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The Human Power Spectrum – Maximum Physical Power in Competitive Swimmers: Sports and Gender Specific Performance

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Zusammenfassung

Einleitung

Die maximale körperliche Leistung, welche immer im Zusammenhang mit der zeitlichen Dauer zu sehen ist, ist in Sportarten, wie dem Schwimmsport, in denen der Körper beschleunigt werden muss, ein wesentlicher Faktor für den sportlichen Erfolg. Viele sportmedizinische Tests beurteilen nur eine einzelne Zeitspanne. Im Gegensatz dazu ermöglicht die Leistungsevaluation, basierend auf dem Human Power Spectrum (HPS), eine umfassende Beschreibung des gesamten physischen Leistungspotentials eines Athleten, vom Millisekundenbereich bis über Stunden.

Methode

In vier durchgeführten Tests konnten fünf Werte gemessen werden um das gesamte Leistungsspektrum zu evaluieren. Für die Zeitspannen von 0,01s bis 0,1s und 0,1s bis 1s wurde ein Sprungkrafttest, auf einer Kistler Kraftmessplatte durchgeführt, wobei die Werte Peak Jumping Power (PJP) und Jumping Power (JP) gemessen wurden. Die Tests für Aktivitäten mit einer Dauer von mehr als einer Sekunde wurden auf einem Fahrradergometer durchgeführt. Diese waren der Sprint Power Test (SP; Zeitdomäne 1s-10s), der Transition Power Test (TP; Zeitdomäne 10s-100s) und der Endurance Power Test (EP; Zeitdomäne 1000s-10.000s). Die teilnehmenden Wettkampfschwimmer wurden in sprint- (Gruppe A) und langstreckentrainierte Athleten (Gruppe B) untergliedert und Unterschiede zwischen den beiden Gruppen wurden statistisch ausgewertet.

Ergebnisse

14 Schwimmer erfüllten die Einschlusskriterien (9 männliche und 5 weibliche). Das Alter betrug im Mittel 18 Jahre. 8 wurden der Gruppe A zugeteilt, 6 entsprechend der Gruppe B. Es fanden sich signifikante Unterschiede zwischen den beiden Gruppen. Die Sprinter erreichten signifikant höhere Werte ($p<0,02$) in den Tests für die Zeitspannen unter 100s verglichen mit Gruppe B. Außerdem zeigte sich, dass der Vergleich dieser Werte mit der EP in Gruppe A einen signifikant größeren Unterschied ergab ($P<0,03$). So konnte beispielsweise beobachtet werden, dass die JP in Gruppe A im Schnitt 8,3 mal größer war als die EP in dieser Gruppe. In Gruppe B war die JP 6,7 mal größer als die EP ($p<0.02$). Für alle gemessen Werte des HPS konnte eine signifikante Korrelation ($p<0,01$) mit den persönlichen 100m Freistil Rekorden der Athleten auf der Kurzbahn gezeigt werde.

Diskussion

Bestleistungen in jedem Sport setzen ein unterschiedliches HPS voraus. Diese Testprozedur erlaubt es, sowohl Unterschiede zwischen Lang- und Kurzstreckenathleten als auch die individuelle Leistungsfähigkeit zu messen. Obwohl Leistung im Schwimmsport wesentlich von der Technik abhängt, konnte eine Korrelation zwischen körperlicher Maximalleistung und Leistung im Wettkampf gezeigt werden, was für die Validität der Messung des HPS im Schwimmsport spricht.

Abstract

Introduction

In sports such as swimming, where the body has to be accelerated, maximum physical power, which is a function of activity duration, is a major performance factor. Performance diagnostics in sports medicine often only include tests for one domain of time. On the contrary, evaluation, based on the tests of the Human Power Spectrum (HPS), allows to describe the entire physical potential of an athlete in terms of maximum out-put power for the domains of time from 10 milliseconds to hours.

Methods

Four tests were done to evaluate the HPS, in which five values of maximum power were measured. For the time domains of 0.01s to 0.1s and 0.1s to 1s a Jumping Power Test, performed on a Kistler force plate, was done, from which the Peak Jumping Power (PJP) and the Jumping Power (JP) were derived respectively. Test for activities lasting longer than 1s were carried out on a bicycle ergometer. These were the Sprint Power Test (SP, time domain: 1s-10s), the Transition Power Test (TP, time domain: 10s-100s) and the Endurance Power Test (EP, time domain: 1000s-10,000s).

The participating competitive swimmers, were grouped in sprint- (group A) and endurance-trained (group B) athletes and differences between these subgroups were evaluated statistically.

Results

14 competitive swimmers were included in the study (9 male and 5 female). The mean age was 18 years. 8 of them were assigned to group A, 6 to group B.

Significant differences could be found between these subgroups. Sprinters reached significantly higher values ($p<0.02$) in the test for the time domains less than 100s compared to group B. Furthermore, the relation between these values and the EP, showed a significantly larger discrepancy ($p<0.03$) in group A. It could be observed for example, that JP was in average 8.3 times higher than the EP in group A and only 6.7 times higher in group B ($p<0.02$). The highest PJP reached by a male sprinter was 5226W, which corresponds to 23.3 times his EP.

A significant correlation ($p<0.01$) to the personal record over 100-meter freestyle on the short course could be observed for all absolute values of the HPS.

Discussion

World-class performance in every sport depends on a different HPS. This testing procedure allows to reveal differences between short- and long-distance athletes as well as to assess the individual output power potential. Although performance in swimming largely depends on technique, there was a high correlation between output power and competitive performance, indicating the validity of the output power measurements in the HPS for swimming when time domains of relevance are considered.

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1. Introduction

1.1. The Human Power Spectrum

The Human Power Spectrum is a testing procedure, which has been developed to evaluate the entire output power abilities of an athlete in resistance, in sprint as well as in endurance events. Based on the consideration that different characteristics are important in either short-distance or long-distance competitions the Human Power Spectrum should reveal the individual congenital and acquired qualifications as well as the current training state. Based on the obtained results, indications for adaptation and improvement of training can be deduced.

1.2. Power in Physics

First of all, the dimension of Power has to be defined according to the laws of physics. Later described performance tests are based on these principles. Power P in physics is defined as the work W divided by the time interval. The work, which is the scalar product of force vector and path vector, is equal to the change in kinetic energy (Equation 1-1 and Equation 1-2).

Equation 1-1 $W = \vec{F} \cdot \vec{s}$

Equation 1-2 $P = W / t = \vec{F} \cdot \vec{s} / t = \vec{F} \cdot \vec{v}$

The units used according to the International System of Units (SI) are Watt [W], Joule [J], seconds [s] and meter per second [m/s].

1.2.1. Power Measurement with Force Plate

To analyze power during a jump, a force plate can be used. Power can be determined by means of a measurement of the ground reactions.

The measurement is done according to Equation 1-3.

Equation 1-3 $P(t) = \vec{F} \cdot \vec{v}$, with $v = \frac{1}{m} \int F(t)dt$

1.2.2. Power Measurement with Bicycle Ergometer

Ergometers (Greek: *ergon*: work, *metron*: measure) are instruments used to measure the power output of an athlete, which equals up to the power necessary to overcome a variable frictional resistance (1). Depending on how the flywheel is braked, bicycle ergometers differ: electronically braked and mechanically braked.

According to the mentioned equation for work W, in the case of an ergometer the Force equals the frictional resistance and the Distance equals the Revolutions per minute (rpm). The Power measured on the ergometer therefore results from the frictional force acting on the flywheel multiplied by the circumferential velocity (Equation 1-4). In case of the Monark type ergometer used in the present study the braking mechanism uses a rope on the circumference of the flywheel (1). In this case the frictional force acting on this rope equals the used weight. The load weight is equal to the load mass (m) put on the ergometer times the gravitational acceleration, g ($g = 9.81\ m \cdot s^{-1}$) (Equation 1-5).

Equation 1-4 $P_f = F_f \cdot v_c$

Equation 1-5 $W = m \cdot g$

The cadence has influence on the maximal possible power. High frequencies reduce the maximal power (2). Therefore test should be conducted at a frequency of approximately 50 to 70 rpm (3).

1.3. Power in Sports

One of the most important factors for success in sports, where either masses or the athlete's body have to be accelerated, is the power an individual can produce. This in turn is a function of the duration of the activity (4). Depending on, whether the activity lasts for a longer period, or is fast, with a short duration, different specifications of the cardiovascular system, the muscle's and the body's metabolism will impact on good performance. Alterations in cardiac output, capillary density, muscle configuration, energy substrate storage and metabolic enzymes can be found in individuals. All of them influence the maximal power one can produce, as described later in this chapter. Table 1-1 summarizes different types of activities, the energy sources, which supply them and the aligned muscle fiber type as well as the corresponding performance tests used in the Human Power Spectrum. The following chapters will elaborate on the information given.

Energy Sources of Muscular Work and Performance Tests for Different Types of Activities			
Type of activity	**Power**	**Sprint**	**Endurance**
Duration [sec]	0 to 3	4 to 50	> 120
Example of activity	Starting dive, shot put, weight lifting	50m swimming, 100 to 400m run	1500m swimming, Marathon run
Energy storage	ATP, creatine phosphate	Muscle glycogen and glucose	Muscle and liver glycogen and glucose; Muscle, blood and adipose tissue lipids; Muscle, blood and liver amino acids
Rate of process	Immediate, very rapid	Rapid	Slow, prolonged
Oxygen involved	No	Yes	Yes
Aligned muscle fiber type	Type IIb	Type IIa	Type I
Performance tests	Jumping Power Test, Sprint Power Test	Transition Power Test	Endurance Power Test; MLSS, LTP2
Maximum Power reached in this study [W]	Approx. 4200 W	Approx. 950 W	Approx. 250 W

Table 1-1 Energy sources of muscluar work, fiber type and performance test for different types of activities, modified from Brooks et al. Used with permission. **(3, p. 32)**

1.4. Energy Supply in the Muscle

In order to achieve good performance in sports, the body needs an adequate energy supply. There are three diverse processes in the human body, which are responsible for meeting the muscle's energy demands. These include the immediate energy supply, the rapid nonoxidative energy supply and the slow oxidative energy supply. All of them lead to the common endpoint, the formation of the energy-rich molecule ATP. Although these processes differ from each other, they are closely integrated and operate together (5).

Depending on load and duration of the exercise these energy systems contribute in different proportional degree to the overall energy demand (6). Also the amount of energy, which each of these processes can supply is different.

There are several types of classifications for muscular effort. According to Brooks et al. (3, p. 32) different types of activities can be classified based on the main energy sources of muscular work (Table 1-1):

- power (e.g. starting dive),
- speed (e.g. 50m swimming) and
- endurance events (e.g. long-range competitions).

1.4.1. ATP homeostasis

Adenosintriphosphate (ATP) is an energy-rich molecule, which acts as a transient energy carrier and supplies most of the intracellular metabolic processes (7). It is used to power muscle contractions as well as to power syntheses done by the cell, electric events along the cell membrane and transport of ions or other molecules. Every muscle contraction is carried out through the action of actin and myosin cross-bridge cycling, which is triggered by calcium (8). The degradation of ATP powers the contraction (9,10).

Energy stored in ATP comes from the metabolism of glucose, fatty acids and amino acids, which are taken up as nutritional components by the gut.

The concentration of ATP in the cell stays constant over a wide range of use. In tissues such as skeletal and cardiac muscle, remarkable large-scale changes in ATP turnover rate occur during equally large changes in work. In many skeletal muscles, these changes can exceed the 100-fold (11). However, examinations by Hochachka et al. showed that ATP concentration is nearly universally homeostatic. They observed that almost no change in

ATP concentration can be observed, even while the change in its turnover rate can increase or decrease by two orders of magnitude.

1.4.2. Immediate Energy Supply

The immediate energy source in muscle is composed of three constituents: ATP, ADP, CP. It supplies the muscle with energy very rapidly, however it is sufficient only for a few seconds.

Present ATP in the muscle itself is the first supplier for energy, when a muscle contraction happens. It is degraded by ATPase and the chemical products of the ATP hydrolysis are adenosine diphosphate (ADP) and inorganic phosphate (P_i) (Equation 1-6).

ADP can be reenergized via phosphorylation by creatine phosphate (CP, PCr) (10). The enzyme creatine kinase catalyzes the reaction of CP and ADP to ATP (Equation 1-7). Therefore CP is an important intracellular energy shuttle (12).

The third cellular source of immediate energy is catalyzed by the enzyme adenylate kinase, which generates ATP from two ADPs (Equation 1-8) (10). These three reactions take place throughout all of the cytosol.

