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On-water measurement and analysis system for estimating kayak paddlers' performance

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Abstract - In recent years, the use of computerized measurement systems to help coaching professional kayak paddlers has become rather common. Note that it is not possible to evaluate the quality of the paddling exactly, however the measured inertial signals can provide useful quantitative information. Therefore, it is a challenge to find really good indicators that could help the trainers. Keeping these in mind we have developed a microcontroller-based expandable system that can record the kayak's motion accurately using the built-in 3-axis accelerometers, gyroscopes and various optional sensors. Several hours of paddling can be recorded and the off-line analysis can be done using a PC. After examining many athletes with different age and technical skills at training and races, we have evaluated the commonly used indicators and defined useful additional indicators based on the statistics and fluctuations of the parameters obtained with peak search algorithms and frequency–domain analysis. .

I. INTRODUCTION

Modern training and professional coaching are supported by various devices that can measure and evaluate inertial and biomedical signals, forces and even more [1-9]. There are common analysis techniques that can be easily applied and understood like higher velocity, higher force, elevated heart rate, and so on. However, in a race less than a second can make the difference even though the technique of the athletes can be rather different. During a race the integral of the quantities matter in many cases, a simple example is the distance as the integrated instantaneous velocity. All sensors have a certain accuracy, non-linearity and noise that affect the overall accuracy of the measurement. On should not forget many additional circumstances like weather, mental condition, support of the fans. The above mentioned facts mean that it is really challenging to extract quantitative information that can be used to distinguish between racing techniques at a professional level.

It is very unlikely that one can make so accurate measurements and analysis that can express clearly the differences of different techniques, it seems to be a better approach to find indicators based on the averaging and other statistical processing of the sensor signals. Of course, trend of these averaged quantities with a certain time resolution can be very informative as well. Engineers and scientists of different fields work together with coaches and athletes to find the most useful indicators that are simple, informative enough and easily readable – a few numbers, some curves.

We have followed the above mentioned approach to develop a special experimental system to evaluate and analysis the technique of kayak paddlers. Our device is universal, allows connection of many different sensors and the analysis is done off-line after the data acquisition. There are devices on the market that can do real-time measurements and analysis, can provide a feedback for the athlete, allow the coach to monitor the signals [7, 8], however according to the opinion of the coaches and athletes the information they can get is still far from ideal, only partial usage is common. Our aim is to provide a hardware and software platform that supports extensive research. In collaboration with coaches we have carried out several measurements and proposed indicators that can be used to evaluate the efficiency of the paddlers.

II. MEASUREMENT SYSTEM

Our device is based on a mixed-signal microcontroller, the C8051F581 [10]. This chip integrates precision analogue peripherals including a multichannel 12-bit analogue-to-digital converter, voltage reference and precision internal oscillator. High performance digital communication peripherals allow glueless connection of memory cards and provide easy interfacing to a host computer. Wide variety of analogue and digital output sensors can be used without additional signal conditioning electronics.

The block diagram and the photo of the device are shown on Fig. 1 and Fig. 2, respectively.

A three-axis accelerometer and a three-axis gyroscope are integrated on the printed circuit board as a basic set of inertial sensors. Since the sample rate is kept much higher – 1000 Hz per channel – than in commercial devices [7-9], the aliasing and noise reduction could be performed by simple one pole passive filters with cutoff frequencies of 50 Hz, on the other hand, further digital signal analysis can be applied to determine the optimum sample rate later.

We have chosen inertial sensors (LIS352AX, LPR530AL, LPR503AL, LY503ALH [11]) considering low noise, proper signal range and availability. We have selected sensors with the following dynamic ranges: ±2 g for the three-axis acceleration, ±300 ^{o}/s for the roll axis angular velocity, ±30 ^{o}/s for the pitch axis and yaw axis angular velocities, respectively.

