

# Bioenergetics and energy systems in sport performance: A narrative review

Poulami Ghosh<sup>1</sup> , Arnab Ghosh<sup>1</sup> , Kishore Mukhopadhyay<sup>1,2</sup> 

<sup>1</sup> Department of Physical Education, Union Christian Training College, Berhampore, Murshidabad, West Bengal, India. <sup>2</sup> Faculty of Health and Wellness, Sri Sri University, Cuttack, Odisha, India.

## Abstract

**Background:** Activity is the basis of life and this quality is already present in our DNA. Performing any forms of activities or exercises energy is required. The chemical energy is stored and regenerate in the form of ATP. The three energy systems of our body that is responsible for the liberation of energy depending upon the volume and intensity of work namely ATP PC, oxidative, and glycolytic which is again dependent upon three major types of muscle fiber. The dominance of these systems varies across different sporting events. Therefore, understanding bioenergetics helps in selecting the most suitable sport based on an individual's physiological capacity. **Objective:** The objective is to understand the role of bioenergetics and different energy systems (ATP-PC, anaerobic, and aerobic) in determining the energy demands of various sporting events. It also aims to relate an athlete's physiological capacity to appropriate sports selection, thereby improving performance and guiding talent identification. **Content Summary:** Understanding bioenergetics helps in the scientific selection of sporting events, talent identification, and training specialization. It enhances performance, delays fatigue, and reduces the risk of injury by ensuring that athletes participate in sports best suited to their energy system efficiency. A review-based study was conducted to draw the inference of the study. **Practical Implications:** Bioenergetics helps in selecting suitable sporting events by matching an athlete's dominant energy system with the specific demands of the sport. It also guides training, recovery, and nutrition strategies to improve performance and reduce fatigue and injury risk. **Conclusion:** All types of muscle fiber are present in the human body but their quantity is largely dependent upon the genetic endowment of an individual and partly adaptation of sports training. The present article discussed scientifically the various aspects of bioenergetics and the method of training for the development of particular muscle fiber in relation to sporting action.

**Received:**  
January 17, 2026

**Accepted:**  
April 20, 2026

**Online Published:**  
May 26, 2026

**Keywords:**  
Energy metabolism, energy systems, muscle fiber types, sport performance.

## Introduction

Energy is fundamental to all forms of life and to every process occurring throughout the universe. Within the human body, energy drives and regulates intrinsic physiological functions, supports cellular repair and tissue regeneration, facilitates muscle development, and plays a key role in maintaining homeostasis. As environmental conditions become more demanding, greater amounts of energy are required to sustain internal balance (Tara Energy, 2021). Adequate energy intake through proper nutrition is particularly important for athletes. Nutritional requirements vary according to fitness level, intensity of activity, and internal and external environmental conditions. Optimal nutrition supports normal growth, good health, and an enhanced quality of life, whereas undernutrition (deficiency of essential nutrients) and overnutrition (excess intake leading to obesity) can have adverse health consequences. In sports science, the type,

quality, and quantity of nutrients consumed are crucial, as they directly influence energy availability, athletic performance, and recovery. Nutrients are broadly classified into macronutrients, which are required in larger amounts, and micronutrients, which are needed in smaller quantities (Maughan et al., 2018).

An optimal steady state occurs when energy intake adequately compensates for total energy expenditure while supporting appropriate growth in children and reproductive demands in women, without causing metabolic, physiological, or behavioural limitations that restrict the full expression of an individual's biological, social, and economic potential (Hafekost et al., 2013).

The concept of energy balance is grounded in the fundamental law of thermodynamics, which states that energy cannot be destroyed but can only be gained, lost, or stored by an organism. Energy balance is defined as the condition in which energy intake equals energy expenditure. This principle explains changes in body weight over time in response to variations in energy

✉ K. Mukhopadhyay, e-mail: kishore.km2007@gmail.com

consumption and energy use. When energy balance is maintained, body weight remains stable (Hill et al., 2012; Caspersen et al., 1985).

Physical activity is inherently encoded in human biology. All forms of movement require muscle contraction, which depends on the metabolic release of energy. It is important to distinguish between physical activity and energy expenditure, as they represent related but distinct concepts. Physical activity refers to any bodily movement produced by skeletal muscles that results in energy expenditure (Ainsworth, 2009), whereas energy expenditure is the outcome of such activity. In simple terms, physical activity or exercise is a behaviour that increases energy use above resting levels. Although these terms are often used interchangeably, they are conceptually different and can be measured using different methodologies (Atalay & Hänninen, 2010).

Skeletal muscle exhibits unique characteristics in energy metabolism. In addition to its high aerobic capacity, it can temporarily shift to anaerobic metabolism, enabling both fitness adaptations and short-term energy production. The rate of adenosine triphosphate (ATP) utilization in skeletal muscle is highly variable and can increase more than one hundredfold. Such rapid changes in ATP demand require corresponding adjustments in circulatory, cardiovascular, and respiratory functions. At rest, skeletal muscle receives approximately 5 ml of blood per 100 g of tissue. During intense exercise, especially in trained individuals, skeletal muscles may receive up to four-fifths or more of total cardiac output. Oxygen extraction also rises significantly, as indicated by an increase in arterio-venous oxygen difference from about 25% at rest to 80% or more during maximal exercise. Although substantial, this increase is relatively modest compared to certain animal species, where oxygen extraction can rise up to a thousand fold (Glaister, 2005).

Muscle contraction during exercise is driven by the breakdown of adenosine triphosphate (ATP) and the subsequent release of free energy required for mechanical work (Bigland-Ritchie & Woods, 1984).

**ATP — (ATPase) → ADP + Pi + energy →** (The released energy is used to power actin–myosin cross-bridge cycling, leading to muscle contraction).

ATP muscle contraction is not an energy store, but in combination with ADP, AMP, and each Pi is an essential

requirement for optimal cell function. In addition, any ATP muscle reduction is associated with cellular conditions associated with rapid growth of fatigue, which is defined as a decrease in muscle strength to produce energy or strength, or a reduction in ATP turnover of skeletal muscle (Søgaard et al., 2006; Bogdanis et al., 1995). Fatigue is vital physiological process that it can cause irreversible rupture or muscle damage (Bogdanis et al., 1996; Bogdanis et al., 1998; Jacobs et al., 1982; Vollestad & Sejersted, 1989; Corsini, 2021).

**Research Gap:** Despite the recognized importance of bioenergetics in athlete profiling and event specialization, several research gaps still exist. Most studies rely on generalized classifications of energy systems, with limited emphasis on individual variability in metabolic efficiency, adaptability, and transition between energy pathways during real-game situations. Additionally, there is a lack of longitudinal research examining how bioenergetic profiles evolve over time with training, age, and environmental influences, making it difficult to predict long-term suitability for specific sporting events.

Furthermore, current research often isolates bioenergetics from other critical factors such as biomechanics, psychological traits, and genetic predisposition, leading to incomplete athlete profiling models. Therefore, future research should focus on creating holistic models that combine bioenergetics with multidimensional performance indicators for more accurate and dynamic event specialization.