Equation 1-6 $ATP + H_2O \xrightarrow{ATPase} ADP + P_i$

Equation 1-7 $CP + ADP \xrightarrow{Creatinekinase} ATP + C$

Equation 1-8 $ADP + ADP \xrightarrow{Adenylatekinase} ATP + AMP$

1.4.3. Rapid Nonoxidative Energy Supply – Glycolysis

If activities must be sustained for a longer period than a few seconds, other energy sources than the immediate energy supply are required. The breakdown of glucose in the cytosol, glycolysis, can quickly provide ATP in a muscle without the need of oxygen (13). Glucose is either available as free single sugar or stored in glycogen. The process of breaking down glycogen, which is made up of several glucose subunits is called glycogenolysis (14). Nonoxidative energy sources can sufficiently supply energy for muscle contractions, while running for about 50 to 100 seconds (15).

Glycolysis leads to the formation of pyruvate and delivers two ATP (Equation 1-9). The intermediate pyruvate can be further reduced to lactate (16). Lactate as well as pyruvate

can be further metabolized to supply additional ATP via oxidative mechanisms in the mitochondria, however these processes need oxygen and proceed slower (17-19).

Equation 1-9 $$Glucose \xrightarrow{Glycolysis} 2\ ATP + 2\ Lactate^{-} + 2H^{+}$$

1.4.4. Slow Oxidative Energy Supply

ATP, created when nutritional components are catabolized by oxidative mechanisms, powers longer lasting activities. Possible energy sources for this metabolic pathway include carbohydrates, fats as well as amino acids (20). The muscle cell obtains these fuel sources via the blood, as for example glucose from liver glycogen. Fats and certain amino acids, which exist in the muscle itself as well as in depots in other parts of the body, are also provided via the blood flow and therefore are dependent on circulation. The degree to which each energy source is used depends mostly on the relative intensity of the exercise as given by % VO_2max (17). At the beginning of an exercise both fuels, fat and carbohydrates, are utilized. When the intensity of exercise increases both fuels are increasingly metabolized with a peak value for fat utilization at intensity of about 50% of VO_2max. Thereafter, the combustion of fat decreases, in both, absolute and relative terms (6).

All these chemical agents are broken down to one identical substance, and enter as acetyl-CoA the Krebs cycle, were they are further broken down to produce CO_2, $NADH/H^+$, $FADH_2$ and GTP (20). Along the electron transport chain (ETC), located in the mitochondrial inner membrane, a chemical potential is built up, which is finally used to create ATP from ADP and P_i (Equation 1-10 and Equation 1-11) (9). The end product formed by the electrons and oxygen, needed in the ETC is water. The oxidative metabolism of this foodstuff thus needs oxygen and therefore again presupposes the supply of oxygen by blood circulation (21).

More energy can be extracted from a substance through oxidation, however this pathway works slower than those described above. Especially the metabolism of lipids is slowly activated and proceeds at slower rates. Still fats are an important part of all energy sources

during athletic activities lasting for a longer period, and therefore impact on the athlete's endurance (17,22).

Equation 1-10 $Glucose + O_2 \xrightarrow{Oxidative\ metabolism} 36\ ATP + CO_2 + H_2O$

Equation 1-11 $Palmitate + O_2 \xrightarrow{Oxidative\ metabolism} 129\ ATP + CO_2 + H_2O$

1.4.5. Relative Contribution and Interaction of Energy Systems

Depending on the duration of a muscular effort the above mentioned energy systems contribute to the overall need of energy in different proportional degrees. Furthermore, during exercise, fuel selection depends on the intensity of exercise, the recruitment pattern of fiber type and the availability of fuels (6).

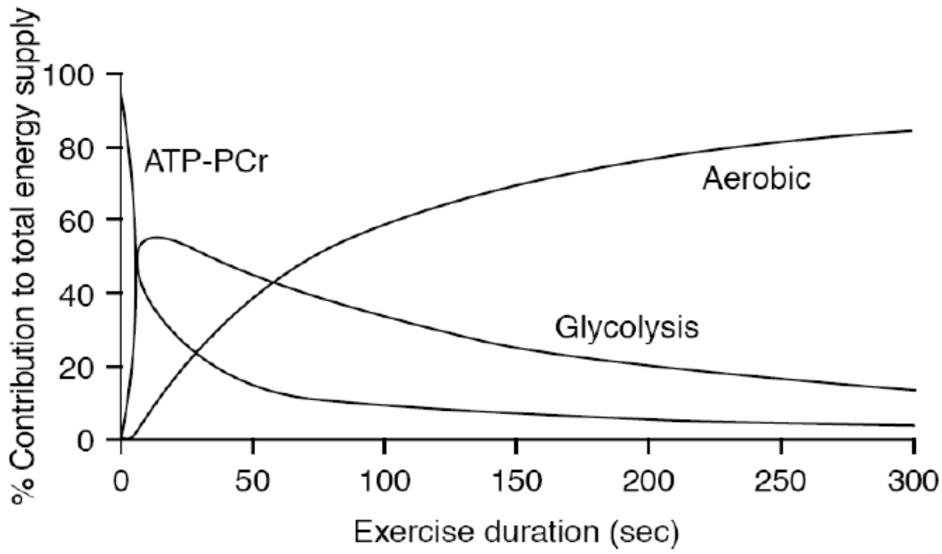


Figure 1-1 Relative energy system contribution to the total energy supply for any given duration of maximal exercise. Used with Permission. **(5)**

Gastin showed that only about 40 to 46% of the total energy need during 60 seconds swim bench exercise is provided by aerobic energy systems (5), while Faina et al. reported that up to 82% aerobic energy contribution can be found in 302 seconds lasting swim in a flume (23). In exercises lasting for ten or less seconds up to 95% of the energy need was supplied via non-oxidative, rapid pathways (24). Furthermore, it was shown that the significantly higher peak power output in sprint trained athletes is supported by higher

peak rates of ATP resynthesis from the ATP-PCr and glycolytic systems as shown in Figure 1-2 (5).

Figure 1-1 and Table 1-2 from Gastin show the estimated contribution of energy systems as a function of exercise duration.

Duration of exhaustive exercise [sec]	Percentage of anaerobic contribution	Percentage of aerobic contribution
10	94	6
15	88	12
20	82	18
30	73	27
45	63	37
60	55	45
75	49	51
90	44	56
120	37	63
180	27	73
240	21	79

Table 1-2 Estimates of anaerobic and aerobic energy contribution during selected periods of maximal exercise. Used with Permission. **(5)**

1.5. Adaptation of the Body to Exercise, Sprint versus Endurance

Via training the body adapts to the stress he is confronted with. Most of the body's structures and mechanisms that are involved in physical activity can adjust to training. These are: the cardiovascular system, the muscle itself and the metabolic pathways for energy supply. Specific differences in the adaptation can be observed, following either sprint or endurance training, which are also reflected in tests for physical power.

1.5.1. Adaptation of the Cardiovascular System

Cardiovascular changes induced by endurance training include higher capillary density in skeletal muscle (25), augmented blood volume and decreased heart rate at similar exercise intensities (26). The specific adaptations to endurance training have been well documented, whereby cardiac output can be significantly increased following endurance training (27). Furthermore significant improvements in the maximum capacity of individuals to transport

and utilize oxygen during exercise, the VO_2max (maximal oxygen consumption), were reported following endurance training (22).

1.5.2. Adaptation of the Muscle and Metabolic Pathways

Skeletal muscle is an adaptable organ, which is able to change its configuration in response to emerged stress (28). The type and amount of protein in the muscle cell can be altered to a degree, which is determined by training volume, intensity and frequency as well as the half-life of the protein (29). Muscle contractions lead to an increase of messenger RNA (mRNA), which results in an increase of transcription and protein synthesis (26,30). The phenomenon of muscle plasticity can be found in all vertebrates (31), however a large variability in the extent of the adaptability is know to exist among species as well as within a species' individuals (32). This variability partly explains the noticeable differences in aspects of physical performance, such as endurance or strength, between individuals. Figure 1-2 shows differences in the metabolism of sprint- and endurance-trained cyclists (5).

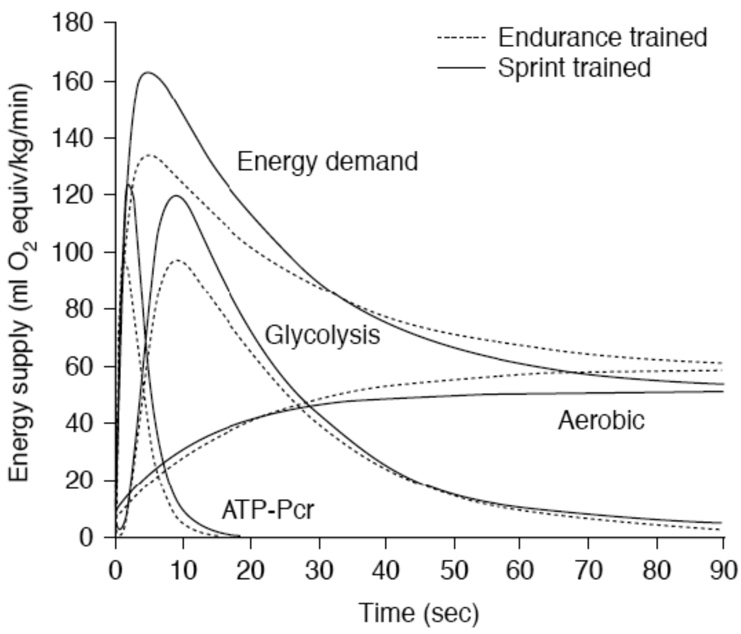


Figure 1-2 Relative contribution of the 3 energy systems to the total energy supply during 90 seconds of all-out cycle exercise. Participants were 6 male sprint-trained cyclists and 8 endurance-trained triathletes. Used with Permission. **(5)** ATP-PCr = alactic component of the anaerobic energy system.

In humans three different types of muscle fibers are known. Based upon histochemical and immunocytochemical staining, muscle fibers are classified as type I, slow twitch (ST), which stain dark or red, and type II, fast twitch (FT), which stain light or pale (32). A further subdivision of the FT fibers characterizes the more oxidative fast twitch fiber as type IIa, and the more glycolytic fiber is as type IIb. The specific fibers differ in their characteristics such as speed of contraction, enzyme activity and morphological properties as illustrated in Table 1-3.

In world-class athletes, specialized muscle fiber type characteristics can be observed. Type I fibers predominate in the muscles of the endurance athletes, while type II fibers prevail in sprint runners, however in general a wide variety of fiber populations can be observed (33). There is a strong genetic influence on fiber type meaning that specific training can hardly influence them, nonetheless physical training can still affect the muscle's biochemistry and therefore its histochemical appearance (3, p. 436).

Clearly, it is not the fiber type alone, which determines the performances of elite athletes, because in fact while an athlete's muscle fiber type is an important morphological component, which is related to several contractile and metabolic properties, other physiological factors, like for example VO_2max, maximal cardiac output, and speed/power output at the lactate threshold, also exert considerable influence on the upper limits of an athlete's capacities (34).

Characteristics	**Type I**	**Type IIa**	**Type IIb**
Alternative Terminology	Slow twitch (ST) Slow Slow, oxidative (SO)	Fast twitch (FT) Fast, fatigue-resistant (FR) Fast, oxidative glycolytic (FOG)	Fast twitch (FT) Fast, fatiguable (FF) Fast, glycolytic (FG)
Contractile characteristics			
Time to peak tension	1.0	0.4	0.4
Ca^{2+} myosin ATPase	1.0	3.0	3.0
Mg^{2+} actomyosin ATPase	1.0	2.8	2.8
Enzyme activities			
Creatine phosphokinase	1.0	1.3	1.2
Phosphfructokinase	1.0	1.5	2.1
Glycogen phosphorylase	1.0	2.1	3.1
Citrate synthase	1.0	0.8	0.6
Metabolic properties			
Oxidative potential	1.0	0.7	0.2
Gyloclytic potential	1.0	1.5	2.0
[Phosphocreatine]	1.0	1.2	1.2
[Gylcogen]	1.0	1.3	1.5
[Triacylglycerol]	1.0	0.4	0.2
Morphological properties			
Capillary density	1.0	0.8	0.6
Mitochondrial density	1.0	0.7	0.4

Table 1-3 Characteristics of different muscle fiber types, modified from and **(32)**. Values are expressed as a fold-change relative to type I fibres.

Via a complex signal transduction pathway, endurance training leads to a sequence of morphological and metabolic alterations, including mitochondrial biogenesis (35), fast-to-slow fiber-type transformation (32) and substrate metabolism (36). Endurance adaptations result in increased glycogen stores in muscle and glycogen sparing at submaximal workloads via increased fat oxidation and enhanced lactate kinetics (29,37). The activities of key enzymes of the mitochondrial electron transport chain increases and concomitant the mitochondrial protein concentration. Furthermore increased capillary density can be observed (38). Altogether these morphological changes lead to a greater reliance on fat as a fuel. Taken collectively, these adaptations result in an enhanced performance capacity (39).