Typical calibrated accuracy of the sensors was below 3%, which was sufficient for our estimation, especially

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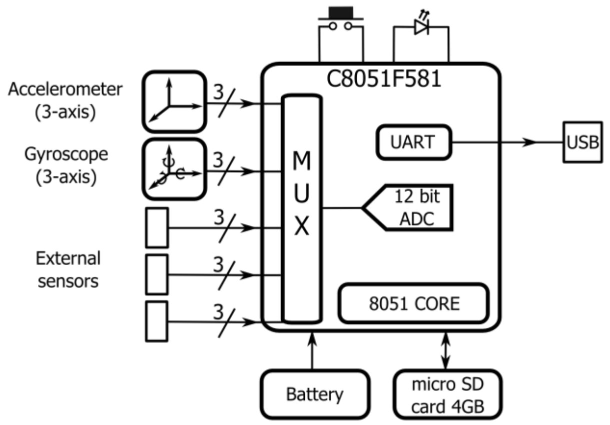

Figure 1. Block diagram of the developed device

because our analysis is rather based on the relative changes and the timing of the signals. Examples include the stroke rate, the symmetry factor and pull time.

The device incorporates a rechargeable battery and charger circuitry that is enabled upon connection to the host computer via the external USB 2.0 interface dongle. The applied Li-ion 3.6 V, 1.2 Ah battery ensured 8 hours of active operation. We have used a 4GB micro SD card for data storage that allowed data acquisition with high sample rate and many channels for hours. The microcontroller code is written in C and compiled with the open source SDCC compiler. The embedded software measures the raw signal data based on the parameters (sample rate, included channels, configuration) received from the host computer. It monitors a simple button to start and stop the acquisition and provides audible and light signals to inform the user about the status.

The device is housed in a water-proof aluminum enclosure and can be mounted easily under the seat. Besides the six degrees of freedom inertial sensors there are three available universal sensors ports. These five-pin ports provide power for external sensors, can accept both analogue and digital sensor output signals and can be flexibly set up to accommodate the needs. We have used one of the ports for monitoring the instantaneous velocity, but paddle force sensors or biomedical sensors can also be connected.

The host computer software is written in JAVA and can communicate with the device via the USB 2.0 port. The application allows setting up the sample rate, selecting the sensor signals to be recorded, setting the configuration for external sensors. The measured data can be uploaded form the device and can be used for extensive signal processing. The simple and informative graphical user interface helps the user to visualize and analyze data quickly.

Figure 2. The developed device

In the following we show the main implemented analysis functions and evaluated indicators briefly. Our results we obtained using a large set of experiments with many paddlers.

III. Processing the Motion Signals

As it was mentioned already the sampling frequency of the motion signals was set to 1000 Hz in our measurements. This value provides sufficient accuracy for motion analysis and allows to modify the method of evaluation and do further processing or filtering procedures in the digital domain.

The built-in six degrees of freedom inertial sensors (three-axis acceleration, three-axis angular velocity) were used as follows. Naturally, the forward (x-axis) acceleration signal plays the most important role in the analysis of the motion, in addition, information about other directions displacement is needed for accurate evaluation of paddling technique. However, measuring acceleration in the other two directions is rather sensitive to mechanical effects and the rotations of the kayak, so the measured signals were quite noisy. On the other hand, the three-axis angular velocity that is measured by gyroscope, was much less noisy, so it suited better for detecting the main characteristics of the movements, helping also in the interpretation of the forward acceleration signal and determining the estimated parameters with sufficient accuracy, as will be shown later.

Video analysis was used to interpret the measured x-axis acceleration, whereby the signal of pitch axis angular velocity (kayaks "nodding") was very useful to compare video frames with the signals (see Fig. 3). A stroke is divided for two phases: underwater phase (which have "catch", "power" and "exit" stages), and air-work recovery phase [4]. As it can be seen, the placing of the

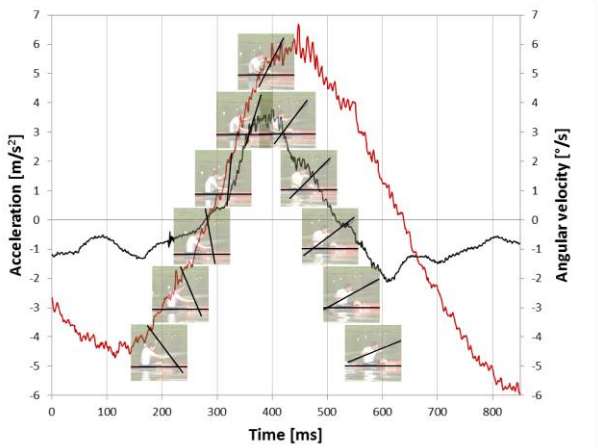

Figure 3. Comparison of video frames with measured signals using pitch axis angular velocity (red curve), to interpret x-axis accerelation (black curve)