**Purpose of the Study:** The purpose of this study was to examine the role of bioenergetics in determining the suitability of athletes for different sporting events based on their energy system efficiency. It aimed to provide a scientific basis for athlete profiling and event specialization by linking physiological capacities with the specific energy demands of sports.

Additionally, the study seeks to promote a more effective approach to talent identification, training design, and performance enhancement. By integrating bioenergetic principles into sports selection, it aims to improve athletic outcomes while reducing fatigue, injury risk, and inappropriate event placement.

## Method

Research articles meeting the inclusion criteria were selected for further meta-synthesis. This study employed a systematic review design conducted in accordance with the Preferred Reporting Items for

Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The PRISMA framework was adopted to ensure transparency, methodological rigor, reproducibility, and comprehensive reporting.

**Table 1**  
Research findings on bioenergetics, muscle fiber types & sports performance.

Category	Research Finding	Key Outcome / Implication	References
<b>Bioenergetics</b>			
	Energy systems (ATP-PC, glycolytic, oxidative) operate simultaneously during exercise	Challenges in isolating contributions; important for training prescription	Rios et al., 2026
	Skeletal muscle metabolism adapts at molecular level with training	Enhances efficiency of energy utilization and endurance	Smith et al., 2023
	Exercise maintains mitochondrial structure and function with aging	Prevents decline in muscle energy systems	Protasi et al., 2026
	Exercise enhances mitochondrial bioenergetics and oxidative enzymes	Improves endurance and fatigue resistance	Gorgey et al., 2025
	Muscle metabolic efficiency depends on contraction velocity	Optimal efficiency occurs at specific shortening velocity	Xu & Chen, 2026
	Muscle-tendon models can predict metabolic cost during movement	Helps estimate energy expenditure in locomotion	Luis et al., 2023
<b>Muscle Fiber Types</b>			
	Type I fibers dominant in endurance athletes; Type II in power athletes	Fiber distribution determines sport specialization	Plotkin et al., 2021
	Fiber-type composition strongly linked to team-sport performance traits	Influences speed, strength, and repeated sprint ability	Hopwood et al., 2023
	Sprint cyclists with higher fast-twitch fibers produce greater power	Fiber typology predicts maximal sprint performance	Wackwitz et al., 2024
	Sex differences exist in fiber distribution (men: more Type II; women: more Type I)	Explains strength vs endurance differences	Nuzzo, 2024
<b>Training Adaptations</b>			
	Exercise induces fiber-type specific proteomic adaptations	Different fibers adapt uniquely to training stimuli	Hostrup & Deshmukh, 2025
	Endurance training promotes transition toward oxidative (Type I/IIa) fibers	Enhances aerobic capacity and efficiency	Li et al., 2024
	Power training increases fast-twitch fiber function and rate of force development	Improves explosive strength and jumping ability	Methenitis et al., 2020
	Training-induced fiber transitions are complex and not always linear	Mixed evidence on conversion between fiber types	Plotkin et al., 2021 (24)
	Electrical stimulation training improves muscle size and mitochondrial function	Useful in rehabilitation and performance enhancement	Gorgey et al., 2025
	Muscle activation patterns change with fatigue and recovery	Important for performance monitoring	Nguyen et al., 2023
<b>Sports Performance</b>			
	Muscle fiber typology influences sprint, strength, and endurance performance	Key determinant in talent identification	Hopwood et al., 2023
	Start and turn performance in swimmers linked to fiber composition	Fast fibers enhance explosive aquatic performance	Mallett et al., 2021
	Individual bioenergetic profiles guide sport-specific training	Helps optimize performance and reduce fatigue	Rios et al., 2026
	Muscle plasticity enables sport-specific adaptations with training	Supports long-term athlete development and specialization	Smith et al., 2023
	Fast-twitch dominance enhances explosive performance (cycling, sprinting)	Improves peak power output	Wackwitz et al., 2024
	Low energy availability reduces endurance performance despite unchanged mitochondria	Highlights importance of nutrition in bioenergetics	Caldwell et al., 2024
	Muscle synergy and coordination adapt with training and fatigue	Influences running and movement efficiency	Ma et al., 2025

The review aimed to systematically identify, screen, critically appraise, and synthesize empirical evidence examining "Bioenergetics," "energy metabolism," "muscle fiber types" and "sports performance". A comprehensive and structured literature search was conducted across four major electronic databases: PubMed, Scopus, Web of Science, and SAGE Journals. A Boolean search strategy was employed using combinations of the following keywords: "Bioenergetics," "energy metabolism," "muscle fiber types" and "sports performance". Additionally, reference lists of eligible articles were manually screened using the snowballing technique to identify further relevant studies. The search included studies published between January 2020 and June 2026, capturing the most recent evidence in the context of increasing digitalization and post-pandemic learning environments.

The selection criteria included only peer-reviewed articles, randomized controlled trials, clinical trials, review literature, and observational studies.

## Results and Discussion

The findings of the different research studies have been discussed categorically in the following.

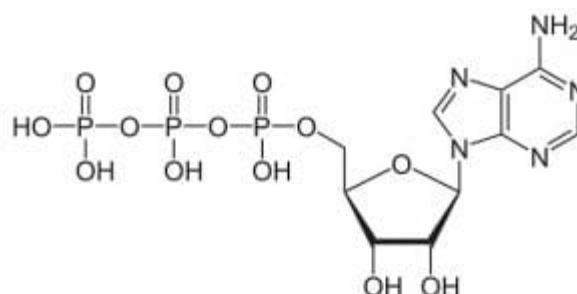
### Bioenergetics

Bioenergetics is a major branch of biochemistry that examines energy transformations within living systems and the efficiency of energy transfer both within and between organisms (Nelson et al., 2013; Green & Zande, 1981). It represents a dynamic area of biological research that investigates how energy is converted and utilized in living cells, encompassing numerous cellular processes such as cellular respiration and a wide range of metabolic and enzymatic reactions responsible for the generation and use of energy, primarily in the form of adenosine triphosphate (ATP) (Omics Publishing Group, 2026). Although all living organisms depend on energy, they differ in how it is acquired and utilized. For instance, plants harness energy in a way that releases oxygen as a by-product, whereas animals, including humans, rely on oxygen for survival. The central aim of bioenergetics is to explain how organisms obtain, convert, and utilize energy to carry out biological work, making the study of metabolic pathways fundamental to this field (Omics Publishing Group, 2026; Biology Dictionary, 2017).

In skeletal muscle, energy is derived mainly from glucose and fatty acids, which are stored within muscle fibers as glycogen and triglycerides, respectively. The

chemical energy stored in carbohydrates, lipids, and proteins is ultimately converted into ATP, which serves as the immediate source of energy for muscular activity.

Bioenergetics also focuses on the energy changes associated with the formation and cleavage of chemical bonds in biological molecules. Energy metabolism encompasses the complete set of chemical reactions occurring within an organism, typically organized into complex intracellular metabolic pathways classified as catabolic or anabolic. In living systems, bioenergetics describes the flow and utilization of energy, particularly emphasizing how macromolecules such as carbohydrates, fats, and proteins are broken down to supply usable energy for growth, repair, and physical activity. Conversely, anabolic pathways utilize chemical energy, primarily from ATP, to drive cellular work and biosynthetic processes (Rayner, 2018).



