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Technology in Sports

Recent Advances, New Perspectives and Application

Edited by Thomas Wojda

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Meet the editor

Dr. Thomas Robert Wojda is an Assistant Professor of Family Medicine at the University of Pittsburgh Medical Center (UPMC), PA, USA. He completed his residency in family medicine at St. Luke's University Health Network, PA, USA, and pursued fellowships in sports medicine at Conemaugh Memorial Medical Center and University Orthopedics Center, PA, USA. With a focus on leadership, he earned his MBA summa cum laude from Ohio Dominican University, USA. Dr. Wojda is a practicing primary care and sports medicine physician, as well as a clinical informatics fellow.

Contents

Preface

Welcome to *Technology in Sports – Recent Advances, New Perspectives and Application*. This compilation represents a comprehensive exploration of the intersection between technology and sports, showcasing the latest innovations, insights, and practical applications in this dynamic field.

As the editor of this volume, it has been a privilege to collaborate with a diverse group of experts who have contributed their knowledge and expertise to elucidate various facets of technology in sports. From biomedical advancements to legal considerations and technological innovations, each chapter offers valuable insights into how technology is shaping the landscape of sports performance, injury prevention, and athlete management.

The chapters in this volume cover a wide range of topics, reflecting the multidisciplinary nature of the field. We begin with an examination of the biomedical, legal, and technological aspects of nutrition for athletes, providing a comprehensive overview of the role of nutrition in optimizing athletic performance. This is followed by a discussion on computer simulation techniques aimed at reducing the metabolic costs of running, tailored to individual athlete characteristics.

Subsequent chapters delve into specific conditioning strategies for previously injured players, the development of quantitative motion analysis software for boxing competitions, and the utilization of electrocardiography (ECG) in assessing athlete health. Additionally, we explore the significance of lactate levels in determining anaerobic thresholds and highlight new discoveries in this area.

Furthermore, this volume addresses the emerging field of sport analytics, emphasizing the transition from speculative “alchemy” to data-driven decision-making in sports management. We also delve into talent identification and recruitment in top-flight football, examining conceptual frameworks and predictive models for talent evaluation.

Finally, we explore the application of blockchain technology in sports medicine, highlighting its potential to revolutionize data management, athlete health records, and performance tracking.

I would like to express my sincere gratitude to all the contributors who have enriched this volume with their expertise and insights. Their dedication and commitment have been instrumental in shaping this comprehensive overview of technology in sports.

I would also like to thank the editorial and production teams for their diligent work in bringing this project to fruition.

It is my hope that this volume serves as a valuable resource for researchers, practitioners, coaches, and athletes interested in harnessing the power of technology to enhance sports performance, injury prevention, and overall athlete well-being.

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Chapter 1

Biomedical, Legal and Technological Aspects of Nutrition for Athletes

Alla Novokshanova and Dmitriy Nikityuk

Abstract

The relevance of the development, production and sales of specialized food products for athletes is due to the growing interest of ordinary people in sports activities and the need to adjust the diet of professional athletes. Biomedical research has established widespread violations of the optimal food structure, food and energy value of athletes' diets and substantiated the need to develop specialized food products for athletes of various qualifications. Furthermore, the search for reliable methods and diagnostic tests that most accurately reflect the picture of metabolic changes during high-intensity physical activity is of great importance. Legal aspects of athlete nutrition, including the development of technical regulations, standards, etc., contribute to the development of this industry. The technology for the production of food products for athletes is dominated by fractionation of macronutrients of food raw materials into individual components, extraction of trace elements and minor ingredients from food raw materials, and use of modified ingredients. To develop the sports nutrition industry and optimize the nutrition of athletes, it is necessary to consolidate specialists in the field of medicine, legal regulation and production technology.

Keywords: nutrition for athletes, sports nutrition, food products for athletes, food value, energy value

1. Introduction

The relevance of the development, production and sales of specialized food products for athletes is due to the growing interest of ordinary people in sports activities and the need to adjust the diet for professional athletes.

