as it provides a brief temporal window within which the primary hypoventilatory actions of O2-induced CB inactivation can be expressed in isolation (Dejours, 1962). That the carotid bodies mediate this transient hypoventilation is indicated by (a) the latency of the initial ventilatory decline corresponding to the lung-to-carotid body transit delay (Dejours, 1962) and (b) the transient hypoventilatory response

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[2] It is important to recognize that dopamine can exert both inhibitory and excitatory effects at the CBs, through pre- and post-synaptic actions at the glomus cell-nerve ending synapse; effects which reflect in part dose-dependency and also species differences (reviewed in Gonzalez et al., 1995).

being absent in CBR subjects (Whipp & Wasserman, 1980) (Fig. 3). However, the use of the Dejours technique to quantify the proportional CB contribution to the exercise hyperpnea during $\phi2$ is a challenging prospect, as account has to be taken of the kinetics of the developing $\phi2$ $\dot{V}_E$ response over the period both for which the hyperoxia is transiently administered and the ensuing hypoventilation is subsequently manifest. Studies of this kind have yet to be reported.

Regardless, it is evident that the CBs dictate the precision with which PaO_2, $PaCO_2$ and pHa are regulated in $\phi2$. Thus, as $\tau \dot{V}_E$ is appreciably slower than $\tau \dot{V}_{O_2}$, PaO_2 will fall transiently during $\phi2$ (Young & Woolcock, 1978; Oldenburg, McCormack, Morse, & Jones, 1979). Any equivalent tendency towards CO_2 retention will be less marked, owing to the normally-small kinetic dissociation between $\dot{V}_E$ and $\dot{V}_{CO_2}$, the corresponding transient increase of $PaCO_2$ is small and less easily discerned (Whipp, Wasserman, Casaburi, Juratsch, Weissman, & Stremel, 1978), but readily predictable in terms of maximum amplitude ($\Delta PaCO_{2max}$) and point of occurrence (t_{max}) (Whipp, Griffiths, & Wasserman, 1983):

$$\Delta PaCO_{2max} = \{\tau \dot{V}_{CO_2} / \tau \dot{V}_E\} \cdot \{\Delta \dot{V}_{Ess} / \Delta \dot{V}_{CO_2ss}\} \cdot e^{-\{(t_{max}/\tau \dot{V}_E\} - (t_{max}/\tau \dot{V}_{CO_2})\}} \qquad (3)$$

$$t_{max} = \{\tau \dot{V}_E \cdot \tau \dot{V}_{CO_2}\} / \{\tau \dot{V}_E - \tau \dot{V}_{CO_2}\} \cdot \ln(\tau \dot{V}_E / \tau \dot{V}_{CO_2}) \cdot (\Delta \dot{V}_{CO_2ss} / \Delta \dot{V}_{Ess}) \cdot \Delta PaCO_{2max} \qquad (4)$$

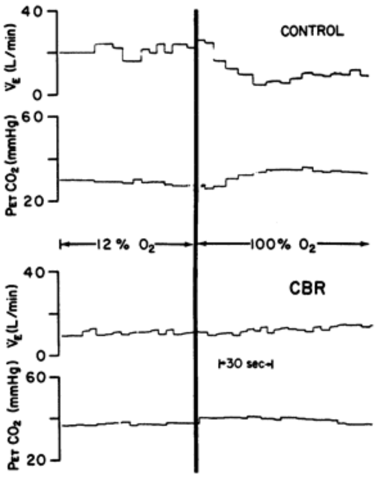

Figure 3. Responses of $\dot{V}_E$ and end-tidal PCO_2 ($P_{ET}CO_2$) to abrupt inhalation of 100% O_2 from a background of 12% O_2 in a normal subject (above) and a subject who had previously undergone bilateral carotid body resection, CBR (below). The magnitude of the $\dot{V}_E$ decrease from the prior control to the nadir of the decline provides an estimate for the oxygen-labile component of the $\phi3$ hyperpnea. Note that, in the CBR subject, there was no decrease of $\dot{V}_E$ in response to the hyperoxia. Taken from Whipp & Wasserman (1980), with permission.

Thus, in the absence of any CB chemoreflex contribution to the $\phi2$ hyperpnea, it is evident that the $PaCO_2$ overshoot (and the PaO_2 undershoot) will be more prominent and will occur earlier. This raises the issue of whether, under normal (i.e. normoxic) conditions, the developing asphyxic condition might provide a feedback drive to $\dot{V}_E$ in $\phi2$ through the CBs - given their location and low CO_2 capacitance (relative to that of the local environment of the CCRs). However, it is difficult to envisage the asphyxic condition being sufficiently profound to evoke any significant amplification of the developing $\phi2$ $\dot{V}_E$ response through conventional CB CO_2 and hypoxic ventilatory responsiveness. That is, hypoxia is known to elicit prompt inactivation of CB hypoxia-sensitive K^+ channels (e.g. Gonzalez et al., 1995; Lopez-Barneo et al., 1999, Peers, 2002), while hypercapnia (through a fall in glomus cell intracellular pH) inhibits CB calcium-activated K^+ channels (e.g. Buckler & Vaughan-Jones, 1994), with consequent increase in carotid sinus nerve afferent discharge (Fitzgerald, Leitner, & Liaubet, 1969; Black, McCloskey, & Torrance, 1971; Ponte & Purves, 1974). However, the corresponding chemoreflex CO_2 and hypoxic gains (i.e. based on the $\dot{V}_E$ responsiveness to iso-oxic hypercapnia and to isocapnic hypoxia in the normoxic to mildly-hypoxic region) are insufficiently large to expect anything other than a rather minor contribution, even in exercise (Clark, Sinclair, & Lennox, 1980; Poon & Greene, 1985; Weil & Swanson, 1991; Ward, 1994a).

These recognitions have led to the search for alternative propositions. One which has received considerable attention is the "oscillations" hypothesis (Yamamoto, 1960), whereby features such as the amplitude and/or rate of change of the respiratory-related H^+-$PaCO_2$ oscillation in arterial blood, and its "phase-coupling" (Whipp, 1981) characteristics to the ongoing respiratory cycle, have been argued to provide a CO_2-linked ventilatory drive operating through the CBs (e.g. Hornbein, Griffo, & Roos, 1961; Biscoe & Purves, 1967; Black & Torrance, 1967; Band, Cameron & Semple, 1970; Black, McCloskey, & Torrance, 1971; Eldridge & Millhorn, 1991; Cross, Stidwell, Hughes, Peppin, & Semple, 1995; Torrance, 1996) not only in the steady-state of exercise, but also in $\phi2$. However, while there is evidence that the rate of change and amplitude of the pHa oscillation increases soon after exercise onset (Band, Wolff, Ward, Cochrane, & Prior, 1980), Murphy, Stidwell, Cross, Leaver, Annastasiades, Phillips, et al. (1987) found the pHa oscillation increasingly difficult to detect as work rate was increased. In addition, no consistent change could be discerned in the phase-coupling characteristic that would predispose towards increased CB reflex responsiveness in $\phi2$ (Ward, Swain, & Frye-Kryder, 1984) or in $\phi3$ (Petersen, Whipp, Drysdale, & Cunningham, 1978).

It has also been proposed that arterial $[K^+]$ may influence the $\phi2$ $\dot{V}_E$ kinetics via CB activation, through an increased glomus cell K^+ reversal potential (e.g., Band, Lim, Linton, & Wolff, 1985; Paterson, 1992; Nye, 1994). However, more-recent studies using sinusoidal work-rate forcings (with the associated higher discriminability than for single square-wave tests) have shown arterial $[K^+]a$ kinetics to be sufficiently faster than those of $\dot{V}_E$, to render a simple causal link unlikely (Casaburi, Stringer, & Singer, 1995).

Any realistic control scheme should, however, accommodate the maintained exponentiality of the $\phi2$ response with altered degrees of CB modulation. That is, despite changes in $\tau\dot{V}_E$ of some three-fold with altered CB drive, the $\phi2$ hyperpnea retains its exponentiality (Fig. 2) (Griffiths et al., 1986). This places constraints on models of the $\phi2$ $\dot{V}_E$ control process. Ward, Lamarra & Whipp (1987b) formulated a two-compartment model, with physiologically reasonable parameter values, that met this criterion (Fig. 4). A "fundamental" exponential component reflecting operation of the $\phi2$ control process in the absence of CB drive was assumed to be approximated empirically by the hyperoxic condition (Fig. 2), with $\Delta\dot{V}_{Ess} = 30$ $L \cdot min^{-1}$ and $\tau = 120$ s and a prolonged delay term reflecting the additional time required for any humoral stimulus to reach the CCRs (Ward & Bellville, 1983). The second CB component (induced by sustained inhalational hypoxia) required overshooting characteristics for the overall $\phi2$ $\dot{V}_E$ response ($\Delta\dot{V}_{Ess} = 40$ $L \cdot min^{-1}$, $\tau = 30$ s) to maintain exponentiality (Fig 3, left). The precise stimulus spectrum that might yield such an overshooting profile is presently unclear; a simple proportional drive deriving from the $\phi2$ asphyxia appears an unlikely (single) source (see above). As an alternative, the overshooting characteristic was deconvoluted into an initial rapid exponential "excitatory" component, ($\Delta\dot{V}_{Ess} = 28$ $L \cdot min^{-1}$, τ

= 10 s) that interacted additively with a delayed exponential "inhibitory" component ($\Delta\dot{V}_{Ess}$ = -18 L·min^{-1}, τ = 140 s and δ = 65), reflecting possibly the constraining influence on the CBs of the arterial hypocapnia resulting from the hypoxic-induced CB-induced hyperventilation. Experimental evaluation of this model has not yet been undertaken, however.

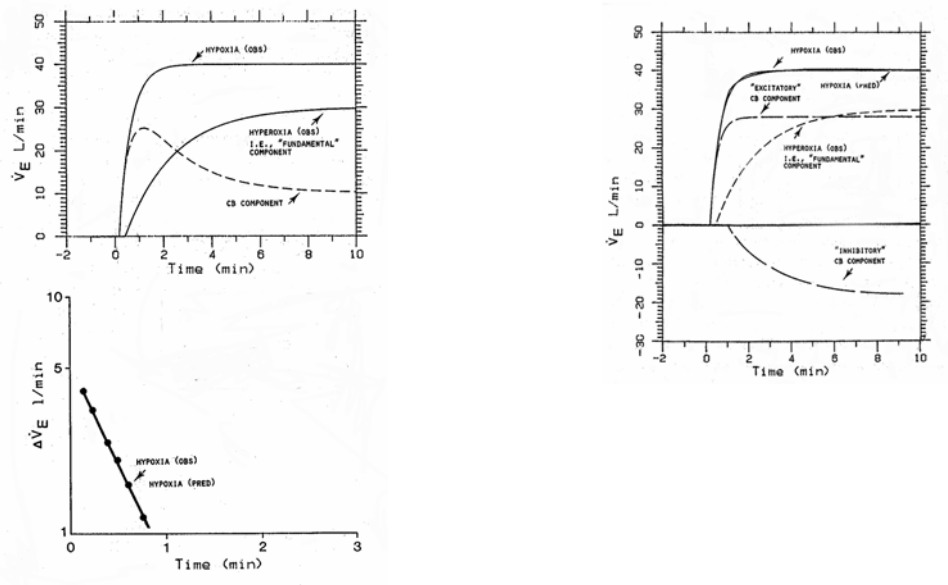

Figure 4. Model responses from a two-compartment additive model of CB modulation during $\phi 2$. See text for details. Taken from Ward et al. (1987b), with permission.

Steady-state Responses

Although the few available reports in animals indicating that CB afferent discharge frequency is not increased during exercise (Davies & Lahiri, 1973; Aggarwal, Millhorn & Lee, 1976), CB chemosensitivity in humans is greater in the steady state of moderate exercise than at rest. For example, the ventilatory responsiveness to isocapnic hypoxia is modestly augmented (Weil & Swanson, 1991), as is the O_2-labile component of the $\phi 3$ hyperpnea estimated using the Dejours O_2 test (Dejours, 1962; Stockley, 1978; Griffiths et al., 1986; Jeyaranjan, Goode, Beamish, & Duffin, 1987; MacDonald, Ward & Whipp, 1990; Whipp, 1994). However, in contrast to the substantial CB modulation of the $\phi 2$ $\dot{V}_E$ response, the available evidence favors a more modest contribution in $\phi 3$. This has been reported to range from fine-tuning (e.g., Dempsey et al., 1995; Waldrop et al., 1996) to the ~20% that has been estimated from the Dejours technique (c.f., ~10-15% at rest) (Dejours, 1962; Stockley, 1978; Griffiths et al., 1986; Jeyaranjan et al., 1987; MacDonald et al., 1990; Whipp, 1994).

Concern has been raised that the Dejours technique may actually underestimate the CB contribution in exercise, as the nadir of the decline of $\dot{V}_E$ following the transition to 100% O_2 typically occurs some 25 sec after the transition into hyperoxia (Fig. 3). It is possible, therefore, that the secondary CCR-mediated $\dot{V}_E$ increase (see above) might be initiated before the full effect of the reduced CB component is manifest (Whipp, 1994). MacDonald et al. (1990) have modeled this effect, making the reasonable assumption that the kinetics of the initial hyperoxic-induced $\dot{V}_E$ decline are first-order (e.g. Gardner, 1980), and then comparing the predicted asymptotic $\dot{V}_E$ nadir with that actually observed; for both moderate and high-intensity exercise (at work rates where steady states were attainable). This analysis indicated that the actual $\dot{V}_E$ response to the hyperoxia was likely to have been underestimated at most by some 7%, on average.

As for $\phi 2$, uncertainty surrounds the stimuli that provide this CB contribution to the $\phi 3$ hyperpnea. For example, arterial levels of CB stimuli such as $[K^+]a$ and rate of change of the arterial H^+-$PaCO_2$ oscillation (but not its phase-coupling characteristic) all increase during exercise, as do levels of putative stimuli such as adenosine, catecholamines and plasma osmolarity (see later). The extent of their involvement is presently unclear, however. Also not readily explained are the observations that CBR subjects evidence a reasonably normal $\phi 3$ hyperpnea (Wasserman et al., 1975; Whipp et al., 1993). Is this a manifestation of redundancy in the $\phi 3$ control process, whereby the CB component can be taken over by some other mechanism(s)? If so, why is this not the case for $\phi 2$?

HIGH-INTENSITY EXERCISE

Above θL, $\dot{V}_E$ becomes challenged by the consequences of the metabolic acidosis and hence increases proportionally more than for moderate-intensity work rates (reviewed in Wasserman et al., 1986; Whipp & Ward, 1991). This reflects: (a) the increased demand for pulmonary CO_2 clearance caused by buffering of protons associated with the lactate production by intracellular and blood bicarbonate, and (b) the additional demand to provide respiratory compensation for the metabolic acidemia, to constrain the fall of pHa. Substantial system nonlinearities are thus introduced into both $\dot{V}_{CO_2}$ and $\dot{V}_E$ kinetics, whose characterization presents a substantial analytical challenge which has not yet been formally confronted.

The CBs appear to be the dominant (or even exclusive) mediators of the respiratory compensation for the metabolic acidemia, based on studies with CBR subjects (Wasserman et al., 1975; Honda, Myojo, Hasegawa, & Severinghaus, 1979a; Whipp & Wasserman, 1980). Similarly, in normal subjects, hyperoxia attenuates the supra-θL $\dot{V}_E$ response (reviewed in Whipp, 1994; Ward, 1994a). It has been proposed that the respiratory compensation for the metabolic acidosis is mediated largely by stimuli such as $[H^+]$, $[K^+]$, catecholamines, increased body temperature, adenosine and osmolarity (reviewed in Wasserman & Casaburi, 1991; Whipp & Ward, 1991; Ward, 1994a; Dempsey et al., 1995), although their individual roles remain to be determined.

There are several apparently perplexing issues, however. For example, despite the low pHa, the proportional contribution of the O_2-labile $\dot{V}_E$ drive above θL is not appreciably different from moderate exercise (i.e., ~20%), as judged by the results of Dejours O_2 testing (Jeyaranjan et al., 1987; MacDonald et al., 1990; Whipp, 1994). Furthermore, as was the case below θL, this increased only modestly when the observed $\dot{V}_E$ nadir was corrected to the predicted $\dot{V}_E$ nadir (MacDonald et al., 1990).

A further challenging feature of the control process is the surprisingly slow kinetics of the respiratory compensation, evident both with square-wave- and ramp work-rate forcings (e.g., Whipp, Davis, & Wasserman, 1989; Rausch, Whipp, Wasserman, & Huszczuk, 1991).

This behavior contrasts with the rapid response of the CBs to experimentally-induced changes in pHa (e.g., Buckler & Vaughan-Jones, 1995; Buckler et al., 2000), and has been suggested to reflect the existence of some time- or amplitude-related threshold for $[H^+]$ chemotransduction above θL (Whipp & Ward, 1991). An additional complication is the report that infused dopamine had no effect on the degree of respiratory compensatory, despite hypoxic $\dot{V}_E$ responsiveness being markedly suppressed (Henson, Ward, & Whipp, 1992).

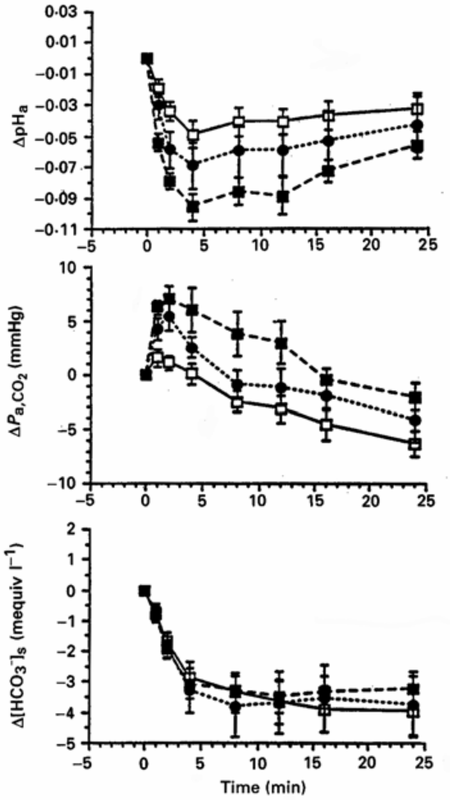

Figure 5. Average responses of arterial pH (ΔpHa), PCO2 (ΔPaCO2) and standard [bicarbonate] (Δ $[HCO_3^-]$s) to supra-θL square-wave cycle-ergometer exercise at three inspired O_2 fractions (0.80 O2 (solid squares), 0.21 O2 (solid circles), 0.12 O2 (open squares); the responses are expressed as changes (Δ) from unloaded cycling. Taken from Rausch et al. (1991), with permission.

Does this imply that, during high-intensity exercise, the primary metabolic-acidemic drive from the CBs may be being held in check by other influences, acting at the receptor level or some point downstream in the reflex itself? For example, it is known that CB afferent discharge can be inhibited when cerebrospinal fluid is made alkaline (Majcherczyk & Willshaw, 1973). Furthermore, while plasma hyper-osmolarity has been reported to increase CB afferent discharge (Gallego, Eyzaguirre, & Monti-Bloch, 1979), more recent reports describe hypo-osmolarity as depolarizing the glomus cells via inactivation of Cl^- channels consequent to cell volume expansion (Molnár, Petheö, Fülöp, & Spät, 2003). Similarly, adenosine has been reported to inhibit voltage-gated Ca^{2+} channels, via adenosine A1 receptors (Rocher, Gonzalez, & Almarez, 1999), which contrasts with the excitatory effects resulting from A2 receptor activation (reviewed in Gonzalez et al., 1995).

CONCLUSIONS

It is evident from studies in humans that (a) the precise manner in which the carotid bodies contribute to ventilatory control varies with both exercise intensity and the temporal domain of the exercise, and (b) uncertainties surround the magnitude of these contributions. Recent advances in carotid body glomus cell chemotransduction provide some clues that may help to resolve these issues. It should be emphasized, however, that little if anything is known about glomus cell function under the stress of exercise. While technically daunting, without such advances, the formulation of robust competing control models of ventilatory control during exercise will necessarily be constrained.

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Intensity-Dependent Limitations to Exercise Tolerance: Clues from Dynamic Analysis of Pulmonary Gas Exchange

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Abstract

Below the lactate threshold (θL), muscle O2 consumption ($\dot{Q}O_2$) is expressed at the lung as O2 uptake ($\dot{V}O_2$) with 1^o-order kinetics:

$$d\dot{V}O_2/dt.\ \tau + \Delta\dot{V}O_2(t) = \Delta\dot{V}O_{2ss}$$

where $\Delta\dot{V}O_{2ss}$ is the steady-state response, and τ the time constant (within $\underset{\sim}{~}$10% of $\tau\dot{Q}O_2$). Putative $\dot{Q}O_2$ controllers include: ADP-linked negative feedback (for which intramuscular [PCr] may act as proxy); PDH complex feedforward activation (controlling substrate flux through the electron transport chain); and/or feedforward mechanisms linked to Ca^{++}. A caveat to interpreting the "well-fit" exponential is that numerous units of similar $\Delta\dot{V}O_{2ss}$ but with a wide τ distribution can also yield a response with an apparent single τ. This τ is significantly inversely correlated with θ_L and $\dot{V}O_2\,max$ (but poorly predictive), consistent with τ not characterizing a compartment with uniform kinetics. Above θL, the fundamental kinetics are supplemented with a delayed, slowly-developing phase (with complex time- and intensity-related dynamics), setting $\dot{V}O_2$ on a trajectory towards $\dot{V}O_2\,max$. As this slow-component is also demonstrable in [PCr], the decreased efficiency therefore predominantly reflects a high phosphate-cost of force-production rather than a high O_2-cost of phosphate-production. Also, the O_2-deficit for the slow-component is more likely to reflect shifting $\Delta\dot{V}O_{2ss}$ rather than a single one with a single τ.

KEY WORDS, MUSCLE OXYGEN CONSUMPTION; FEEDBACK CONTROL; FEEDFORWARD CONTROL; $_{31}$P-NMR SPECTROSCOPY; MODELING

INTRODUCTION

Exercise intolerance in normal humans is typically a result of a complex interplay between intra-muscular mediators, such as depletion of local energy resources and/or the build up of metabolites that impair effective force generation, their perceptual consequences and the “stoicism” with which the perceptions are treated. The currency of the intolerance therefore, schematized in Figure 1, has “can-but-won’t” and “will-but-can’t” as its obverse and reverse, such that when one is apparently evident the other lurks closely behind. In some events, sprinting or power lifting for example, the latter clearly dominates; in others, the distinction is by no means as clear. We shall, here, address the issue of the physiological factors that reduce the build-up of fatigue-inducing metabolites and the depletion rate of accessible stored energy resources.

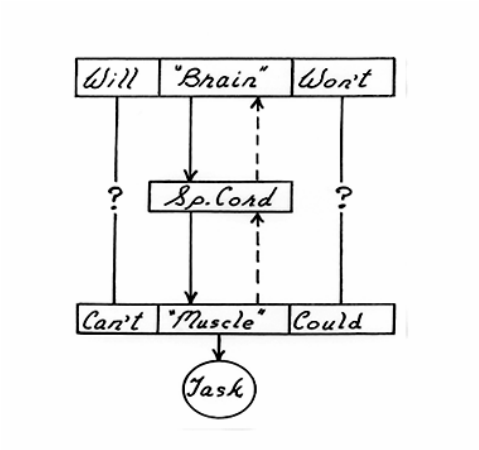

Figure 1. Routes of fatigue

The ability to sustain dynamic exercise is largely dependent on the ability to transport and utilize O_2 at rates commensurate with the energy demands of the muscle fibers recruited to generate the required force and power. For high-intensity exercise, this is characterized by the upper limit of utilization - conventionally defined as the maximum O_2 uptake ($\dot{V}O_2 max$) - and by the $\dot{V}O_2$ response contour towards that limit. However, many of the nonsteady-state details of the muscle O_2 utilization ($\dot{Q}O_2$) dynamics still remain to be conclusively characterized. Consequently, as the bulk of the information on the $\dot{Q}O_2$ control systems resides in its transient rather than its steady-state behavior, crucial features of the control mechanisms remain poorly understood.