**Figure 1.** Molecular composition of ATP (Bernaciková, 2026).

Adenosine triphosphate (ATP) is a fundamental molecule responsible for energy transfer within cells and serves as the primary energy currency of biological systems. It is produced as a final product of photophosphorylation, cellular respiration, and fermentation. ATP is utilized by all living organisms to support a wide range of cellular activities. Beyond its central role in energy provision, ATP also participates in intracellular signalling pathways and functions as a precursor molecule incorporated into deoxyribonucleic acid (DNA) during DNA synthesis (Kravitz, n.d.).

### Energy System

During digestion, carbohydrates, fats, and proteins are broken down into simpler molecules—glucose, amino acids, and fatty acids—which are transported to cells throughout the body. Within these cells, these energy-yielding nutrients are converted into adenosine triphosphate (ATP), the immediate fuel for cellular activity. The body relies on three distinct energy systems to generate ATP and meet its energy demands. Most physiological activities draw on all three systems

simultaneously, operating along a continuum to maintain a continuous supply of energy (Kravitz, n.d.).

The essential Energy systems of the body are as follows: (I) ATP-PC System, (II) Lactic Acid System, (III) Aerobic System.

**ATP-PC System:** The ATP-PC system operates anaerobically, as it does not require oxygen for energy production. It is capable of generating very high-power output, but only for brief durations, typically lasting about 10–15 seconds. This rapid energy release places considerable acute stress on the nervous system and quickly exhausts the limited intramuscular stores of adenosine triphosphate (ATP). Consequently, extended recovery periods are necessary between repeated maximal efforts, as neural recovery occurs more slowly than muscular recovery. Muscles contain small, readily available reserves of ATP that can be utilized immediately, since the ATP-PC system involves the fewest biochemical steps among the three energy systems. In addition, locally stored phosphocreatine serves as a high-energy compound that can rapidly resynthesize ATP to meet the demands of intense muscular activity, but only for a short duration. This system predominates during explosive movements such as Olympic weightlifting, throwing events, and sprinting (PT Direct, n.d.).

ATP and creatine phosphate (CP) serve as the immediate energy sources for muscle contraction (Fig. 2, 3). Energy production for this form of muscular activity occurs through anaerobic pathways, independent of oxygen availability.

During short-duration, high-intensity activities, muscles must generate large amounts of power, resulting

in a rapid demand for adenosine triphosphate (ATP). The phosphagen system, also known as the creatine phosphate (CP)-ATP system, is the fastest mechanism for ATP resynthesis. Creatine phosphate, stored in skeletal muscle fibers, donates its phosphate group to adenosine diphosphate (ADP) to regenerate ATP. During periods of rest, ATP produced through other metabolic pathways is used to replenish creatine phosphate stores.

In this process, enzymatic activity supports rapid ATP resynthesis rather than ATP degradation, allowing sustained high-power output during brief, intense efforts (PT Direct, n.d.).

**Lactic Acid System:** The lactic acid system also generates ATP through anaerobic pathways, meaning energy is produced without the involvement of oxygen. In this system, the primary energy source is carbohydrate, which is metabolized into the simple sugar glucose. Glucose can be used immediately to produce energy or stored in the liver and skeletal muscles in the form of glycogen for later use. When glucose or glycogen is broken down to supply energy in the absence of oxygen, lactic acid accumulates in the muscles and bloodstream. Elevated levels of lactic acid are associated with the onset of muscular fatigue.

Carbohydrate is the only macronutrient whose stored energy can be rapidly utilized to generate ATP through glycolysis. During high-intensity exercise, glucose or glycogen undergoes partial oxidation rather than complete mitochondrial oxidation. Under anaerobic conditions, the breakdown of one molecule of glucose yields a net gain of two ATP molecules (PT Direct, n.d.).



Figure 2. ATP resynthesis from CP (PT Direct, n.d.).

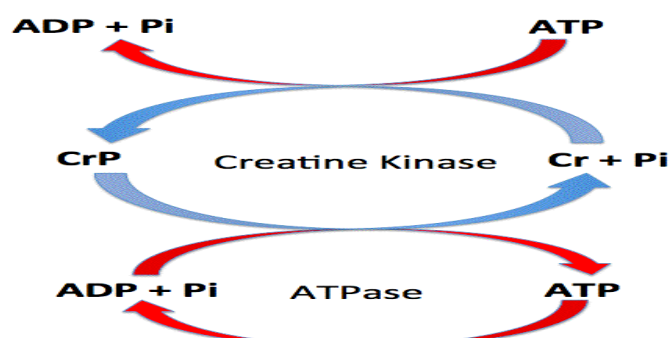
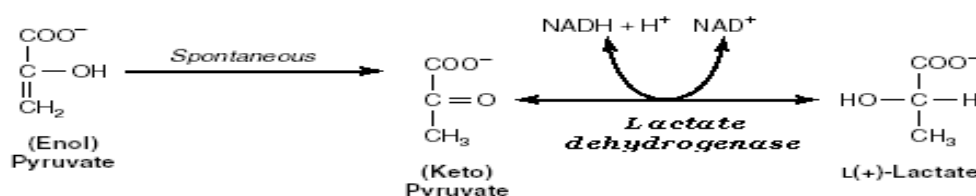


Figure 3. Phosphagen system (PT Direct, n.d.).



**Figure 4.** Anaerobic glycolysis (Heydari, et al., 2012).

This system produces ATP at a fast rate and can produce a lot of ATPs. The lactic acid system produces 2 ATP for each glucose molecule it breaks down; however, it also produces lactic acid in the process. The lactic acid system lasts between 30 seconds and 3 minutes depending on the intensity. The less intense the activity the longer it will last, because it will be producing lactic acid at a slower rate at the lower intensity levels.

**Aerobic System:** The aerobic system, also known as the oxidative energy system, is the primary pathway for energy production during prolonged, low-to-moderate intensity physical activities. It relies on the presence of oxygen to generate ATP (adenosine triphosphate), the energy currency of the body, through the oxidation of carbohydrates, fats, and to a lesser extent, proteins. This system operates mainly within the mitochondria of muscle cells and supports activities lasting longer than 2–3 minutes, such as distance running, cycling, and swimming.

Unlike the phosphagen and anaerobic glycolytic systems, the aerobic system produces ATP at a slower rate but with a much higher yield. For example,

complete oxidation of one molecule of glucose can yield approximately 36–38 ATP molecules, making it highly efficient for endurance performance. The system involves complex biochemical pathways including glycolysis, the Krebs cycle, and the electron transport chain. Oxygen acts as the final electron acceptor, allowing continuous ATP resynthesis without the accumulation of fatigue-inducing by-products like lactic acid.