On the contrary, resistance training, which is important for competetive athletes, taking part in short distance competitions, leads to hypertrophia of skeletal muscle, an increase in percentage of type IIa fibre in muscle and furthermore to metabolic changes like increase

in glycolytic enzyme activity (40). Other metabolic adapdations affect the key regulatory enzymes of energy systems that contribute to ATP turnover during short-term bouts of brief maximal intensity exercise (41). These are high-energy phosphagens, glycolysis and oxidative metabolism. Furthermore Chu et al. observed an increased volume of the sarcoplasmic reticulum, which plays a critical role in muscle contraction (42).

Training also influences the metabolism of lactate. Reduced lactate concentrations during submaximal exercise after training in humans could be shown to be a combined result of a decreased rate of lactate appearance and an improvement in the rate of lactate clearance (43). However MacRae et al. suggested that the improvement in the rate of lactate clearance is likely to be more important than the change in rate of lactate appearance.

1.6. Gender Specific Characteristics

Anthropometric differences can be observed between men and women. The body composition is different for male and female persons. A typical female body has relatively more fat and less muscle and bone than an average male body (3, p. 634).

Due to their larger body size and muscle mass, men usually have higher abolute strength and power (44). However Maud and Schultz showed that no significant differences between men and women in anaerobic power can be observed, when values were given relative to FFM. Males and females produce similar forces per cross-sectional area of muscle (3, p. 444). Also adaptations to training seem to be comparable in men and women (3).

1.7. Exercise Testing

1.7.1. The Objective of Performance Testing

Exercise test are used to describe the present performance of an athlete and measure the impact of training. Performance protocols allow researchers to simulate sporting performance, or aspects thereof, in a controlled scientific manner (45). This enables researchers to manipulate certain variables to measure their impact on sporting performance. Results obtained from performance test are the basis for exercise prescription and for prognoses of an athlete's individual physical abilities (3, p. 681).

Performance in this context is the result of certain physical activities, influenced by endogenous and exogenous variables, measured and related to a certain norm (45). The endogenous and exogenous variables, which can be technical, mental and tactical, interact to form the construct of sports performance (46).

1.7.2. Quality Factors of Performance Tests

Quality factors for performance testing, which should be fulfilled by good performance protocols are objectivity, reproducibility, and validity (1,45).

Objectivity describes, to which extend a test is free from personal bias. It applies to the testing procedure itself as well as to the evaluation of the results. A test has high objectivity if different examiners obtain similar results.

Reproducibility or reliability is a criterion, which refers to the precision of a test. It is achieved if a test produces consistent results in several separate occasions and the protocol provides a similar result from day to day when no intervention is used (47).

Validity describes whether or not the data, which should be collected with a test, is actually recorded with the applied test. High validity can be reached if the protocol resembles the performance that is being simulated as closely as possible (48).

1.7.3. Methods of Performance Testing

Ergometric performance tests are used to expose test subjects to reproducible physical stress for assessment of their cardiopulmonal and muscular performance and metabolic

capacities. Measured values are primarily the absolute and relative power, heart frequency, blood pressure and the concentration of lactate in the blood. Furthermore respiratory values can be evaluated (49, p. 33).

1.8. Specific Exercise Tests

There are several different types of excercise test. On the one hand there are test performed in laboratories, such as test done on ergometers and on the other hand there are field test, such as running or swimming tests. The tests mentioned first have the benefit of high reproduceability and objectivity, however do not always represent the specific skills and abilities needed in a certain kind of sport. The tests described here are typical test performed in laboraties and clinical setting as they allow precise measurement of maximal output power.

1.8.1. Jumping Tests

The vertical jump can be used to test the maximal power in the lower extremities (50). It is performed on a force platform, which measures the ground reaction forces during the jump. Different types of jumps can be performed, however it is essential to define the precise motion sequence very accurately to reach high precision in this test. A squat jump is commonly used to achieve the abovementioned precision, however the arms may not be moved during the test, as this would improve performance (51).

In this test the subject has to bend their knee to an angle of about 90 degrees and stand still for a moment on the force plate before jumping. Values obtained are the Peak Jumping Power (PJP), which is the maximum power achieved at the end of the jump during takeoff in a time span less than 0.1 seconds as acceleration takes place and the Jumping Power (JP), which is the average power reached during the test (4).

With the help of this test activities, which are supplied by immediate energy sources, can be evaluated (52).

1.8.2. Transition Power Tests

Transition power ergometer tests, often referred to as anaerobic tests, are used to record the maximum power that can be reached in activities lasting for less than 60 seconds, which correlates to the time span in which nonoxidative energy supplies are predominant (53,54).
Such tests are the Sprint Power Test and the Transition Power Test. The Sprint Power (SP) is the maximum power an athlete can reach in a few seconds on a bicycle ergometer. The athlete performs a short sprint to obtain maximum power (55).
The Transition Power Test measures the power in the time domain of 30 seconds (55,56). The mean power over 30 seconds is referred to as Transition Power (TP). This test is closely related to a 25m swim (3, p. 708).

1.8.3. Endurance Ergometer Test

Testing endurance power is closely linked to cardiorespiratory and metabolic capacities of an athlete. The time domain of this test exceeds several minutes, so oxidative mechanisms of energy supply become most important. The Endurance Power (EP) describes the power at the lactate turn point 2 (LTP2). The LTP 2 allows a reliable estimation of the maximal lactate steady state (MLSS) (1,57-60). This is the point at which the amount of lactate produced, would start to exceed the amount of lactate metabolized if output power is further increased, thus leading to an exponential increase of lactate concentration that can be measured in the blood (61).
Different test protocols can be used, however they have to fulfill certain criteria. Important for the validity of a step test protocol are: initial load, the level of increase of load and the duration of each step.

1.9. Performance Evaluation of Swimmers

Performance in swimming depends on several factors. Not only the maximum power an athlete can produce is relevant but also to a large extend his technique and ability to use mechanical power to overcome drag forces in water. Stroke rate and stroke length are important parameters in swimming, which can only be assessed in water. A swimmer, covering a greater distance per stroke at a given speed, spends less metabolic power in giving masses of water kinetic energy change (wasted power) and more into overcoming drag (useful power) (62).

Other physiological values that are often studied, besides swimming speed and technical aspects, include oxygen uptake, heart rate and blood lactate concentration (63). The best way to describe performance in swimming is the examination and video analysis of the performance in competitions. However to be able to observe effects of training and the fitness status of an athlete other reproducible test are needed, which has led to the development of several different swimming tests, as for example Constant Distance Tests (CDT), Constant Time Tests (CTT) or Constant Velocity Tests (CVT) (64). Critical swimming speed (CSS), which is mathematically defined as the intensity that could theoretically be maintained indefinitely without exhaustion, is one value that can be obtained from such tests (65).

All values obtained in the test mentioned above, allow comparison only among swimmers, but cannot be compared to performance in other sports. This is why standardized test such as bicycle ergometer test are a useful device to evaluate the overall fitness of an athlete, although of course not being the ideal device to predict performance in a specific kind of sport. In cycling a learning effect could be shown. In a study by Martin et al. subjects not used to cycling could improve their results by getting used to the specific motion on an ergometer, while cycle-trained men did not (66).

1.10. Aim of the present study

The main questions to be answered via the present study were:

- What does the power spectrum of competition swimmers look like?
- Is it possible to reveal differences between sprint and endurance athletes with the help of the human power spectrum test?
- To which extend can these differences be quantified and is it possible to set up standard values or normal ranges for specific characteristics?

As described above, there are individual differences in an athlete's abilities of energy supply in muscles, as well as in the configuration of the muscle itself. Depending on the sport performed, the training and congenital characteristics in an athlete's performance in power, speed or endurance events can vary. The maximum power, an athlete can produce, is a function of the duration of the activity and therefore dependent on the characteristics of his muscles and energy sources.

Based on these considerations, the aim of this study was to evaluate the entire Human Power Spectrum of competitive swimmers, which is important to objectify the requirements for good performance and, in addition, makes it possible to adjust the training according to these needs. Furthermore, the gender specific differences should be evaluated.

According to the three types of biochemical mechanisms for energy supply, the maximum power output of a test person should be determined for the time domains of 0.01s to 0.1s, 0.1s to 1s, 1s to 10s, 10s to 100s and 1000s to 10,000s, with tests including a Jumping Power Test, a Sprint Power Test, a Transition Power Test and an Endurance Power Test, based on a step test protocol, respectively.

Based on the results obtained, the differences in the Human Power Spectrum between sprint and endurance athletes as well as between male and female athletes will be quantified with the help of statistical methods.

2. Methods

To answer the main research questions, as mentioned in the introduction, competitive swimmers should undergo the human power spectrum test and values obtained should be statistically analyzed.

2.1. Informed consent

All test persons, and if under age their parents, were informed and educated about the test procedures and any accompanying risks prior to the test and had to sign an informed consent (Figure 2-1). They were told that the data obtained from the test would be handled confidentially, used for statistical evaluation and be published only in anonymized form.

EINVERSTÄNDINSERKLÄRUNG

DATUM: ___ / ___ / 2008
ORT: ________________

Ich erkläre, dass meine Teilnahme an der Forschungsstudie (The Human Power Spectrum in Swimming) freiwillig ist und, dass die erhaltenen Daten für wissenschaftliche Zwecke verwendet werden können. Ich bestätige, dass alle damit zusammenhängenden Fragen in völlig zufrieden stellender Weise beantwortet wurden. Ich wurde darüber informiert, dass die Daten für statistische Auswertungen verwendet werden und, dass meine persönlichen Daten im Rahmen der Forschungsstudie vertraulich behandelt werden.

NAME: ____

GEBURTSDATUM: ____

UNTERSCHFRIFT: ____

Figure 2-1 Informed Consent, that had to be signed prior to the tests.

2.2. The Human Power Spectrum Test

The Human Power Spectrum describes the maximum mechanical output power of a test person for five time domains from 0.01s to 10,000s. To evaluate the power profile of an individual it combines four exercise tests, from which the five values of power can be derived (Table 2-1).

Time Domain	Value	Test
0.01 - 0.1	PJP ... Peak Jumping Power	Vertical jump on force plate
0.1 - 1.0	JP ... Jumping Power	Vertical jump on force plate
1.0 - 10	SP ... Sprint Power	Sprint Power Test
10 - 100	TP ... Transition Power	Transition Power Test
100 – 10,000	EP ... Endurance Power	Ergometer Step Test protocol

Table 2-1 The Human Power Spectrum Test, tests used, corresponding domain of time and values obtained

2.2.1. Jumping Power and Peak Jumping Power

The jumping power test is used to evaluate the maximum power of a test person in the time domains of 0.01s to 0.1s (PJP...Peak Jumping Power) and 0.1s to 1s (JP...Jumping Power). To analyze the jumping power and peak jumping power, the force plate was used, on which the test person had to perform one vertical jump. The Kistler Quattro Jump system was used. The jump had to be done without swinging the arms, as this would improve the performance (3, p. 707).

The measurement was done according to $P(t) = \vec{F} \cdot \vec{v}$, with $v = \frac{1}{m} \int F(t)dt$.

2.2.2. Sprint Power Test

To analyze the maximum power an individual can produce in the time domain of 1s to 10s the Sprint Power Test was used. This test measures the maximum power an athlete can produce in a few seconds as a function of load (55). The Sprint Power test was performed on a Monark weight ergometer.

The test persons had to perform a short sprint of only a few seconds at 4% load until maximum power was reached. The test was then repeated with the next load step until the maximum power obtained, declined for the first time. The load steps were: 4, 8, 10, 12 and

14%. After each step there was a five minute interval of rest. Weight accuracy was ± 0,1 % and the velocity of the flywheel was measured with similar accuracy by means of a hall sensor and an electronic device (power analyzer).

2.2.3. Transition Power

For the time domain of 10 to 100 seconds, a modified Wingate test (Transition Power Test) with 10% of body weight as load was performed. This load was chosen, because Müller W. observed that the Wingate test underestimates maximum power, as Pmax is not reached at a load of 7,5% (67). Only after the tests for this study were completed, Müller W. published that the maximum Power in the Transition Power Test is reached at a load of 11% (68).

The mean power over 30 seconds was used to describe the maximum power an athlete can produce in this time domain. The Transition Power Test was performed on a Monark weight ergometer. Weight accuracy was ± 0,1 % and the velocity of the flywheel was measured with similar accuracy by means of a hall sensor and an electronic device (power analyzer), which also allowed determination of rotational energy of the flywheel.