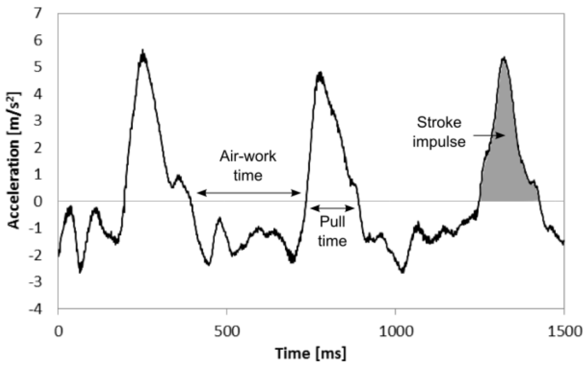

Figure 4. Parameters of a stroke cycle on the x-axis acceleration

paddle into the water happened in the negative acceleration range, however, defining the pull phase as the positive parts of x-axis acceleration signal could be a good approximation, that supposes the power stage starts at zero-intersection of x-axis acceleration.

Therefore, a period of the x-axis acceleration signal, i.e. a stroke cycle is divided to two parts: the time of *pull* and the time of *air-work*, as it demonstrated on Fig. 4. Using the time of a stroke cycle we can calculate the *stroke rate*, which is very important parameter for trainers in the kayak-canoe sport. Integrating the positive (pull) part of the signal, we can calculate the *stroke impulse* (as in [3]) (see Fig. 4), which is a speed-dimension quantity that could be interpreted as the speed-growth caused by the actual pulling. Multiplying it with the weight of the paddler and the boat, we can calculate the mechanical impulse, however, as we can see hereinafter, this is not necessary for estimating the paddlers performance.

These four physical quantities provide the basis of paddlings' analysis. Using yaw axis gyroscope signal (rotation around vertical axis) we can detect easily, the actual stroke was produced by left or right hand, so we can examine the symmetry of the mentioned quantities. Furthermore, examination of the fluctuations and trends of a longer training section or a race provides further parameters and indicators, as will be discussed later. Therefore, sufficient accuracy at the calculations of these quantities is substantial.

Fig. 4 and Fig. 5 (a) show an x-axis acceleration signal of a professional athletes (Paddler 1) paddling, who has a clear, good technique and the rowing performed at training, therefore the basic parameters are rather easily definable. Unfortunately, in many cases the signals are more complex, for example at a 200 m sprint race, the detection of the strokes is a more difficult task. Furthermore, in some paddlers' signals, a negative acceleration period shows up on the middle of the pull phase of a stroke, and one or more positive period on the air-work phase, as depicted on Fig. 5 (b), which shows Paddler 2's paddling at training. This effect, which was discussed by another work [3], indicates a technical fault, therefore its presence is useful information for trainers.

On the other hand, with this effect it is easy to come across detecting errors, such as detecting two separate strokes instead of one real pull phase. To avoid these errors, our algorithm filters out the wrong peaks by using time limits and the gyroscope signals, which are much less sensitive to the mentioned effects. Of course, this method makes the calculation of parameters defined above less accurate.