One of the key features of the aerobic system is its ability to utilize fat as a major fuel source, especially during prolonged exercise when glycogen stores become depleted. This metabolic flexibility is crucial for endurance athletes, as it delays fatigue and enhances performance sustainability (Brooks et al., 2005; Kenney et al., 2020; McArdle et al., 2015; Powers & Howley, 2018; Gastin, 2001; Joyner & Coyle, 2008). Comparison of different energy systems are shown in Table 2.

The summary of reaction for aerobic system is as below;

**Glucose/Fat → Glycolysis → Acetyl-CoA → Krebs Cycle → Electron Transport Chain → ATP + CO<sub>2</sub> + H<sub>2</sub>O**

**Table 2**  
Comparison of different energy systems.

Feature	ATP-PC System (Phosphagen System)	Anaerobic Glycolytic System (Lactic Acid System)	Aerobic System (Oxidative System)
Oxygen requirement	Does not require oxygen (anaerobic)	Does not require oxygen (anaerobic)	Requires oxygen (aerobic)
Primary fuel	Stored ATP and phosphocreatine (PC)	Carbohydrate (glucose / glycogen)	Carbohydrates, fats, and proteins
Rate of ATP production	Very rapid (fastest)	Rapid	Slow
ATP yield	Very low (1 ATP per PC molecule)	Low (net 2 ATP per glucose)	High (≈30–38 ATP per glucose)
Duration of activity	~0–10 seconds	~10 seconds to 2 minutes	>2 minutes to several hours
Power output	Very high	High	Low to moderate
By-products	Creatine and inorganic phosphate	Lactate and hydrogen ions	Carbon dioxide and water
Site of activity	Cytoplasm (muscle cell)	Cytoplasm	Mitochondria
Main limitation	Rapid depletion of PC stores	Accumulation of hydrogen ions causing fatigue	Oxygen delivery and substrate availability
Typical activities	Sprinting, jumping, Olympic lifting	400–800 m running, repeated high-intensity efforts	Long-distance running, cycling, swimming
Primary function	Immediate energy supply	Short-term high-intensity energy	Sustained, long-duration energy

References: Trapp et al., 2008; Guyton & Hall, 2021; Powers & Howley, 2020; Staron, 1997; Pette & Staron, 1997.

## Types of Muscle Fibers Associate with Energy Systems

Muscle fiber types may be characterized using histochemical, biochemical, morphological, or physiological criteria; however, classifications based on different techniques do not always produce consistent results (Barany, 1967). Early classifications divided muscles into fast and slow types based on differences in contraction speed and mass loss (Scott et al., 2001). These distinctions were also associated with visible characteristics, as fast muscles often appeared pale, whereas red coloration was linked to higher myoglobin content and greater capillary density. Subsequent investigations demonstrated a relationship between myosin ATPase activity and contraction speed, which formed the basis for the initial histochemical classification of muscle fibers into type I (slow-twitch) and type II (fast-twitch) categories (Pette & Staron, 1997; Pette et al., 1999).

The most widely used system for muscle fiber classification relies on myosin ATPase histochemistry, combined with qualitative enzyme histochemical analysis that reflects the metabolic capacity of the fibers. Based on myosin ATPase activity, muscle fibers are categorized as type I or type II, corresponding to slow- and fast-twitch fibers, respectively (Betts et al., 2022). Enzymatic analyses further differentiate fibers according to their predominant metabolic pathways, either aerobic (oxidative) or anaerobic (glycolytic) (Grgić, 2016). This approach results in three principal fiber types: slow oxidative (SO), fast oxidative–glycolytic (FOG), and fast glycolytic (FG).

Slow oxidative (SO) fibers contract slowly and rely primarily on aerobic metabolism, utilizing oxygen and glucose to generate ATP. Fast oxidative–glycolytic (FOG) fibers display faster contraction speeds and possess both high oxidative and glycolytic capacities, enabling them to sustain repeated contractions. Fast glycolytic (FG) fibers contract rapidly and depend largely on anaerobic glycolysis for ATP production. Most human skeletal muscles contain a mixture of all three fiber types, although the proportion of each varies among individuals and muscle groups.

### Energy System and Training

Energy systems do not function in isolation; rather, they operate concurrently during exercise, with their relative contributions varying according to the intensity and duration of physical activity. It is well established that endurance-trained athletes typically exhibit a greater proportion of slow-twitch (type I) muscle fibers

compared with fast-twitch fibers, whereas athletes engaged in explosive activities such as Olympic weightlifting tend to possess a higher proportion of fast-twitch (type II) fibers. Research by Costill et al. (1976) reported that untrained individuals generally display an approximately equal distribution of slow- and fast-twitch muscle fibers. In contrast, endurance athletes commonly show 60–70% type I fibers, while sprinters may possess 70–80% type II fibers (Costill et al., 1976).

The distribution of muscle fiber types suggests a considerable capacity for fiber-type adaptation in response to appropriate training stimuli. The most frequently observed transformation occurs between type IIa and type IIb fibers, whereas evidence supporting direct conversion between type I and type II fibers remains limited. However, findings by Howald et al. (1985) demonstrated a 12% increase in type I muscle fibers accompanied by a 24% reduction in type IIa fibers, indicating that under certain conditions, a shift from fast-twitch to slow-twitch characteristics is possible. Table 3 represents the comparison characteristics of three energy systems.

Energy systems contribute directly to the development of speed, strength, endurance, and power. These components represent specific athletic skills or fitness attributes, which are influenced by different energy systems operating simultaneously within the body. A similar principle applies when distinguishing between strength and power in relation to the aerobic energy system. Maximum aerobic power can typically be sustained for approximately 6 minutes (Véronique et al., 2013), whereas aerobic energy output can be maintained for up to 15 minutes if the intensity is appropriately regulated (Billat, 1999). Consequently, any activity lasting between 1 and 15 minutes demands a high level of aerobic capacity. For events exceeding 15 minutes, the requirement for sustained aerobic energy increases in proportion to the duration of the activity.

Numerous sports rely heavily on the aerobic system, including long- and middle-distance track events, swimming (1000 m and above), rowing, cross-country skiing, cycling (road racing), triathlon, skiing, synchronized swimming, and combat sports. Athletes participating in these disciplines gain significant benefits from training that enhances moderate- to long-term muscular

endurance (Grgić, 2016; World Triathlon, 2007). Table 3 represents the comparison of characteristics of Energy system and Table-4 summarizes methods and training strategies for the development of the different energy systems.