As the $\dot{Q}O_2$ contour, most commonly estimated through the more readily-measured $\dot{V}O_2$ response, is intensity-dependent, an appropriate functional definition of exercise intensity is required: the $\% \dot{V}O_2 max$ is not adequate. The parameters which partition the range of potential work rates into clusters of common intensity (i.e. the lactate threshold (θ_L), the critical power (CP) and $\dot{V}O_2 max$) have highly variable relationships to each other in different subjects. Consequently, assigning intensity domains on the basis of a single parameter, such as a given percentage of $\dot{V}O_2 max$ or of θ_L, can lead to markedly different physiological stress characteristics in different subjects at what would otherwise appear to be the same work intensity.

The profiles of muscle metabolic and pulmonary gas exchange response to constant-load exercise, however, provide a means of assigning exercise intensity which, to a large extent, overcomes these concerns. For example, taking the arterial blood acid-base status as a simple frame of reference, moderate-intensity exercise can be considered to represent that range of work rates (WR) for which there is no sustained metabolic acidosis with its concomitant increase in arterial blood [lactate] ($[lactate]_a$) and decrease in arterial pH (pH_a) relative to the resting or unloaded pedaling baseline (i.e. below θ_L). Above θ_L, a range of WRs (heavy-intensity) can be identified in which the metabolic acidosis is sustained with an increase in $[lactate]_a$ and a decrease in pH_a, but with time these responses either stabilize to a constant level or even decline back towards baseline. The upper limit of the heavy-intensity domain is CP. Above CP, the tolerable duration of the task declines in a hyperbolic fashion as WR increases - yielding the hyperbolic power-duration relationship, the curvature constant of which has the units of work or energy. In the very-heavy intensity domain, the increase in $[lactate]_a$ and decline in pH_a do not stabilize, but develop progressively to the limit of tolerance, with fatigue rapidly ensuing. Finally, a severe intensity can be identified for which

WRs are supra-maximal with respect to the expected $\dot{V}O_2$ requirement. As will be described below, significant kinetic dislocations in the $\dot{V}O_2$ contour are introduced by both θL and CP.

Moderate-Intensity Exercise

In response to square-wave exercise, following an initial brief phase 1 ($\phi 1$) or cardiodynamic component of $\dot{V}O_2$ response (reflecting initial increases in pulmonary blood flow (Krogh & Lindhard, 1913; Whipp, Ward, Lamarra, Davis, & Wasserman, 1982), the normally more-dominant phase 2 ($\phi 2$) or fundamental component is widely assumed to be exponential as it is determined to a major degree by the enzymatically-controlled $\dot{Q}O_2$ (e.g. Chance & Williams, 1955; Veech, Lawson, Cornell, & Krebs, 1979; Chance, Leigh, Clark, Maris, Kent, Nioka, et al., 1985; Funk, Clark, & Connett, 1990; Brown, 1992; Jeneson, Wiseman, Westerhoff, & Kushmerick, 1996; Meyer & Foley, 1996) (Fig. 2), being characterized as:

$$d\dot{V}O_2/dt \cdot \tau + \Delta\dot{V}O_2(t) = \Delta\dot{V}O_{2ss} \tag{1}$$

where $\Delta\dot{V}O_{2ss}$ is the steady-state or asymptotic response, $\Delta\dot{V}O_2(t)$ is the $\dot{V}O_2$ increment at time t, and τ the time constant.

At the muscle level, $\dot{Q}O_2$ responds mono-exponentially (consistent with 1^o-order control characteristics) which, for square-wave or step WR forcings, may be characterized as:

$$\Delta\dot{Q}O_2(t) = \Delta\dot{Q}O_{2\,ss} \cdot (1 - e^{-t/\tau}) \tag{2}$$

where $\Delta\dot{Q}O_{2\,ss}$ is the steady-state $\dot{Q}O_2$ increment above baseline, $\Delta\dot{Q}O_2(t)$ is the $\dot{Q}O_2$ increment at time t, and τ is the $\dot{Q}O_2$ time constant (Mahler, 1985; Meyer, 1988). The direct expression of this $\dot{Q}O_2$ response profile at the lung, however, is delayed as a result of the vascular transit delay between the exercising muscles and the pulmonary capillaries (some 15-20 s), during which alterations of muscle venous composition do not yet influence gas exchange at the lung (e.g. Linnarsson, 1974; Whipp et al., 1982; Barstow, Lamarra, & Whipp, 1990). $\phi 1$ is thus a period of time, and not a pattern of response, with the subsequent $\phi 2$ $\dot{V}O_2$ response also being well described as a mono-exponential (e.g. Linnarsson, 1974; Hughson & Morrissey, 1982; Whipp et al., 1982; Özyener, Rossiter, Ward, & Whipp, 2001):

$$\Delta\dot{V}O_2(t) = \Delta\dot{V}O_{2ss} \cdot (1 - e^{-(t-\delta)/\tau}) \tag{3}$$

where δ is a delay term reflective of (but not necessarily equal to) the limb-to-lung transit time (Whipp et al., 1982). $\tau\dot{V}O_2$ has been shown by both modeling and estimation from the time course of its Fick equation determinants to be within ~10% of $\tau\dot{Q}O_2$ (Barstow et al., 1990; Grassi, Poole, Richardson, Knight, Kipp Erickson, & Wagner, 1996). Consequently, to this degree of uncertainty, the $\phi 2$ $\tau\dot{V}O_2$ may be used as a proxy function for $\tau\dot{Q}O_2$. However, because of the confounding influence of breath-to-breath "noise" (Lamarra, Whipp, Ward, & Wasserman, 1987), it is often necessary to superimpose several replicates of a particular test to establish a sufficiently high signal-to-noise ratio for the acceptable discrimination of these kinetic features. $\tau\dot{V}O_2$ is typically of the order of 30-40 s in healthy young individuals, tending to be smaller in endurance-trained individuals (Hagberg, Hickson, Ehsani, & Holloszy, 1980) and to be appreciably larger in elderly sedentary individuals (Babcock, Paterson, Cunningham, & Dickinson, 1994) and in patients with pulmonary diseases (Nery, Wasserman, Andrews, Huntsman, & Whipp, 1980) and cardiovascular disease (Sietsema, Ben-Dov, Zhang, Sullivan, & Wasserman, 1994).

Additional support for the $\phi 2$ $\dot{V}O_2$ control process involving a 1^o-order control process is provided by its on-off symmetry and by $\tau\dot{V}O_2$ having been reported not to differ appreciably for moderate WR steps of different amplitudes - i.e. the early transient rise in [lactate]a which is not uncommon at WRs in the higher reaches of the moderate-intensity domain (Cerretelli & di Prampero, 1987) appearing not to influence $\tau\dot{V}O_2$ discernibly (reviewed in Whipp, Rossiter, & Ward, 2002), presumably due to the small O_2-deficit equivalent of lactate production (Whipp, Lamarra, & Ward, 1995).

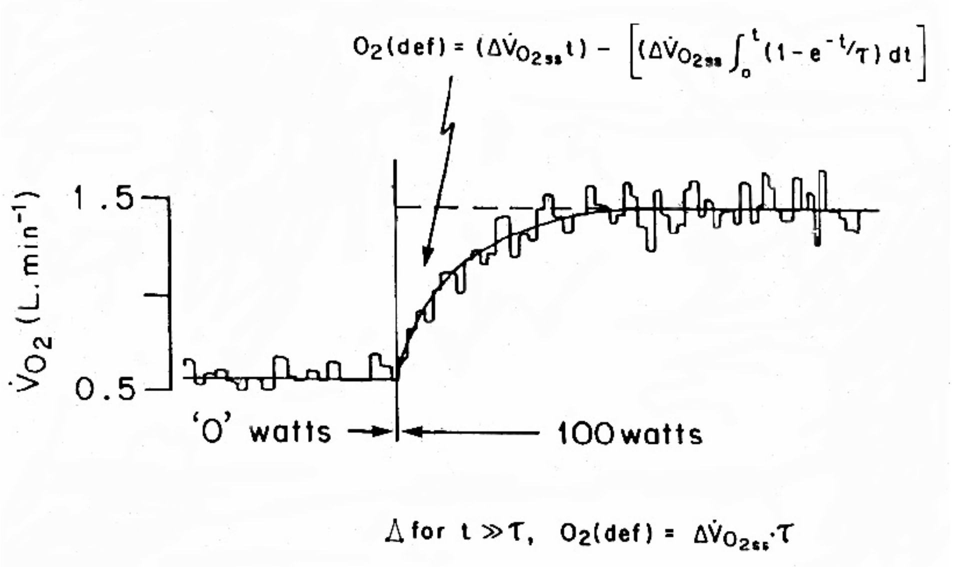

Figure 2. $\dot{V}O_2$ response to *moderate* square-wave cycle-ergometer exercise for a representative subject, with superimposed mono-exponential best-fit, illustrating computation of the O_2 deficit. See text for details.

In contrast, however, is the recent demonstration (utilizing multiple WR transitions to confer a sufficiently-high signal-noise characteristic) that $\tau\dot{V}O_2$ for a given WR increment in the high end of the moderate-intensity domain is longer than for the same WR increment at the low end (Brittain, Rossiter, Kowalchuk, & Whipp, 2001), an observation which coheres with earlier reports on single WR transitions (Hughson & Morrissey, 1982; di Prampero, Mahler, Giezendanner, & Cerretelli, 1989).

Assuming the total O_2 requirement of the WR to be $(\Delta\dot{V}O_{2ss} \cdot t)$, the resulting O_2 deficit (O_2def) for a given WR can be quantified as:

$$O_2def = (\Delta\dot{V}O_{2ss} \cdot t) - \Delta\dot{V}O_{2ss} \int_0^t (1 - e^{-t/\tau'})\, dt \qquad (4)$$

where t is the duration of the exercise bout (Fig. 2). When t becomes substantially greater than τ', eq. 2 simplifies to the practically useful expression:

$$O_2def = \Delta\dot{V}O_{2ss} \cdot \tau' \qquad (5)$$

It should be emphasized, however, that the τ' value used in the O_2 deficit computation is not that of the fundamental (i.e. $\phi 2$) component, but rather that derived from the best-fit exponential for the entire nonsteady-state data set (i.e. including the cardiodynamic phase) (Whipp et al., 1982). Thus, the O_2 deficit in the moderate-intensity domain increases as a linear function of WR (and therefore of $\Delta\dot{V}O_{2ss}$) for a given τ', and as a linear function of τ' for a given WR (i.e. $\Delta\dot{V}O_{2ss}$). For example, there will be a larger O_2 deficit in an individual with slow $\dot{V}O_2$ kinetics than in a healthy active individual exercising at the same WR.

For moderate exercise, the O_2 deficit is determined by changes in the accessible high-energy phosphate and O_2 stores with a small contribution from the transient lactate elevation. At higher intensities, the lactate-related contribution is proportionally greater. Take, for example, a subject with a 10 kg active muscle mass and an intramuscular PCr store which has decreased from a resting value of 22 $mmol \cdot kg^{-1}$ (wet weight) to 2 $mmol \cdot kg^{-1}$ during high-intensity exercise. The 20 $mmol \cdot kg^{-1}$ PCr depletion consequently contributes ~ 200 mmol of high-energy phosphate to the deficit - the contribution from a decrease of ATP concentration is likely to be small until extremely high work rates. Consequently, taking a $\sim P:O_2$ of ~ 6, this results in an O_2 equivalent of approximately 33 mmol. And, as each mmol of O_2 is equivalent to 22.4 ml, then the O_2 equivalent of the total depletable high-energy phosphate pool is approximately 750 ml (i.e. 33mmol · 22.4 $ml \cdot mmol^{-1}$ $\underline{\sim}$ 750ml).

The other alactic component of the O_2 deficit is provided by the blood O_2 stores. A reduction in mixed venous O_2 content from 150 $ml \cdot L^{-1}$ at rest to 50 $ml \cdot L^{-1}$ during high-intensity exercise in an adult with a 3 L venous blood volume provides approximately 300 ml (i.e. 3 L·100 $ml \cdot L^{-1}$) of the deficit - the arterial O_2 content not changing appreciably even in those normal subjects who manifest hypoxemia at high WRs. The contribution from oxymyoglobin and from plasma and muscle water is also likely to be small (on the order of 100ml or less) (Whipp & Özyener, 1998). Consequently, the total O_2 deficit available for such exercise from these sources in the adult is only about 1 L. $\tau\dot{V}O_2$ is pivotal in this regard. A subject with a τ of 30 s will deplete the alactic sources of the O_2 deficit at a WR of ~ 200 W (i.e. eq. 5), while with a τ of 1 min this naturally would occur at ~ 100 W, making anaerobic lactate production obligatory; its subsequent oxidation during the exercise, costing no "apparent" additional O_2, allows the task to be continued.

The magnitude of the O_2 deficit is naturally linked to both the kinetics of $\dot{V}O_2$ and the O_2 equivalent of the total energy demands of the task. $\dot{V}O_2$ can thus be viewed both in terms of the convective fluxes ventilation and cardiac output (and thence muscle blood flow), through the corresponding Fick equations:

$$\dot{V}O_2 = \dot{V}A \cdot (FIO_2 - FAO_2) \qquad (6)$$

and

$$\dot{V}O_2 = \dot{Q}T \cdot (C[a-\bar{v}]O_2) \qquad (7)$$

where $\dot{V}A$ and $\dot{Q}T$ are alveolar ventilation and cardiac output, ($FIO_2 - FAO_2$) is the inspired-alveolar O_2 fractional concentration difference, and $C[a-\bar{v}]O_2$ is the arterio-venous O_2 content difference. And recognizing that $\dot{Q}O_2$ and $\dot{Q}M$ each have their own control characteristics, eq. 7 can usefully be rearranged (in the context of the muscle):

$$CvO_2 = CaO_2 - (\dot{Q}O_2 / \dot{Q}M) \qquad (8)$$

such that, for a particular CaO_2, the O_2 content of the muscle-venous effluent (CvO_2) will be defined by the ratio of the muscle O_2 consumption to muscle perfusion ($\dot{Q}O_2 / \dot{Q}M$).

Importantly, these relationships do not imply that $\dot{V}A$ and $\dot{Q}T$ necessarily contribute to the control of O_2 utilization. In the anesthetized dog, for example, $\dot{V}O_2$ kinetics were not affected by experimentally altering the associated ventilatory kinetics (Casaburi, Weissman, Huntsman, Whipp, & Wasserman, 1979) (Fig. 3). Similarly (also in the anesthetized dog), experimentally elevating $\dot{Q}T$ to the steady-state exercise level at rest had no effect on $\dot{Q}O_2$ kinetics for a subsequent moderate exercise bout or (by inspection) in most of the study animals at high WRs (Grassi, Gladden, Samaja, Stary, & Hogan, 1998). Despite an O_2 availability apparently in excess of demand, this latter demonstration supports earlier assertions of Mahler (1985) that $\dot{Q}O_2$ kinetics (in frog sartorius muscle) are determined largely, if not exclusively, by intracellular mechanisms. This view is supported in humans by both $\tau\dot{Q}T$ (Davies, di Prampero, & Cerretelli, 1972; De Cort, Innes, Barstow, & Guz, 1991;

Yoshida & Whipp, 1994; Tschakovsky & Hughson, 1999) and femoral artery $\tau\dot{Q}$ (Grassi et al., 1996; Whipp, Ward, Smith, & Hussain, S.T., 1995) for square-wave exercise being appreciably shorter than $\tau\dot{V}O_2$.

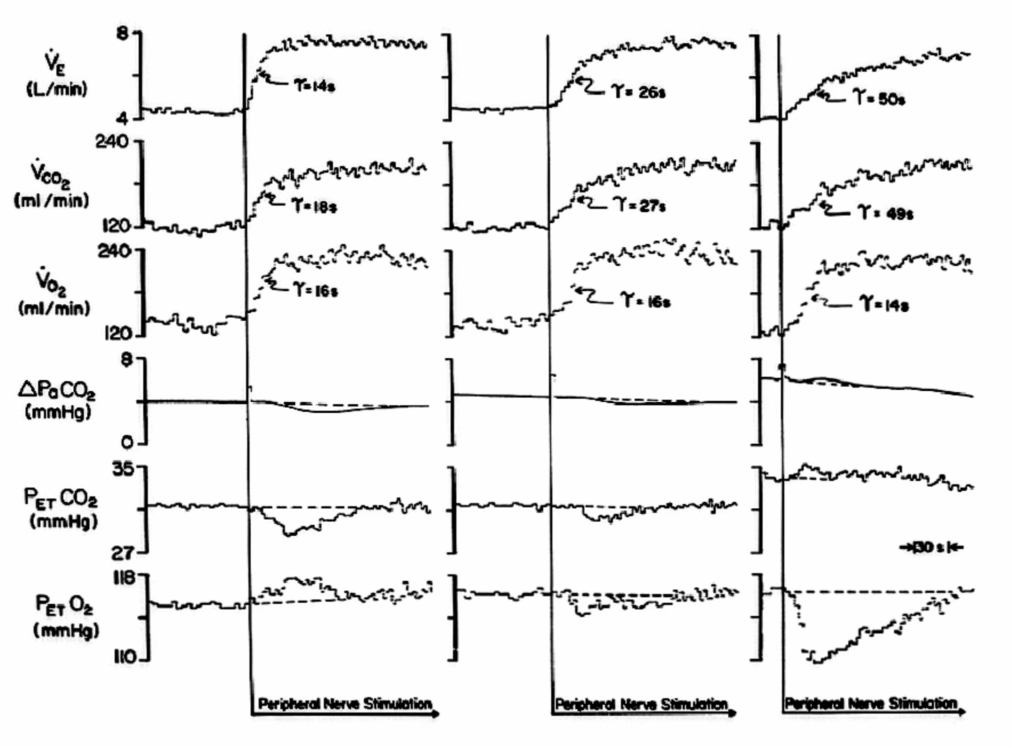

Figure 3. Ventilatory ($\dot{V}E$) and gas exchange ($\dot{V}O_2$, $\dot{V}CO_2$) responses to electrically-induced hindlimb exercise in an anesthetized dog, with three different imposed $\dot{V}E$ response time constants (14, 26 and 50s). Taken from Casaburi et al. (1979), with permission.

Closed-loop feedback control of intramuscular $\dot{Q}O_2$ during moderate exercise could occur via creatine kinase catalyzed PCr kinetics, induced by changes in intramuscular [creatine], [ADP] and/or the phosphorylation potential (i.e. [ATP]/[ADP]·[Pi]) (e.g. Chance & Williams, 1955; Veech et al., 1979; Chance et al., 1985; Funk et al., 1990; Brown, 1992; Jeneson et al., 1996; Meyer & Foley, 1996). The role of phosphocreatine (PCr) turnover in $\dot{Q}O_2$ control has been investigated in humans using ^{31}P-nuclear magnetic resonance (NMR) spectroscopy, simultaneously with $\dot{V}O_2$ (Whipp, Rossiter, Ward, Avery, Doyle, Howe, et al., 1999). Support for an involvement of PCr (either directly or as a proxy) derives from the recent demonstration that the τ of [PCr] decline and of the $\phi 2$ $\dot{V}O_2$ increase are closely correlated (Rossiter, Ward, Doyle, Howe, Griffiths, & Whipp, 1999) (Fig. 4).

Additional control schemes have also been proposed that rely on feedforward mechanisms linked to substrate provision (H^+, e^-) to the mitochondrial electron transport chain, with the pyruvate dehydrogenase complex functioning as a variable "stenosis" to the overall flux (reviewed in Greenhaff, Campbell-O’Sullivan, Constantin-Teodosiu, Pouchera, Roberts, & Timmons, 2002) and/or intracellular [Ca^{++}] serving as a proposed "trigger" (Hansford, 1994).

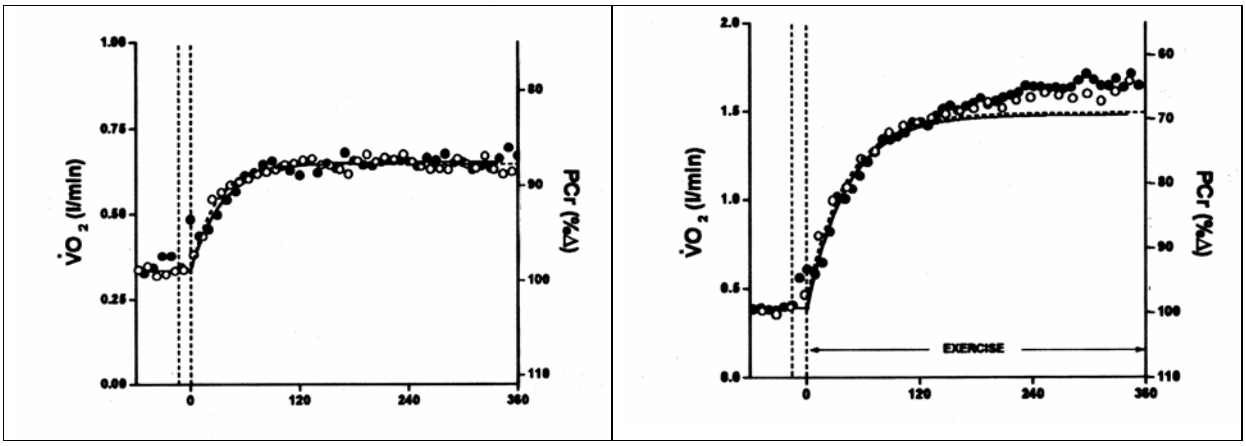

Figure 4. Simultaneously-determined $\dot{V}O_2$ (•) and [PCr] (o) responses to *moderate* (left) and *heavy* (right) square-wave knee-extensor exercise test for a representative subject, with superimposed mono-exponential best-fit model to the phase 2 and fundamental components, respectively. The [PCr] scale has been both inverted and normalized to that of the $\dot{V}O_2$ response to facilitate kinetic comparisons.

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Supra-θ_L Exercise

Above θ_L, $\dot{V}O_2$ kinetics become more complex (e.g. Linnarsson, 1974; Barstow & Molé, 1991; Poole, Schaffartzik, Knight, Derion, Kennedy, Guy, et al., 1991; Whipp, 1994; Özyener et al., 2001; Whipp et al., 2002) (Fig. 5). In the heavy-intensity domain, there is evidence of a delayed, slow component ($\dot{V}O_{2\,SC}$) superimposed on that of the fundamental. As a result, the attainment of a $\dot{V}O_2$ steady state is appreciably delayed, by as much as 10-15 min (e.g. Barstow & Molé, 1991; Poole et al., 1991; Özyener et al., 2001; Whipp et al., 2002), with the corresponding steady-state gain ($\Delta\dot{V}O_{2ss}/\Delta WR$) being markedly increased (e.g. Özyener et al., 2001; Whipp et al., 2002).