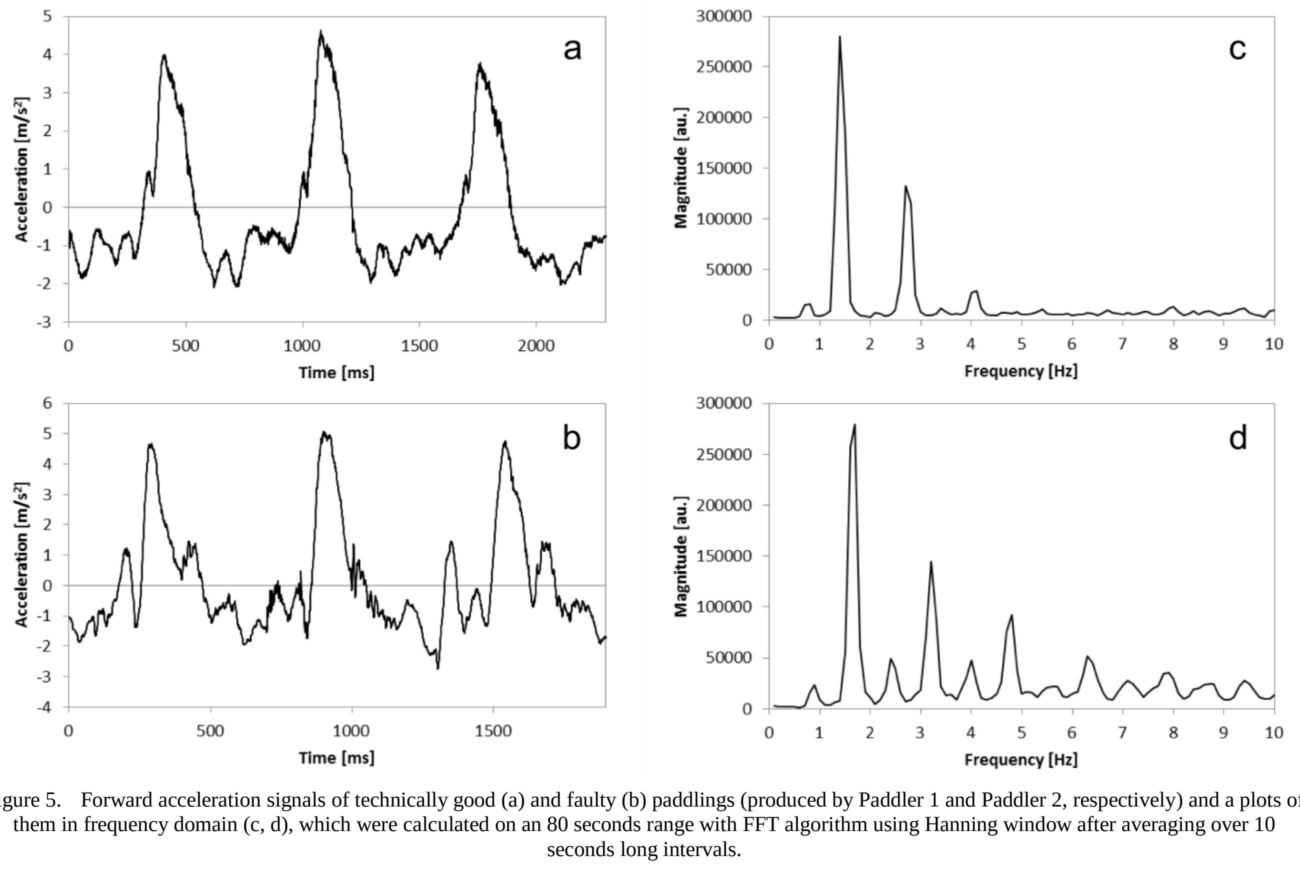

Figure 5. Forward acceleration signals of technically good (a) and faulty (b) paddlings (produced by Paddler 1 and Paddler 2, respectively) and a plots of them in frequency domain (c, d), which were calculated on an 80 seconds range with FFT algorithm using Hanning window after averaging over 10 seconds long intervals.

Besides detecting technical faults, its characterization is useful for athletes and trainers. On Fig. 5, we can see both paddlers respectively with technically good and faulty paddling, and a plots of them in frequency domain, which were calculated on an 80 seconds range with Fast Fourier Transform (FFT) algorithm using Hanning window after averaging over 10 seconds long intervals. As depicted on Figure 5, in case of the technically faulty paddling, we can observe much more intensive harmonics, therefore the factor representing the harmonic distortion can be used to characterize the technical faults.

Frequency domain analysis could help at calculating other useful parameters also, for example to calculate the paddling symmetry factor. As shown on Fig. 5 (c-d), the highest peak is the first harmonic, which represents the frequency of one stroke cycle. The fundamental frequency (which has much smaller magnitude) represents a period, where a left and a right hand stroke occurs. Therefore, the ratio of these two frequencies provides information about symmetry of the paddling. Examining the other measured signals at frequency domain provides further possibilities, such as analysis of transient periods of paddling (start, sprint), which will be discussed in detail in our subsequent work [12].