**Table 3**  
Comparison of characteristics of energy system (Grgić, 2016).

Characteristics	Aerobic (long term)	Anaerobic Lactic (short term)	Anaerobic Alactic (immediate)
Fuel Source	Circulated nutrients (oxygen as a catalyst)	Glycogen (stored carbohydrates) in the muscle and liver	Stored ATP and CP (creatine phosphate)
Limit of fuel source	The body's ability to process oxygen.	At 100% intensity; 10 seconds to 2 minutes	Up to 10 seconds
By products	ATP, CO <sub>2</sub> , H <sub>2</sub> O	ATP, Lactic acid	ATP, Creatine
Intensity of exercise when system is dominant	Low to moderate; higher intensities for efforts lasting longer than 2 minutes	High to very high for longer than 10 seconds (up to 2 or 2.5 minutes at maximum intensity)	Very high intensity; explosive movements (up to 10 seconds, unless stores have time to replenish)
Recovery of fuel stores after use	Highly dependent on intensity. Lower intensity, 6 to 24 hours. Higher intensity, 24 to 36 hours.	Rate of lactic acid removal 25% in 10 minutes 50% in 25 min. 100% in 75 min. Replenishment of glycogen following continuous, high intensity endurance activities 60% in 10 hours 100% in 48 hours Replenishment of glycogen following intermittent activity: 40% in 2 hours 55% in two hours 100% in 24 hours	50% replenished in 30 seconds 2 minutes for complete restoration (if resting)
Athletic abilities developed by training this system	Aerobic power (highest intensity that still involves the aerobic (oxygen) system) Aerobic endurance (ability of the body to supply muscles with oxygen for long periods) Muscular endurance	Muscular endurance (repeated muscle contractions) Speed (moving as fast as possible; 10 seconds to 2 minutes)	Power (moving against resistance or a force as fast as possible) Maximum speed (up to 10 seconds)

**Table 4**  
Training methods for different energy systems.

Means and Methods	Aerobic system (Lower intensities)	Aerobic-anaerobic mixed systems (high intensities for longer than 2 min)	Anaerobic system	Anaerobic Alactic system
Number of sessions per week	3 to 5 times a week	1 to 2 times a week	2 to 3 times a week	1-2 times a week
Recovery time between sessions	6 to 36 hours	24 to 48 hours	24 to 36 hours	24 to 48 hours
Duration or time	Longer than 15 min per interval or segment	10-to-30-min efforts (moderate to high intensity) 2 to 10 min (shorter, higher intensity efforts)	20 seconds to 2 min intervals	5 to 10 second intervals
Number of intervals or repetitions	Usually just one repetition per practice (e.g. a long run)	1 for 10-30 min efforts 2 to 10 repetitions for 2-10 min efforts	4 to 12 repetitions	8 to 18 repetitions
Rest between intervals	N/A	2 to 10 min work: Rest ratio 1: 0.5 or 1:1 or 1:1.5	60 seconds to 8 min work: Rest ratio 1: 3 or 4	20 seconds to 5 min
Intensity	Easy pace to moderate pace	Race pace to near maximum effort	Near maximum effort	Explosive, maximum effort

## Energy system wise training

### 1. Training for the ATP–PC System (Anaerobic Alactic):

*Goal:* Increase stored ATP and creatine phosphate and the rate of ATP resynthesis (Sahlin, 2014).

#### Key Methods

- Short sprints / bursts: 5–10 seconds at near-max intensity
- Explosive strength work: Olympic lifts, plyometrics, jump training
- Work-to-rest ratio: Very high rest (e.g., 1:12 to 1:20) to fully replenish phosphates
- Example session:  
*10 × 10-second maximal sprints on bike or track with 3–5 min rest each.*

#### Physiological Rationale

- Very short, maximal efforts use ATP–PC as the dominant source.
- Full recovery allows CP stores to reset and maximize each effort.

### 2. Training for the Anaerobic Glycolytic System (Anaerobic Lactic):

*Goal:* Improve glycolytic enzyme activity, lactate tolerance, and transport (MacInnis & Gibala, 2016; Liu et al., 2024).

#### Key Methods

- High-Intensity Interval Training (HIIT):
  - 20–60 seconds at 85–95% effort
  - Work: rest ratios ~1:1 to 1:3
  - Repeated across 6–12 sets per session
- Strength endurance sets:
  - 8–15 reps with moderate–high loads and limited rest
- Tabata protocol (a variant):
  - 20 s max effort: 10 s rest × 8 cycles (4 minutes total) – develops both anaerobic and aerobic contributions.

#### Sport Examples

- 200–400 m track intervals
- 60-second bike sprints
- Short aggressive bursts in team sports

### 3. Training the Aerobic (Oxidative) System:

*Goal:* Increase mitochondrial density, improve oxygen delivery and utilization, and enhance endurance.

#### Key Methods

- Long Slow Distance (LSD):
  - Continuous low-moderate intensity for 30–90+ minutes
  - Improves cardiovascular efficiency and fat fuel use.
- Tempo Runs: Sustained effort near lactate threshold for 20–40 min
- Interval Aerobic Sessions: 3–5 min work with short rest
- Fartlek Training: Alternating fast and slow paces to stress both aerobic and anaerobic work (less structured but effective).

#### Physiological Adaptations

- Increases heart stroke volume, capillarization, and mitochondrial ATP production (Hughes et al., 2018; Mølmen et al., 2025).

### 4. Combined & Sport-Specific Conditioning:

Many sports require simultaneous development of multiple systems:

#### Mixed Methods

- Fartlek: Stress both aerobic and anaerobic systems through speed variation.
- Game-simulation intervals: Design drills to reflect competition work/rest patterns (e.g., soccer: 4–10 s sprints with 20–40 s recovery).

*Concurrent training:* Pair strength/power with metabolic conditioning within the same week (Billat, 2001; Franchini, 2023).

### Bioenergetics to Athlete Profiling and Event Specialization

A critical examination of bioenergetics reveals that while it provides a foundational framework for athlete profiling and event specialization, its application is more complex than the traditional classification of sports into aerobic, anaerobic, and phosphagen categories. Contemporary research shows that all three energy systems operate simultaneously, with their relative contribution varying based on intensity, duration, and task structure, rather than functioning in isolation (Rios, 2026). This challenges the oversimplified approach often used in athlete selection, where individuals are categorized rigidly (e.g., “sprinter” vs “endurance athlete”). Moreover, methodological limitations in accurately quantifying energy contributions—such as reliance on indirect measures like oxygen uptake and blood lactate—create variability in bioenergetic profiling, reducing its precision for individualized decision-making (Rios, 2026). Therefore,

while bioenergetics is essential, it cannot serve as the sole criterion for athlete profiling.

In modern sport science, athlete profiling has evolved into a multidimensional construct, integrating bioenergetics with biomechanics, psychology, genetics, and data analytics. Recent studies highlight the use of wearable sensors, metabolomics, and machine learning models to create comprehensive performance profiles that go beyond energy system dominance (Jianjun et al., 2025). Additionally, molecular and metabolic adaptations differ significantly between endurance- and strength-trained athletes, indicating that long-term specialization is shaped by both training and inherent biological factors (Stefan et al., 2024). This suggests that event specialization should be dynamic and evidence-based, incorporating longitudinal monitoring rather than early rigid classification. Critically, over-reliance on bioenergetic profiling alone may lead to premature specialization and overlook late-developing athletes or transferable skills across sports. Hence, bioenergetics should be viewed as a core but integrative component within a holistic athlete profiling system for effective and scientific event specialization.