An integral part of such concepts as "healthy lifestyle", "physical culture and sports" is a balanced diet, in which the metabolites consumed by the body must be replenished with high-quality food products, maintaining a balance of basic macro- and micronutrients. According to the World Health Organization, harmonizing the dilemma "nutrition-physical activity" reduces the risk of developing functional limitations by 25–50% in older age, thereby people might live on their own 10–20 years longer.

Considering the fact that the physical exertion of athletes of different specializations at various stages of the sports macrocycle and of people actively involved in sports at various periods of life differ significantly, to restore the body and maintain its adaptive potential, specialized food products with certain macro- and micronutrients composition per unit of food density are required.

Most of the information present in the Internet environment including that related to sports nutrition is in the public domain and quickly spreads among an interested audience. However, sources of information about such products on the websites of specialized stores can mislead consumers regarding the correct choice of a particular specialized food product [1]. As a result, both professional athletes and the population involved in sports activities may experience undesirable consequences after consuming specialized food products for athletes.

For example, in a survey of the target audience (n = 1267), conducted by means of an online questionnaire, while studying the consumer preferences and the provision of athletes by specialized food products, it was found that the tendency to maintain and improve the health through regular exercise stimulate the population to pay attention to specialized food products for athletes. However, as can be seen from the diagram in **Figure 1**, more than 55% of athletes (n = 697) made a decision to use one or another specialized food product, relying not on the opinion of specialists, but at one's own instigation, and almost a quarter of those surveyed were guided by the advice of a coach or instructor, which competence in terms of nutrition one cannot be sure of.

To prevent and eliminate contradictions in the sports nutrition industry, a competency-based approach is required with respect to medical and biological substantiation, legal regulation, and technology for the production of food products for athletes.

In general, several methodological aspects can be distinguished in the subject under consideration: biomedical, legal, and technological ones.

The unique contribution of this chapter is its assessment of multidisciplinary research in the field of sports nutrition.

The purpose of this work is to analyze the impact of biomedical research, regulatory documentation and the current state of food technology on the sports nutrition industry.

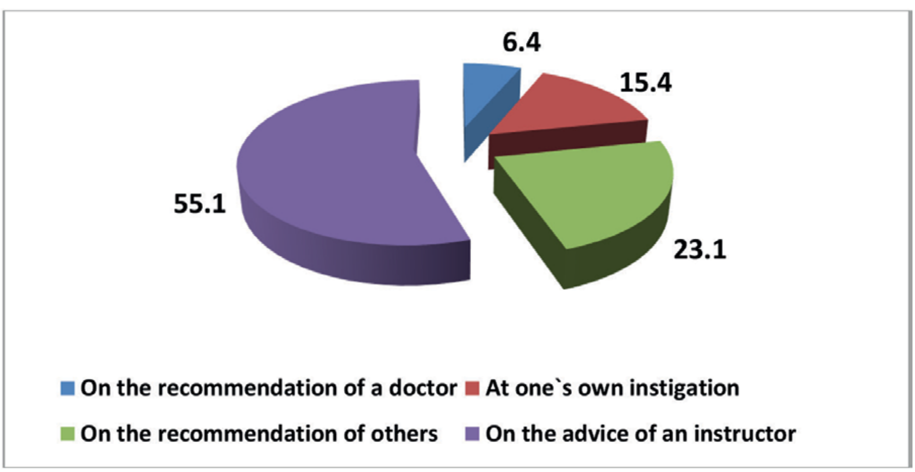

Figure 1.
Distribution of answers to the question: "Whose initiative do athletes use specialized food products in their diet at?"

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2. Biomedical aspects of nutrition for athletes

For specialists working in the field of sports biochemistry and medicine, the search for reliable methods and diagnostic tests that most accurately reflect the picture of metabolic changes during high-intensity physical activity is of great importance.

When performing any muscular activity, energy expenditure increases significantly compared to the resting state. In absolute terms, energy expenditure during regular exercise is 1050–1400 kcal per day more than in individuals with low physical activity. And for highly qualified male athletes during the training period, this difference reaches 1650–1800 kcal per day. Therefore, physical activity is one of the key parameters in the modern nutritiology.