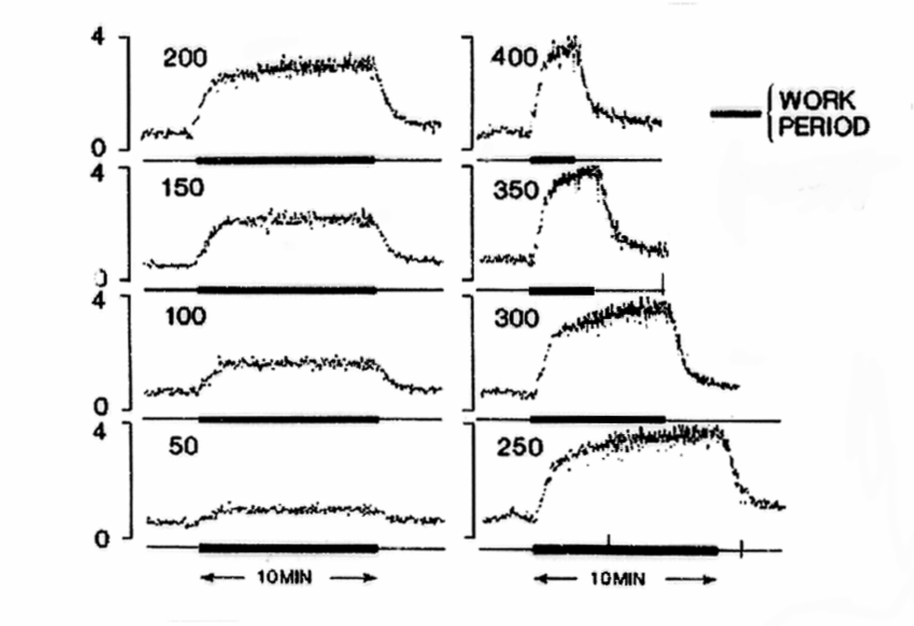

Figure 5. $\dot{V}O_2$ responses to bouts of square-wave cycle-ergometer exercise to 50, 100, 150, 200, 25, 300, 350 and 400 Watts in a representative subject, performed for 10 minutes or to the limit of tolerance (whichever came sooner). Note that for work rates of 250 Watts or greater, the subject attained $\dot{V}O_2$ max.

Precisely how the $\dot{V}O_2$ slow phase begins and, whether it is in fact delayed at all, depends on a constellation of assumptions. What is defensible is that it can be discerned emerging from the fundamental component at the time of the apparent delay. But as the degree of “overlap” between the confidence limits of the fundamental and slow components is considerable, there is doubt about the “when”. This is further compromised by the lack of justification for the $\dot{V}O_2$ slow phase actually being exponential. Thus, its τ should be considered a parameter of convenience, rather than a control parameter with a physiological equivalent.

Interestingly, the fundamental $\dot{V}O_2$ component remains well described as an exponential (despite the elevated $[\text{lactate}]_a$) and has a projected asymptotic gain (i.e. $\Delta\dot{V}O_2/\Delta WR$) and τ similar to moderate exercise (e.g. Barstow & Molé, 1991; Özyener et al., 2001; Whipp et al., 2002). Not only are the 1^o-order on-transient characteristics of moderate exercise lost in the heavy domain, but so is the on-off symmetry: i.e. the $\dot{V}O_2$ off-transient features remain well described by a mono-exponential function, albeit slightly slower than for moderate exercise (Özyener et al., 2001).

For very-heavy intensity exercise (above CP), $\dot{V}O_2 SC$ sets $\dot{V}O_2$ on a trajectory to or towards $\dot{V}O_2 max$, with fatigue ensuing at or soon after $\dot{V}O_2 max$ - if it is reached (Poole, Ward, Gardner, & Whipp, 1988; Özyener et al., 2001): the higher the WR, the shorter is its tolerable duration (Fig. 5). The off-transient $\dot{V}O_2$ response loses its exponential profile, however, requiring a double exponential for adequate characterization (Özyener et al., 2001). Naturally, there is no delay term similar to that for the on-transient, as any functional metabolic compartments will be operative at the cessation of the work, regardless of when they were recruited.

For severe-intensity exercise, the tolerable duration of the work becomes so truncated that the $\dot{V}O_2 SC$ has insufficient time in which to develop - at least during the exercise itself (Fig. 5). Thus, the $\dot{V}O_2$ on-transient can be adequately fit by a single exponential having a τ similar to that for moderate-intensity exercise (i.e. pseudo 1^o-order); however, the $\dot{V}O_2$ off-transient still requires a double-exponential structure for adequate fitting (Özyener et al., 2001).

The physiological determinants of the $\dot{V}O_2$ kinetics above θ_L, and especially that of the slow component, remains controversial. For the latter, a range of putative mediators have been proposed, including: lactate; altered oxyhemoglobin dissociation (Bohr shift) induced by the metabolic acidosis; serial recruitment of additional, presumably fast-twitch, muscle fibers having low aerobic efficiency; and increased cardiac and ventilatory muscle work (reviewed in Poole, Barstow, Gaesser, Willis, & Whipp, 1994; Whipp, 1994; Whipp et al., 2002). Less likely to be significantly involved are increased levels of circulating catecholamines (Gaesser, Ward, Baum, & Whipp, 1994) and increased muscle temperature (Koga, Shiojiri, Konda, & Barstow, 1997), as neither induce a discernible increase in $\dot{V}O_2sc$. Poole et al. (1991) have concluded that lower-limb $\dot{Q}O_2$ manifests a progressive slow component which contributes more than 80% of that seen in $\dot{V}O_2$. Also, the demonstration that the $\dot{V}O_2sc$ is accompanied by an appreciable slow component of intramuscular [PCr] decline (Rossiter, Ward, Kowalchuk, Howe, Griffiths, & Whipp, 2002) (Fig. 4) argues strongly for a high phosphate cost of force production, rather than a high O_2 cost of phosphate production as the determinant (or at least the dominant component) of the $\dot{V}O_2sc$.

Clues to the control process may be discerned from experiments in which supra-θ_L exercise is recently preceded by a similar supra-θ_L "priming" bout. That is, the induction of a metabolic acidosis by a priming work bout can speed the on-transient $\dot{V}O_2$ kinetics above θ_L (e.g. Gerbino, Ward, & Whipp, 1996; MacDonald, Pedersen, & Hughson, 1997; Bohnert, Ward, & Whipp, 1998; Burnley, Jones, Carter, & Doust, 2000; Koppo & Bouckaert, 2000) (Fig. 6), and reduce the increase in $[\text{lactate}]_a$ and $[H^+]_a$ (e.g. Gerbino et al., 1996; Burnley et al., 2000; Koppo & Bouckaert, 2000); however, the high-intensity priming bout does not speed the $\dot{V}O_2$ kinetics of a subsequent sub-θ_L bout (Gerbino et al., 1996; Burnley et al., 2000). Gerbino et al. (1996) reported that $\dot{V}O_2sc$ was reduced by the priming exercise (subsequently confirmed by Bohnert et al. (1998), Burnley et al. (2000) and Koppo & Bouckaert (2000)), and also suggested that the fundamental $\tau\dot{V}O_2$ was speeded. The $\dot{V}O_2$ gain ($\Delta\dot{V}O_2/\Delta WR$) of the fundamental component for the supra-θ_L bout (i.e. with a coterminous metabolic acidosis) did not differ from that of sub-θ_L exercise. In the context of eq. 1, the demonstrably faster the rate of $\dot{V}O_2$ change at a given $\dot{V}O_2$ can be explained either by a shorter τ and/or a larger asymptotic $\dot{V}O_2$ value. It was thought likely that the effect of the prior exercise was a result of the speeding of τ, as the fundamental $\dot{V}O_2$ asymptote had been reported not to be influenced (on a single work bout) by a developing lactic acidosis. However, using the higher-confidence averaged responses of several like transitions in each subject, Burnley et al. (2000) and Koppo & Bouckaert (2000) subsequently showed this not to be the case. Thus, they found the fundamental $\tau\dot{V}O_2$ to be unaltered by the priming exercise, but its asymptotic $\dot{V}O_2$ to be increased. The underlying mechanism(s) remains to be elucidated, although account should be taken of the demonstration that, for high-intensity knee-extension exercise, priming high-intensity exercise speeded both the fundamental $\tau\dot{V}O_2$ and the fundamental τ[PCr] (Rossiter, Ward, Kowalchuk, Howe, Griffiths, & Whipp, 2001).

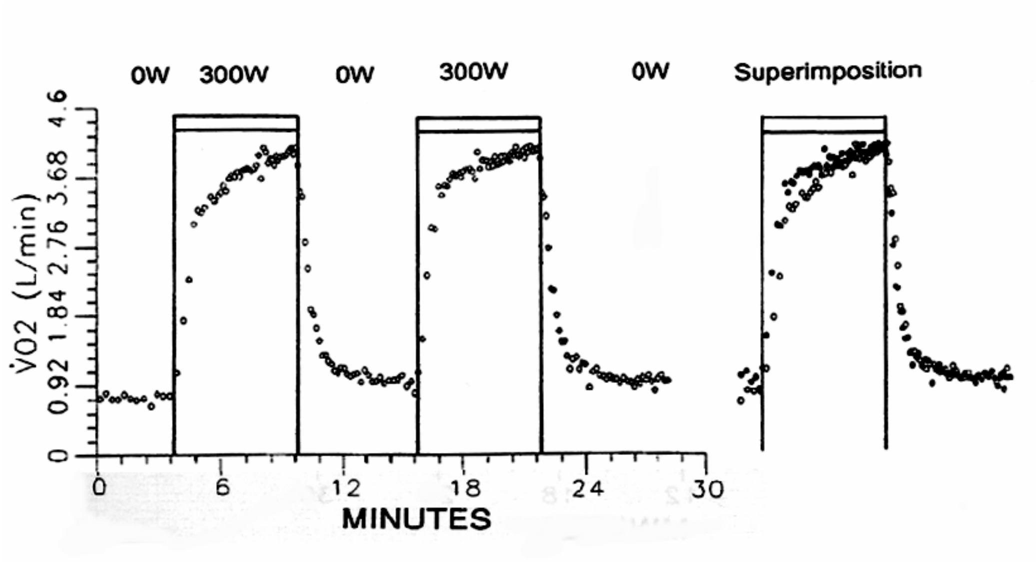

Figure 6. $\dot{V}O_2$ responses to two successive 6-minute bouts of *high-intensity* square-wave cycle-ergometer exercise in a representative subject (left); and superimposed (right) to illustrate speeding of response kinetics on bout 2. Taken from Gerbino et al. (1996), with permission.

The asymmetry of the $\dot{V}O_2$ kinetics between the on- and the off-transient for heavy-intensity exercise (Özyener et al., 2001; Rossiter et al., 2002) suggests that the O_2 costs of proposed mediators such as the Q_{10} effect and of increased respiratory and/or cardiac work are likely to be minor, as each contribution to the $\dot{V}O_2SC$ would be expected to influence both the on- and off-transient responses. Similarly, were the $\dot{V}O_2SC$ to be the result of the recruitment of a metabolic compartment having a single (and high) asymptotic gain and slow τ (e.g. Barstow, Jones, Nguyen, & Casaburi, 1996; Bearden & Moffatt, 2000; Kindig, McDonough, Erickson, & Poole, 2001), then its influence should be apparent also at the off-transient. These $\dot{V}O_2$ on-off asymmetries thus seem more consistent with continued recruitment of additional contractile units throughout the slow phase (Shinohara & Moritani, 1992; Borrani, Candau, Millet, Perrey, Fuchslocher, & Rouillon, 2001). In this case, the $\dot{V}O_2$ gain factor would be expressed as a variable rather than a constant, with the corresponding τ(s) of the recruited units being plausibly closer to that of the fundamental τ than that of the apparent slow component. The off-transient τ could then be not discernibly different from that of the on-transient fundamental (Özyener et al., 2001). That a second exponential is discernible following very-heavy exercise presumably reflects the continued influence of the greater proportional contribution of the further recruited units.

Control Heterogeneities

A "well-fit" mono-exponential $\dot{V}O_2$ response should not, however, necessarily suggest the operation of a single metabolic “compartment” in moderate exercise. Consider, for example, how numerous compartments having a wide range of τs might sum to characterize the overall $\dot{V}O_2$ response. Using a 10-compartment model as an example, with widely-varying individual τs (20-65s) (Fig. 7), the summed response differs from a pure mono-exponential only subtly - hardly, if at all discernible with even a small component of breath-to-breath noise (e.g. Lamarra et al., 1987; Rossiter, Howe, Ward, Kowalchuk, Doyle, Griffiths, et al., 2000).

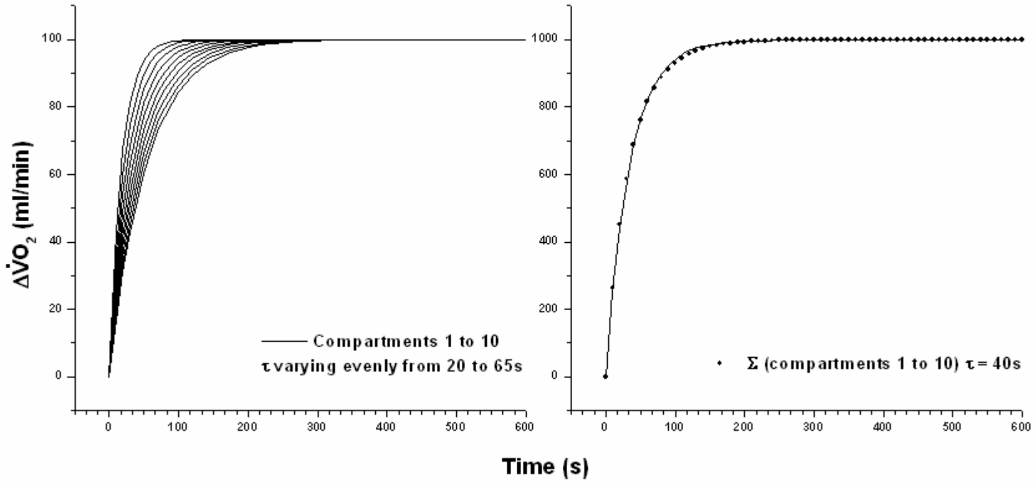

Figure 7. Left: Individual responses of a 10-compartment model of the $\dot{Q}MO_2$ response to *high-intensity* square-wave exercise. Each compartment is assumed to have a different τ, but to contribute equally to the magnitude of the overall $\dot{Q}O_2$ response. Right: the overall $\dot{Q}MO_2$ response (•) is well fit with a mono-exponential function (—). Note that while the overall $\dot{Q}MO_2$ response is weighted by the slower compartments, it is functionally indistinguishable from a single first-order compartment having a τ of 40 s. Taken from Whipp et al. (2002), with permission.

What therefore might the apparent kinetic τ conceal rather than reveal? For example, consider two subjects with ostensibly the same overall τ but with one having a narrow distribution and the other a wide distribution of regional τs. Naturally, the metabolic demands in the long-τ units of the more widely distributed model would be appreciably greater. This would be manifest as an increased demand for supplemental regional energy transfer from lactate-yielding mechanisms. This could plausibly yield different regional θLs and, consequently, a different $\dot{V}O_2max$, despite the same average τ' $\dot{V}O_2$.

There is a growing body of evidence that such heterogeneities of metabolism are characteristic of human muscular exercise. Wide regional variations in muscle T_2 relaxation time have been demonstrated during exercise (using MR imaging) (Prior, Foley, Jayaraman, & Meyer, 1999) - considered to reflect regional muscle recruitment. Similarly, Richardson, Haseler, Nygren, Bluml, & Frank, (2001) have reported a wide distribution of metabolism to perfusion ($\dot{Q}O_2/\dot{Q}M$) in calf muscle during plantar flexion exercise, using the MR-based techniques of chemical shift imaging (2D CSI) and arterial spin labeling. Also, regional MR imaging of the quadriceps during high-intensity exercise in humans has revealed marked regional differences in [PCr] and [Pi], and also in the chemical shift between the PCr and Pi peaks - evidence of regional variations in intramuscular pH and metabolic "stress" (Whipp et al., 2002). The issue of distributed metabolic function under conditions for which uniformity is assumed is of concern because the mean response of a group of muscles or even a particular muscle (as determined by ^{31}P-NMR spectroscopy, for example, or from a femoral-venous blood sample) is likely to mask important regional variations; a single muscle-biopsy sample from an individual muscle may be just as misleading.

Conclusion

In conclusion, a control model of exercise $\dot{V}O_2$ kinetics in humans appears to incorporate a dominant linear 1^o-order component, presumably reflecting cellular ~P turnover, but supplemented by a slowly-developing component of delayed onset with complex time- and intensity-related dynamics, which progressively reduces work efficiency and accelerates the time to exhaustion (Fig. 8).

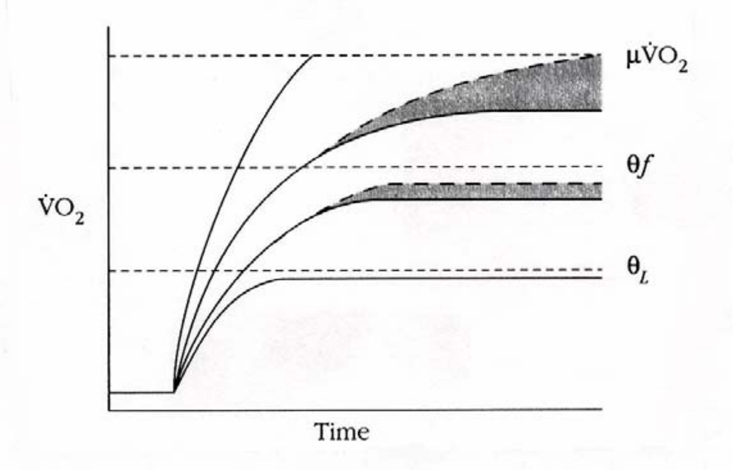

Figure 8. Schematic representation of the $\dot{V}O_2$ response kinetics to square-wave exercise at different work intensities. See text for details.

Parameter estimation of these responses, with appropriate model discrimination, can consequently provide important clues to the physiological determinants of exercise tolerance. However, it is, almost certainly, not the O_2 utilization itself but the consequences of the non-aerobic components of the energy transfer that leads to the fatigue. These are, by their nature, intensity-dependent - where intensity is decisively not simply the $\% \dot{V}O_2 \max$. That is, as shown in Figure 9, two subjects exercising at the same projected $\% \dot{V}O_2 \max$ manifest markedly different profiles of physiological response.

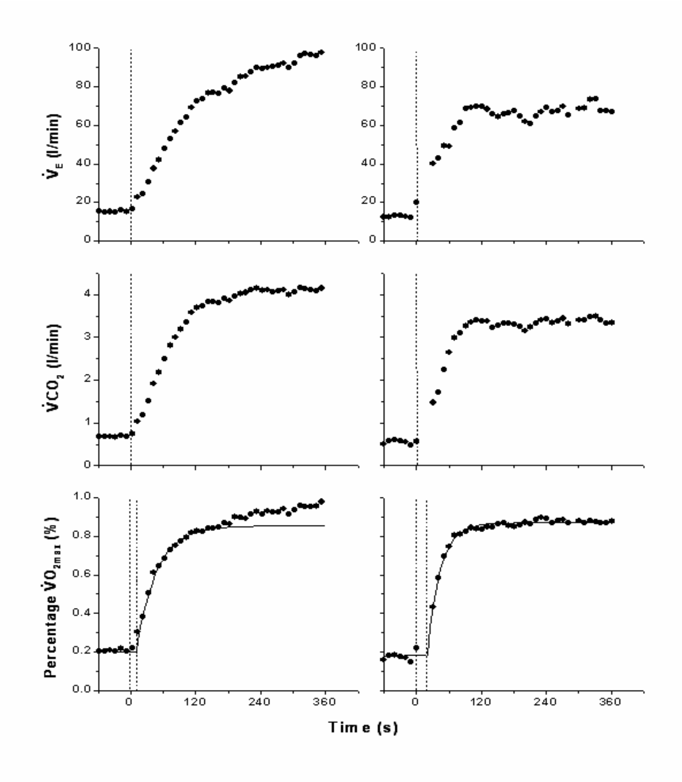

Figure 9. $\dot{V}O_2$ (and $\dot{V}CO_2$ and $\dot{V}_E$) responses to square-wave exercise in two subjects exercising at the same % $\dot{V}O_2$ max. Note the marked $\dot{V}O_2$ sc (left) and its absence (right).

For events such as marathon running that depend upon conserving the glycogen stores, the lactate threshold is crucial: higher work rates accelerate the rate of glycogen utilization by more than twelve-fold. For heavy-intensity exercise, this can lead to performance limitation despite delayed steady-states of $\dot{V}O_2$, [lactate]$_a$ and [H$^+$]$_a$ being attainable. The trajectory of these variables to, or towards, their maximum attainable levels at work rates above critical power, sets the tolerable performance limits. Whether the maxima are actually attained depends on whether, for example, the high anaerobic energy demand establishes such high rates of local glycogen depletion that it becomes limiting. Using broadly-plausible assumptions, Newsholme, Blomstrand, & Ekblom (1992) suggested that this could prove limiting not just in the marathon (and longer events) but even for the 10,000 or 5,000 M. An excellent recent review of muscle fatigue by Lännergren & Westerblad (2003) posits the importance of the duration of the event for the nature of the fatigue; the closely-related context of intensity domains, however, could provide even finer focus on the mechanisms.

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Oral Presentations of the 1st Meeting of Complex Systems and Sport

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Detection of Real-Time Patterns in Sports: Interactions in Soccer

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Introduction

In the pursuit of generating quantitative information on performance sport researchers have traditionally used frequency of event occurrence as their index of performance (Borrie, Jonsson & Magnusson, 2002). However, frequency of event occurrence has been shown to be an inadequate index of performance that cannot differentiate between effective performances (Borrie & Jones, 1998). If performance analysis is to continue to advance understanding of sports performance then it must find better methods of collecting and analyzing match analysis data. The analysis approach used here is based on a process known as T-pattern detection which allows the detection of the temporal and sequential structure of data sets. The method has been developed on the assumption that complex streams of human behaviour have a temporal/sequential structure than cannot be fully detected through unaided observation or with the help of standard statistical and behaviour analysis methods. Given that observational records of human behaviour have both a temporal and sequential structure an analysis tool that can describe this structure will enhance understanding of the behaviour (s) being studied. A generic observational software package called Theme has been specifically developed to operationalise T-pattern detection as an analysis process (Magnusson, 1996, 2000).

Method

Twenty soccer matches were coded (25 frames per sec.) using pitch position, player and match events. The primary event categories for data collection were: pass; tackle; header; run; dribble; clearance; shot; cross; set-play; lost control; foul. Additional qualifying statements could be tagged to each event category. All data was analyzed using the Theme software package.

Results and Discussion

The data show that a high number of temporal patterns exist in soccer. The number, frequency and complexity of the detected patterns, indicates that sport behaviour is more synchronized than the human eye can detect. A typical within-team event pattern from the soccer analysis is shown in Figure 1. This figure displays a detected T-pattern that occurred three times during the first half of a European Championship qualifying match (1998). The pattern describes how player A moves the ball towards the opponents goal by receiving the ball in, and then passing it out of, pitch zones 8, 11 and then 14 consecutively. Player A then completes the sequence by passing it on to player B who receives it in zone 15. The pattern describes an attacking movement through the middle of the pitch. Traditional frequency analysis of passing would have identified the ball reception and subsequent pass from each zone as discrete events but would not have linked the consecutive actions in the four zones. The movement from zone 11 to 14 also occurred on another five occasions during the first half further suggesting that player A was working effectively through the central channel of the pitch. This integrated form of analysis would potentially enhance the information given to the coach. Figure 2 shows a T-pattern from a club match (English Premiership) in which the pattern involves players from both teams and relates to the critical incident of shots on goal. The pattern occurred on three occasions during the second half of the match and includes two shots on goal within each pattern. The total time period covered the three patterns therefore includes six shots by Team A which represents 75% of their total shot on target during the second half. Even more significantly two of the three pattern occurrences resulted in goals.