### Bioenergetics and Talent Identification

Bioenergetics—the study of how the body produces and utilizes energy through systems such as the phosphagen (ATP-PCr), glycolytic, and oxidative pathways—plays a critical role in modern talent identification in sport. Different sports demand distinct energy system contributions; for example, sprinting and weightlifting rely heavily on anaerobic alactic power, whereas middle-distance events require a balance between anaerobic glycolysis and aerobic metabolism, and endurance sports depend predominantly on oxidative capacity. By assessing physiological markers such as maximal oxygen uptake ( $VO_2\text{max}$ ), lactate threshold, anaerobic power, and recovery kinetics, coaches and sport scientists can match athletes to events that align with their inherent bioenergetic profiles. This approach enhances early identification of potential and reduces mismatches between athlete capacity and sport demands.

Recent advances integrate bioenergetics with wearable technology, metabolomics, and performance analytics to improve talent detection accuracy. Tools such as portable gas analysers, blood lactate testing, and GPS-based workload monitoring allow real-time assessment of energy system utilization in training and competition. Moreover, longitudinal tracking of bioenergetic adaptations helps identify “trainability” and future elite potential rather than relying solely on

current performance. However, contemporary research emphasizes that bioenergetics should be combined with genetic, psychological, and skill-based assessments to create a multidimensional model of talent identification, ensuring a holistic and inclusive approach (Joyner & Coyle, 2021; Jones & Vanhatalo, 2017; MacInnis & Gibala, 2016; Hecksteden et al., 2015).

### Conclusion

Movement is only possible for systematic muscle contraction. As we know without energy no work is possible, so for muscular contraction energy is prerequisite in the form of chemical energy. Bioenergetics provides a scientific foundation for understanding how different energy systems support performance in specific sporting activities. Its integration into sports training enables the design of individualized programs that enhance efficiency, endurance, and overall athletic output. In talent identification, bioenergetic profiling helps match an athlete’s physiological strengths with suitable sports or events, improving long-term success. Therefore, the combined application of bioenergetics, training principles, and talent identification creates a more precise and evidence-based approach to athlete development. Additionally, the distribution of muscle fiber types (slow-twitch and fast-twitch) plays a crucial role in determining an athlete’s suitability for endurance or power-based events within this framework.

### References

- Ainsworth, B. E. (2009). How do I measure physical activity in my patients? Questionnaires and objective methods. *Br J Sports Med*, 43(1), 6–9. <https://doi.org/10.1136/bjism.2008.052449>.
- Atalay, M., & Hänninen, O. O. P. (2010). Muscle energy metabolism. In O. O. P. Hänninen & M. Atalay (Eds.), *Physiology and maintenance* (Vol. IV). Encyclopedia of Life Support Systems (EOLSS). <https://www.eolss.net/sample-chapters/c03/E6-54-08-01.pdf>
- Barany, M. (1967). ATPase activity of myosin correlated with speed of muscle shortening. *J Gen Physiol*, 50, 197–218.
- Bernaciková, M. (2026, January 17). *Physiology*. Faculty of Sport Studies, Masaryk University. <https://www.fsp.muni.cz/emuni/data/reader/book-4/04.html>
- Betts, J. G., Young, K. A., Wise, J. A., Johnson, E., Poe, B., Kruse, D. H., Korol, O., Johnson, J. E., Womble, M., & DeSaix, P. (2022). Types of muscle fibers. In: *Anatomy and Physiology*. OpenStax. <https://open.oregonstate.edu/aandp/chapter/10-5-types-of-muscle-fibers>
- Bigland-Ritchie, B. & Woods, J. J. (1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle Nerve*, 7(9), 691–699.