2.2.4. Endurance Power

To evaluate the endurance power of the athletes an ergometer step protocol was performed and the second lactate turn point (LTP2) was used to evaluate the maximum endurance power. The test started with a load of 40 Watt in male athletes and 20 Watt in females for 3 minutes and increased by 20 Watt in males and 15 Watt in females every minute. In the end a 3 minutes recovery phase at initial load followed suit (Figure 2-2). The athletes were instructed to cycle at a frequency of about 60 rpm. Blood samples for measurement of lactate concentration were taken before the test, after every step and at the end of the test. Furthermore heart rate, blood pressure and respiration were recorded.

The evaluation of the LTP2 was done with the help of a computerized software program.

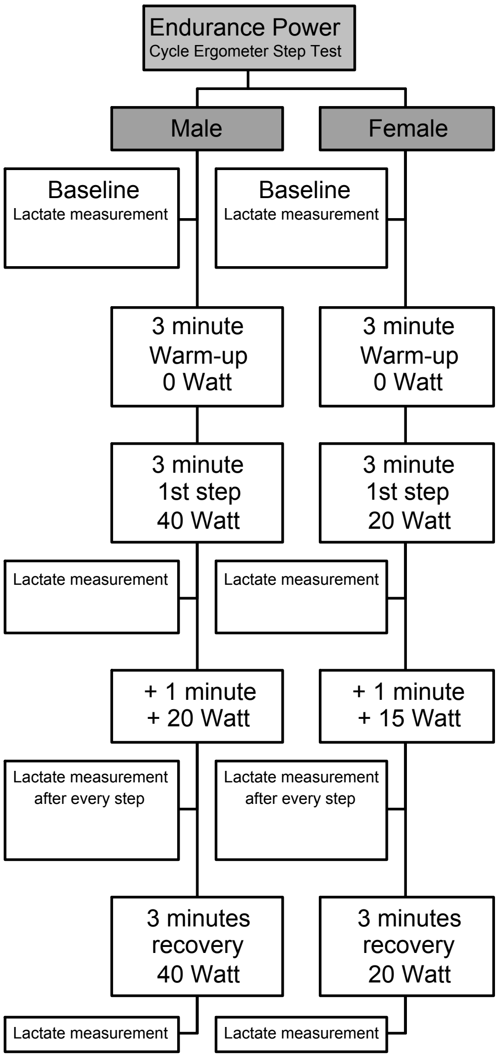


Figure 2-2 Protocols for the Endurance Power Cycle Ergometer Step Test for male and female

2.3. Test Persons

2.3.1. Inclusion Criteria

Test persons for this investigation were recruited from a swimming sports club. To participate in this investigation the subjects had to be training for at least four years and to be participating regularly in national or international competition for at least two years. Minimum training was defined as at least three times two hours of swimming per week. Further inclusion for this survey was an age of 13 years or older and good physical health to be able to accomplish all exercise tests.

2.3.2. Exclusion Criteria

The exclusion criteria were defined as any diseases or health problem, which could cause damage to the test person's health under maximal stress during the exercise test and lack of regular participation in training.

2.3.3. Data of Test Persons

All test persons had to complete a questionnaire to evaluate their current state of training and competition level. To do so, they were asked about the frequency and duration of training, their preferred competition distances and stroke as well as their personal records. All probands were asked about their characteristics of training structure and were classified as sprint (group A) or endurance (group B) athletes according to their preferred competition distance, their training concept and their self-evaluation as well as their trainer's assessment and their best results in competitions. Events of a duration of less than 60s, which corresponds to the competition distances of 50 and 100m were considered as short distance events, those of a longer distance as long distance events respectively.
Further more the weight and height of the test persons were measured and the Body Mass Index (BMI, Equation 2-1) and Mass Index (MI, Equation 2-2) were calculated (m…mass, h…height, s…sitting height). In comparison to the BMI, the MI has to be the preferred, as it does not ignore different body properties of individuals (69). The MI considers the individual leg length: A person with longer legs than average has an MI > BMI, and vice versa (70,71).

Equation 2-1 $BMI = \frac{m\ [kg]}{h^2\ [m^2]}$

Equation 2-2 $MI = 0.53^2 \times \frac{m\ [kg]}{s^2\ [m^2]}$

The personal record over 100 meters freestyle on short course was further data collected, to evaluate whether the tests of the Human Power Spectrum show any correlation to actual performance in swimming. Furthermore the best performance over a 100m freestyle was expressed in percentage of the world record of 2008, which was 44.94s in male and 51.7s in female (Equation 1-1, $t_{WR} \ldots time\ world\ record, t_P \ldots time\ personal\ record$). Table 2-2 shows a list of all basic data obtained from the subjects in addition to the actual performance tests.

Equation 2-3 $\%WR = t_{WR} \div t_P \times 100$

Value / Characteristic	Unit / Parameter value
Age	Years
Sex	Male / female
Height	Meter
Sitting height	Meter
Weight	Kilogram
BMI	kg/m^2
MI	kg/m^2
Years of training	Years
Amount of training per week	Hours
Participated Competitions	National / International
Preferred stroke	Butterfly / Backstroke / Breaststroke / Freestyle
Preferred distance	50 / 100 / 200 /400 / 800 / 1500 meter
Personal record	Distance / Stroke / Seconds
Type of athlete	Sprint / Endurance
Personal record 100m freestyle	Seconds

Table 2-2 Characteristics of probands and their corresponding units evaluated in this study in addition to the actual tests of the HPS

2.4. Test procedure

A medical doctor, specialized on sports medicine, supervised all test.

The tests were performed on two days with two days of recovery in between. JP, SP and TP were done on one day, the more exhausting EP on the second day.

All athletes had to do a warm up prior to the exercise tests, in order to achieve their best results and prevent injuries (72,73).

2.5. Comparison of Human Power Spectrums

The HPS of sprinters (group A) and long-distance swimmers (group B) were compared to each other in order to reveal differences between these two subgroups. To do so each of the following values, PJP, JP, SP and TP, were divided by EP to see the relation between those tests within the groups.

2.6. Data processing and evaluation

All data surveyed in this study was processed with the statistics program SPSS 16. Also the tests for significance were done with the help of SPSS 16.

2.7. Statistical analysis

In order to assess the significance of differences in the test results that have been observed between different subpopulation, statistical analyses had been done. To test the significance between two independent subgroups with normal distribution the T-Test was used. A p-value smaller than 0.05 was considered as a significant result. When data was not distributed normally the Mann-Whitney-U Test was done.

To see whether data was normally distributed a histogram was done and the Kolmogorov-Smirnov Test was used for evaluation.

To test the correlation between personal records over 100-meter freestyle and the results in the Human Power Spectrum the Pearson's correlation coefficient was calculated.

2.8. Diagrams

Diagrams were generated either with SPSS or with Microsoft Excel. In order to visualize the information different diagrams were used. To show frequency distributions of attributes, bar charts were used. Correlations were viszualized using scatter plots.

Boxplots were used to display differences between two groups. The bottom and top of the box represent the 25th and 75th percentile. The band near the middle of the box is represents the 50th percentile, the median. The ends of the whiskers represent values being less than 1.5 times the hight of the box lower than the 25th or higher than the 75th percentile. Any data not included between the whiskers was plotted as small circles.

3. Results

3.1. Study Population

A number of 14 persons fulfilled the inclusion criteria and were assessed in the course of this study. Of these 14 test persons, 9 (64.3%) were male and 5 (35.7%) female (Figure 3-1). The mean age was 18.07, ranging from 13 to 27 years (standard deviation 3,9; Figure 3-2).

8 (57,1%) test persons were assigned to group A (sprint) and 6 (42.9%) to group B (endurance) (Figure 3-3).

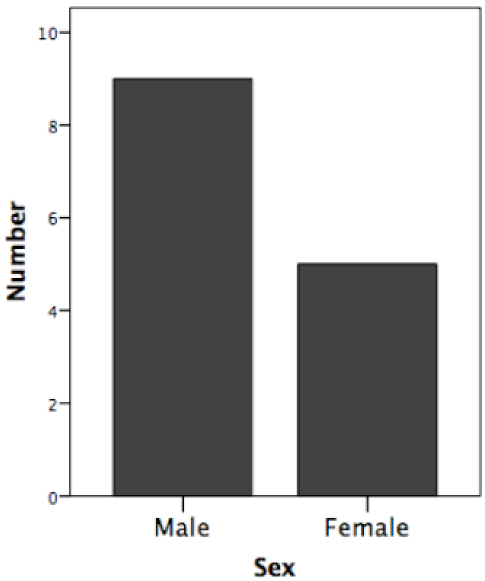


Figure 3-1 Number of male and female swimmers

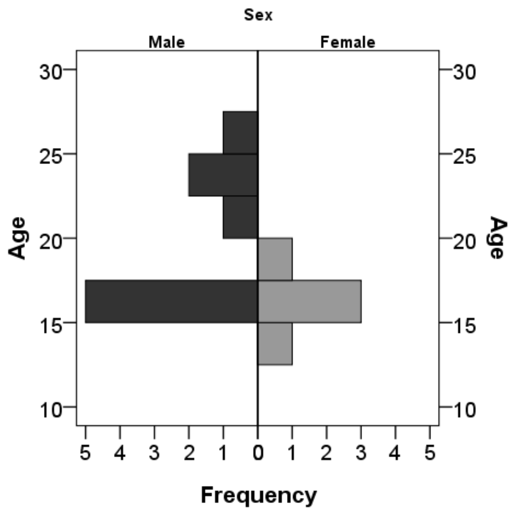


Figure 3-2 Population pyramid of the study population (age and sex)

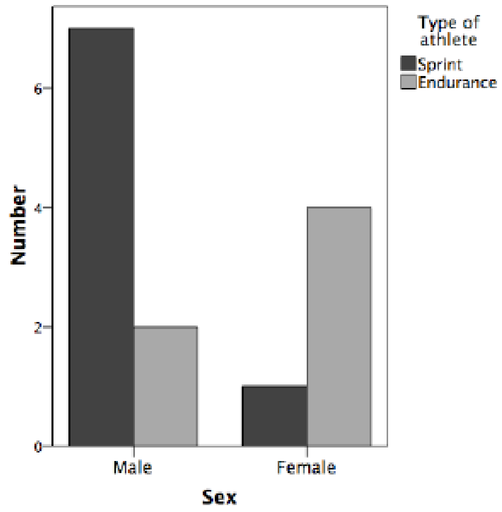


Figure 3-3 Number of Sprint (A) and Endurance (B) athletes per sex

3.1.1. Anthropometric data

The average height of the test persons was 1.8m, ranging from 1.61m to 1.93m (standard deviation 0.09). The average height of male persons was 1.85m (range 1.78 – 1.93), in females it was 1.71 (range 1.61 – 1.75). The mean sitting height was 0.95m (range 0.85 - 1.01, standard deviation 0.04). Sitting height in males was 0.97 in average (range 0.925 – 1.01), in females 0.906 (range 0.852 - 0.937). The probands weighed in average 71.9kg (range 47 – 91.4kg, standard deviation 12.3). Female weighed in average 60.6kg (range 47 – 70kg), males weighed in average 78.2kg (range 65.5 – 91.4). The average BMI was 21,98 (range 18,13 - 25,32, standard deviation 2,13), in males 22.7 (range 20.08 – 25.32), in female 20.7 (range 18.13 – 23.66). The mean MI was 22,29 (range 18.13 – 27.36, standard deviation 2,34), in male 23.24 (range 20.99 – 27.36), in female 20.57 (range 18.13 – 22.32).

All anthropometric data in average is summarized in Table 3-1.

		Minimum	Maximum	Average	Standard deviation
Height	All	1.61	1.93	1.8	0.01
	Male	1.78	1.93	1.85	0.06
	Female	1.61	1.745	1.71	0.06
Sitting height	All	0.852	1.01	0.947	0.04
	Male	0.925	1.01	0.97	0.03
	Female	0.852	0.937	0.906	0.03
weight	All	47	91.4	71.9	12.3
	Male	65.5	91.4	78.2	9.2
	Female	47	70	60.6	8.6
BMI	All	18.13	25.32	21.98	2.13
	Male	20.08	25.32	22.71	1.88
	Female	18.13	23.66	20.67	2.06
MI	All	18.13	27.36	22.29	2.34
	Male	20.99	27.36	23.24	2.19
	Female	18.13	22.32	20.57	1.58

Table 3-1 Anthropometric data of the test persons: Minimum, maximum an average values.

3.1.2. Training and Sport Attributes

The probands had been training for at least 4 years, in average for 8.3 years (range 4 to 17, standard deviation 3.97). In average 7 trainings (range 3 – 10) session per week were done. The total amount of swim training per week was in average 14.3 hours, ranging from 6 to 20 hours (standard deviation 4.2). The preferred stroke was freestyle in 8 persons, back stroke in 3, butterfly in 2 and breast stroke in 1 case. The average training attributes are summarized in Table 3-2.