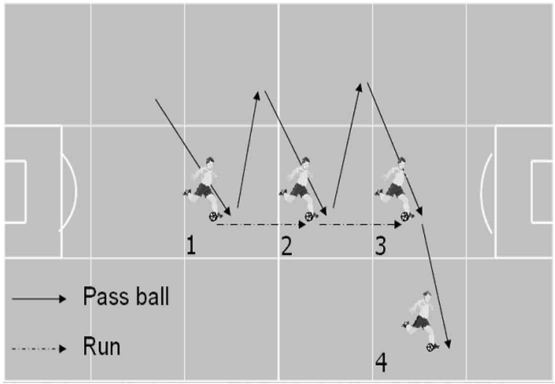

Figure 1. Attacking movement of the ball through the centre of the pitch.

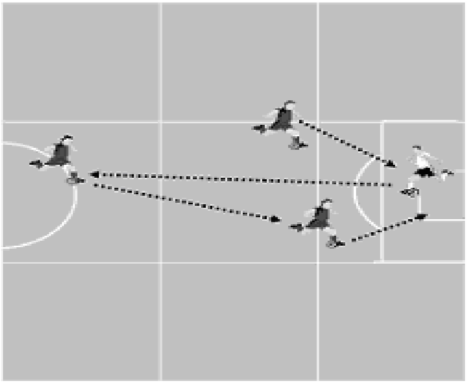

Figure 2. A temporal pattern relating to scoring a goal.

The potential interrelationship between performance rating by coaches and the degree of structure in team performance was also analyzed. Experienced coaches observed the matches and rated the performance of players on both teams. Team performance ratings were then correlated against the number of patterns each player participated in. The data show that the coaches' ratings of team performance were significantly correlated to pattern participation of players ($r=0.81$, $p<0.05$). The link between performance rating and pattern participation suggests that coaches were recognizing, albeit at a potentially subconscious level, the structure within a team's play.

Conclusions

The preliminary data shown in this paper highlights the potential for T-pattern analysis to make a significant contribution to sport performance analysis. Current analytical methods that focus on simple frequency analysis cannot identify the temporal patterns within a sports performance. Consequently without this form of analysis meaningful information is not being made available to the coach. If this information is not available then it possible that performance is not being optimized.

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Decision-Making as Phase Transitions In Sport

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Introduction

Changes in the macroscopic order of a dynamical system are called phase transitions, and are based on a symmetry-breaking process (Kelso, 1995). Araújo et al (2003) showed that, in a typical 1 v 1 sub-phase of basketball, the distance between an attacker-defender dyad and the basket changed dramatically as a consequence of the attacker's success in dribbling past the defender. Goal path selection in de-stabilising dyads formed with defenders was an emergent process for attackers. For this reason, goal path selection can be intentionally constrained but cannot be specified completely in advance. The results showed that the decision ”when to drive” to the basket by a successful attacker was an example of *symmetry-breaking* in a stable dyad. In the present study, we aimed to investigate whether the theoretical tenets of dynamical systems theory could be generalized to the sport of sailing. This study addressed how the local environment plays a large role in selecting functional behaviours. Athletes' decision making is a means of using active strategies that leave much of the information out in the context, and carefully using real-time sequences of body-world interactions to solve problems in a robust and flexible way. Solutions emerge from this interaction of organismic and contextual constraints. The purpose of a sailing regatta can be described as attempting to master the use of the wind in order to arrive at the finish line as quickly as possible. This goal must be obtained through performance manoeuvres that aim to control the direction and the speed of the boat. According to regatta rules, five decreasing minutes before the start, sailors initiate the so-called starting procedures in order to be in the optimal position (relatively to the wind) at the starting line (“second zero”). We expected to observe transition phases in the starting line location as a function of by manipulating the wind-line angle. We also expected to observe this phenomenon when participants started with and without adversaries.

Methods

Two digital cameras registered the displacement of a boat to capture its position at the starting line in twenty-six regattas (equally distributed between two different sailors). The horizontal plane trajectory (2D) of the base of the boat's mast was recorded and image treatment was made by AnaMovH systems (Fernandes, 2001). The sailor's task was to perform a short regatta (not just the start). The control parameter was designated as the angle between the wind direction and the starting line, and the order parameter was the position of the boat on the starting line at second zero, based on ideas from experiential and coaching knowledge (e.g., Dahon, 1997).

Results

In manipulating the angle between the wind direction and the starting line, we observed discontinuities in the decision “where to start”. On the left hand side of Figure 1 it can be seen that the boat's positions tend to be on the extremities with the higher |angle| values (> ±10º).

In fact when the wind favoured one of the extremities of the starting line, the nearer to that extremity the boat was positioned, the more direct was the required trajectory (to the 1st mark of a regatta). However, in the zone where the wind was neutral (between about –10º and +10º) there was higher variability in start location, because there was no advantage from boat positioning for the required trajectory.

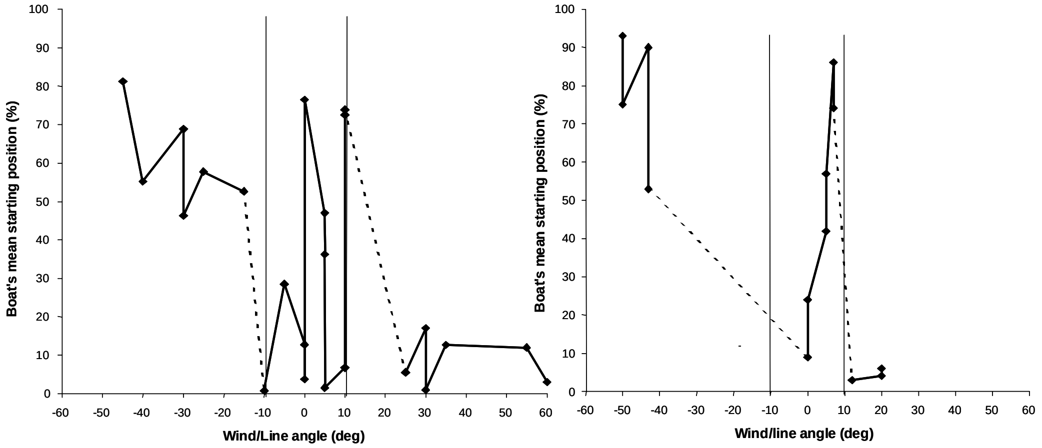

Figure 1. Mean starting positions of a boat according to the wind/line angle; Left side – performed without opponents; Right side – performed with opponents.

Following similar procedures, we analysed if the same phase transition occurred with the presence of opponents. With seven different sailors we measured the starting position of 14 starts. In the right hand side of Figure 1, it can be seen that phase transitions occurred in the same region (between about –10º and +10º) as without opponents. This region is also characterised by enhanced fluctuations, estimated by the magnitude of the SD around the boat's mean starting position.

Conclusion

Phase transitions in sports such as basketball and sailing emerge from the interaction of multiple factors (cognitions, speed, morphology, space constraints, etc.). This interplay of forces eliminates the need to posit any inordinate role for a single controlling factor (e.g., the mind). The data from this study suggest that decision making is an emergent process that can be developed through the active exploration of situational constraints.

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An FMRI Study on Auto-Determined and Etero-Determined Finger Movements

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The relationship between perception and action can be considered a starting point for a study on motor control and learning. Direct and indirect theories can be studied from a phenomenological or structural perspective. Among the ecological theories the dynamic system approach believes that movement patterns arise from complex interactions among the various motor elements, and consequently hypothesizes that new movement learning might occur through a self-organization process. Aim of this study was to verify by means of fMRI what cortical areas are activated and what learning processes are triggered during the execution of voluntary movements under different boundary conditions. Ten volunteers (6 males, age between 22 and 26 years, estimated to be neurologically normal) participated to the study after informed consent. A Siemens Vision Whole Body Scanner, 1.5 T permanent magnet, was used for MR imaging. The experimental protocol consisted of a blocked-trial paradigm in which five rest phases alternated with four task phases, consisting in the execution of a bimanual anti-phase flexion-extension of the index fingers. During the first and the second task phases volunteers could choose the execution velocity, which had to be maintained slow during the first and rapid during the second task phase. On the other hand, during the third and fourth task phases execution velocities were pre-set at 1.5 Hz and 3.4 Hz respectively for the slow and the rapid movements. Functional scans were acquired with Echo Planar Imaging (EPI) sequences and processed with SPM96 and MEDx software packages. Different patterns of activation were observed for control and learning processes during auto- and etero-determined movement execution. The most important results obtained for the comparison between the rapid and the slow movements executed in free modality were the activation of the frontal and inferior pre-frontal cortex, associated to planning processes. Moreover the activation of the cingulate gyrus, the parietal lobes, the basal ganglia, the thalamus and the cerebellum was observed, probably in relation to a movement re-organization following a phase-transition. The activation of these structures devoted suggests that an implicit learning may occur when the execution velocity increases to the point that a phase transition takes place. On the other hand, maps obtained for the comparison between the rapid and the slow movements executed under acoustic guidance show no significant activation, probably because the execution velocity was not too high even during the forth task phase, and no phase transition took place.

A Systemic View of the Aspects that Constitute Human Motricity

Dra. Marta Castañer & Dr. Oleguer Camerino
Inefc-Lleida

The first virtue of eloquence is clarity. (Quintillian)

Our aim is only to show some ideas, we consider to be very plain -but not simple-, that we have been observing, that paradoxically are blanks on the knowledge of many professionals on Physical Education and Sport.
In recent years we have been doing our teaching and different publications in order to develop a systemic and cosystemic point of view of motricity. It combines the analysis and synthesis capabilities because, we can see, that motor language, in contrast with the linearity of verbal language, is always simultaneous.
The objective arises from the need, we think exists, to identify and organize, in a coherent and functional way, all aspects that constitute human motricity. For example in order to deal with, in a exhaustive way, the contents of good Physical Education and Sport programs.
The systemic approach combines the analysis and synthesis human capabilities. The analysis from the systematic way and the synthesis from the holistic one. This is our aim in the graphics and ideograms that we will show you now

The contents, the epicenter of Physical Education and Sport

We start from de distinction between the following terms, we can title: Physic Quality *versus* Motor Capacity

Motor Capacity For us it is like the ***potencial*** of human corporal and motor languages that nurtures the motor skills. (according to Aristotle: a seed has potential, but is not yet a plant or a tree)
Motor Skill . For us the motor skill is the ***action*** that is always observable and in our verbal language we name through the infinitive verbs like: jump; turn; run; pull, and so on (according to Aristotle: the tree is the visible act once the seed has been germinated)
Motor Quality it is the state that shows each capacity in a period of evolution . While the term capacity is more pertinent for the educative sense, the quality term is more pertinent for training and health tendencies of motricity.

In short, we think that it is important to understand motor capacity like human motor potential. Both, capacities and skills, aid each other to optimize the individual motor development.

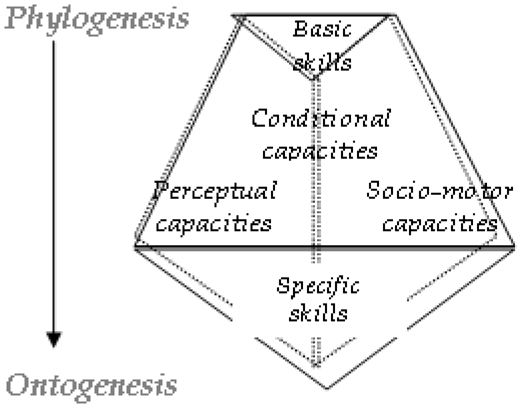

Figure 1. A systhemic prism of motricity. (Castañer & Camerino 1995)

This prism shows us the systemic guide between the motor capacities and motor skills in order to built the singular motricity of each individual.

From the phylogenetic level (that is the genetic gift of the human) we are not born from zero but with a sort of protoskills that are the reflexive movements of the neonatal period
At the ontogenetic level (that is the individual and singular development of each of us) motor skills increase in a specific and also in a specialized way. The optimal development of this prism depends on the good quality and quantity of the motor and sport experience that a person has had in his life.
The bases of the prism correspond to the motor skills like observable actions and they increase throughout our life, only if the PE and S we have had the opportunity to do has been good.
The faces of the prism correspond to each cosystem of motor capacities and, like the skills, we, as professionals have to take care to offer a good programs of his quality and quantity

In real programs, this prism has never a perfect form because it depends on the face we prioritize, because the important thing is to avoid this prism from becoming a plane figure, in other words, only one face, for example when programs of PE are focused only on playing football matches, or doing gymnastic skills or only promoting psycomotor activities.We insist, as professionals, that we have to take care of all of these faces.

Each face is like a cosystem with it's own essence that focuses a sort of PE contents. To illustrate each one we use the form of sets (Castañer and Camerino 1995) that permit the coherent intersection between the contents, in order to take care of the analysis and synthesis we talked about before.

The architecture of motricity

Until here we have talked about the map that can aid us to program and acquire and integral view of the contents that PE and Sport demand.
In the same way, in order to have an integral view of the elements that constitute human motricity, we start from the *Kinema*, like the motor unit (*a brick*), to the *Motor Profiles* (*buildings*) through the *Motor Action (a flat).*

Finally, we wish to show here, in a clear way, the mosaic that includes the different levels or dimensions of motricity that can be treated like cosystems.

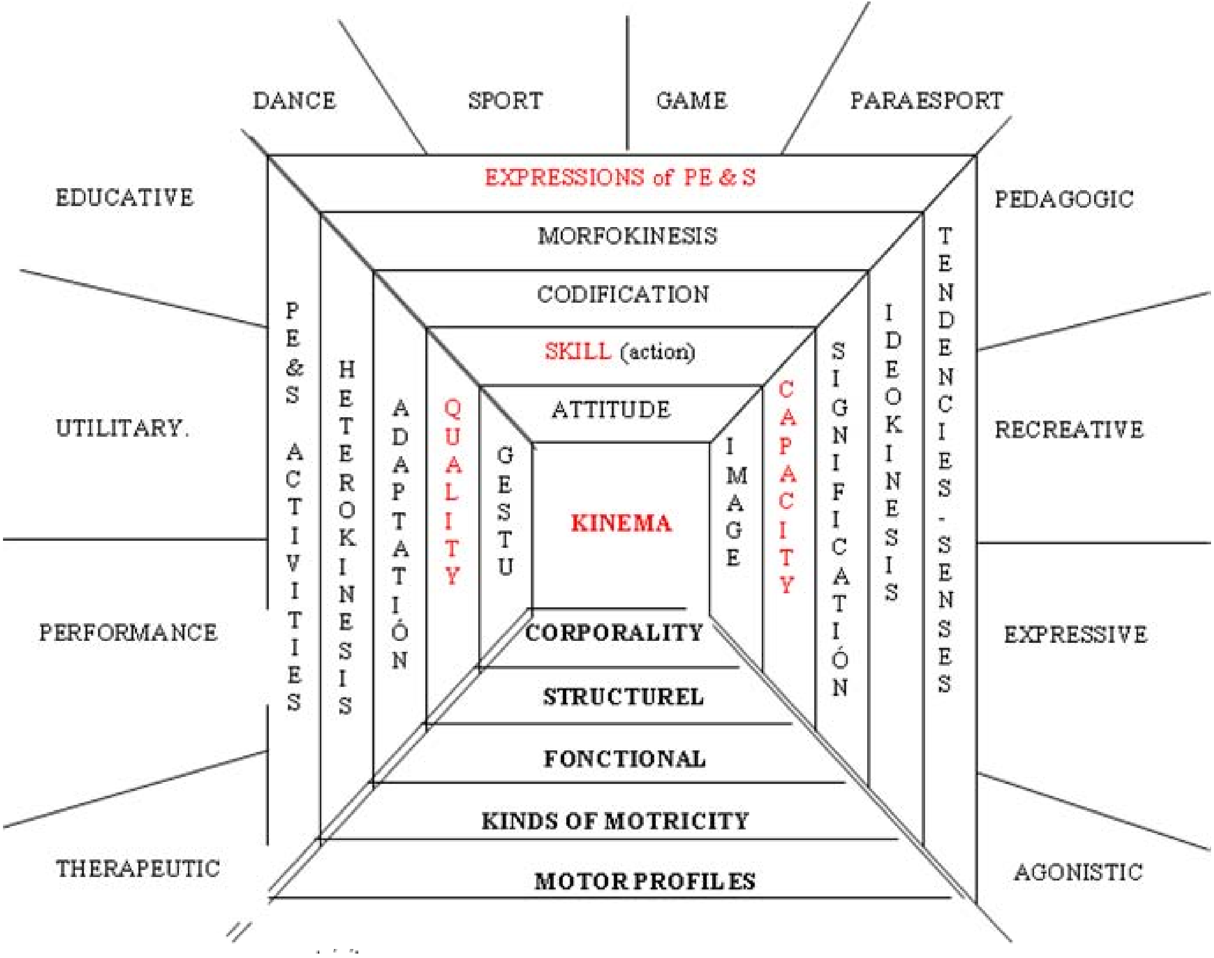

Figure 2. Cosystems of human motricity

To sum up, for us, motricity is like a music score, all singular motor expression is not only a continuos sequence. In fact sequential aspects exist like a melody and simultaneous ones like harmony.

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Myoelectric Signs of Fatigue During Constant and Rhythmic Isometric Contractions

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Introduction

In many sport activities (gymnastic, weight lifting, sailing, climbing etc) isometric or quasi-isometric contractions endured until exhaustion are often requested. During isometric contractions the surface electromyographic signal (sEMG) exhibits amplitude and frequency content changes, which reflect central and peripheral modifications of the neuromuscular system (Farina, Fosci & Merletti., 2002). In skilled weight lifters these changes are paralleled by a rhythmic burst-like activity related to force fluctuations during fatiguing isometric contractions, possibly due to motor unit (MU) synchronization (Felici, 2001a). Recently, "non linear" tools have been introduced to quantify the presence of regular i.e., deterministic, structures within the sEMG and the recurrence quantification analysis (RQA) by means of its parameter (the percent of determinism - %DET) was shown particularly promising. This approach was tested by means of a sEMG modelling simulation (Farina et al., 2002) and confirmed on real data (Felici, 2002b). The present work was aimed at investigating the effects of two different muscle activation patterns on myoelectric signs of fatigue and on the deterministic behaviour of the sEMG. We believe that contractions involving MU recruitment/de-recruitment should affect the sEMG spectral content changes. Moreover, this kind of exercise could better detect the sensitivity of RQA to the presence of synchronization within the sEMG.

Methods

Subjects 8 male healthy subjects (age: 34±6 years) participated in this study. *Procedure* Subjects were seated comfortably on an anatomic device that allowed the elbow angle to be placed at 90°. The hand was maintained halfway between pronation and supination. Maximal voluntary isometric contraction (MVC) of the elbow flexors muscles of the dominant arm was measured, then they were requested to perform four steady state (SS) isometric contractions (duration: 30s) of the elbow flexors at 20, 40, 60 and 80% MVC spaced each other by 10 min recovery time. In a separate session subjects performed two rhythmic (R) contractions oscillating at 0.5 Hz by 20% around a central value of 40 and 60% of the actual MVC. Subjects performed all the contractions (SS and R) matching a visual feedback on the screen of a computer. During the tests the sEMG signal from biceps brachii muscle (BB) was recorded using a 4 electrodes linear array and stored on a computer. D*ata analysis* As global indexes of myoelectric fatigue the sEMG Root Mean Square (RMS), the average conduction velocity (CV) and the Median Frequency (MDF) were computed. As it concern the

Recurrence Quantification Analysis, we computed the %DET as index of deterministic behaviour on signal. The values were computed every second and they were interpolated by first order polynomials; the slope of the regression line divided by the initial value and expressed in percentage was considered. The initial values were also considered. The comparisons between values in different conditions were carried out using the Student t-test for dependent samples.

Results

During both, SS and R contraction, the sEMG data showed the well-known pattern of myoelectric fatigue. RMS increased during the effort at all force levels and the slope of this increase was function of the force level. MDF and CV decayed during the SS and R exercises and the slope resulted strictly correlated with the force level, being steeper at 80%MVC while initial values were not different at different force levels. The %DET also increased during the SS and R exercises and the slope correlated with the force level. The comparison between SS and R conditions showed that at both level of force (40% and 60%MVC) only the slope of the increase in % DET was significantly different, being steeper during the SS contractions.

Discussion

The similar behaviour of the classical parameters (RMS, CV and MDF) in SS and R contractions seem to show that MU recruitment/de-recruitment involved in R does not affect the signs of myoelectric fatigue. Instead "*non linear*" analysis (%DET) shows a different behaviour between type of exercise. These suggest us that modifications occur to regard MU synchronization. In conclusion, the two type of contraction seem to engage the neuromuscular system at the same level but using different MU synchronization strategies.

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Linear & Non-Linears EMG Analysis Improves Knowledge of Neuromuscular Motor Control

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Abstract

The possibility of investigating the motor control strategies (i.e., motor unit (MU) recruitment and rate coding) from the myolelectric signal recorded non-invasively has been variously addressed with controversial results. Anyhow, by one consent, it was generally established that both amplitude (e.g., the root mean square (RMS)) and frequency (the median power spectral frequency (MDF)) content of the surface electromyogram (sEMG) reflect central and peripheral modifications of the neuromuscular system. More recently, the refinement of techniques for the estimation of the average muscle fibre conduction velocity (CV) together with the application of new non-linear approaches to sEMG time-series analysis provided further information on muscle dynamic. In the present work, three muscle efforts increasing with different slopes from 0% to 100% of the maximal voluntary contraction (MVC) were administered to the biceps brachii of 9 young healthy subjects. These ramps were followed by a 10 sec hold phase at the maximal contraction. In the present work we show that MDF, CV and RMS time-course were characterized by an increase up to a maximum, reached during the ramp or the hold phase depending on the speed of the ascending phase. After the maximum, these parameters decreased with different slopes. The improvement in terms of CV estimation allowed a more refined evaluation of the processes of fast twitch MU recruitment/derecruitment along the course of the experiment. Moreover, especially during faster ramp experiments, RMS showed a two step exponentially behaviour with a break point consistently positioned within the ramp phase. Concerning the non-linear analysis, %DET provided further important information on MU synchronization.

Introduction

The central nervous system (CNS) implements several complicated strategies to respond to force and/or movement individual demands. Such neuromuscular tasks are mainly accomplished through motor unit (MU) *recruitment/derecruitment* and MU firing rate modulation (the so-called *rate coding*). These two mechanisms are part of the so-called motor control which operates differently and in different proportions depending on the muscle and the motor task. Other conjoint phenomena intervene during physical exercise, such as MU *synchronization*, muscle *fatigue*, body heating, pO_2 and PCO_2 alteration with consequent blood pH modification, etc.