The daily energy expenditure of an adult consists mainly of the intensity of the basal metabolic rate and the activity-related energy expenditure [2]. It is by the indicator of energy expenditure that all types of sports can be ranked depending on the intensity, duration and volume of physical activity. However, it is advisable to give recommendations on the levels of consumption of the most important macronutrients (proteins, carbohydrates and fats) not in average values, but in the form of specific indicators, that is, taking into account anthropometric characteristics, age, and gender characteristics in terms of kilogram of body weight (kgBW) of the athlete, as listed in **Table 1** [3].

When an athlete's energy expenditure is high, it is quite possible to formulate his or her diet from common food products so that it will satisfy the athlete's needs for energy and nutrients. Athletes at risk are those who have to watch their calorie intake

Sports types and main features	Examples	Energy expenditure, kcal/kg BW	Daily requirement, g/kg BW		
			proteins	fats	carbohydrates
Cyclic sports (long distances)	Skiing, marathon, triathlon	45–60	1.2–1.6	1.0–1.5	7–10
Speed-strength sports (short distances)	Alpine skiing, sprinting, cycling (track)	45–55	1.4–1.7	1.0–1.2	7–9
Strength sports (maximum display of strength)	Weightlifting	40–50	1.4–1.8	0.8–1.2	5–7
Team sports (variable intensity)	Football, basketball, volleyball	40–50	1.2–1.6	0.8–1.0	7–9
Complex coordination sports (showing agility and strength)	Gymnastics, figure skating	37–45	1.2–1.4	08–1.0	6–7
Technical sports (skills in one exercise)	Ski jumping, archery	32–38	1.0–1.2	0.8–1.0	5–6

Table 1.
Classification of sports types by physical activity groups.

in some sports due to the benefits that the athletes with lighter weight have. It has been established that the prevalence of relative energy deficiency syndrome (Relative Energy Deficiency in Sport, RED-s) in athletes of various sports ranges is from 22 to 58% [4]. This can cause hormonal and metabolic dysfunctions and reduce athletic productivity.

It has been proven that in calorie-limited diets, especially those with an energy value of less than 2000 kcal, it is almost impossible to include all the necessary macro- and micronutrients.

However, both in the case of a high energy value of the diet and in the case of caloric restriction, an imbalance of essential nutrients is a common phenomenon in sports. This is confirmed by many studies dedicated to the athletes` diet.

One of the common research methods in the field of sports nutrition is the analysis of the actual diet of athletes and its correspondence to energy expenditure. Most often, two varieties of this method are used: a 24-hour nutrition reproduction method and a frequency method [5]. Using these methods, a series of studies were conducted with the participation of athletes of different specializations: basketball players, hockey players, female members of the ice hockey team, archery athletes and rowing athletes [5–7]. Based on studies of the actual nutrition of athletes, conducted by the 24-hour nutrition reproduction method and the frequency method, we detected widespread violations of the optimal food structure, nutritional and energy value of diets. The majority of the examined athletes were found to have:

- discrepancy between the daily calorie intake and actual energy expenditure;
- the share of fat and saturated fatty acids in the structure of diet calorie intake exceeds the recommended levels by 20–40%;
- total carbohydrate consumption is below the recommended level by 10–35%;
- increased consumption of added sugar (18–24%) and salt [5–8].

At the same time, the majority of athletes did not analyze the nutritional value of their diet, including the amount of vitamins and minerals in it, but additionally took specialized food products and dietary supplements containing the same biologically active substances that were present in food products. The danger of this situation is that if several specialized food products and dietary supplements are taken simultaneously, a systematic overdose of biologically active substances may occur. Ultimately, not only a decrease in sports effectiveness is possible, but also health problems can appear [5].

In our opinion, regular monitoring of actual nutrition, intake of specialized food products and dietary supplements, medications, and parameters of the nutritional status of athletes is necessary to identify individual violations of the diet structure and identify interconnections as the intensity of training changes. It seems to us that the most accurate method for assessing the daily energy expenditure of athletes is the "Method for quantitative determination of personalized daily energy expenditure of a person" [9].