Of the 14 athletes 8 (57.1%) athletes were classified as sprinters and 6 (42.9%) as endurance athletes (Figure 3-1).

All athletes had been taking part regularly in national of international competitions. The mean performance of the test persons for the 100m freestyle short course was 56.9 ± 3.47s in males and 63.1 ± 2.1s in females, corresponding to 79.3 ± 5.2% (W.R. 44.94s) and 82 ± 2.7% (W.R. 51.7s) of the 2008 world record for this event respectively.

Training attributes		Average	Minimum	Maximum	Standard deviation
Years	All	8.3	4	17	3.97
Hours /w	All	14.3	6	20	
Sessions /w	All	7	3	10	

Table 3-2 Training attributes of test persons: Minimum, maximum and average values.

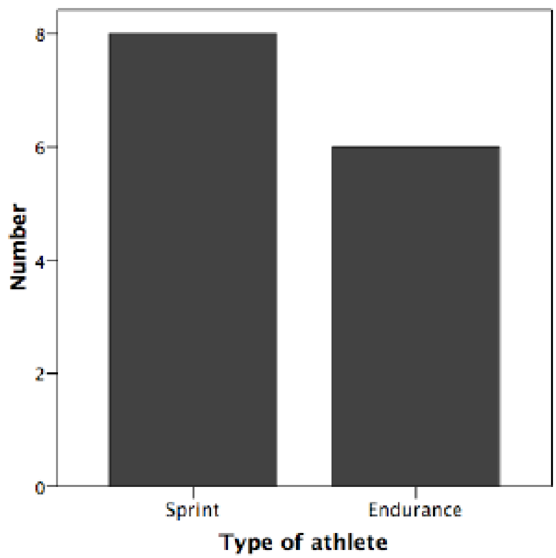


Figure 3-4 Number of sprint (group A) and endurance (group B) athletes

3.2. Test results

All 14 athletes could complete the four tests of physical power. No complications or injuries were observed in the course of the testing procedure.

The average results for every test are listed in Table 3-3 and illustrated in Figure 3-5.

The average value obtained in the jumping power test was 58.7W/kg (range 32 – 57.7; standard deviation 8.7) for the peak jumping power (PJP) and 19W/kg (range 10.9 – 26.8; standard deviation 4.5) for the jumping power (JP). In the sprint power test (SP) an average value of 11.5W/kg (range 8.2 – 16.6; standard deviation 2.5) was reached. The mean power in the 30 seconds transition power test (TP) was 8.4W/kg (range 5.7 – 11.5; standard deviation 1.8). The endurance power (EP) was in average 2.7W/kg (range 2.1 – 3.2; standard deviation 0.3).

The absolute values were as follows: The mean PJP was 3396W (range 1984 – 5226; standard deviation 990.7). JP reached a mean value of 1479W (range 763 – 2278; standard deviation 428). SP averaged 844W (range 435 – 1515; standard deviation 301.1). TP was in average 613W (range 340 – 1054; standard deviation 212.2). The mean absolute value for EP was 190W (range 113 – 227; standard deviation 37.8).

The maximum power an athlete could produce in the time domain of 0.01s to 0.1s (PJP) exceeded the power that could be kept up over several minutes (EP) in average by the 17.9 fold.

		Minimum	Maximum	Mean	Standard Deviation
PJP	Absolute [W]	1984	5226	3396	990.7
	Relative [W/kg]	32.0	57.7	46.0	8.7
JP	Absolute [W]	763	2278	1480	473.0
	Relative [W/kg]	10.9	26.8	20.0	4.5
SP	Absolute [W]	435	1515	844	301.1
	Relative [W/kg]	8.2	16.6	11.5	2.5
TP	Absolute [W]	340	1054	613	212.2
	Relative [W/kg]	5.7	11.5	8.4	1.8
EP	Absolute [W]	113	227	190	37.8
	Relative [W/kg]	2.1	3.2	2.7	.3

Table 3-3 Mean absolute and realtive minimum, maximum and average power in the test of the Human Power Spectrum

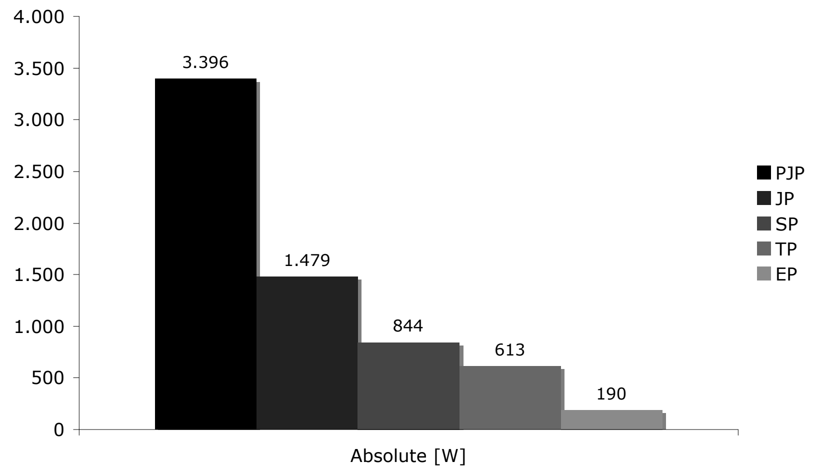


Figure 3-5 Avarage absolute Human Power Spectrum

In average the PJP was 17.7 (range 13.82 – 23.33) times as high as the EP. JP divided by EP was in average 7.6 (range 5.37 – 10.17). The SP was 4.4 (range 3.11 – 6.76) times as high as the EP. TP was 3.2 (range 2.39 – 4.71) times as high as EP (Table 3-4 and Figure 3-1).

	Minimum	Maximum	Mean	Standard Deviation
PJP / JP [W]	2.0	3.2	2.3	0.30
PJP / SP [W]	3.4	5.9	4.1	0.69
PJP / TP [W]	4.8	6.9	5.7	0.68
PJP / EP [W]	13.8	23.3	17.7	2.66
JP / SP [W]	1.1	2.8	1.8	0.39
JP / TP [W]	1.9	3.2	2.4	0.38
JP / EP [W]	5.4	10.1	7.6	1.28
SP / TP [W]	1.1	1.7	1.4	0.16
SP / EP [W]	3.1	6.8	4.4	1.07
TP / EP [W]	2.4	4.7	3.2	0.68

Table 3-4 Relation between different values of the Human Power Spectrum

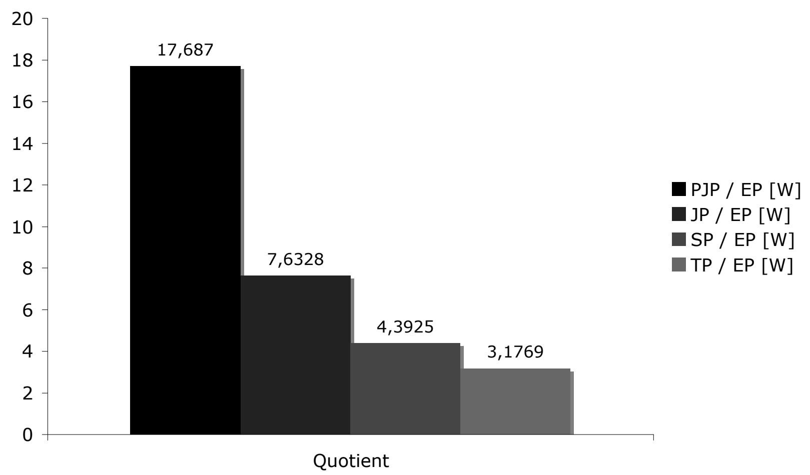


Figure 3-6 Relation between different values of the Human Power Spectrum

3.2.1. Gender specific differences

9 (64.3%) male and 5 female (35.7%) female athletes were participating in this study. The ratio sprint to endurance was 7 (77.8%) to 2 (22.2%) in males and 1 (20%) to 4 (80%) in females respectively.

Overall, significantly higher absolute power values have been observed in male athletes. The mean PJP in males was 1.7 times as high as the according value in females. The average male JP was a multiple of 1.8 of the female JP. SP was 1.7, TP 1.9 and EP 1.4 as high in males as in females.

		Minimum	Maximum	Mean	Standard Deviation	p-value
PJP [W]	Male	3068	5226	3995	628.1	0.003
	Female	1984	2891	2319	378.1	
JP [W]	Male	1519	2278	1768	260.8	0.003
	Female	763	1351	959	255.2	
SP [W]	Male	705	1515	995	260.8	0.004
	Female	435	711	571	120.3	
TP [W]	Male	578	1054	739	149.1	0.003
	Female	340	421	386	38.5	
EP [W]	Male	187	227	214	13.1	0.003
	Female	113	175	146	22.5	

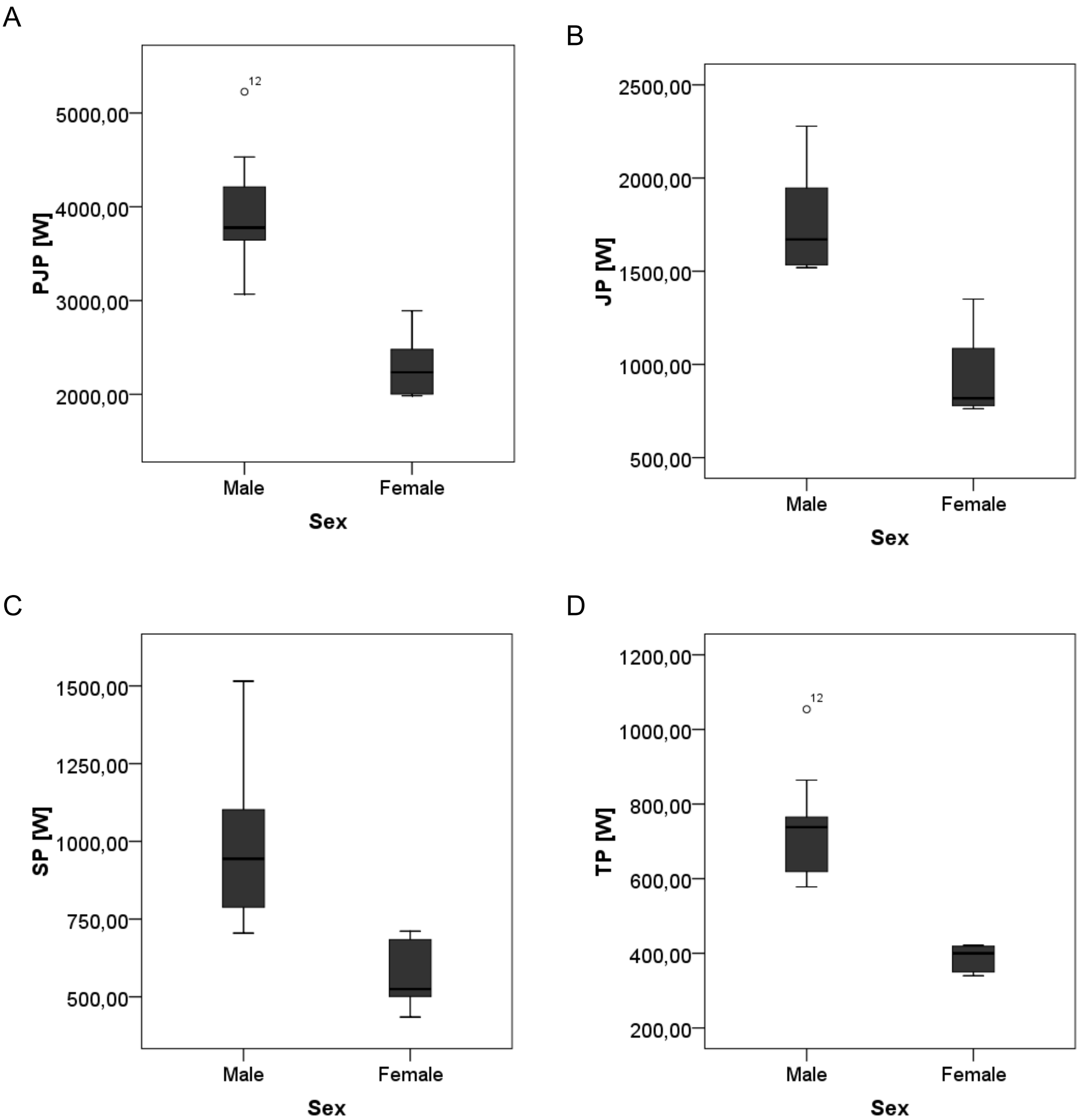
Table 3-5 Differences in absolute Power values between Male and Female athletes.

Differences were not that high when the power was related to weight, but still showed significant differences. The smallest difference was observed in EP given relative to the weight. Here, EP in male was only 16.7% higher than in female athletes. However there was higher percentage of endurance-trained athletes (group B) among the female group than among the male swimmers.