IV. PERFORMANCE ESTIMATION

The interpretation of the measured paddling signals and the analysis of a stroke cycle are very complex and have been discussed in several publications [13-19]. Nevertheless, at everyday work of coaches and athletes, fast and easily useable but still accurate indicators are needed. Therefore, we were looking for informative and revealing trend curves and factors, which will help the involved coaches, these results are detailed below.

Plotting the above mentioned quantities' evolution in time is highly informative for the coaches. The task at training is producing a particular type of paddling and performance steadily, conversely at simulated or real competition the purpose is rawing a distance as fast as possible using a specific strategy.

Evidently enough, examination of stroke rates evolution is substantial. Because the detection of stroke cycles is needed for stroke rate calculation, the measured gyroscope signals are suitable for this task. Moreover, the angular velocity signals are not influenced by the mentioned technical faults, so these signals can produce more accurate results than x-axis acceleration in most cases. The trend curve of stroke impulse provides important information about the quality of pulls and paddlers' performance. This indicator allows to examine the stability of the performance at training and the strategy and fatigue at race. For raising velocity in a race situation, paddlers are often increasing the stroke rate, nevertheless it could make the strokes quality worse. Therefore it is interesting to examine the two curves together, as well as combining the analysis of the two quantities with introducing a total impulse/min metric, which denotes sum of impulses of strokes occurred in one minute. On Fig. 6 one can see two trend curves of a paddling of Paddler 2 at a 500 m race, without the transient phases at start and finish. The trends of stroke impulses shows apparently the fatigue of the athlete.

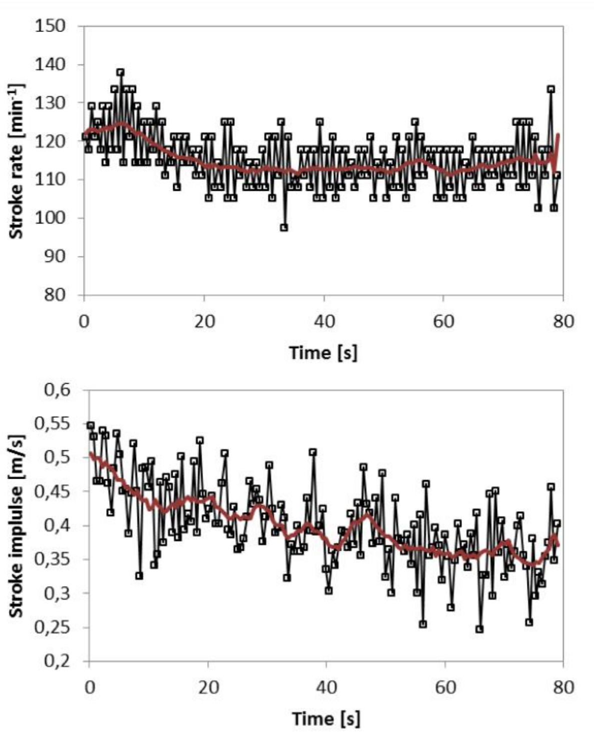

Figure 6. Trend curves calculated for paddling of Paddler 2 at a 500 m race, without the transient phases at start and finsih. While the stroke rate (upper plot) does not change significantly in time, the stroke impulse (lower plot) decrease indicates the fatigue of the athlete. Smoothed curves (red curves) was calculated using 10 samples long moving avarage.

Visualization of pull time, air-work time and their rate indicates the stroke rythm, and its stability. Comparison of paddlings produced at training and race situations showed that when the stroke rate increases, the air-work time decreases only, the time of pull phase does not change significantly. Plotting the stroke impulses of the two hands with two separate curves provides information about the symmetry of produced paddling. As depicted on Fig. 7, for professional athlete Paddler 1, the average impulse of left hand strokes more than 10% greater than impulse right hand strokes. The mentioned rates of stroke parts and left-right hand impulses are different for different athletes, therefore it characterizes the personal paddling technique.

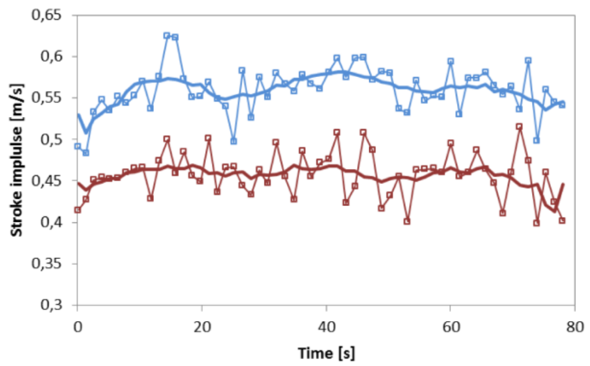

Figure 7. Trend curves of stroke impulses of left and right hands (blue and red curves, respectively) calculated for paddling of Paddler 1 at training. Smoothed curves (thicker curves) was calculated using 10 samples long moving avarage.