- Billat, V. L. (2001). Interval training for performance: A scientific and empirical practice - Special recommendations for middle- and long-distance running. *Sports Med*, 31(1), 13–31.
- Billat, V. L., B Flechet, B Petit, G Muriaux, J P Koralsztein (1999), Interval training at VO<sub>2</sub>max: effects on aerobic performance and overtraining markers. *Med Sci Sports Exerc*, 31(1), 156-163.
- Billat, V., Petot, H., Karp, J. R., Sarre, G., Morton, R. H., & Mille-Hamard, L. (2013). The sustainability of VO<sub>2</sub>max: effect of decreasing the workload. *Eur J Appl Physiol*, 113(2), 385–394. <https://doi.org/10.1007/s00421-012-2424-7>
- Biology Dictionary. (2017, January 20). Adenosine triphosphate (ATP). <https://biologydictionary.net/atp/>
- Bogdanis, G. C., Nevill, M. E., Boobis, L. H., & Lakomy, H. K. A. (1996). Contribution of phosphocreatine and aerobic metabolism to energy supply during repeated sprint exercise. *J Appl Physiol*, 80(3), 876-884.
- Bogdanis, G. C., Nevill, M. E., Boobis, L. H., Lakomy, H. K. A., & Nevill, A. M. (1995). Recovery of power output and muscle metabolites following 30 s of maximal sprint cycling in man. *J Physiol*, 482(2), 467–480. <https://doi.org/10.1113/jphysiol.1995.sp020533>
- Bogdanis, G. C., Nevill, M. E., Lakomy, H. K. A., & Boobis, L. H. (1998). Power output and muscle metabolism during and following recovery from 10 and 20 s of maximal sprint exercise in humans. *Acta Physiol Scand*, 163(3), 261–272. <https://doi.org/10.1046/j.1365-201x.1998.00378.x>
- Brooks, G. A., Fahey, T. D., & Baldwin, K. M. (2005). *Exercise physiology: Human bioenergetics and its applications* (4th ed.). McGraw-Hill.
- Caldwell, H. G., Jeppesen, J. S., Lossius, L. O., Atti, J. P., Durrer, C. G., Oxfeldt, M., Melin, A. K., Hansen, M., Bangsbo, J., Gliemann, L., & Hellsten, Y. (2024). The whole-body and skeletal muscle metabolic response to 14 days of highly controlled low energy availability in endurance-trained females. *FASEB J*, 38(21), e70157. <https://doi.org/10.1096/fj.202401780R>
- Caspersen, C. J., Powell, K. E., & Christenson, G. M. (1985). Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research. *Public Health Rep*, 100(2), 126-131.
- Corsini, D. (2021, November 2). Bioenergetics: Definition & Theory. Study.com. <https://study.com/academy/lesson/bioenergetics-definition-theory.html>
- Costill, D. L., Daniels, J., Evans, W., Fink, W., Krahenbuhl, G., & Saltin, B. (1976). Skeletal muscle enzymes and fiber composition in male and female track athletes. *J Appl Physiol*, 40, 149-154. <https://doi.org/10.1152/jappl.1976.40.2.149>
- Franchini, E. (2023). Energy system contributions during Olympic combat sports: A narrative review. *Metabolites*, 13(2), 297. <https://doi.org/10.3390/metabo13020297>
- Gastin, P. B. (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Med*, 31(10), 725–741.
- Glaister, M. (2005). Multiple sprint work: physiological responses, mechanisms of fatigue and the influence of aerobic fitness. *Sports Med*, 35(9), 757–777.
- Gorgey, A. S., Khalil, R. E., Carter, W., Rivers, J., Chen, Q., & Lesnefsky, E. J. (2025). Skeletal muscle hypertrophy and enhanced mitochondrial bioenergetics following electrical stimulation exercises in spinal cord injury: a randomized clinical trial. *Eur J Appl Physiol*, 125, 1075–1089. <https://doi.org/10.1007/s00421-024-05661-6>
- Green, D. E., & Zande, H. D. (1981). Universal energy principle of biological systems and the unity of bioenergetics. *Proc Natl Acad Sci USA*, 78(9), 5344–5347. <https://doi.org/10.1073/pnas.78.9.5344>
- Grgić, J. (2016, June 2). Muscle fiber types and training. EliteFTS. <https://www.elitefts.com/education/muscle-fiber-types-and-training/>
- Guyton, A. C., & Hall, J. E. (2021). *Textbook of medical physiology* (14th ed.). Philadelphia: Elsevier.
- Hafekost, K., Lawrence, D., Mitrou, F., O'Sullivan, T. A., & Zubrick, S. R. (2013). Tackling overweight and obesity: does the public health message match the science? *BMC Med*, 11, 41. <https://doi.org/10.1186/1741-7015-11-41>
- Hecksteden, A., Kraushaar, J., Scharhag-Rosenberger, F., Theisen, D., Senn, S., & Meyer, T. (2015). Individual response to exercise training - a statistical perspective. *J Appl Physiol* (1985), 118(12), 1450-1459. <https://doi.org/10.1152/jappphysiol.00714.2014>
- Heydari, M., Freund, J., & Boutcher, S. H. (2012). The effect of high-intensity intermittent exercise on body composition of overweight young males. *J Obes*, 2012, 480467. <https://doi.org/10.1155/2012/480467>.
- Hill, J. O., Wyatt, H. R., & Peters, J. C. (2012). Energy balance and obesity. *Circulation*, 126(1), 126–132. <https://doi.org/10.1161/CIRCULATIONAHA.111.087213>
- Hopwood, H. J., Bellinger, P. M., Compton, H. R., Bourne, M. N., & Minahan, C. (2023). The relevance of muscle fiber type to physical characteristics and performance in team-sport athletes. *Int J Sports Physiol Perform*, 18(3), 223-230. <https://doi.org/10.1123/ijssp.2022-0235>
- Hostrup, M., & Deshmukh, A. S. (2025). Fiber type-specific adaptations to exercise training in human skeletal muscle: lessons from proteome analyses and future directions. *Scand J Med Sci Sports*, 35(5), e70059. doi: 10.1111/sms.70059
- Howald, H., Hoppeler, H., Claassen, H., Mathieu, O., & Straub, R. (1985). Influences of endurance training on the ultrastructural composition of the different muscle fiber types in humans. *Pflügers Arch*, 403, 369-376. <https://doi.org/10.1007/BF00589248>
- Hughes, D. C., Ellefsen, S., & Baar, K. (2018). Adaptations to endurance and strength training. *Cold Spring Harb Perspect Med*, 8(6), a029769. <https://doi.org/10.1101/cshperspect.a029769>
- Jacobs, I., Bar-Or, O., Karlsson, J., Dotan, R., Tesch, P., Kaiser, P., & Inbar, O. (1982). Changes in muscle metabolites in females with 30-s exhaustive exercise. *Med Sci Sports Exerc*, 14(6), 457–460. <https://doi.org/10.1249/00005768-198206000-00009>
- Jianjun, Q., Isleem, H. F., Almoghayer, W. J. K., & Khishe, M. (2025). Predictive athlete performance modeling with machine learning and biometric data integration. *Sci Rep*, 15, 16365. <https://doi.org/10.1038/s41598-025-01438-9>
- Jones, A. M., & Vanhatalo, A. (2017). The ‘critical power’ concept: Applications to sports performance with a focus on intermittent high-intensity exercise. *Sports Med*, 47(Suppl 1), 65–78.