The highest PJP observed in males was 5226W, in females 2278W. The highest endurance power in women was 175W. The best endurance trained male athlete reached an EP of 227W.

		Minimum	Maximum	Mean	Standard Deviation	p-value
PJP [W/kg]	Male	41.4	57.7	50.7	6.3	0.009
	Female	32.0	42.8	37.3	4.7	
JP [W/kg]	Male	18.9	26.8	22.5	2.5	0.006
	Female	10.9	20.0	15.5	3.8	
SP [W/kg]	Male	9.8	16.6	12.7	2.3	0.009
	Female	8.2	10.9	9.4	1.1	
TP [W/kg]	Male	8.1	11.5	9.4	1.1	0.003
	Female	5.7	7.4	6.4	.7	
EP [W/kg]	Male	2.4	3.2	2.8	.3	0.032
	Female	2.1	2.7	2.4	.2	

Table 3-6 Differences in mean relative power values between Male and Female athletes.



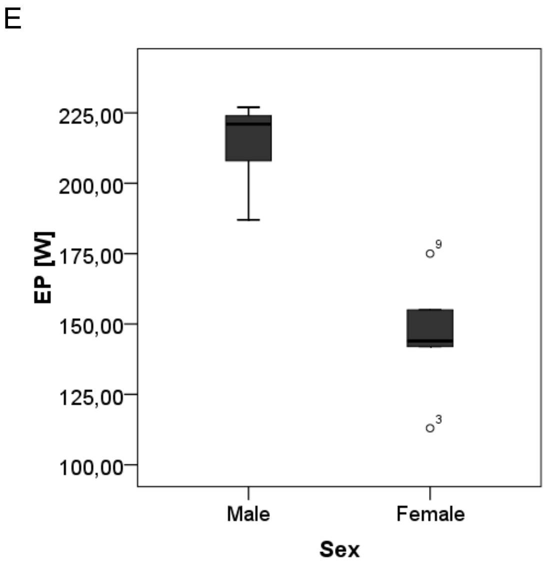


Figure 3-7 a-e Differences in the absolute values of the Human Power Spectrum between male and female (p<0.01).

3.2.2. Differences between Sprint and Endurance Athletes

Of the 14 participating athletes 8 (57.1%) athletes were classified as sprinters and 6 (42.9%) as endurance athletes. The group of sprinters (n=8) was composed of 7 (87.5%) male and 1 (12.5%) female athletes. 4 (66.7%) female and 2 (33.3%) male swimmers were classified as endurance athletes (n=6). No significant differences (Table 3-7) between the two groups were found in the values for the age (sprint 18.6 vs. endurance 17.3 years), years of training (8.8 vs. 7.7 years), hours of training per week (14.3 vs. 14.3 hours) and BMI (22.9 vs. 20.8). A significant difference (p=0.043) was found in the MI, which was in average 23.4 (range 21.4 – 27.3) in sprinters and 20.9 (range 18.1 – 22.8) in endurance athletes, suggesting a greater muscle mass in sprint-trained athletes.

		Mean	Range	p-value
Age	*Sprint*	18.6	15 – 23	0.558
	Endurance	17.3	13 – 27	
Years of training	*Sprint*	8.8	4 – 15	0.633
	Endurance	7.7	5 – 17	
Training h/week	*Sprint*	14.3	6 – 20	0.973
	Endurance	14.3	12 – 20	
BMI	*Sprint*	22.86	20.08 – 25.32	0.073
	Endurance	20.81	18.13 – 23.66	
MI	*Sprint*	23.35	21.43 – 27.36	0.043
	Endurance	20.86	18.13 – 22.82	

Table 3-7 Comparison of basic characteristics of sprint and endurance athletes.

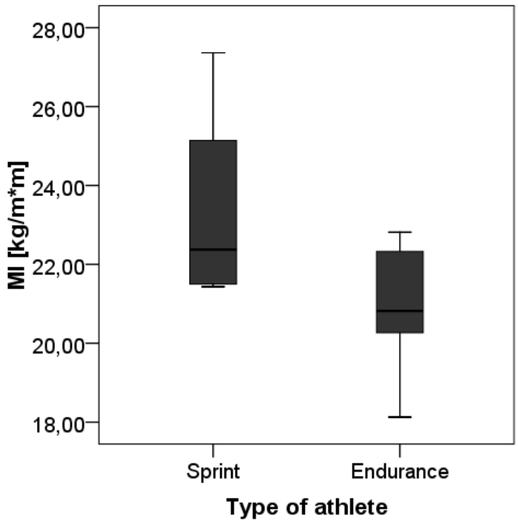
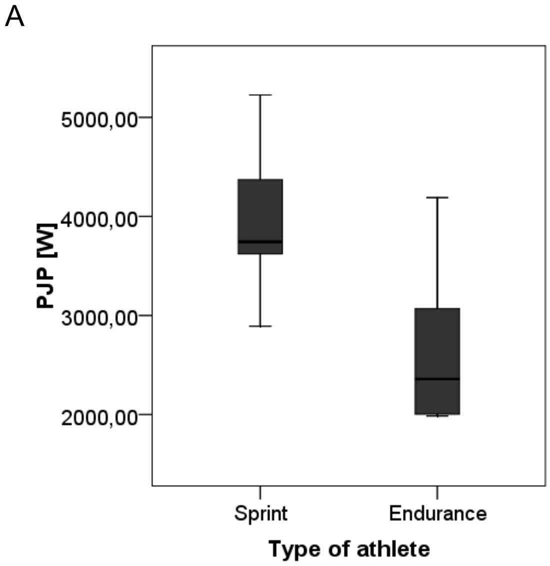


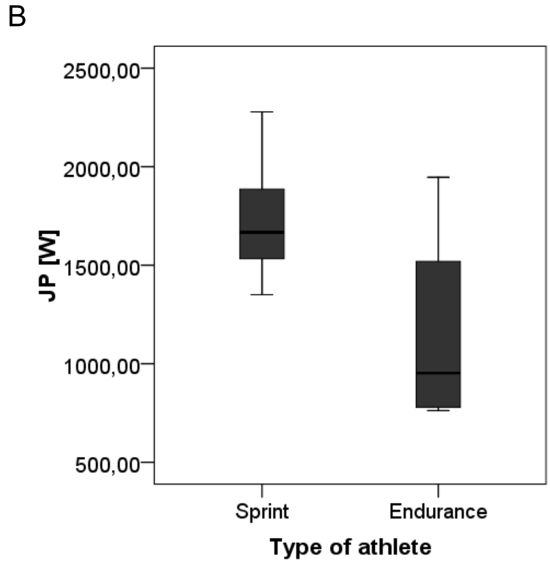
Figure 3-8 MI of sprint (group A) and endurance (group B) athletes (p=0.043)

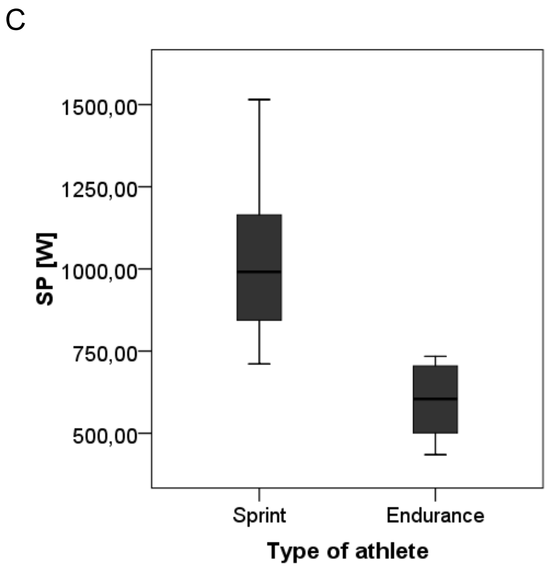
Sprint athletes reached significantly higher absolute values in PJP (p=0.009), JP (p=0.017), SP (p=0.003) and TP (p=0.007) (Table 3-8 and Figure 3-9). The mean PJP in group A was 3948W (range 2891 – 5226), in group B it was 2660W (range 1984 – 4190). JP was 1725W (range 1351 – 2278) in average in group A compared to 1152W (range 763 – 1945) in group B. Short distance swimmers reached a mean SP of 1028W (range 711 – 1515) and TP of 735W (range 421 – 1054). In the group B these value were 597W (range 435 – 734) and 451W (range 340 – 619) respectively. The highest PJP reached by a sprint athlete was 5226W compared to 4190W in the endurance group B. No significant difference could be observed in EP.

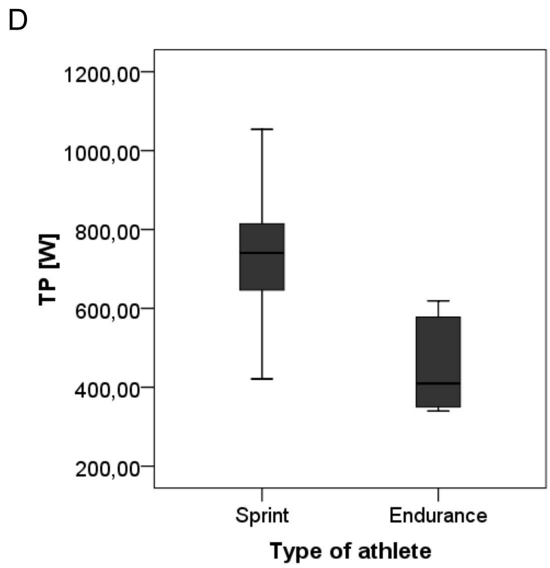
		Minimum	Maximum	Mean	Standard Deviation	p-value
PJP [W]	Sprint	2891	5226	3948	703.0	0.009
	Endurance	1984	4190	2660	849.4	
JP [W]	Sprint	1351	2278	1725	295.2	0.017
	Endurance	763	1945	1151	484.1	
SP [W]	Sprint	711	1515	1028	257.4	0.003
	Endurance	435	734	597	125.4	
TP [W]	Sprint	421	1054	735	184.7	0.007
	Endurance	340	619	451	118.7	
EP [W]	Sprint	175	226	207	18.0	0.09
	Endurance	113	227	167	46.6	

Table 3-8 Comparison of absolute power between Sprint and endurance athletes









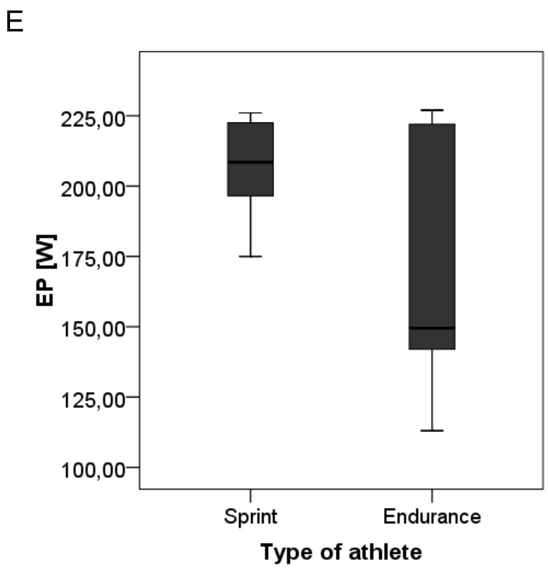


Figure 3-9 a-e Differences in the absolute values of the Human Power Spectrum between sprint and endurance athletes; **a** PJP ($p<0.01$) **b** JP ($p<0.02$) **c** SP ($p<0.01$) **d** TP ($p<0.01$) **e** EP ($p=0.09$)

The power relative to the weight showed significant differences (Table 3-1) in the test for PJP (p=0.038), SP (0.001) and TP (p=0.01). No significant differences were observed in JP and EP.

		Minimum	Maximum	Mean	Standard Deviation	p-value
PJP [W/kg]	Sprint	41.4	57.2	49.0	5.9	0.038
	Endurance	32.0	57.7	40.5	9.3	
JP [W/kg]	Sprint	18.9	24.8	21.8	2.2	0.073
	Endurance	10.9	26.8	17.5	5.8	
SP [W/kg]	Sprint	10.4	16.6	13.1	2.1	0.001
	Endurance	8.2	10.3	9.4	.8	
TP [W/kg]	Sprint	6.5	11.5	9.3	1.5	0.01
	Endurance	5.7	8.6	7.1	1.2	
EP [W/kg]	Sprint	2.4	3.2	2.7	.3	0.6
	Endurance	2.1	3.2	2.6	.5	

Table 3-9 Comparison of relative power between Sprint and Endurance athletes.

A comparison of the average power values within each group of athletes showed that significant differences can be observed between sprint- and endurance-trained athletes (Table 3-10 and Figure 3-10). These significant differences could be observed for the comparison of PJP, JP, SP and TP to EP.