The developed PC software plots a smoothed version trend curves too, similar that were shown on Fig. 6 and 7. The smoothed curve was calculated using 10 samples long moving average. In addition, the mean and standard deviation of parameters for the examined stage of signals are also shown.

The classical parameters presented above allows the analysis of paddlings for strategy, technical and other aspects [4]. Nevertheless, the coaches, who supervise the work of many athletes every day, have no possibilities to do a detailed analysis in many cases. Easily understandable indicators and factors could help at quick evaluation of performance and at detecting of the technical faults. Searching helpful parameters and defining new indicators, statistical analysis of classical parameters was carried out on data of 26 athletes with different age, gender and technical skills. In all cases, a typical 80 second paddling phases have been studied, the transient stages were skipped.

Although technical skills are not characterized by the age of athletes perfectly, as well as the speed of technical improving different in different ages of paddlers, it allows demonstration of the evolution of the parameters and the detection of certain effects.

As it was mentioned above, the stroke rate, stoke rythm and paddling symmetry characterize personal paddling techniques and can be irrespective for technical skills. Naturally, the stroke impulse (and mechanical impulse) increases with the age of athletes, however the effect of stroke impulses' standard deviaton is more interesting. As Fig. 8 shows apparently, the standard deviaton of impulses decresases for older athletes. This effect is shown at examining the impulse trend curves of paddlers: while values of a world champion athletes stroke impulse are changing slightly, values of a young, less-practiced paddlers the stroke impulses vary significantly. Naturally, this effect influences the kayak's speed and position in the water and much more kinetic energy is dissipated by unoptimal movements. Consequently, a factor calculated from stroke impulses standard deviaton could be useful marking paddlers technical skills.

The standard deviaton of stroke impulses and relative standard devitaton of mechanical impulses show the mentioned effect too, therefore both impulse quantites are suitable. As we can see, the temporal fluctuations of the calculated physical parameters provides useful additional information about paddlers' performance. Detailed analysis of this fluctuations and more detailed parameter evaluation will be shown elsewhere [12].

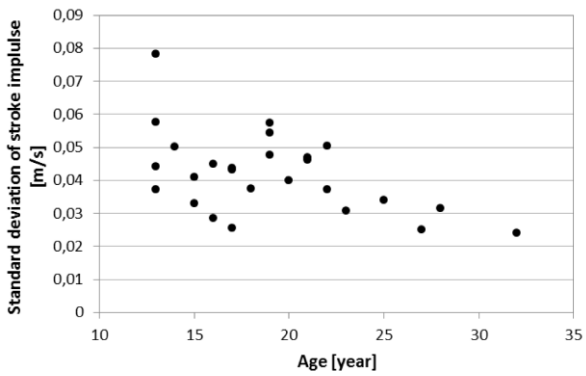

Figure 8. Standard deviaton of stroke impulse as a function of paddlers age.

The technical fault detection and characterization, as well as standard deviation of stroke impulse is clearly proved to be a useful indicator of paddling technique, while the trend curve and the total impulse/min proved to be useful in current performance assessment.

V. CONLUSION

We have shown a universal and flexible hardware based on six degrees of freedom inertial sensors and software platform especially developed for the evaluation of the performance of kayak paddlers. We have carried out several experiments, reviewed analysis methods and proposed additional evaluation methods to aid professional training. Our hardware solution provides universal ports for several additional external sensors and can be used in other sports including canoe movement analysis.

We have found that taking the raw six degrees of freedom inertial data can be efficiently used with statistical and spectral analysis to optimally describe most of the characteristics of paddling accurately enough, therefore not paddle force and other signal measurements are needed. The statistical and spectral parameters are discussed and proved to be rather straightforward and simple to use for the trainers and athletes as well. Further fluctuation analysis methods are planned to find more useful performance indicators.

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