The challenging hypothesis is centered in the main idea that it is possible to infer several aspects of motor control strategies from linear & non-linear analysis of the myoelectric signal non-invasively recorded on the skin (sEMG). Several papers, some of which referenced here (Hagg, 1992; Solomonow et al. 1990; Farina 2002 a,b), demonstrated that:

- amplitude content of sEMG senses the corresponding muscular effort exerted;
- spectral content is inflenced by conduction velocity (CV) variations, firing rate statistic, action potential modification, additional recruitment at fatigue followed by a sudden derecruitment;
- MU synchronization improves the presence of recurrent patterns in sEMG;
- fatigue improves the low frequencies spectral content of the signal;
- during an increasing effort, CV is characterized by a first increase up to a maximum with a firm decrease in presence of concomitant fatigue.

The parameters extracted from sEMG are:

- Root Mean Square (RMS);
- Median Frequency (MDF);
- Percentage of Determinism (%DET), a non-linear parameter extracted by means of the Recurrence Quantification Analysis, described elsewhere (Farina et al., 2002b; Filligoi & Felici, 1999; Felici et al., 2001; Clancy et al., 2003);
- Average muscle fibre Conduction Velocity (CV).

In this paper, it is presented the strategy we used to analyse the above set of parameters extracted from sEMG (together with the force time corse) in order to interpret the physiological mechanisms involved in motor control during the muscle task.

Methods

Nine young healthy subjects (29±7 years, height 1.69±0.88, body mass 60±15 Kg) were asked to exert an isometric contraction with the *biceps brachii* muscle of the dominant arm. The muscular task was composed of 5 repetitions of the following efforts:

- ***Ramp-phase*** from rest to the Maximal Voluntary Contraction (MVC) with different slopes of 5, 10 and 20 %MVC·sec^{-1}, followed by an
- ***Hold-phase*** at 100 %MVC for 10 sec.

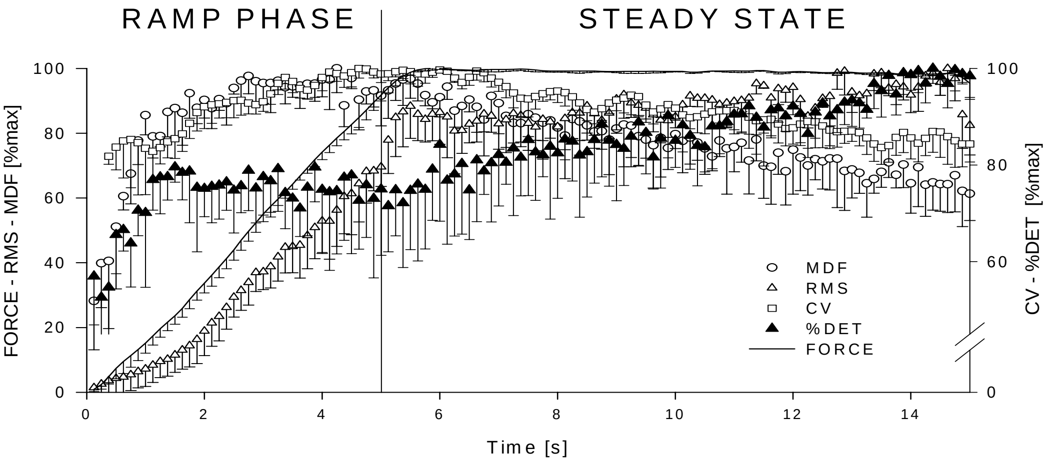

Figure 1. Time course of the parameters along the muscular effort

Results and Conclusion

For sake of space saving, we present in Fig.1 only the results for ramps up at 20 %MVC·sec-1 since the relative behaviour is substantially the same for the other slopes. The results represent the average results for all subjects in all tasks. During the ramp phase we may observe that:

- MDF increases up to a maximum, presumably corresponding to a Maximum Motor Unit Recruitment (M.M.U.R.) point (Solomonow et al., 1990)
- CV increases till the end of the ramp phase, since the faster MUs are last recruited, according to the Hennemann size principle;
- %DET, after a rapid increase, flattens for a long interval at the middle of the ramp, as a result of the equilibrium between the opposite effects of CV increase and MU synchronization increase (Farina et al., 2002a);
- RMS increases with the force. During the *steady-state*, the main observations concern:
  - MDF decreases for the presence of fatigue phenomena;
  - the same behaviour for CV;
  - %DET increases for the concomitant effects of CV decrease and MU synchronization increase;
  - **RMS** increases till the end of the trial, along the 10 sec hold phase.

The above discussed results point to the primary role of the modulation of the interplay between MU maximal recruitment and MU rate coding control mechanisms. The introduction of a non-linear technique for the evaluation of a parameter sensitive to MU synchroniztion gives a further tool for the investigation of motor control strategies. The technique of investigating a pool of parameters extracted with both linear and non-linear technique from sEMG is highly promising. The role of afferent feed-back on the modulation of the central control mechanism of the individual MUs remains to be investigated in more details.

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From Deterministic to Constructivist Paradigm: An Overview of the F.S.F. Research Program

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The main approaches in sport sciences are based on conventional scientific deterministic paradigm. These studies appear not situated, out of context, parcelled (Schön, 1983) and, consequently, very far from coaches practical knowledge (Saury & Durand, 1998). Constructivist paradigm and complex sciences framework seem to be closer to practitioner representations and better suited to practical training situations (Hellard et al., 2002). These situations are characterised as they are by the specificities proper to each athlete, and by the intervention, at any one time, of a series of factors in complex interaction together, not to mention the transformation of the athlete through time.

Our processes draws on a constructivist paradigmatic framework, characterised by the will to sustain a permanent reconstruction of the knowledge arrived, in terms of the finality which is being pursued, the context which prevails, and the precise nature of the problems arising out of the actual practice of training. The results thus arrived at can be deemed to constitute a body of operational knowledge, whose elaboration takes into account a criterion of pragmatic validity (the knowledge produced must be of practical applicability), and also its epistemological pertinence (the manner in which the findings have been arrived at, relative to the nature of the practice in question) (Le Moigne, 1995). Recognition of these two epistemological requirements implies the search for a series of indicators liable to be of practical significance for the coach, and which will enable the latter to objectify (Avalos et al., 2003; Hellard et al., 2002). The second step is to link local scientific knowledge to systemic meta-models. These models will be deemed a satisfactory one, if they comply with the criteria of pragmatic validity, and if they give rise to a body of thinking liable to contribute to a fuller understanding of the phenomenon involved.

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Determination of the Margin for Error when Dismounting from the Asymmetric Bars

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Introduction

The margin for error when releasing the A-bars may be quantified in terms of the timing error for which the gymnast has suitable linear and angular momentum for performing the required dismount. If the gymnast releases with less error than this she will have sufficient linear and angular momentum to complete the dismount. A computer simulation model of a gymnast on the asymmetric bars is used to determine the margin for error of dismounts performed at the Sydney Olympic Games.

Method

Eight performances of double straight somersault dismounts from the asymmetric bars at the Sydney Olympic Games were chosen for video analysis. A four segment planar model of a gymnast comprising arm, torso, thigh and lower leg segments was used to simulate the movement around the bar. The bar and the gymnast's shoulder structure were modelled as damped linear springs. Input to the simulation model took the form of joint angle time histories obtained from the video analyses. Individual segmental inertia data were obtained for each gymnast by scaling a “mean” data set using segment lengths determined from the video analysis. Output from the model included the linear and angular momentum. The simulation model was implemented with an optimization algorithm which was used to manipulate certain model parameters and initial conditions in order to minimize the difference in orientation and release parameters between the actual and simulated performances. The matching simulation was used to determine the margin for error within which the model had sufficient linear and angular momentum to perform a double straight somersault dismount.

Results and Conclusion

The average margin for error for the 8 gymnasts was calculated to be 30 ms. This value is considerably less than the mean value of 59 ms calculated for the eight finalists of the men’s high bar competition. The male finalists used a scooped technique in the final giant circle rather than an extended traditional technique and this lead to a greater margin for error. The female gymnasts used a traditional rather than a scooped technique and this would account for their smaller margins for error.

Spontaneous Formation of Team Fitness Stratums in Transfer Networks of Athletes with High Degree of Local and Global Connectivity

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A simple model of transfer dynamics on a network was developed. The network was considered as an open dynamical system on which transfer of traits (athletes) exists. Control parameters (i.e. context variables) of the dynamics were defined spatially with respect to 25 regions as: 1. population of athletes belonging to some sport branch 2. selection-production ability of the region and 3. wealth of the team (i.e. its ability of investment in transfers). The local and global differences of the control parameters introduce nonequilibrium conditions and several robust collective and individual effects can be observed.

The robust characteristics of the **collective behavior** are the following:

- Symmetry breaking of the initial (Fig 1, 2) team fitness distribution and spontaneous formation of few layers of stability i.e. stratums of fitness (Fig. 3,4);
- b. Rapidly decreasing number of teams with the higher level of fitness (Fig 3,4);
- c. Different transfer interactions (traits admixtures) between the teams with high investment and those with lower investment abilities;
- d. Similarity between the global and local scale fitness distributions; e. Time dependent thresholds of the team fitness level;
- f. Strong dependence of the number of the highest fitness level teams on the local and global context variables (Fig 3,4).

The **individual behavior** is characterized by existence of thresholds in control parameters that divide the attractors of individual fitness dynamics. These attractors can be defined as:

- high fitness (elite team) attractor;
- Medium fitness attractor and
- Low fitness (traits resource) attractor (Fig. 5,6) .

Figure 1. Initial Distribution of Fitness Levels on the Transfer Network

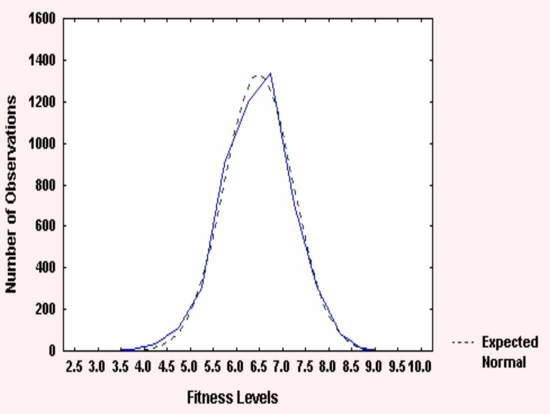


Figure 2. Initial state of the fitnes levels of teams

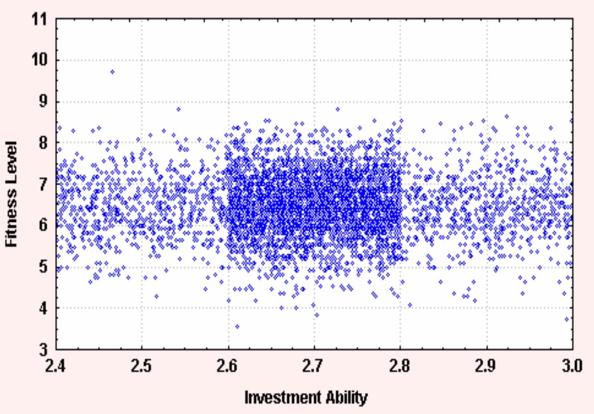


Figure 3. Final Distribution of Fitness Levels on the Transfer Network

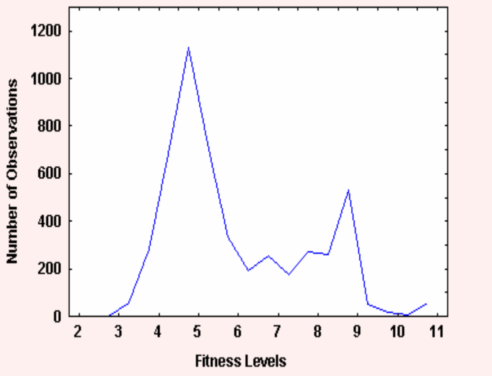


Figure 4. Final structure of the fitness level of teams with respect to one of the control parameters (Investment Ability). The remaining two control parameters were kept constant.

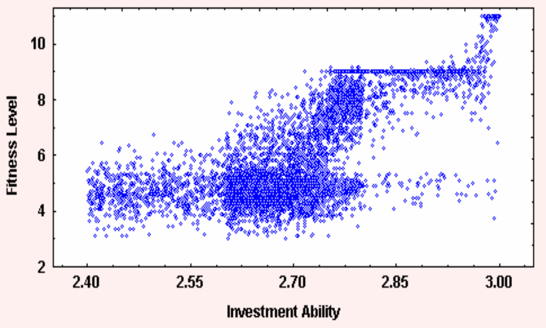


Figure 5 . Plot of the initial and final state means for each fitness level cluster

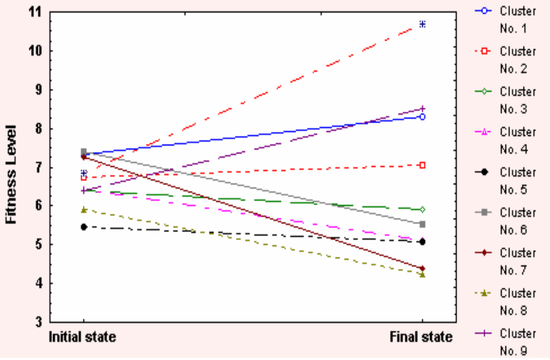
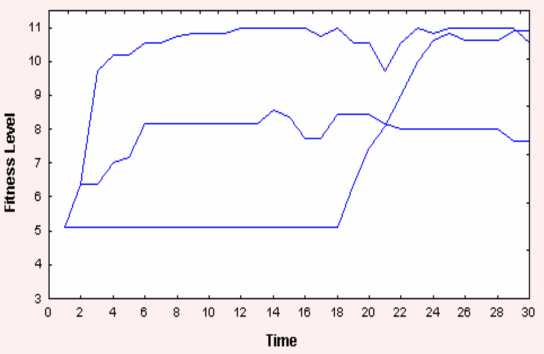


Figure 6. Trajectories of the fitness level of the same team for different values of the investment ability



Allowing variation of the values of control parameters (e.g. investment ability) the stratification landscape considerably changes. For example, when the system is partialized with respect to the remaining two control parameters, the probability of teams with much lower investment abilities to reach the top fitness levels increases, however their survival times on the top are shorter than those of the high investment ability.

Generally speaking, in our model, the stratification of the team fitness levels as a global (macroscopic) phenomenon arises as an emergent structure and is a result of the interactions (transfers of traits) among the individual elements of the system. This results, on the other hand give some possibility that the dynamics of the sport traits (athletes) transfer system could be analyzed on a macroscopic level and could be subject to analytical treatment.

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Determination of Knee Joint Moments During Running Jumps Using a Constrained Forward Dynamics Simulation Model

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Introduction

Inverse dynamics and quasi-static calculations are often used to estimate the net joint torques exerted during sporting movements but such methods make a number of assumptions that may not be appropriate for high loading impact situations. These assumptions include the use of rigid segments to represent the limbs in the body and the use of simple frictionless pin joints to connect these segments. This paper uses a constrained forwards dynamics model for determining the net joint torque at the knee during running jumps and compares the results with the moments calculated using quasi-static and pseudo inverse dynamics.

Methods

An eight segment subject-specific, angle / force driven planar computer simulation model of the takeoff phase in running jumps (Figure 1) was developed using the software package AutolevTM3. The eight segments comprised the foot, shank and thigh of the takeoff leg, the shank and thigh of the free leg, the trunk, a single upper arm and a single lower arm. Wobbling masses within the shank, thigh and trunk segments of the takeoff leg were represented by mass-spring-damper systems.

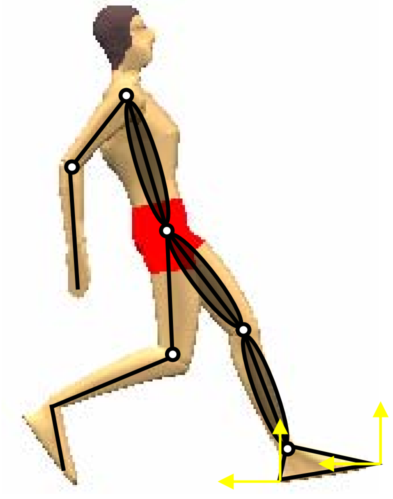

Figure 1. Eight segment computer simulation model of the takeoff phase in running jumps.

High speed video and force data were collected during two running jumps (one jump for maximum height and one jump for maximum distance) performed by an elite male high jumper. Quintic splines (Wood and Jennings, 1979) were fitted to time histories of the joint angles and the horizontal and vertical ground reaction forces acting at the toes and heel of the subject during the takeoff phase. Subject-specific inertia parameters were determined from 95 anthropometric measurements taken on the high jumper (Yeadon, 1990). The inertia parameters and the time histories of the ground reaction forces and the joint angles were input into the simulation model. Simulated Annealing (Goffe et al., 1994) was used to minimise the difference between simulated and recorded performances of the running jumps until the best match was found (12 degrees of freedom: 2D location and orientation of each wobbling mass relative to its corresponding rigid segment, orientation of the trunk, and 2D location of the toe).

Results

The peak knee torques calculated using quasi-static, pseudo inverse dynamics, and constrained forward dynamics were 747 Nm, 682 Nm and 620 Nm for the jump for height and 1202 Nm, 1002 Nm and 1029 Nm for the jump for distance. Although the torque time histories followed the same general profile for each jump, the inclusion of the segment accelerations resulted in lower peak values and the inclusion of wobbling masses resulted in a smoother knee torque time history. However, all the calculated peak knee torques were in excess of the eccentric maximum that could be exerted by the subject, which was estimated to be 277 Nm (from isovelocity experiments with the subject).

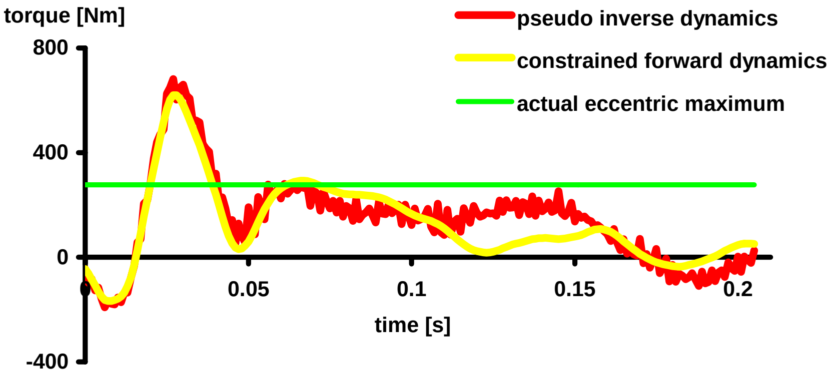

Figure 2. Knee joint torque calculated using pseudo inverse dynamics and constrained forward dynamics.

Conclusion

A constrained forward dynamics model has the potential to improve estimates of the joint torques exerted during running jumps. However there still remains the problem of unexplained systematic error that may result from the use of simple pin joints or may be a consequence of errors in the digitised data.

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Why Team Sport Game Is Complex System?

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In this paper team sports games, as are: water polo, soccer, basketball and handball, were analysed using bottom-up approach. Based on (*kinesiolgical*) *activity analysis*, and, referring to the fields of game theory, robotics (AI) and complex system theory, *granule* is identified as basic ingredient of team sports games. Obtained lump of such non-atomic elements (e.g. moving, passing, dribbling, orientation, positioning, player role, playing rules, playing field, tactic etc.), i.e., *granules*, is found to be structured in such a way that micro, intermediate, and, macro levels can be identified. While each level in the structure is internally consistent set of simple elements, to explain their collective properties, or, moving upward along structure levels, the well-known emergence property was necessary to be employed. Thus, the necessity of introduction of complex system theory in modelling of team sports games is concluded. Aim of this analysis was formalization of team sports games to enable computer simulation. Simulation is suggested to be most appropriate scientific tool of today for modelling of team sports games. Some existing software packages and/or platforms (Soar, SDML, Swarm, RoboCup simulator) are shortly discussed and evaluated for the possible use in modelling and simulation of team sports games. Since different complex systems, in general, can be grouped according to some common features, intuition and insight gained in one can be transferred to another, it is suggested that studying of team sports games can yield to the development of complex system theory itself, and, also, beside kinesiology/sportscience to some other scientific fields as are sociology, organizational theory, or biology.

A Quantitative Explanation of Differences Between Male and Female World and Olympic Championship Performances Using Physiology and Physics

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Introduction

It is the intention of this paper to explain the differential performance of elite male and female athletes. Average performances for Olympic and world championship performances are used since these performances are widely published and often used to compare the genders.

Methods

Physiologists note that elite, equally trained men and women create about the same power output per unit of lean body mass. By using the ratio of lean body mass for elite women athletes divided by lean body mass for elite male athletes, women are expected to produce about 28 % less power output in running and jumping events and 29% less output power in swimming events. These are average figures for the entire body. Women have a somewhat greater disadvantage for events requiring upper-body strength and a somewhat lower disadvantage for events requiring lower-body strength. The laws of physics are applied to those same events, using average Olympic and world championship performances.

Results

Table 1 summarizes the results. Using physics, a force diagram symbolically represents an athlete's performance.

Efficiency (e) force (f)←——●——→Physical law

The athlete applies a force, some of which (*e f*) is governed by an equal and opposite physical law, while some of that force may be lost as useful output, hence the efficiency may be less than one. The athlete's power output in watts is the product of the athlete's applied force times velocity or $p=f\ v$. In running, good technique requires efficient tailoring of stride length and stride frequency to the athlete's physique. The laws of viscous friction may be employed here. Body area is proportional to $m^{1/2}$. Canceling constants, power is proportional to $m^{1/2}\ v^2$. The average percent difference in power (%DP) of 28% is close to the value predicted from differences in lean body mass. %DP is lowest in the shortest sprint distances, which tend to emphasize lower body strength.

For jumping events and the pole vault, the laws of ballistic trajectory, may be used. The jumper is at the top of the jump when the vertical velocity is zero. The average vertical force applied by the jumper is the jumper's weight (proportional to mass). Power is proportional to the jumper's mass times velocity, which is proportional to the square root of the ballistic distance (or height). For the long jump, high jump and triple jump the %DP averages 28% (less in the high jump where women are at less of a disadvantage based on lower body strength and conversely more in the pole vault)

It may be surprising that power output in speed skating power satisfies the same relationship as for jumping events, since a short sideways jumping motion maintains forward velocity.

The result is that power is proportional to $m\ v$. The average %DP values are near 27%. The small variation is time and power, is caused by the very low friction environment, in which the average velocity winning varies little versus distance.

The same hydrodynamic laws that govern large ships and aircraft govern swimming and rowing events. For swimming, efficiency is approximately proportional to body mass. Whetted surface area depends on mass raised to the exponent 2/3. For swimming, power is proportional to $m^{-1/3}\ v^{3}\ C_D$. I used a ratio of 0.9 for women's /men's drag coefficients using results from the literature. Average %DP is 28%, the value predicted based only on lean body mass. Variations in %DP are due to the differing upper body versus lower body demands and differing drag coefficients (noting that only one common drag coefficient ratio was used for all events).

For rowing efficiency was assumed to be one. Power is proportional to $m^{2/3}\ v^{3}\ C_D$. The average %DP is 32%, above the 28% average value for the other events, due to the significant upper body demands placed on the rowers, wherein female rowers are at an above average disadvantage, compared to the other events.

Conclusion

The laws of physics were applied to 33 events contested in the sports of athletics (including running, jumping and the pole vault), speed skating, swimming and rowing. The average female Olympic or world champion produced 28% less power than her male counterpart, exactly the percent difference in lean body mass for equally trained elite athletes. Prior to the 1970's, elite female power output lagged an additional 3-6% behind their male counterparts, depending on the event. The higher rate of improvement enjoyed by women at that time appears to have been due to the closure of that 3-6% power performance lag due to less opportunities for elite female athletes compared to male athletes. The fact that elite women no longer improve faster than elite men is perhaps a consequence of (reasonably) equal opportunity in sport today and not of diminished accomplishment.