We believe that the insertion of specialized food products and dietary supplements into an athlete's diet must necessarily be preceded by an assessment of the adequacy of actual nutrition to ensure that the nutritional and energy value of the diet corresponds to the level and type of physical activity. Great opportunities for collecting this data and increasing their accuracy are provided by the use of software on mobile devices with an image function [10–12]. The results of a systematic review show that storing images of foods consumed facilitates and improves self-reporting, and online nutrition counseling becomes an effective tool for monitoring nutrition. The ability to quickly receive feedback from a specialist through instant messenger chats motivates athletes to improve their eating habits [13, 14].

In addition to assessing actual nutrition before introducing specialized food products and dietary supplements into the diet, it is necessary to take into account anthropometric characteristics, age and gender differences, as well as the phase of the sports macrocycle of athletes.

The energy expenditure of athletes, the qualitative and quantitative composition of sports food and the diet as a whole are not the main indicator, but only one side of the problem of nutrition for athletes. Biochemists, physiologists, nutritionists and other specialists involved in sports technologies are also interested in the mechanisms of energy extraction during muscle activity, issues of restoration of the body, and replenishment of expended substrates after physical activity. However, the researchers themselves emphasize the lack of a unified methodology in solving this problem and the difficulties of comparing data due to differences in experimental conditions [15–21].

Researches in the field of sports biochemistry are aimed, first of all, at obtaining data on the effect of physical activity on the body, as well as at studying the response and the adaptive capabilities of athletes to organize the training process better and achieve maximum sports results. Thanks to such works it has been established that distinctive features of muscle structure appear under the influence of various training, e.g. endurance, speed, and strength development one. **Figures 2** and **3** provide information about morphological and biochemical changes in muscle fibers that occur under the influence of training of various types [22].

The identified structural differences in skeletal muscles, due to the nature of the functional load, were first described by Russian biochemists back in the 70s of the 20th century [16, 17]. They formulated the principle of specific adaptation of the body and its muscular system to various types of muscular activity:

- hypertrophy of physical exercise, in which the most significant changes concern protein mass;
- increase in the aerobic capacity, at which the greatest changes occur in the system of muscular respiration and oxidative phosphorylation;
- increase in the anaerobic capacity, as evidenced by the increased potential of creative kinase and glycolytic resynthesis of ATPh [23].

Modern biochemical and biophysical studies, focused on the level of molecular biology, have confirmed these data and, despite the lack of clear quantitative guidelines for the characteristics of the body response to physical activity, according to medical, biological, and biochemical studies, the main sources of energy for muscle work have been determined. It has been established that in different sports with equal energy expenditure the predominant sources of energy of working muscles are different and energy, when performing different loads, is extracted from different processes, as shown in **Table 2**.

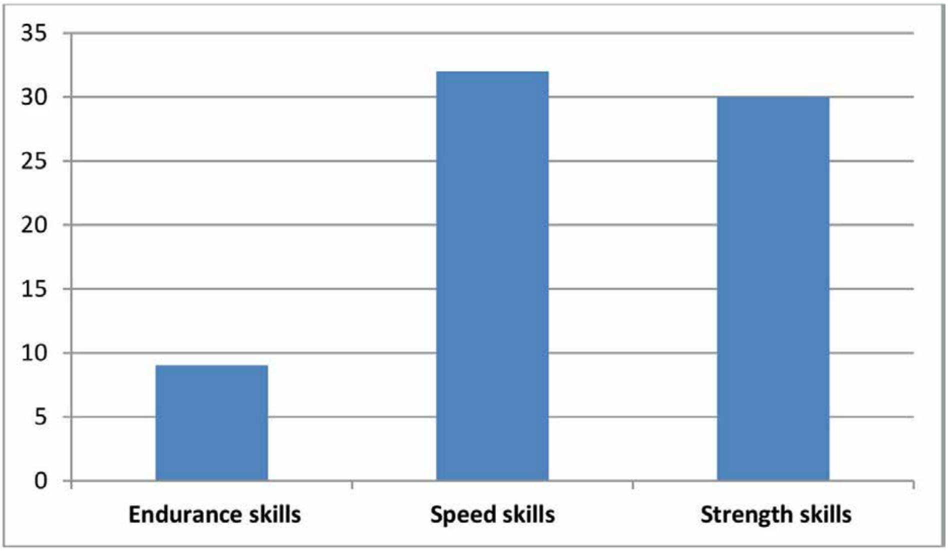

Figure 2.
Relative muscle mass (% of body weight) during the development of different training skills.