The PJP in sprinters was 19 (range 16.49 – 23.33) as high as their EP. In endurance-trained swimmers this value was 15.9 (range 13.82 – 18.46). This difference was significant with p=0.026.

The average JP in short distance swimmers divided by their EP equaled 8.3 (range 7.44 – 10.17) in average. In endurance athletes the same calculation resulted in a value of 6.7 (range 5.37 – 8.57). This difference, again, was significant (p=0.017).

When dividing average values of SP by EP the result was 4.9 (range 3.83 – 6.76) in sprinters and 3.7 (range 3.11 – 4.75) in long-distance swimmers, resulting in a difference being significant with a p-value of 0.019.

The TP was in average 3.5 (range 2.41 – 4.71) as high as the EP in group A and 2.7 (range 2.39 – 3.1) as high in group B. This difference was significant (p=0.28)

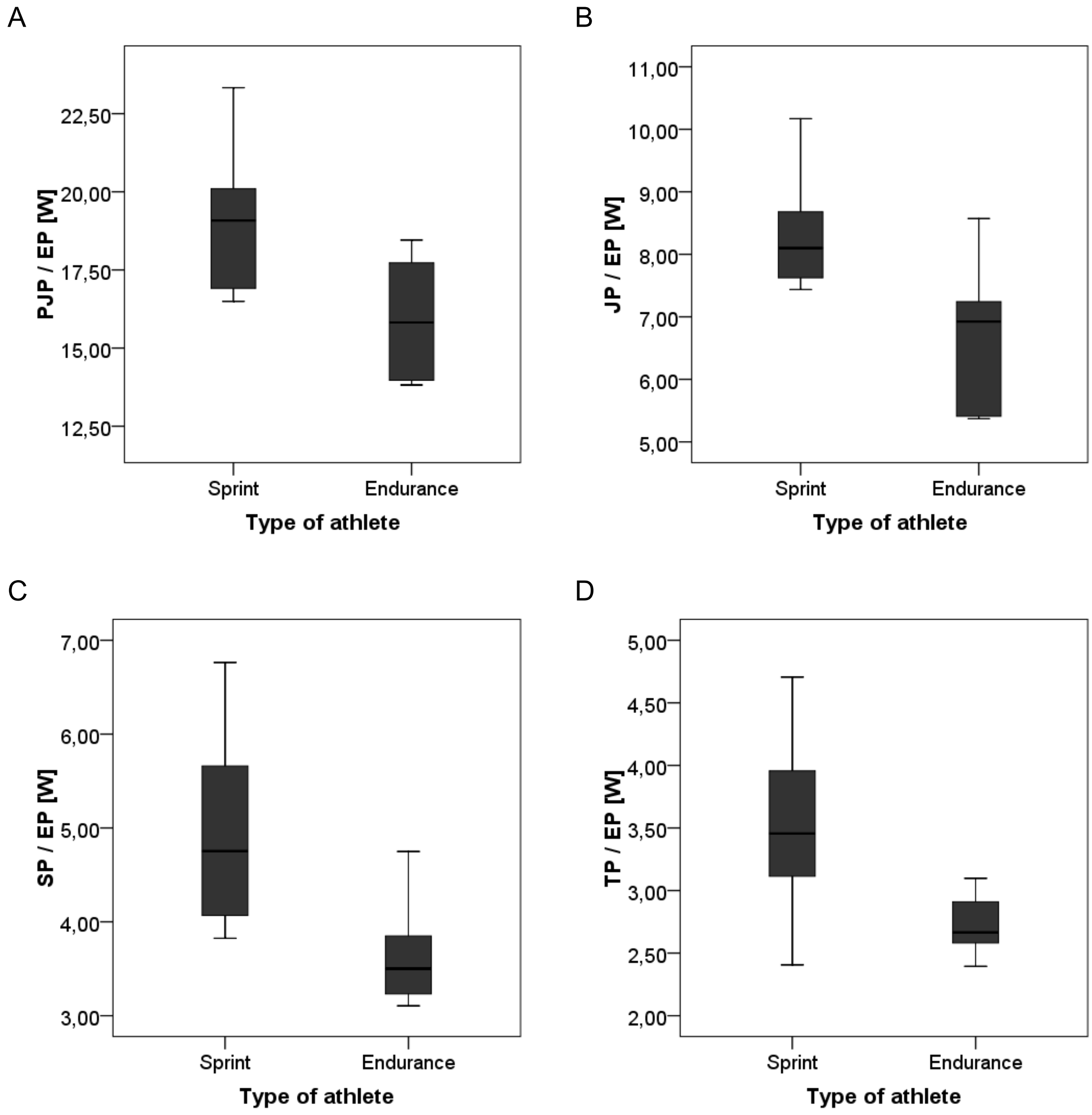


Figure 3-10 a-e Differences in the relation between values of the Human Power Spectrum between sprint and endurance athletes; **a** PJP/EP ($p<0.03$) **b** JP/EP ($p<0.02$) **c** SP/EP ($p<0.02$) **d** TP/EP ($p<0.03$)

		Minimum	Maximum	Mean	Standard Deviation	p-value
PJP/EP	Sprint	16.49	23.33	19.00	2.32	0.026
	Endurance	13.82	18.46	15.94	2.01	
JP/EP	Sprint	7.44	10.17	8.30	0.90	0.017
	Endurance	5.37	8.57	6.74	1.2	
SP/EP	Sprint	3.83	6.76	4.94	1.03	0.019
	Endurance	3.11	4.75	3.66	0.61	
TP/EP	Sprint	2.41	4.71	3.52	0.71	0.028
	Endurance	2.39	3.1	2.72	0.25	

Table 3-10 Comparison of the relation between values of the Human Power Spectrum in sprint and endurance athletes

3.3. Selected cases

In the following the Human Power Spectrums of two athelets who have been doing swim training over several years, one from group A and one from group B, will be described in detail.

The first case reported is a 23-year-old male swimmer from group A (sprint), who has been training for 11 years, with a current average amount of 20 hours per week. He has been taking part in several international competitions and holds several Austrian records in short distance disciplines. The size of this swimmer was 1.9m, his sitting height 0.995m. The weight was 91.4kg, the BMI 25.32 and the MI 25.85. Prefered strokes were butterfly and freestyle. His Human Power Spectrum is described in Table 3-11 and Figure 3-11.

The PJP divided by EP was 23.3. The JP was 10.2, SP 6.8 and TP 4.7 times as high as the EP.

	PJP	JP	SP	TP	EP
Relative [W/kg]	56.9	24.8	16.6	11.5	2.4
Absolute [W]	5226	2278	1515	1054	224

Table 3-11 Human Power Spectrum of a male sprint athlete

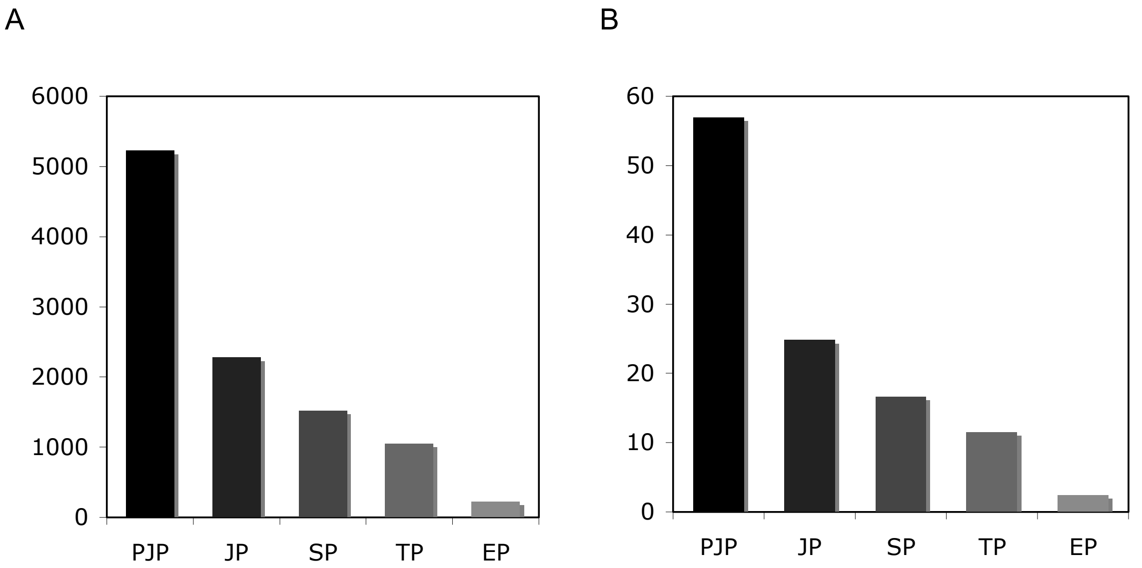


Figure 3-11 a,b Human Power Spectrum of a male sprint athlete **a** absolute [W] **b** relative [W/kg] values

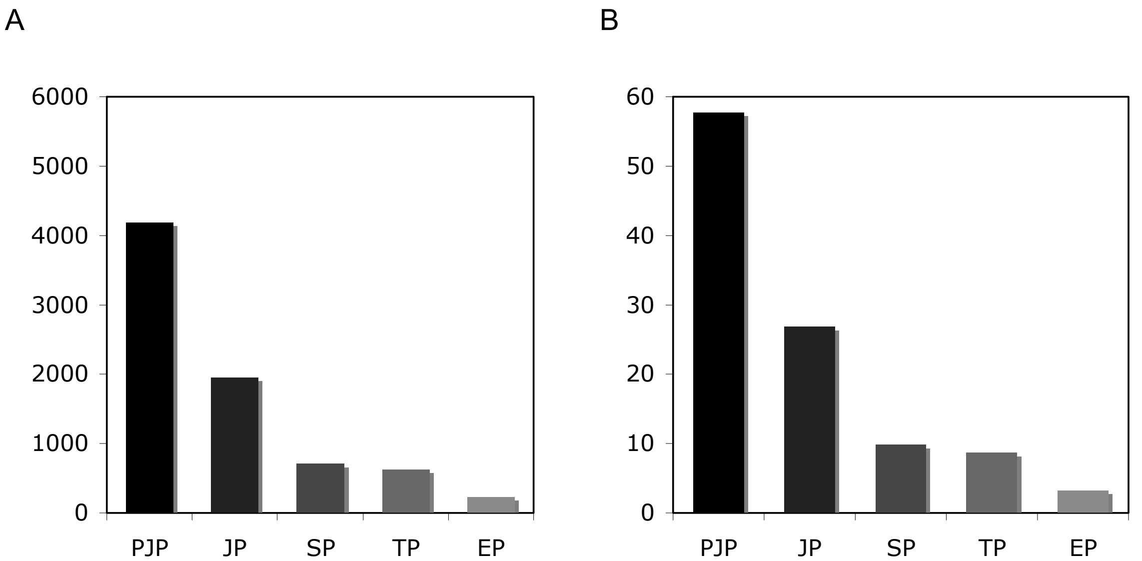


Figure 3-12 a,b Human Power Spectrum of a male endurance athlete **a** absolute [W] **b** relative [W/kg] values

The second athlete on whose HPS will be looked at more closely was a 27-year-old male long distance swimmer (group B). He had been participating in swim training for 17 years, with a current average amount of 20 hours per week. Preferred strokes were freestyle and breast stroke. The anthropometric characteristics were: height: 1.82m, sitting height: 0.94m, weight: 72kg, BMI: 21.74, MI: 22.82. The corresponding Power Spectrum is illustrated in Figure 3-12 and Table 3-12.

The PJP divided by EP was 18,5. The JP was 8.6, SP 3.1 and TP 2.7 times as high as the EP.

	PJP	JP	SP	TP	EP
Relative [W/kg]	57.7	26.8	9.8	8.6	3.2
Absolute [W]	4190	1945	705	619	227

Table 3-12 Human Power Spectrum of a male endurance athlete

The comparision of this two athletes shows us that the difference between the test for 0.01 seconds up to 100 seconds and the endurance power test is much larger in short distance athletes. Furthermore short distance athletes reach typically higher absolute value in the PJP, JP, SP and TP tests as seen in the comparision of these two athletes. In contrast the long distance swimmer has a higher EP in absolute values as well as in relatve values.

3.4. Correlation to 100m freestyle record

For all absolute values of the Human Power Spectrum a significant correlation ($p<0.01$) to the personal record over 100-meter freestyle on the short course could be observed (Figure 3-14). Furthermore a significant correlation could be observed with the quotient of PJP/EP and JP/EP ($p<0.01$). The correlation with the quotient of TP/EP was significant with $p<0.05$. No significant correlation could be observed with the quotient of SP/EP.

The avarage personal record over 100-m freestyle was slightly better in group A (mean 57.4 s, range 51.17 – 63.5) than in group B (mean 61.43, range 56.5 – 65.7), however the difference did not show significancy (Figure 3-13).