Table 1. Male/Female Percent Differences in Power Output Using Physics

Type of Event	Number of Events	Olympic Comp.	World Comp.	Power Prop. to	Smallest %DP	Largest %DP	Average %DP
Running	8	8	8	m1/2 v 2	25.5 (100m)	30.2 (10km)	28.3
Jumping and Pole Vault	4	8	8	m d1/2	26.7 (High Jump)	31.1 (Pole Vault)	28.2
Speed Skating	4	8	8	m v	26.9 (500m)	27.6 (1500m)	27.2
Swimming	12	8	8	m -1/3 v 3 CD	24.3 (400m free)	30.1 (200m breast)	28.0
Rowing	5	3	0	m 2/3 v 3 CD	28.8 (Quad sculls)	33.5 (Pairs w/o cox)	31.6
Total	33						28.5

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Myoelectric Signs of Fatigue and Force Failure During Endured Isometric Contractions in Elderly

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Age-related muscle morphological alterations are associated to changes in the motor units' (MU) control properties, to a decrease in maximal isometric torque and to an higher resistance to fatigue. This study is aimed at investigating how these age-related physiological modifications are reflected by peculiar signs of myoelectric fatigue and/or changes in the deterministic content of the surface electromyographic signal (sEMG). For this purpose the sEMG was analysed in time and frequency domains using as global indexes of myoelectric fatigue the sEMG Root Mean Square (RMS), average conduction velocity (CV) and the Median Frequency (MDF). Concerning the non-linear approach, the recurrence quantification analysis (RQA) was applied, and one of its parameters, the percent of determinism (%DET), was computed. Besides, we also sought to test if the above indicators correlate with the ultimate end-point (endurance time, ET) for the task.

Five healthy young (Y) subjects (27+-4) and five healthy elderly (E) subjects (72+-1) participated in the study. After the assessment of right biceps brachii maximal voluntary contraction (MVC), they were asked to perform three endurance test at 80, 50 and 30% MVC, spaced each other by one week. The task consisted in matching a target value displayed on a PC screen for as long as they can and eventually to continue also after the ET point was reached. Biceps brachii sEMG signals were detected using a 16 electrodes linear array. The ET was defined as the interval between the beginning of the steady state phase in force recording and the point at which subjects were unable to maintain the force within a 2.5% of the target for more than 0.25s. Normalized MVC (N/BMI) was greater in Y than in E subjects. Elderly seemed to show greater endurance at low force level (30%MVC) than Y; MDF and CV decays in E group were lower at higher (80%MVC) force level, while %DET increase behaved similarly in the two groups as function of force. Finally, MDF, CV and %DET were all well correlated with ET.

These preliminary results lead us to conclude that sEMG reflects neuromuscular changes associated with ageing process, although the overall control scheme is not changed. Interestingly, it seems that the studied parameters are suitable predictors of ET in young and elderly subjects, being the CV the more robust.

Complex Systems and Functional Dynamic Processes of Brain Activity

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The main purpose of this communication is to show the relationship that we thought one could establish between complex system's theories of sport training and the functional dynamics of the brain. Both partake a common space, which is the ”effect” they have and their repercussion in the “cause”; obviously this action modifies any organization. If one takes an accurate look on brain activity one can distinguish two kinds of processes that take part: the dynamic ones mentioned before and the lineal ones. Although at first sight they seem opposites, from a neuronal point of view, the dynamic processes include the lineal model in most of the cases. Anyway we can usually observe the functional lineal action in an isolated way, for example in the neurological interpretation of a fall. The mentioned neural dynamic refers to the difference that sure there is for all of us, between the cortical space (the one with a dynamic action) and the subcortical with its lineal action. One single movement of an articulatory lever generated by a unique muscular group, is a clear example of cortico-subcortical interrelation. That means that when the order is established and executed by motor areas, the information returns to the cerebellum, which then informs to the cortical cortex (“programmer” and “efferent”) of what happened. As we all know there isn't just a single contraction, in fact there is an unconscious contraction chain, what we call “engramas”. The order is dynamic but the execution is lineal; whenever we do not obtain a desired motor act, a new and conscious order is remade and executed.

If we take again the example of a fall, and look at this action from a procedural memory stance, the action is acting for a lineal and quick way. This is a concept older, in functional terms, than the dynamics from a functional and genetic point of view. Finally this complex interpretation has its basis in Luria's theory with its functional and complex system, made up by three blocks: Activator-inhibitor, receptor and programmer. All of them act according to the “all or nothing” law, and in the encephalic dynamics the part and the hole, are functionally the same.

Improving Training Methods by Means of Dynamic Systems Research Background

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Some of the deficiencies of training methods come probably nowadays from the influence of the computer metaphor, the model of lineal causality (stimulus-effect) and the division of the human being into parts. Research is also based on this approach and new technologies appear that try to improve each component or each part of the training plan independently. Some examples can be cited to illustrate the previous statement:

The common use of power lifting machines to develop strength. They isolate the muscles and "protect" the most feeble parts of the body with artificial support, ignoring that human body acts synergistically in any movement, has to be prepared to live without supports and has to adapt to constant internal and external changes;

The practice of classical stretching exercises, overlooking muscular chains;

The technical training, based on repetitions of external models without taken into account the individual and variant characteristics of the athlete;

The current analytic testing methods...

Development of dynamic systems theory and its application to the study of movement coordination have created a new scientifically background that give a chance to new approaches for applying to training methods. Principles described by holistic theories suggest the limits of the division of training in individual parts because of the evidence that modifying a small component of the system can modify the whole system. Multiple studies also show how a perturbation of the system by a minute change of a control parameter results in bifurcations that alter all the distribution of attractors in the state space (Kelso, 1999).

Based on such principles and the research realized in this area some proposals for improving training methods are discussed and suggested:

- Integrating the different parts of the training components and considering the whole person with all the necessities of the sport. Typical exercises proposed for improving strength, for instance, are easy modifiable using free weights, working with closed chains, increasing the variety of the exercises affecting all the state space, and integrating the development of stabilising muscles.
- Analysing the initial state of the athlete and the distribution of attractors for orienting and prescribing the practice. It could be done evaluating the fluctuations that appear performing the exercises (Torrents et al. 2002), and can be a method to control and optimise the training process.
- Using "errors" and taking advantage of fluctuations to improve performance. Perturbing the execution of the athlete proposing new conditions for training can give rise to these desired fluctuations. Exploring the individual state space, using varied exercises, and taking advantage of the fluctuations should help to find the optimal technique without following external models. For getting this technique, specificity of practice is also needed to construct a new attractor in the desired direction, but the variations will construct an adaptable and flexible individual performing that

movement. Sport is characterized by the constant new situations (perturbations) that the athlete has to overcome.
- Analysing the external factors to contribute to the perception-action cycle (Buekers et al. 1999).

Specific new training or learning methods, as differential learning, have been developed and tested scientifically (Schöllhorn et al, 2001). At the same time old practices based on the integration of the human body as a whole are being promoted (Feldenkrais method, Pilates...) but its application to sport is very limited and the research is nearly absent. The principles of synergetics, the dependency on initial conditions, or variability as a measure of change, complicates research in this area using traditional tools of testing and analysis. Tools from dynamical systems can be used to create a scientific background that supports the new proposals with the aim of improving training methods.

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Time and Frequency Domain Analysis of Ground Reaction Forces in Jumping with Elite Rhythmic Gymnasts

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Introduction

Testing in sport is based traditionally in evaluation of states and discrete parameters instead of processes and changes in the evolution of performance. Introduction of tools from dynamical systems in sport research has opened new ways of testing and interpreting data. These tools have mainly been used in sport for modelling rhythmic cyclic movements and analysing the phenomena of human coordination (Kelso, 1995). However they can also be used for analysing non-cyclic movements and the behaviour of the athlete performing technical exercises. Frequency domain analysis of time series, that has been used to study gait patterns, can help us to study the variations and features of the shape of force records. The aim of this study is to study the fluctuations of the time series of ground reaction forces during jumps of rhythmic gymnasts using the frequency domain analysis in order to identify individual patterns and changes with training (instead of the more commonly applied statistical analysis of discrete variables).

Methods

Ten high level rhythmic gymnasts from the National Spanish Team were tested. They performed two different exercises in two different periods of the training season: a fouette-split and a stag leap with half turn. Two trials of each jump were registered using two Dinascan-IBV force platform (situated under a carpet) and a registration frequency of 500 Hz. Traditional time domain analysis of discrete parameters was computed analysing forces and times in the three axes (Ferro et al. 1999). A frequency domain analysis, which describes periodic signals and therefore quantifies the oscillation pattern of the force time curves was also applied. Fourier coefficients of ground reaction forces patterns were used in order to obtain discrete parameters for functional evaluation and comparison. Concretely, the higher frequency included in the 95% of the signal amplitude was computed as this value has been recommended in studies of different gait patterns as more appropriate to examine differences because the representation of the waveform is sufficiently detailed (Giakas et al. 1997).

Results

Analysis of the time series of the forces show that a characteristically pattern of jumping of each gymnast and of each jump exists. The value obtained by the Fourier analysis can identify these individualities in the three force axes. An evolution in the frequency domain is observed in the performance of the jumps in all the gymnasts during the season, as there is a decrease in the values of fluctuations in the vertical force. An example of this phenomena is given in figure 1.

Results of the discrete analysis show an increase in the maximum and medium vertical force. The Fourier analysis of different trails of the same jump by each athlete allows to identify individual patterns. Changes with training are observed in the frequency domain of the jumps in all the gymnasts.

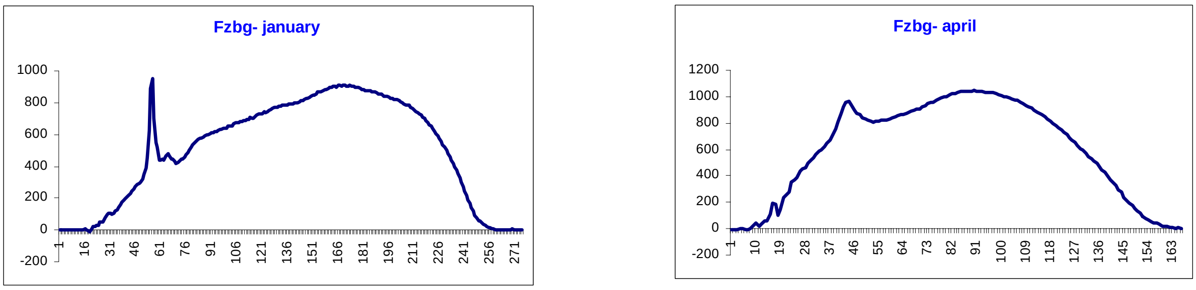

Figure 1: Time series of the vertical force of the stag leap in one of the gymnasts, in January and in April

Discussion/Conclusion

Principles of dynamical systems can help to explain the utility of analysing the frequency domain in jumping (Torrents et al. 2002), and it could be a very sensitive method for evaluating the initial state of the athlete, variations or evolution in the ground reaction forces during the performance of sport exercises.

In conclusion, fluctuations of ground reaction forces seem to be useful to identify individual patterns of jumping and to give new information about the individual athlete.

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Function as Constitutive Feature of Movements in Sport

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Introduction

Movements in sport can be considered a comparably complex aggregate of elements that constitute a specific structure. Function can serve as a constitutive feature in order to determine these elements of movements and their relations. Function may also serve as a criterion to determine freedom and constraints of movements.

Functional analysis from this point of view is important for practitioners for at least three reasons: First, functional analysis allows to determine the particular elements that require specific practice; second, functional analysis may serve as a basis for extrinsic feedback; and third, functional analysis may convey criteria for movement evaluation.

Two important functional concepts in German Sport Science

In German Sport Science, two basic concepts have been proposed that allow for functional analysis of movement structure:

- Functional movement analysis by Göhner (1979)
- Constitutive movement structure by Kassat (1995)

Functional movement analysis proposed by Göhner

Based on five constraints (goals, rules, environment or situation, attributes of the object to be moved, person), Göhner (1979) determines functional phases of movement. These phases are evaluated according to functional dependency and temporal order. Therefore, main functional phases are distinguished from auxiliary functional phases. The auxiliary functional phases are depending on the main functional phases, i.e., they support the main function of the movement. A run-up for the long jump, e.g., can not be fully understood without considering the take-off. So, every motor operation of the run-up, particularly the last strides, depends upon the take-off. In this regard, the run-up is an auxiliary functional phase for the take-off. Depending on the temporal order, preparatory, simultaneous and bridging auxiliary functional phase can be distinguished. Preparatory functional phases are preceding the respective superordinate functional phase, whereas simultaneous auxiliary functional phases take place synchronous. Bridging auxiliary functional phases follow the respective superordinate functional phase.

Within this framework proposed by Göhner, the functional elements of movement can be determined by looking for the relevance of operations for the five constraints. The most important aspect is the relation of operations and goals.

Using the example of the long jump, we can ask for the function of the run-up, the different operations during take-off, flight and landing.

Constitutive movement structure proposed by Kassat

Kassat (1995) analyses movements according to the abstract relation of actions and effects (Figure 1). Basic motor actions show a specific amount of variability, i.e., there is a set of possible actions. On the other hand, effects exerted by motor actions also show a special area of variability. Action-effect relations reflect the fact that actions and effects are related in a specific way, i.e., if an action is varied in a particular way there is good reason to expect that the effect (outcome) of this action may also change in a specific way. If we apply more force during take-off, e.g., we expect that we shall increase height. Kassat proposes two types of couplings between the action-effect relations, i.e., action- and effect-related couplings. These relations enhance or restrict the freedom of movements. Action-related couplings mean that two action-effect relations are referring to the same action. In the long jump, e.g., the stretch-shortening cycle of the jumping leg brings about two effects, i.e., netto decrease of horizontal velocity and at the same time gain of vertical velocity. Because these two effects need to be coordinated in order to perform a good long jump degrees of freedom decrease. Effect-related couplings, on the other hand, enhance degrees of freedom, because at least two actions serve the same effect. This means that one action may compensate the other one. In the long jump, e.g., swinging arms and legs and extending the knee increases vertical impulse. Therefore, if leg extension and leg swing show sufficient dynamics, the arm swing need not be as dynamical as compared to less dynamics of the respective actions.

Kassat also proposes a systematic procedure for movement analysis. This procedure comprises six steps: analysing the task, the movement form, the situation, and kind of movement, developing an idea for the solution, and analysing the attributes of the person.

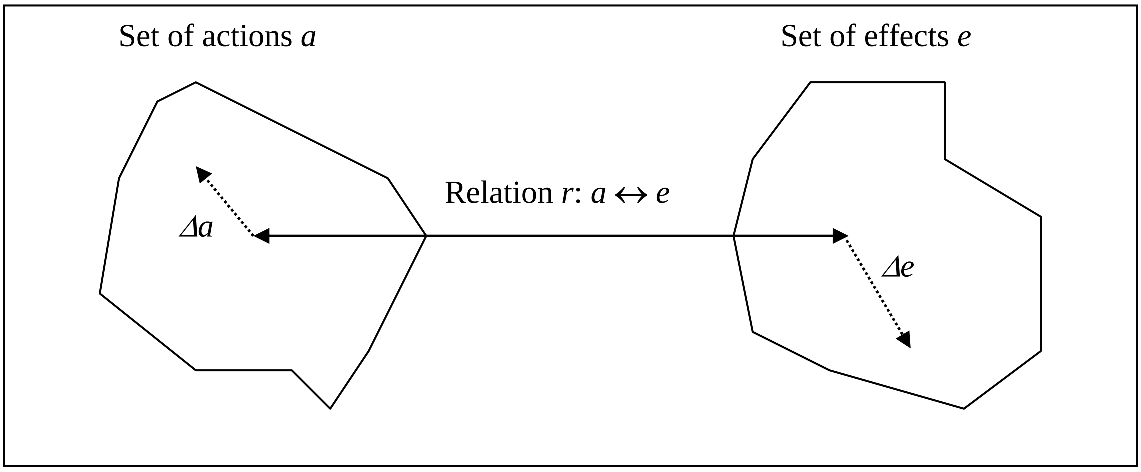

Figure 1. Illustration of action-effect couplings as abstract relations of actions a and effects e. Broken lines indicate that certain changes of action (Δa) may cause certain changes of effect (Δe).

Conclusions

A functional point of view allows researchers and also practitioners to understand order and variability of movements. The conceptual frameworks proposed by Göhner and Kassat are also appropriate for dealing with functional equivalence, functional compensation, and functional substitution at a qualitative level.

However, functional analysis is not exhaustive, for several structural aspects of the human movement system have also to be taken into account.

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Modelling Differential Activation of Knee Joint Extensors

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Introduction

The force exerted by a muscle is a function of the activation level and the maximum force which depends upon the muscle length and velocity of shortening. The relationship between muscle force and velocity may be described by a rectangular hyperbola in the concentric mode (Hill, 1938, Proc Royal Soc London B 126, 136-195) and by an inverted hyperbola in the eccentric phase. In voluntary knee extensions the activation is less than maximum in eccentric mode but reaches maximum in concentric mode (Westing et al., 1990, Acta Physiol Scand 140, 17-22). The aim of this study was to model this “differential activation” in order to calculate the maximum voluntary knee extensor torque over the full range of knee angular velocities.

Method

Torque data were collected during maximal eccentric-concentric knee extensions using an isovelocity dynamometer with crank velocities ranging from $50^{o}s^{-1}$ to $400^{o}s^{-1}$. The maximum torque / angular velocity relationship was modeled using a four parameter function comprising two rectangular hyperbolas while the activation / angular velocity relationship was modelled using a three parameter function that rose from submaximal activation for eccentric velocities to full activation for high concentric velocities. The product of these two functions gave a seven parameter function which was fitted to the torque / angular velocity data.

Results

The unbiased root mean square difference between the seven parameter function fit and the torque data was 2.7% of the maximum torque achieved. The corresponding fits to the maximum torque and activation functions had unbiased root mean square deviations of 2.1% and 2.3% respectively.

Conclusion

Differential activation accounts for the non-hyperbolic behaviour of the force-velocity data for low concentric velocities. The maximum voluntary knee extensor torque that can be exerted may be modelled accurately as the product of functions defining the maximum torque and the maximum voluntary activation level. Failure to include differential activation considerations will lead to errors in the estimation of torque in the concentric phase.

Poster Presentations
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Effects of Symmetry Breaking on Learning a Bimanual Coordination Pattern

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Viewed from a dynamical systems perspective, *learning* corresponds to a modification of the coordination dynamics in the direction of a to-be-learned pattern through the interplay of cooperation-competition between *behavioral information* (i.e., information specifying the to-be-learned pattern) and existing coordination tendencies. In the present experiment, we study the effect of a control parameter, namely the eigenfrequency difference between the coordinated limbs (Ω), on the acquisition of a bimanual coordination pattern. It has been shown that $\Omega \neq 0$ results in *symmetry breaking* of the coordination dynamics by (1) a change in mean of ϕ (i.e., the phase difference between the limbs) and (2) a change in the standard deviation of ϕ. Thus, by manipulating Ω before learning, it is possible to induce a shift of a pre-existing attractor toward a to-be-learned relative phase. As a result, the initial situation of competition becomes one of cooperation, prompting several important questions: Does learning in a symmetry breaking condition facilitate a stabilisation of the to-be-learned pattern? And, if so, does it help learning? And does learning in an asymmetric situation transfer to a symmetric situation ?

To examine these questions, 16 subjects were instructed to perform a relative phase of 30° specified by an auditory metronome. They were assigned to 2 groups: one in which the moment of inertia (which is related to the eigenfrequency) of one of the limbs was manipulated in such a way that the relative phase difference of 30° constituted a stable fixed point for the coordination between the arm movements ('symmetry breaking' group) and one in which such a manipulation was absent ('symmetric' group). Throughout the learning process (which entailed 3 consecutive daily sessions), regular tests were conducted to compare the ability of the subjects in both groups to perform $\phi = 30°$ in the symmetric situation. In addition, the effects of learning on the underlying dynamics were monitored using a "scanning procedure" (for details, see Zanone & Kelso (1992). *Journal of Experimental Psychology: Human Perception and Performance, 18 (2),* 403-421). The outcome of the experiment will be presented in terms of means, constant errors and standard deviations of relative phase and its theoretical implications will be discussed.

Methodological and Dynamical Perspective to Determine Critical Moments on Sport Game

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Introduction

Sport games are characterized by cooperation-opposition nature (Moreno, 1989). This reality gives to the sport competition a non-linearity essence that can be observed when two teams are performing their cooperation and opposition tasks during the game. One game has its own history and its course could be completely different from each other but with a similar final result. McGarry et al. (2002) compare the sport competition with a dynamical system, where small and singular events can introduce high alterations on normal organization of whole parts that are playing. Hughes et al. (1998) designated as a "*critical incident*" any type of alterations in rhythmic flow of a match. Nevertheless, it is possible to define not only critical incidents, but also periods of a match, where the events provoke some instability in the equilibrium of contest. In the case of Basketball, Knight and Newell (1989) named these moments as "*critical moments of game*". The main goal of this paper is to discuss the new criteria that allow us to identify the critical moments of a sport game, considering the game as a dynamic and open system.

Methods

Each game was viewed as an independent case. Two variables X and Y were considered as corresponding to the scores by each side. These variables follow the Poisson distribution, where two parameters λ_1 and λ_2 are the expected numbers of each team's score. The random variable *Pd* was taken into consideration to express the point's difference between teams in each minute of the game, which doesn't submit a Poisson distribution. The equation 1 represents the densities function of *Pd* variable.

$$P\left[X-Y=k\right]=\sum_{j=0}^{+\infty}P\left[X-Y=k/Y=j\right]P\left[Y=j\right]=\sum_{j=0}^{+\infty}P\left[X=k+j\right]P\left[Y=j\right]=\sum_{j=m\acute{a}x(0,-k)}^{+\infty}\frac{e^{-(\lambda_1+\lambda_2)}(\lambda_1\lambda_2)^j\lambda_1^{\;k}}{(k+j)!\,j!}$$

Equation 1. Mathematical representations of density function of Pd variable.

The *Pd* variable could be considered for two consecutive minutes of the game (Pd_1 and Pd_2 respectively). The difference between Pd_2 and Pd_1 leads to the definition of the *Variation Coefficient of Point's Difference* (*VCPD*). The |*VCPD*| can assume only positive and entire, or zero values. Based on these values it's possible to determine the percentiles that allow to subdivide the game moments according to their potential criticality. Equation 2 represents the probability percentiles.

$$X_p = min\ \{\ x : |VCPD|(x) \geq p\ \}.$$

Equation 2. Percentiles probability of |VCPD| variable.

Results

The examples of time series results of Basketball and Handball games were used to check these new criteria. Table 1 shows the process of determination of VCPD variable and the phase portrait, which allow us to describe the variable behaviour during this particular game. After describing the phase portrait of VCPD variable, it's possible to define criticality levels of the game moments through the determination of percentiles probability of this time series. If we divide the percentiles probability in three categories (percentiles <=25; percentiles between 25 and 75; percentiles >=75) we are on presence of the critical moments of game according the score dynamic during its course (figure 1).