- Joyner, M. J., & Coyle, E. F. (2008). Endurance exercise performance: The physiology of champions. *The Journal of Physiology*, 586(1), 35–44.
- Joyner, M. J., & Coyle, E. F. (2021). Endurance exercise performance: The physiology of champions. *Journal of Physiology*, 599(1), 35–48.
- Kenney, W. L., Wilmore, J. H., & Costill, D. L. (2020). *Physiology of sport and exercise* (7th ed.). Human Kinetics.
- Kravitz, L. (n.d.). Phosphagen energy system. University of New Mexico. <https://www.unm.edu/~lkravitz/Exercise%20Phys/PhosphagenSystem.html>
- Li, J., Zhang, S., Li, C., Zhang, X., Shan, Y., Zhang, Z., Bo, H., & Zhang, Y. (2024). Endurance exercise-induced histone methylation modification involved in skeletal muscle fiber type transition and mitochondrial biogenesis. *Sci Rep* 14, 21154. <https://doi.org/10.1038/s41598-024-72088-6>
- Liu, Y., Abdullah, B. B., & Abu Saad, H. B. (2024). Effects of high intensity interval training on strength, speed, and endurance performance among racket sports players: A systematic review. *PLoS One*, 19(1), e0295362. <https://doi.org/10.1371/journal.pone.0295362>
- Luis, I., Afschrift, M., De Groote, F., & Gutierrez-Farewik, E. M. (2024). Insights into muscle metabolic energetics: Modelling muscle-tendon mechanics and metabolic rates during walking across speeds. *PLoS Comput Biol*, 20(9), e1012411. <https://doi.org/10.1371/journal.pcbi.1012411>
- Ma, Y., Lin, S., Fu, S., Liu, Y., Guo, C., Liu, D., & Hou, M. (2025). Muscle Synergy Patterns During Running: Coordinative Mechanisms From a Neuromechanical Perspective. *arXiv preprint*. <https://doi.org/10.48550/arXiv.2512.24654>
- MacInnis, M. J., & Gibala, M. J. (2016). Physiological adaptations to interval training and the role of exercise intensity. *J Physiol*, 595(9), 2915–2930. <https://doi.org/10.1113/JP273196>
- Mallett, A., Bellinger, P., Derave, W., Lievens, E., Kennedy, B., Rice, H., & Minahan, C. (2021). Muscle fiber typology and its association with start and turn performance in elite swimmers. *Int J Sports Physiol Perform*, 16(6), 834–840. <https://doi.org/10.1123/ijsp.2020-0548>
- Maughan, R. J., Burke, L. M., Dvorak, J., Larson-Meyer, D. E., Peeling, P., Phillips, S. M., Rawson, E. S., Walsh, N. P., Garthe, I., Geyer, H., Meeusen, R., van Loon, L. J. C., Shirreffs, S. M., Spriet, L. L., Stuart, M., Vernec, A., Currell, K., Ali, V. M., Budgett, R. G., Ljungqvist, A., ... Engebretsen, L. (2018). IOC consensus statement: Dietary supplements and the high-performance athlete. *Br J Sports Med*, 52(7), 439–455. <https://doi.org/10.1136/bjsports-2018-099027>
- McArdle, W. D., Katch, F. I., & Katch, V. L. (2015). *Exercise physiology: Nutrition, energy, and human performance* (8th ed.). Wolters Kluwer.
- Methenitis, S., Mpampoulis, T., Spiliopoulou, P., Papadimas, G., Papadopoulou, C., Chalari, E., Evangelidou, E., Stasinaki, A. N., Nomikos, T., & Terzis, G. (2020). Muscle fiber composition, jumping performance, and rate of force development adaptations induced by different power training volumes in females. *Appl Physiol Nutr Metab*, 45(9), 996–1006. <https://doi.org/10.1139/apnm-2019-0786>
- Mølmen, K. S., Almquist, N. W., & Skattebo, Ø. (2025). Effects of exercise training on mitochondrial and capillary growth in human skeletal muscle: a systematic review and meta-regression. *Sports Med*, 55(1), 115–144. <https://doi.org/10.1007/s40279-024-02120-2>
- Nelson, D. L., Cox, M. M., & Lehninger, A. L. (2013). *Lehninger principles of biochemistry* (6th ed.). W.H. Freeman.
- Nguyen, V. H., Luu, G. T., Van Luong, T., Trang, M. X., Ravier, P., & Buttelli, O. (2023, October). After-fatigue condition: a novel analysis based on surface EMG signals. In *2023 Asia Pacific signal and information processing association annual summit and conference (APSIPA ASC)* (pp. 272–277). <https://doi.org/10.1109/APSIPAASC58517.2023.10317458>
- Nuzzo, J. L. (2024). Sex differences in skeletal muscle fiber types: A meta-analysis. *Clin Anat*, 37(1), 81–91. <https://doi.org/10.1002/ca.24091>
- Omics Publishing Group. (2026, January 17). Bioenergetics metabolism. <https://www.omicsonline.org/bioenergetics-metabolism-peer-reviewed-open-access-journals.php>
- Pette, D., & Staron, R. S. (1997). Mammalian skeletal muscle fiber type transitions. *Int Rev Cytol*, 170, 143–223.
- Pette, D., Peuker, H., & Staron, R. S. (1999). The impact of biochemical methods for single muscle fibre analysis. *Acta Physiol Scand*, 166, 261–277.
- Plotkin, D. L., Roberts, M. D., Haun, C. T., & Schoenfeld, B. J. (2021). Muscle fiber type transitions with exercise training: shifting perspectives. *Sports (Basel)*, 9(9), 127. <https://doi.org/10.3390/sports9090127>
- Powers, S. K., & Howley, E. T. (2018). *Exercise physiology: Theory and application to fitness and performance* (10th ed.). McGraw-Hill.
- Powers, S. K., & Howley, E. T. (2020). *Exercise Physiology: Theory and Application to Fitness and Performance* (10th ed.). New York: McGraw-Hill.
- Protasi, F., Serano, M., Brasile, A., & Pietrangelo, L. (2026). Exercise protects skeletal muscle fibers from age-related dysfunctional remodeling of mitochondrial network and sarcotubular system. *Cells*, 15(3), 248. <https://doi.org/10.3390/cells15030248>
- PT Direct. (n.d.). Anatomy and physiology. [www.ptdirect.com/training-design/anatomy-and-physiology/](http://www.ptdirect.com/training-design/anatomy-and-physiology/)
- Rayner, S. (2018, September 1). Energy systems: Part 2 – Alactic phosphocreatine. The sustainable training method. [www.thesustainabletrainingmethod.com/tstm-blog/2018/9/1/energy-systems-part-2-alactic-phosphocreatine](http://www.thesustainabletrainingmethod.com/tstm-blog/2018/9/1/energy-systems-part-2-alactic-phosphocreatine)
- Reitzner, S. M., Emanuelsson, E. B., Arif, M., Kaczowski, B., Kwon, A. T., Mardinoglu, A., Arner, E., Chapman, M. A., & Sundberg, C. J. (2024). Molecular profiling of high-level athlete skeletal muscle after acute endurance or resistance exercise – A systems biology approach. *Mol Metab*, 79, 101857. <https://doi.org/10.1016/j.molmet.2023.101857>
- Rios, M. J., Pyne, D. B., & Fernandes, R. J. (2026). Bioenergetic profiling in exercise: methods, limitations and practical applications—a narrative review. *Physiologia*, 6(1), 19. <https://doi.org/10.3390/physiologia6010019>
- Sahlin, K. (2014). Muscle energetics during explosive activities and potential effects of nutrition and training. *Sports Med*, 44(Suppl 2), 167–173. <https://doi.org/10.1007/s40279-014-0256-9>

- Scott, W., Stevens, J., Binder-Macleod, S. A. (2001). Human skeletal muscle fiber type classifications. *Phys Ther*, 81, 1810-1816.
- Smith, J. A. B., Murach, K. A., Dyar, K. A., & Zierath, J. R. (2023). Exercise metabolism and adaptation in skeletal muscle. *Nat Rev Mol Cell Biol* 24, 607–632. <https://doi.org/10.1038/s41580-023-00606-x>
- Søgaard, K., Gandevia, S. C., Todd, G., Petersen, N. T., & Taylor, J. L. (2006). The effect of sustained low-intensity contractions on supraspinal fatigue in human elbow flexor muscles. *J Physiol*, 573(2), 511–523. <https://doi.org/10.1113/jphysiol.2005.103598>
- Staron, R. S. (1997). Human skeletal muscle fiber types: delineation, development, and distribution. *Can J Appl Physiol*, 22, 307-327.
- Tara Enegy. (2021). What is energy? A Guide to understanding energy. <https://taraenergy.com/blog/what-is-energy-a-guide-to-understanding-energy/>
- Trapp, E. G., Chisholm, D. J., Freund, J., & Boutcher, S. H. (2008). The effects of high-intensity intermittent exercise training on fat loss and fasting insulin levels of young women. *Int J Obes (Lond)*, 32(4), 684–691. <https://doi.org/10.1038/sj.ijo.0803781>
- Vollestad, N. K., & Sejersted, O. M. (1988). Biochemical correlates of fatigue. A brief review. *Eur J Appl Physiol Occup Physiol*, 57(3), 336–347. <https://doi.org/10.1007/BF00635993>
- Wackwitz, T., Minahan, C., Lievens, E., Kennedy, B., Derave, W., & Bellinger, P. (2024). Muscle-fiber typology is associated with sprint-cycling characteristics in world-class and elite track cyclists. *Int J Sports Physiol Perform*, 20(1), 142-148. <https://doi.org/10.1123/ijsp.2024-0089>
- World Triathlon. (2007). Energy training module 1. [https://www.triathlon.org/uploads/courses/54802/4-Energy-Training-Module\\_1.pdf](https://www.triathlon.org/uploads/courses/54802/4-Energy-Training-Module_1.pdf)
- Xu, J., & Chen, B. (2026). Effects of stimulation frequencies on energy efficiency of a muscle fiber during contraction. *arXiv preprint*. <https://doi.org/10.48550/arXiv.2601.18073>