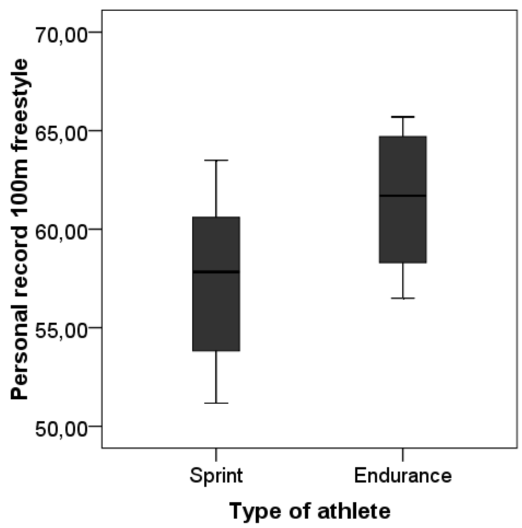
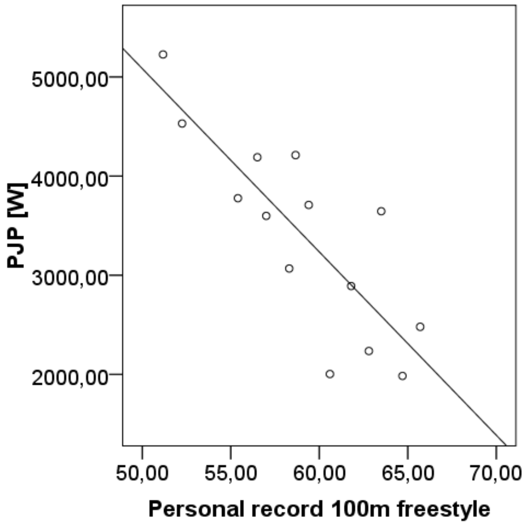
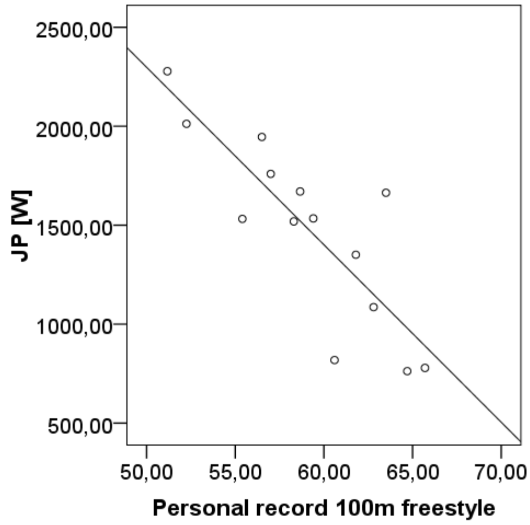


Figure 3-13 Comparison of the mean personal record over 100-m freestyle in group A (sprint) and group B (endurance) athletes

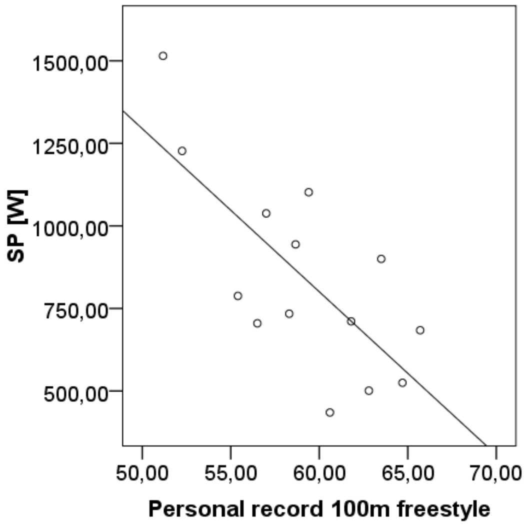
A



B



C



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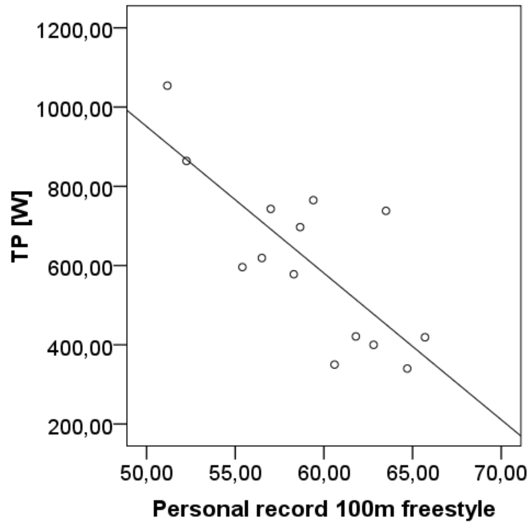

E

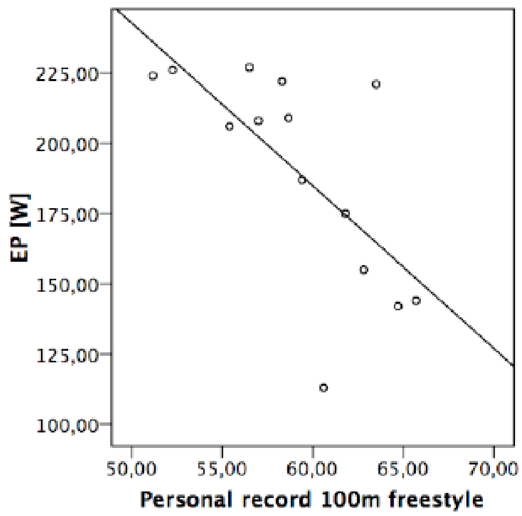

Figure 3-14 a-e Correlation between personal 100-m freestyle record and results in the Human Power Spectrum ($p<0.01$): **a** $r=-0.832$ **b** $r=-0.837$ **c** $r=-0.724$ **d** $r=-0.77$ **e** $r=-0.676$

4. Discussion and Conclusion

4.1. The Human Power Spectrum

The Human Power Spectrum is a test that covers the domains of time from 0.01 seconds up to hours. Due to its design it is possible to accurately describe and evaluate the entire potential of an athlete in terms of output power of the lower extremities.

The absolute values, which were obtained in this test, show the maximum power an athlete can produce. Power values related to the athlete's weight give a good insight into the fitness of the athlete.

The highest values can be achieved in the time domain of 0.01 s to 0.1 s. This power, reached during a vertical squat jump, maximally exceeded the power which could be kept up over a longer period (EP) by a multiple of about 23.3. PJP reached values of up to more than 5000 Watt. EP on the other hand reached values of about 190 Watt in average. This immense difference shows, how important the question about the domain of time is when describing maximum power of an individual.

There is evidence that this test series is a valid instrument to test performance of swimmers, as significant correlations could be observed between the absolute power values in the human power spectrum and the personal record over 100-meter freestyle.

4.1.1. Gender specific differences

In accordance to literature (44) it has been observed that absolute values are higher in males than in females. Furthermore Maud et al. described that in an investigation of college students, differences in maximum power were reduced, when adjusted to the fat free mass of the probands (44). In the present study the fat free mass was not evaluated, however we saw that differences in the maximum power achieved between males and females became smaller when adjusted to weight.

In this study there were more endurance-trained athletes in the female group than in the male group. As literature describes that observed differences might be bigger due to individual characteristics than due to sex (44), the training state could be another reason, besides general gender specific characteristics, for the big differences between males and females in the absolute values of maximum power achieved in the test.

4.1.2. Differences between Sprint and Endurance Athletes

This study showed that significant differences can be observed between differently trained athletes.
In the anthroprometric characteristics of the athlets a higher MI (average 23.4 compared to 20.9, p=0.043) could be observed in group A than in group B, which might be linked to a higher muscle mass, however no tests of the body composition have been performed.
To be successful in short-distance competitions, high power must be achieved in the tests for time domains below 100 seconds. If an athlete wants to compete in long-distance competitions, he should be able to achieve good results in the endurance power test.
According to the literature mentioned above (38,40,41,74,75), sprint athletes reached significantly higher absolute values in the test for the time domains of less than 100s than athletes in group B (PJP: p=0.009, JP: p=0.017, SP: p=0.003 and TP: p=0.007). However no significant difference could be observed in the EP (p=0.09). In fact the mean EP was slightly higher in group A than in group B. The difference of the EP relative to the body weight was smaller than the difference between the absolute values.
The highest PJP reached by a sprint athlete was 5226W compared to 4189W reached by an endurance athlete.
The power relative to the weight showed significant differences in the test for PJP (p=0.038), SP (0.001) and TP (p=0.01). No significant differences were observed in JP and EP.
It was observed that the differences in the relation between the achieved PJP, JP, SP and TP and the EP were larger in group A than in group B. These findings are consistent with our expectations, as short-distance athletes have been reported to have a larger muscle mass, more type II muscle fibres and their metabolism is optimized for rapid nonoxidative energy supply (25-28,32,33,39). Therefore they should be able to reach high levels of power in performance test, which cover actions that are powered by immediate energy sources and nonoxidative gylcolytic pathways. On the contrary their EP is not that high, and therefore leading to a bigger discrepancy between the mentioned power values. Endurance trained athletes on the contrary have better EP but lower PJP, JP, SP and TP, so that the difference between those values is smaller.
In fact it could be observed for example that JP was 8.3 times as high as the EP in group A and only 6.7 times as high in group B. This difference was significant, with a p-value of

<0.02. Similar findings could be observed for the relation between PJP (p<0.03), SP (p<0.02) and TP (p<0.03) to EP.

4.2. Limitations

The informative value of this study is of course limited, due to the small number of test persons. Furthermore the study population was quite heterogenous, especially in terms of age, ranging from 13 to 27 years, however the mean age in the two subgroups was comparable.

However, since it was possible, despite having only a small study population, to obtain significant findings and differences between subgroups we assume that these findings might be valid for performance testing of competitive swimmers.

Bicycle ergometer test are not the ideal instrument to test maximum power of swimmers as they do a lot of work with their upper extremity. Furthermore optimal results can only be reached when trained in cycling and being used to this specific movement. In comparison to elite cyclists, the values for maximum endurance power reached by athletes in this study were not very high, which could be caused by the factors mentioned above. Elite cyclist can reach endurance power values of more than 300 Watt (76,77), while the highest value in this study was 227 Watt.

The percentage of males and females was not the same in group A and B. However based on the literature mentioned above (44), it might be that the differences in the profiles of the human power spectrum between group A and B are rather linked to their individual training and constitution than to their sex. Of course, sex has an impact on the absolute values of the HPS, but not so much on the relation between the values within one's HPS. As similar muscle type and metabolism have been described in males and females, it should be possible to compare the relation between values within the human power spectrum (44). Based on this consideration, we think, that difference in the profiles of the human power spectrums are more likely to be linked to the individual specification and type of training than to sex.

Currently it is possible to see differences in the power spectrums of athletes from group A and group B respectively. However further investigations will be needed to establish limiting values, which would make it possible to clearly classify an athlete as sprinter or endurance athlete due to his Human Power Spectrum.

Since the body can adapt to stress, it is confronted with in training, it could be expected that an alteration of the entire power spectrum takes places, following a specific training. Here again further studies would be needed. With the help of a prospective study it could be revealed to which degree the profile of an individual human power spectrum is due to genetic disposition and to which degree it can be modified with the help of a specific training regime.

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6. Appendix

6.1. List of Symbols and Abbreviations

ADP	adenosine diphosphate
AMP	Adenosine monophosphate
ATP	Adenosine-5'-triphosphate
BMI	Body mass index
Ca^{2+}	Calcium
CO_2	Carbon dioxide
CP	creatine phosphate
EP	Endurance Power
ETC	Electron transport chain
$FADH_2$	flavin adenine dinucleotide
FT	fast twitch muscle fibres
GTP	Guanosine triphosphate
H^+	Hydrogen
H_2O	Water
HPS	Human Power Spectrum
J	Joule
JP	Jumping Power
kg	kilogram
LTP2	second lactate trunpoint
m	meter
m/s	meter per second
Mg^{2+}	Magnesium
MI	Mass index
MLSS	maximal lactate steady state
mRNA	Messenger ribonucleic acid
$NADH/H^+$	Nicotinamide adenine dinucleotide
O_2	Oxygen
Pcr	creatine phosphate
P_i	Phosphate
PJP	Peak Jumping Power
s	second
SP	Sprint Power
ST	slow twitch muscle fibres
TP	Transition Power
VO_2max	maximal oxygen consumption
W	Watt

6.2. Units and Measures

SI units:

Lenght	meter	m
Mass	kilogram	kg
Power	watt	W
Time	seconds	s
Velocity	meter per second	$m \cdot s^{-1}$
Work	joule	J

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6.5. Curriculum vitae

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