Table 1. Determination of VCPD variable according random variables Pd_1 and Pd_2. The last two columns of the table show us the phase portrait that we can define during each game minute. Legend: **X** and **Y**-points scored by each team; **Pd_1** and **Pd_2**-point's difference between teams in each minute; **VCPD**-difference between Pd_2 and Pd_1 in each minute; **(VCPD)+1)**-value of VCPD one minute later; **[((VCPD)+1) – (VCPD)]**-difference between VCPD one minute later and the minute before; **abs**- absolute value.

Min.	X	Y	Pd1	Pd2	VCPD	(VCPD)+1	[(VCPD+1)-(VCPD)]	abs[(VCPD+1)-(VCPD)]
0	0	0	0	0	0	0	0	0
1	4	2	4	2	2	2	0	0
2	6	2	2	0	2	-3	-5	5
3	8	7	2	5	-3	2	5	5
4	12	9	4	2	2	4	2	2
5	16	9	4	0	4	1	-3	3
6	19	11	3	2	1	3	2	2
7	24	13	5	2	3	-3	-6	6
8	26	18	2	5	-3	0	3	3
9	28	20	2	2	0	0	0	0
10	30	22	2	2	0	2	2	2
11	32	22	2	0	2	-3	-5	5
12	32	25	0	3	-3	-4	-1	1
13	32	29	0	4	-4	-2	2	2
14	32	31	0	2	-2	-4	-2	2
15	32	35	0	4	-4	-2	2	2
16	34	39	2	4	-2	0	2	2
17	36	41	2	2	0	-4	-4	4
18	36	45	0	4	-4	-5	-1	1
19	36	50	0	5	-5	0	5	5
20	38	52	2	2	0	0	0	0
21	40	54	2	2	0	-1	-1	1
22	42	57	2	3	-1	1	2	2
23	45	59	3	2	1	-1	-2	2
24	46	61	1	2	-1	5	6	6
25	51	61	5	0	5	-1	-6	6
26	53	64	2	3	-1	4	5	5
27	59	66	6	2	4	2	-2	2
28	61	66	2	0	2	-2	-4	4
29	63	70	2	4	-2	1	3	3
30	66	72	3	2	1	-3	-4	4
31	66	75	0	3	-3	7	10	10
32	73	75	7	0	7	1	-6	6
33	74	75	1	0	1	0	-1	1
34	76	77	2	2	0	3	3	3
35	79	77	3	0	3	0	-3	3
36	81	79	2	2	0	-1	-1	1
37	83	82	2	3	-1	-3	-2	2
38	83	85	0	3	-3	0	3	3
39	85	87	2	2	0	-3	-3	3
40	87	92	2	5	-3		3	3

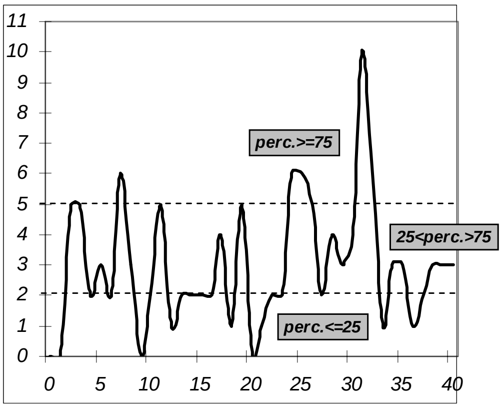

Figure 1. Dynamical behaviour of VCPD during the game. Values of VCPD higher than percentile 75 were considered critical moments of this game.

Discussion/Conclusion

When we compared the Basketball and Handball samples**,** the results showed that the ranges of variation on |*VCPD*| on Basketball were higher than the values has been found for the time series results of Handball game. Differences in scoring systems could account for this fact. A higher difference in scoring system between two teams is more frequent to achieve during a Baskteball game than in the case of Handball game. Using this method, it is possible to define a multidimensional view for classification of the critical moments in sport game. Figure 1 presents three dimensions of critical moment on a sport game: intensity, nature and temporal localization. *INTENSITY* could be defined by the percentile probability of the absolute value of *VCPD* at each minute: low, moderate and high intensity of criticality of game moment. *NATURE* reflects the relationship between score dynamic at the game moment: crating vantage; recovering a disadvantage or an equilibrium moment on the game. *LOCALIZATION* is the temporal contextualise of the moment of game (each sport game has own particular temporal division that is defined by its rules). Despite the intrinsic variability of game, this multidimensional approach of critical moments could be an auxiliary track to find patterns and regularities on game analysis.

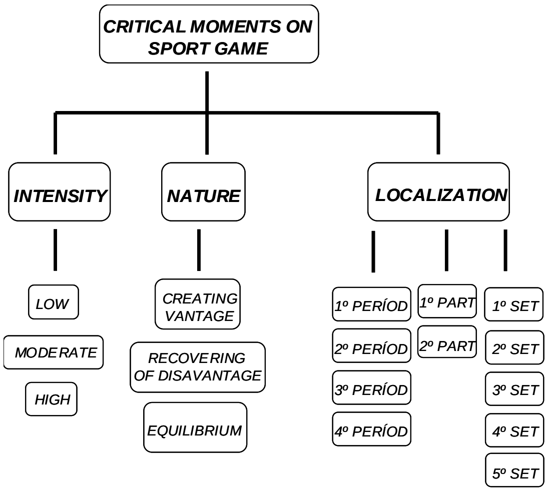

Figure 2. Multidimensional structure of critical moments on sport game analysis

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Influence of Inhibition of Return on Different Components of Action in Two Visually Guided Motor Tasks

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Introduction.

Human action in reaction time tasks is highly dependent on perception. In motor tasks, such as sports that demand high accuracy for hand grasping, adequate processing of visual information is critical. Visual attention maximizes searching of relevant stimuli to optimise human response.In studies of exogenous attentional orientating with variable delays between cue and target (Stimulus Onset Asynchrony or SOA), response time for targets at previously cued locations is longer than for targets at uncued locations, mainly at long SOAs. The effect, known as Inhibition of Return (IOR), has been observed in discrimination as well as detection tasks (Lupiañez et al., 1999; Klein, 2000). We explored how IOR mediates action in two visuallly guided motor tasks.

Methods

Subjects (n=10) saw 2 boxes placed to the left and right of a central visual fixation point. One of the boxes flickered, cueing that location, and randomly 50 or 950 ms after that, the target (‘●’) appeared at the same location as the cue (cued) or at the opposite location (uncued). Participants were instructed to fixate the central point, and when the visual target appeared, quickly react with the ipsilateral hand to the side of the target either to “grasp” or to “reach” the object placed on the table.All subjects performed 2 blocks of grasping and 1 block of reaching trials in a counterbalanced order. MEL software controlled the presentation of stimuli. An accelerometer placed on the object registered time of contact. A Powerlab & BioAMP system collected surface EMG data of deltoid muscles from left and right shoulders, and the other data by CHART 4.0 software. Dependent measures were: Reaction Time (RT): From target onset to the first deltoid EMG burst. Movement Time (MT): From the first EMG burst to the first accelerometer burst. Thus, experimental design was Task (reaching vs. grasping) X SOA (100 ms. vs 1000 ms) X Cueing (cued vs. uncued).

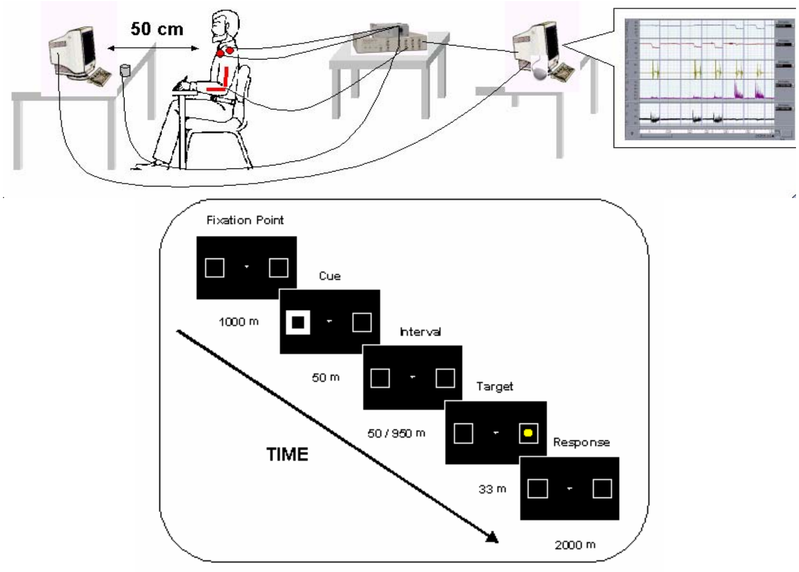

Figure 1. Experimental Set-Up

Results

The results of the experiment are shown in table I.

Table I. Cuing effect and Significant effects of variables on Reaction & Movement Times

		GRASPING TASK				REACHING TASK			
		SOA 100 ms		SOA 1000 ms		SOA 100 ms		SOA 1000 ms	
		CUED	UNCUED	CUED	UNCUED	CUED	UNCUED	CUED	UNCUED
REACTION TIME	Time (ms)	242	230	235	204	230	229	223	195
	CUING effect (ms)	**- 12 (IOR) ***		**- 31 (IOR) *****		**-1 (IOR)**		**- 28 (IOR) ****	
	Global Statistical	**CUING ⇨ F (1, 8)= 50.651, p < .001 (IOR effect ⇨ Uncued Trials 17 ms faster than cued trials) TASK * CUING interaction⇨ F(1,8) = 5.560, p < .05 (IOR effect bigger in grasping task (21 ms) than reaching task (14 ms) SOA * CUING interaction⇨ F(1,8) = 10.722, p < .05 (IOR effect bigger in SOA 1000 ms (30 ms) than SOA 100 ms (6 ms)**							
MOVEMENT TIME	Time (ms)	320	319	326	327	278	268	266	270
	CUING effect (ms)	**-1 (IOR)**		**+ 1**		**- 10 (IOR)**		**+ 4**	
	Global Statistical	**TASK ⇨ F (1, 8)= 51.117, p < .001 (Task effect ⇨ MT 52 ms longer in grasping than reaching task.**							

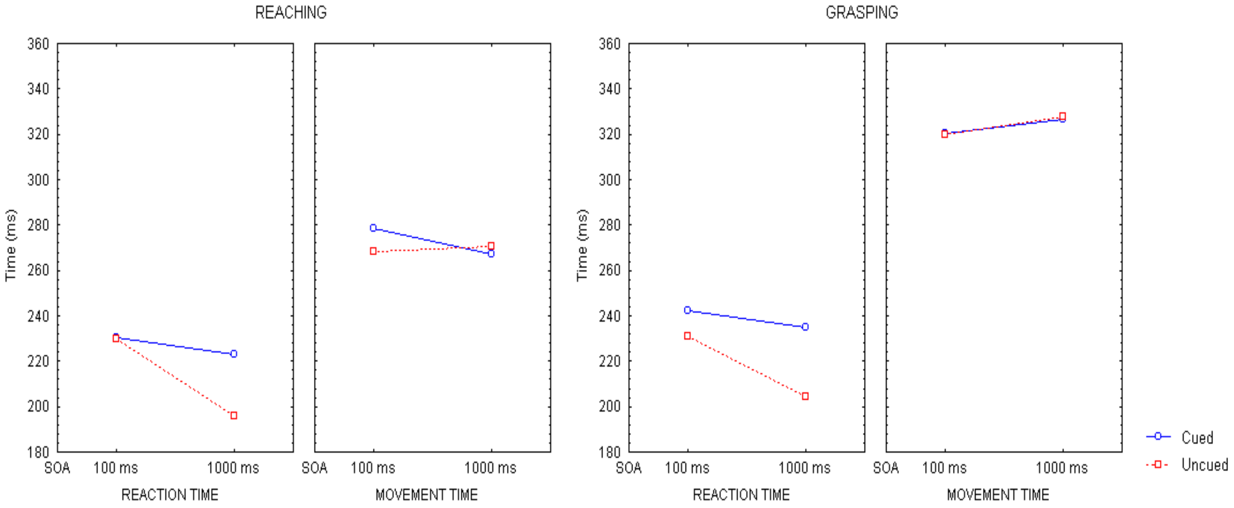

Figure 2. Cueing effect on Reaction Time & Movement Time as a function of SOA for each task.

Conclusion

The IOR effect was larger at the long SOA, and only was observed with RT as dependent variable. Furthermore, the effect was statistically larger in grasping than reaching task. Movement time was only influenced by task; no cueing or SOA effects were observed in this measure. These results are coherent with the previous literature (see review of Lupiañez et al., 1999) and show the importance of task on attentional effects.

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On Context Dependence of Behavioral Variability in Inter-Personal Coordination

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Introduction

Results from recent studies investigating the dynamics of bimanual coordination have led to contrasting viewpoints concerning the relative contribution of perceptual and motor processes in mediating coordinative stability. At one end of the spectrum is the belief that coordination is governed primarily by physical limitations such as neuro-muscular constraints and that perceptual factors play little role (Carson, 2004). At the other end, the stability of bimanual coordination is depicted as completely arbitrary with respect to the physical properties of the individual components, depending instead only on the directional and visuo-spatial relationship between them (Mechsner, 2004).

An alternative to these segregated approaches is provided by coordination dynamics (Kelso, 1995) which proposes that the relative contribution of perceptual and motor processes depends on the context as determined by an ensemble of constraints acting both within (Kelso et al., 2001) and between individuals (Schmidt et al., 1990; Temprado et al., 2003) as well as between stimuli and responses (Kelso et al., 1990). In the present study we investigate the relative role of visual and motor (a)symmetries in finger coordination between individuals. Our aim is to demonstrate that even with no structural coupling between the components, both co-activation of homologous muscles and visuo-spatial constraints influence the stability of the coordination. Further, we hypothesize that stability is determined not only by the relative contribution of these two constraints, but by the mutual influence they have on each other.

Methods

Pairs of participants were required to make index finger flexions while seated facing each other. The first participant (denoted by D, for Driver) maintained a pronated hand position throughout the experiment and produced finger movements synchronized to a metronome that systematically increased in rate every 20 cycles (from 1.5 to 3 Hz in 0.25 Hz increments). The second participant (denoted by F, for Follower) was required to coordinate rhythmic finger movements with D without hearing the metronome (i.e. visual coupling only). To facilitate interactions between D and F, the metronome was silenced for the second half of each frequency plateau and D was asked to continue moving at the rate determined during the first half. F participated in four conditions determined by a combination of coordination mode (in-phase or anti-phase) and hand position (supination or pronation).

The relative phase requirement was always defined by the spatial configuration (i.e. the position of the endpoint of the finger). In this way, co-activation of homologous muscles (finger flexion by F and D) produces both an in-phase (pronated in-phase) and antiphase (supinated anti-phase) relationship between the effector endpoints. If purely directional constraints determine the stability of coordination, a typical anti-phase to in-phase transition should be observed for the supinated anti-phase condition. If there is a tendency towards co-activation of homologous muscles, even between people, two configurations should be equally stable. We expect, however, that a coalition of these constraints will combine in determining stability.

Results

Statistical comparisons reveal a more stable coordination between the driver and the follower when the metronome is off, regardless of the adopted mode and/or hand position. That is, there is evidence for stronger mutual entrainment when the driver no longer has external pacing information. This is indicated by the overall variability in each condition. A visually mediated coupling enables stabilizing coordination between the driver and the follower when the metronome is off.

Each experimental condition represents a combination of musculo-skeletal and visuo-spatial constraint. In-phase is very stable when using homologous muscles in the pronated position (same direction, same muscles recruited by both subjects). Relative degradations in stability in the other conditions are observed in the following order: anti-phase supine (opposite direction, same muscles), anti-phase pronate (opposite direction, opposite muscles) and in-phase supine (same direction, opposite muscles).

Discussion

The primary contribution of this research comes from two observations. First, when coordinating between people, the presence of a metronome, presented to only one participant, can serve as an additional constraint that reduces coordinative stability. Second, coordination stability was determined by a coalition of muscular AND directional constraints. However, these two constraints did not exert equal influence on stability. The coordination between individuals was consistently more stable when homologous muscles were activated, while movement direction played a role in modulating this stability, thereby suggesting a hierarchy of constraints.

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Identifying Reaction Times in Sprint Starts: A Comparison of Wavelet Analysis and Custom Algorithms

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Introduction

In a sprint race the start is an important factor in the overall performance of the event. One important component of the start is the reaction time. The current auditory reaction time limit in sprint starts is set at 100 milliseconds by the IAAF, although it has previously been set at higher levels, (IAAF rule 162.10). However research, along with anecdotal evidence from elite athletes, has suggested that quicker auditory reactions can be achieved (Thompson et al. 1992). Systems used in competition appear to have high detection thresholds. Humans seem to be very capable in identifying the early onset of movement or force from the complex background motion as they make use of information that is not localized to the point in time of interest (Corbetta and Thelen, 1995).

The aim of this study is to develop an automatic detection system to identify the earliest possible onset of active, responsive force to an auditory stimulus in a sprint start by utilizing detection techniques that also use non-localized information.

Methods

A standard set of sprint start blocks had a piezo-electric force transducer incorporated into each footplate under pretension. An electronic start signal was synchronized with the force transducers and placed 1m behind the subjects head. Repeated trials with subjects were performed. Trial data were used for initial development of an algorithm to identify the active, responsive force of either leg from background noise and the natural tremors and motions of the human body. The algorithm low pass filtered the signal at multiple frequencies, calculated the second derivative and determined periods of continuosly increasing force and extrapolated back to determine the onset.

To test the accuracy of the detection method simulated signals and real trial signals were used (Staude, 2001). Six types of simulated force traces were developed that consisted of a baseline component and a rising force component with equivalent signal content to real sprint start force traces to determine detection accuracy**.** Random noise of 1% and 5% were added to each simulated signal. The errors in detecting the onset of the rising force in simulated trials for: the custom algorithm, discrete wavelet analysis, (Haar wavelet), continuous wavelet analysis (Daubechis 2 wavelet), threshold of 3 standard deviations, and skilled subjects observations, were calculated. Six real sprint start trials were also analysed. The skilled subjects were instructed to find the earliest point at which they considered the push off to have started and this was considered the most accurate method for these tests (Staude, 2001).

Results

For the simulated signals the linear and sinx simulated traces were not used as they were unrealistic in their rate of force rise. The accuracies with which the remaining 4 traces were detected are in Table 1. The quadratic and xsinx functions were closest in shape to subject traces. The human estimate was generally comparable to the custom software and discrete wavelet analysis. In nearly all cases for the real sprint trials the quickest reaction time is given by the human estimate then by the custom algorithm (Table 2). In the simulated traces the custom algorithm tended to detect the push slightly too early whereas the discrete wavelet was too late.

Table1

		Error in milliseconds			
	noise	x^2	x^3	e^x	xsinx
Custom Software	1%	-2	-3	+19	-3
	5%	-4	+5	+33	-3
Human Estimate	1%	+1	+8	+2	+0
	5%	+9	+9	+4	+2
Continuous Wavelet	1%	-1	-1	+17	+1
	5%	-1	-1	+24	+2
Discrete Wavelet	1%	+3	+5	+21	+2
	5%	+6	+11	+32	+3
3Sd above mean	1%	+21	+42	+80	+26
	5%	+25	+50	+90	+28

Table 2

Trial	Reaction time in milliseconds		
	Wavelet	Custom	Human
1	167	156	155
2	-97	-97	-84
3	120	105	105
4	165	161	159
5	95	77	78
6	120	110	113

Discussion

The human estimate was almost an order of magnitude better at detecting the exponential push than any other method. This result is interesting as the exponential curve was by far the harder to detect mathematically but proved no greater problem than the others to the human. This is commensurate with humans often being able to identify complex patterns from little data by using the data holistically with other learned information and parallel processing multiple options. As the simulated curves were not as complex as the real curves and the human estimate has already been shown to be more robust in more difficult detection tasks some confidence can be placed in the reaction time results. The custom algorithm is usually within a few milliseconds of the human estimate.

A fast reacting force detection system has been developed that can determine the onset of the active, responsive force of a sprint start with a very low detection threshold even in noisy environments. To be successful the identifying algorithms needed to use information that is not localized in time.

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Tennis Investigation as a Non-Linear Complex System

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Introduction

During the last decade, studies using probabilistic methods (Marcov'process) failed to predict the player's displacement in racket sports by apply (Mc Garry and Franks, 1996). The huge amount of information necessary limits the prediction and reflects the complexity of duals sports. In contrast, theories of self-organization investigate complex systems and use collective variable to characterize invariance and change of collectives mode emerging through the interaction of its components. (Haken, 1983). In the line of the above perspective, the present study investigates tennis as a non-linear complex system. A first step is to identify a so-called collective variable that sums up the invariant features and the changes occurring in the behavior of the players. In tennis, the game makes the players go back to the middle of the baseline after they have moved away from it in order to return the ball. Thus, the tennismen exhibit unceasing to-and-fro displacements about that central "position". Therefore, such periodic motion may be ascribed theoretically to that of an oscillator. Moreover, in order to move in a proper fashion, the players must take into account their own position, as well as those of their opponent and of the ball. This reciprocal attending constitutes an informational linkage, so that theoretically, the two players represent a system formed by two coupled oscillators. A well-established property of coupled oscillators, whatever their nature and their scale, is phase synchronization (Pikovsky *et al*, 2001).Thus, the collective behavior of coupled oscillators is adeptly captured by their relative phase, a measure of their lead-lag relationship. Therefore, we hypothesize that phase lag or relative phase is a pertinent collective variable to characterize the modes of displacements exhibited by two tennis players during the game.

Methods

Four tennis men ranking at a national level were videotaped while they were instructed to realize long games. Forty trials lasting more than seven rallies were thus collected. After digitization, 2D displacements were decomposed according to their Cartesian coordinates. As x-motion (viz. back and forth, from the base line) was very seldom and/or of very small amplitude, only y-motion (viz. laterally, along the base line) was analyzed. A cross-correlation within a moving 5 s window was carried out between the y-motion of both players. The lag value close to a lag 0 with the most significant correlation divided the window length yielded an index of the relative phase between the two time series.

Results

Results showed that among all relative phase modes exhibited across all trials, 0° and 180° are most frequent and stable. For the first two time windows, however, relative motion hovered around 180°. Then, two evolutions of relative phase were observed. For 40% of the trials, relative phase did not change from 180° (see Fig. 1). An ANOVA with repeated measures failed to reveal any significant effect on relative phase across time windows ($p > .05$). Fig. 2

displays an example of the players' displacements typical of the stable category illustrated in Figure 1. In the anti-phase mode, when a curve goes up, the other goes down, that is, in fact, both players moved simultaneously towards opposite direction. For 40 other percents of the trials, relative phase exhibited a marked shift (see Fig. 3). An ANOVA with repeated measures detected a significant effect across time windows (F(5, 5) = 20.03, $p < 0.01$). Fig. 4 displays a typical exemplar of the transition category described in Fig. 3. First, the players were synchronized in the anti-phase mode illustrated in Fig. 2. In a second phase (from 8 to 14 s), such a coherent mode disappears to give rise, in a third phase (after 15 s), to the in-phase mode of relative displacement, in which both curve move in the same direction. In the last 20% of the trials, no significant trend could be detected, as relative phase never stabilized.

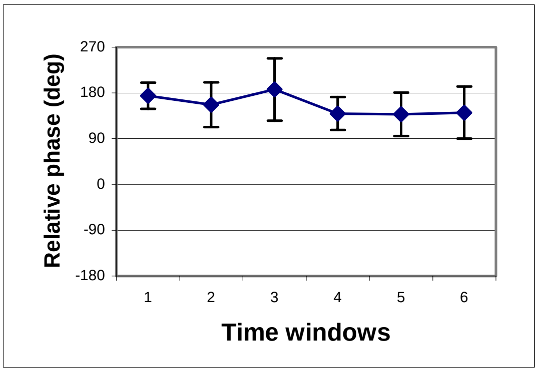

Figure 1

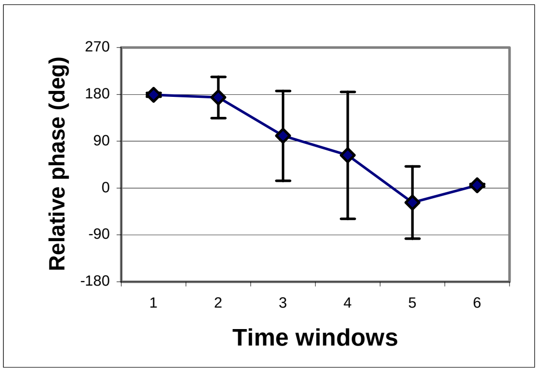

Figure 3

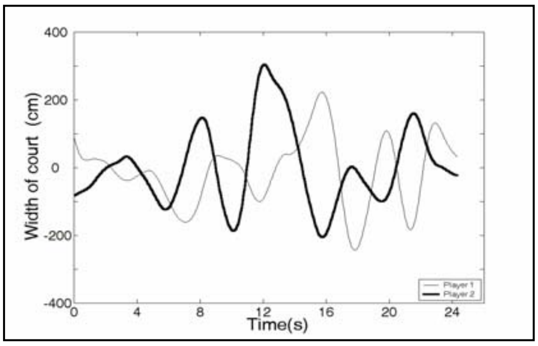

Figure 2

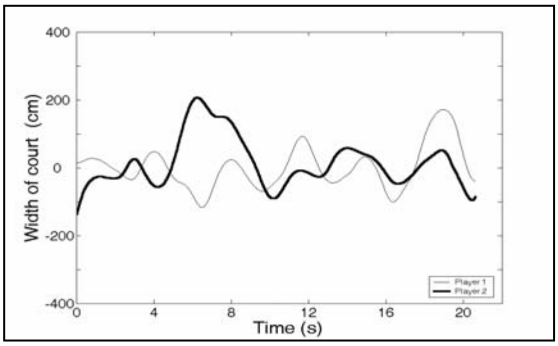

Figure 4

Discussion

The present study corroborates that relative phase is a valid and fruitful collective variable to characterize the relationship between the displacements of tennis players, revealing various types of evolution as the game proceeds. Identifying stable states through preferred, more frequent modes of collective behavior is a step primordial to a complete understanding of what the underlying dynamics may be. The present study provides a first evidence for such stable modes of relative displacements in tennis players necessary to unravel the complete dynamics and to relate such dynamics to the perceptive, energetic or tactical aspects of the game.

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Influence of Technique Variation Training on Technique Variability in Long Distance Running

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The application of complex systems theories in the field of human coordination had been mainly focused on simple movements. In contrast, the present study tried to apply the derived principles on a complex movement: long distance running. In detail the influence of technique variation training on technique variability in long distance running was examined. 16 competitive middle and long distance runners (aged, 21.7 ± 7.4 years) divided into an experimental (n=8) and a control group (n=8) took part in this study. During the investigation period of three months both groups continued their standard endurance training while the experimental group carried out additional technique variation training. Before and after the investigation period both groups were filmed during a stepwise test with two digital high speed cameras. The variability of the running technique was measured by the means of an analysis of the foot-, knee-, hip- and elbow-angle kinetics. The technique variation training was designed considering principles derived from complex systems theory. Running technique was identified as a local attractor while movement variations played the role of fluctuations. The induced fluctuations should provide a mechanism that destabilises local attractors (in this case the initial running pattern) and enabled the system to discover new stable movement modes under the paradigm of self-organization. To support the process of final stabilization the amplitudes of variation were systematically reduced during the investigation period. To determine the individual variability of the running technique a fast Fourier transformation and a comparison of the complex Fourier coefficients of the angle kinetics were carried out. A repeated measure ANOVA showed a significant difference between the two test situations for the experimental group. The technique variability of the experimental group decreased significantly while the control group showed no significant changes. The results show that additional technique variation training can change the stability properties of technique in long distance running. Thus, the consideration of complex system theory in the field of human coordination can lead to direct sport-practical applications.

How the Velocity and the Forewarning of a Target, Can Affect the Relation of Eye and Hand Reaction Times

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Introduction

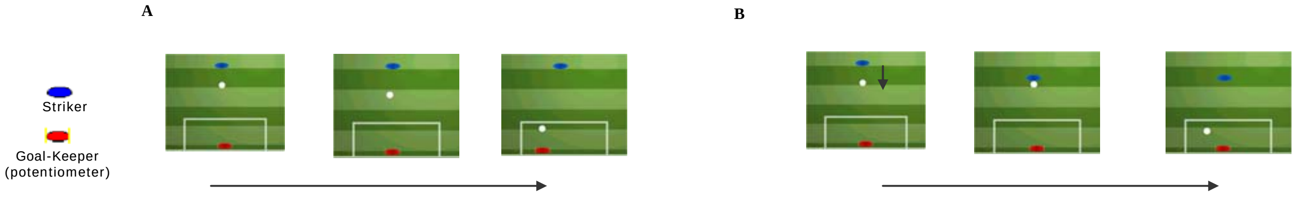
Moving the eyes towards a target is required for an accurate performance in visually-guided hand movement tasks such as grasping an object or stopping a ball. Saccadic eye movements (EM) are usually much quicker than reaching hand movements (HM). Onset of EM was found to precede onset of HM by as much as 100 ms in a pointing task (Prablanc et al., 1979). However, eye and hand movements are not always well correlated (Gielen et al., 1984; Carnahan and Marteniuk, 1991; Biguer et al., 1982; Prablanc et al., 1981). Intercepting a target moving at high speed can be made without even foveating at the target, as in many sports and games. How the motor commands required for an accurate arm movement are constructed from the limited amount of visual information on target position obtained in these instances is not known. Target velocity is an important factor for selection of the type of motor strategy to be used for target interception.

Methods

Eight healthy subjects (4 females and 4 males, aged 26-51 years) took part in the experiment. We recorded eye movements by means of electro-oculographic recordings and hand movement through the output of a hand-driven linear potentiometer that subjects had to use to move the figure of the goal-keeper to try to intercept the ball at the goal-line. We measured onset latency and direction of eye and hand movements.

Experiments were done in two different conditions: with and without a visual cue (flat and forewarning condition) letting the subjects know the exact moment of onset of target movement (figure 1). We varied ball velocity, ranging from very low velocity to a velocity that allowed for a time of the target to reach the goal-line shorter than the shortest reaction time. We also varied ball direction from alternating between left and right edges to random directions covering all the length of the goal-line

Figure 1 Experimental set-up: A: Flat forewarning: subjects had to react to the movement of the ball with only a verbal forewarning given at about 2 s before movement onset
B: Weighted forewarning: subjects had the additional visual cue of the figure of the striker approaching the ball



Results

The results of the experiment are shown at Table 1.

Table 1. Mean onset latencies (ms) and mean percentage latency shortening for hand movements (HM) and eye movements (EM) at low (1000 and 1400 pixels/s) and high (3000 and 4000 pixels/s) target velocities for 'flat' and 'weighted' forewarning conditions.
B.- Mean HM and EM amplitude and velocity for the two different types of forewarning and target velocities. The figures within parenthesis are one standard deviation of the mean.

Forewarning	Target velocity	**HM**	**EM**
Flat	Low	245 (48)	198 (15)*
	High	142 (40)**	166 (25)**
	%	41.3 (17.8)	16.3 (12.1)*
Weighted	Low	187 (50)	176 (28)
	High	119 (39)**	137 (19)**
	%	37.3 (19.7)	21.2 (16.5)*

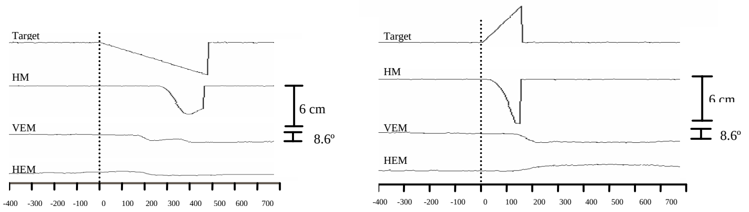
* p<0.05 compared to the corresponding data of HM
** p<0.01 compared to the corresponding data of low target velocity

Table 2. Mean HM and EM amplitude and velocity for the two different types of forewarning and target velocities. The figures within parenthesis are one standard deviation of the mean.

		HM (First 100 ms)			EM (1st Saccade)		
Forewarning	Target velocity	Amplitude (cm)	Velocity (m/s)	Signal shift %a	Amplitude (degrees)	Velocity (degrees/s)	Signal shift %
Flat	Low	1.35(0. 5)	0.13(0.05)	22.6(9.2)	7.4(0.9)	120.6(16.1)	85.6(11.4)
	High	4.15(0.8)*	0.41(0.08)*	69.3(13.3)*	9.5(1.6)	156.1(26.0)	110.9(18.5)
Weighted	Low	1.32(0. 4)	0.13(0.04)	22.1(6.5)	6.9(1.3)	113.0(21.7)	80.3(15.4)
	High	3.80(1.4)*	0.38(0.14)*	64.9(24.1)*	8.6(1.4)	140.8(23.7)	100.1(16.8)

* p<0.05 compared to the corresponding data of HM
** p<0.01 compared to the corresponding data of low target velocity

Figure 2 shows a representative recording at low and high target velocity trials.



A: low target velocity

B: High target velocity

Conclusion

Performance of hand movements in response to fast moving targets are often made without previous visual guidance. In these instances, good performance might depend on previous memory and accurate preparation of reflex circuits. These movements may make use of the reflexly evoked limb movements to visual signas, as reported in the cat (Alstermark et al., 1984)

Increasing the certainty regarding the time of onset of target movement increases the possibility to make a precipitated (and often wrong) hand movement. This can be due to involuntary activation of highly prepared subcortical descending tracts. Highly prepared motor programs may be triggered by external stimuli as it has already been reported with acustic stimuli (Valls-Solé et al., 1999).

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Complex Assessment of Eurofit Tests for Students

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Introduction

According to the World Health Organization's definition of health - health is a state of complete physical, mental and social well – being and not merely the absence of disease or infirmity (WHO 1948). We have decided to analyze one component of health – physical state of the human body. There are a lot of methods for the assessment of physical activity and physical capacity. The most widespread method, known in our country for the physical health assessment is European tests of physical fitness - EUROFIT. These tests are sensitive, individual and reliable instruments for assessing various principal dimensions of the human body's function (cardio – respiratory endurance, strength, muscular endurance and power, flexibility, speed, balance). These tests have number of disadvantages for large epidemiological studies. In order to compare results of certain group of people we have to have reference scales of certain area inhabitants. Research data can't be compared between different countries too.

The aim of this research was to develop model which will help us to compare EUROFIT or other tests data of different age, sex and area people and to create an „express method“ for objective assessment of physical activity.

Methods

134 fourth year students (92 females and 42 males) of Kaunas University of Medicine were tested. Investigated students performed EUROFIT tests of physical fitness: endurance shuttle run; hand grip; standing broad jump; sit-ups; shuttle run 10x5; plate tapping; sit and reach; flamingo balance test. Body mass index (BMI) is widespread parameter for the evaluation of weight standards. This parameter can be high when a person has large amount of muscles or large amount of fat tissue. In order to supplement this index for better reflection of body functionality we used respiratory index (RI). These two complex parameters were calculated: body mass index (BMI) and respiratory index: RI=V_{max} (ml)* / Weight (kg) (* V_{max} – maximal volume of the lungs). Body composition measures (percentage amount of body's muscles and fat tissue), heart rate and arterial blood pressure at rest, power of squats and respiration parameters were estimated. Tests' results were divided into 4 groups according to means (less and more) of BMI and RI indexes (separately males and females): A - BMI>mean, RI≤mean; B - BMI>mean, RI>mean; C - BMI≤mean, RI≤mean; D - BMI≤mean, RI>mean. Hypothetically BMI and RI could be parameters which could predict physical activity level. In order to compare results between groups we have normalized research results according to mean and dispersion of each group. Normalization was calculated by formula:

$$M_{Norm} = \{[(M_{group} – M_{total}) / 4 \text{ x Stdev}] \text{ x } 100\} |_{sex}$$

where - sex = male / female, M_{Norm} – normalized value, M_{group} – mean of data of the group, M_{total} – total mean of the data, Stdev – standard deviation.

Results

Divided and compared results showed, that both gender students with high BMI and RI were with highest physical capacity parameters according to the sum of EUROFIT and other tests results.

A group 85,97	B group 177,10
C group -128,95	D group -51,46

Figure 1. The highest positive number (B group) shows the best group of males according to the tests results of the gender.

A group 22,73	B group 109,89
C group 10,05	D group -78,98

Figure 2. The highest positive number (B group) shows the best group of females according to the tests results of the gender.

An interesting fact was that the groups with the best tests scores for both genders were with the highest body mass and respiratory indexes (statistically significant). The BMI and RI were in hyperbolic relation, it means the higher RI, and the lower BMI is.

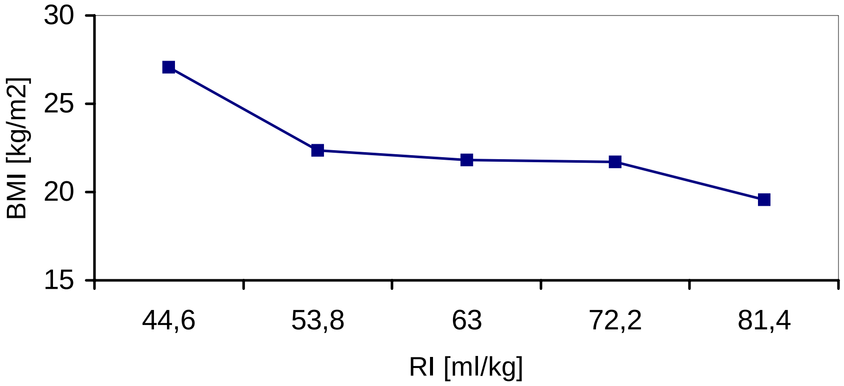

Figure 3. Relation between body mass index (BMI) and respiratory index (RI).

Paradoxical situation was observed, the best fitness results groups (B group) weren’t related to the percentage amount of the body muscles. This fact could point, that in highest fitness groups there were higher effectiveness (or quality) of working muscles.

Conclusion

Developed model of data evaluation let us to compare individual results with the averages of investigated age and gender groups with possibility to define the individual level of physical fitness. Students with high BMI and RI had highest parameters of physical capacity. Theoretically BMI and RI can be used as an “express method” to describe primal level of physical capacity.

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The Role of the Generalized Motor Program and Forward Modeling at the Control of Quick Discrete Movement

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In the last decade numerous theories come out in connection with motor learning and motor control (Richard A. Schmidt, Kawato, Gomi). In these theories the concept of motor program is used to interpret the preparation and initiation of quick, discrete movements. According to the given theories the process of motor learning is interpreted as general rule learning. This article put the emphasis on the role of generalized motor program and forward modeling, in the framework of the movement analysis of a quick, discrete task. The subjects were asked to make a quick extention-flexion in their elbow joint using their palm to generate a vacuum to blow out a candle without any direct connection with the flame. The experimental order and the quick execution of the movement assured to analyze the connection between the generalized motor program and the forward model. 6 sport university students were participated in this experiment. Their age is between 22-27 and all of them are active as sportsmen. One hand the aim of this experiment is to determine the successful movement execution criteria's with movement analysis technique. And the other hand to work out such a measurement method to indicate the relation between generalized motor program and forward model. Our hypothesis is the successful movement execution depends on the precise anticipation of the required movement parameters, and on the basis of the provided parameters the movement will be executed by the generalized motor program. On the basis of our result the main criteria of the successful execution is the wrist joint timing during the movement. It indicates that the chosen of the right generalized motor program was correct but the forward model was not able to provide the correct parameters in connection with timing of the wrist joint and the movement dynamics.

The Relationship between Expert and Non-Expert in Information Processing in Darts Throwing

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Over the last 15 years researchers have tried to explain the differences between experts and non-experts in processing the acquired information by means of more cognitive "software" dimensions. In general, It has been shown that expertise in more cognitive domains such as chess or solving of mathematical problems, is based on the acquisition of, the rapid access to, and the efficient use of semantically rich and, therefore complicated networks of domain-specific declarative and procedural knowledge (Neuman, O. 1996) This experiment is addressed to detect the differences between the expert and non-expert dart players in different kind of information processing. In more detailed, we suppose the novice darts players use forward modeling mechanism for the precise anticipation of the required movement parameters, and on the basis of the provided parameters the movement will be executed by the generalized motor program. Opposing to this, professionals use a special motor program, which includes the forward modeling mechanism, the feedback information mechanism, and the motor program mechanism to reach the highest performance level.

12 darts player participated in this experiment, throwing their darts in four different environmental conditions into the same target area. The additional information about the performance were continuously diminished from task by task, which means at the first (normal) condition, participants were allowed to use both visual and kinesthetic information during execution but at the last condition only the kinesthetic information was allowed to use. According to our results expert players were able to reach the same performance result due to special motor program. Opposing to this, non-experts performance were diminished from task by task. This phenomenon must be caused by the difference in the information processing mechanism between expert and non expert players.

Motor Skill Acquisition: Specificity or General Rule Learning?

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According to the results of the recent experimental research, which deals with the nature of motor control. The researchers strongly believe that, motor learning means general rule learning and not specification. Due to this fact, the special movement control units are missing out of these theories. Studying the quick, discrete movement execution the opposing statement has come out, according to that in this kind of movement the motor learning means specialization, which can be detected by the precision and automatization of the movement. In this paper we suggest to implement a special motor program into the motor control theories, which could give overall explanation for the control of quick, discrete movement. The aim of this article is to prove the existence of the special motor program, which suggested by us in the framework of a motor learning process. A well observed and defined movement served to prove the existence of this special unit. The subjects were asked to make a quick extention-flexion in their elbow joint using their palm to generate a vacuum to blow out a candle without any direct connection with the flame. The experimental order, the quick execution of the movement and the high number of the execution assured to analyze the connection between the generalized motor program, the special motor program (suggested by us) and the forward model. 6 sport university students were participated in this experiment. Their age is between 22-27 and all of them are active as sportsmen. One hand the aim of this experiment is to demonstrate during the motor acquisition process at the mentioned quick, discrete movement means specialization instead of general rule learning.

On the other hand the subjects developed a special motor program for the successful movement execution on the basis of the served movement parameter by the forward model, and feedback.

The Use of Binominal Logistic Regression in Performance Analysis in Handball

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Introduction

Quantitative analysis of performance in Sport Games represents an important component in the coaching process. The use of modern objective and reliable computerized methods provides an exact and detailed record of performance. However not all the obtained information is equally useful and significant for the evaluation of a player’s actions in a competition and their influence on the match result.

The ***purpose*** of this study is to analyse the prediction value of different game indicators for discriminating the winning and loosing teams in Handball.

Methods

The *sample* consisted of 77 games from the 18th Men’s World Championship of Handball. The Pictorial Match Statistics System was used for recording more then 70 offensive and defensive game indicators in each match, which directly and clearly reflect the whole match process.

The sample games were categorized into two groups according to the game’s outcome: winning and losing games (drawn games were not considered). In the process of data collection each match produced data only for one team (the winner or loser) in order to provide the team’s results independency.

A factor analysis was applied in order to extract the independent components retained in the analysis. These components permitted the reduction of variables to 13 to be included in the model.

The predictor or independent variables were: 1) field shot efficiency, 2) line shot efficiency, 3) side shot efficiency, 4) break through efficiency, 5) attack attempts (shots + errors), 6) position play efficiency, 7) fast break efficiency, 8) total attack errors, 9) assists, 10) blocks, 11) steals, 12) intercepts, 13) goalkeeper efficiency.
Binomial Logistic Regression was used to determine which game indicators were associated with the dichotomous variables (win *vs.* lost). The dichotomous variables were defined as win=1, lost=0. There were several steps followed to aid in the selection of independent variables (game indicators) for a logistic regression model.
The first step was to assess the significance of the variables in the model. P£0,25 was used as a screening criterion for variable selection.

The second step was to select the variables by the Forward Stepwise (Conditional) method in order to improve the logistic model (P-value for entry was 0.05 and for removal 0.1).

SPSS 11.0 software was used to implement all of the steps of the logistic regression model.

Results

The final model of logistic regression analysis included 4 variables that had significant effect on the game output:

1) Goalkeeper efficiency /*GKEF*/ (p=0,001);
2) Number of assists /*ASS*/ (p=0,073);
3) Field shot efficiency */FShFF*/ (p=0,024) and
4) Fast break efficiency /*FBEF*/ (p=0,045).

The *Hosmer and Lemeshow Test* showed a good fit for our final logistic model (p-value =0,965) with predictive value equals 94,7%.

The “logit” model for the game outcome in the 18th Men’s World Championship of Handball was found to be

$$Y=30{,}220 + 0{,}541 GKEF + 0{,}207 ASS + 0{,}148 FshEF + 0{,}046 FBEF$$

The probability (r) of winning the game can be calculated using equation:

$$\rho(x)=\frac{e^{30{,}220+0{,}541 GKEF+0{,}207 ASS+0{,}148 FShEF+0{,}046 FBEF}}{1+e^{30{,}220+0{,}541 GKEF+0{,}207 ASS+0{,}148 FShEF+0{,}046 FBEF}}$$

The results of the study support previous researches that suggest the goalkeeper efficiency and field (long distance) shot efficiency as game indicators, which discriminate winning from loosing teams in Handball (Silva, 1998).

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The Electrocardiogram Signal Automatic Analysis: Fiducial Points Detection and Change Representation of the ST Segment

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ST-T complex of electrocardiogram (ECG) signal reflects an important phase of the ventricular repolarization. Many efforts have been made towards the ST-T analysis because of its clinical significance in diagnosing myocardial ischemia, infarction, etc. However, the identification of the ST segment fiducial points has not been standardized yet. The most often used time domain based methods are mainly empirically dependent and noise sensitive. In this research, ST-T complex automatic analysis including fiducial point detection and change representation of the ECG signals was investigated in the wavelet transform domain.

Before ST segment analysis, it was particularly important to remove the baseline wandering for precise measurement of the ST segment. Due to the partial frequency overlap between the ST segment and the baseline wandering, the normally used digital filters cannot remove the overlapped frequency components without distorting the useful signal. Therefore, a wavelet adaptive filter structure was used for this purpose.

Then, taking advantages of the multiple resolution ability of the wavelet transform, by analyzing the corresponding relations between the singular points of the ST segment and the wavelet transforms at different scales, we developed the identification rules at four different wavelet decomposition scales or frequency bands to identify the fiducial points of the ST segment. The proposed methods were tested using the standard MIT/BIH ECG database. The fiducial points identification results were compared with those manually annotated by the cardiologists from the Affiliated Hospital of Auhui Medical University, Hefei, China. This comparison showed a very good matching, which suggested the reliability of the proposed method.

It is the case that some factors such as sport exercise, drugs, etc. may cause ischemia of the myocardial cells, which will change the morphological features of the ST segment and influence the singularity of the fiducial points. Based on this, we also investigated the relations between the ST segment change in time domain and the tendency of the local extrema change in different scales or frequency bands, and proposed a new approach to describe the ST segment change representations. Examples of ST segment change, such as ST elevation and ST depression were given.