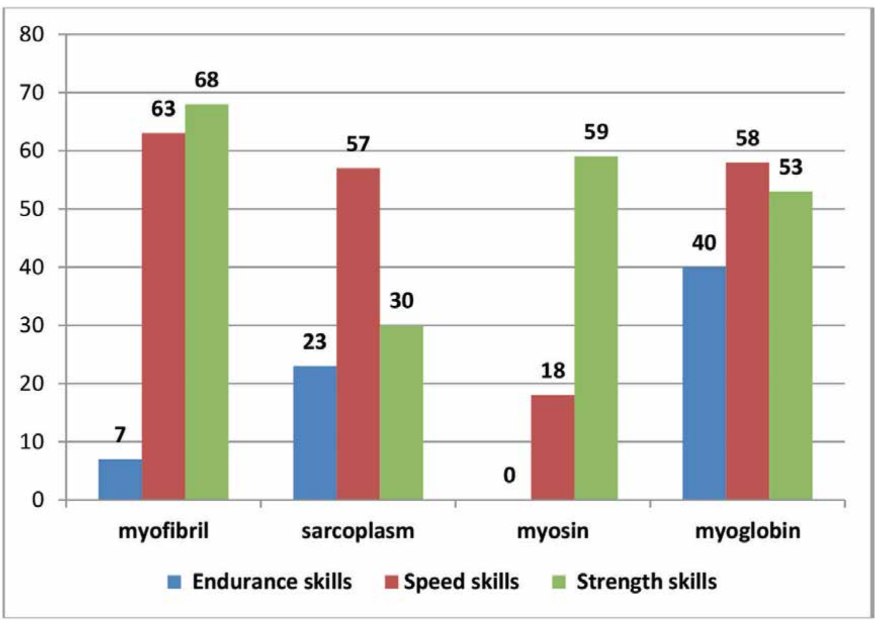

Figure 3.
Protein content in individual structural elements of muscle fiber during the development of various training skills.

Micromorphological and biochemical changes in muscle fibers are associated with the consumption of not only energy, but also various biologically important structures that must be restored during the rest period. Spent biological molecules are replenished mainly through food. That is why the diets of athletes of various qualifications should have a specific focus [24].

Energy process	Examples of physical activity provided by energy
Creatine kinase reaction	Short-term full power exercises – sprinting, jumping, throwing, weightlifting exercises
Glycolysis	Exercises lasting from 30 to 150 s, middle-distance running, 100 and 200 m swimming, track cycling race, etc., as well as acceleration at the distance finish
Krebs cycle	Long-term low power loads
Myokinase reaction	Severe muscle fatigue

Table 2.
Sources of energy when performing muscular work.

However, despite the fact that the number of publications on sports nutrition over the past two decades amounts to hundreds, the number of studies that contain reliable information about the interconnection of a particular food product with the results of physical activity is very limited. And in these studies, the same features can be seen as in the biochemistry of sports in general: the fragmentation of initial data on sports specialization, the number of participants, the experimental conditions, etc.

According to the majority of specialists in the field of sports nutrition, the "gold standard" for studying the influence of components of specialized food products and dietary supplements on competitive results is a prospective, randomized, and controlled scientific study [25]. Also, in order to form a reliable system of biomarkers reflecting the interconnection between physical activity and nutrition, a system of various well-confirmed criteria for performance, health, and recovery of the body is needed [5].

Regulatory issues are of no small importance in the development of this area of research and the sports nutrition industry in general.

3. Legal aspects of nutrition for athletes

The development of specialized food products for athletes is conjugated with the working out of standardized documents regulating terminology, raw materials composition, and other features of specialized food products for nutrition of athletes.

According to the statement adopted by the International Olympic Committee, four types of food products are classified as specialized food products for the nutrition of athletes (**Table 3**).

In Russia and on the territory of the Eurasian Economic Union (EAEU), specialized food products for nutrition of athletes are the subject of regulation by the Technical Regulations of the Customs Union [27, 28]. According to these regulatory documents, "food products for nutrition of athletes are specialized food products of the given chemical composition, increased food value and (or) targeted effectiveness, consisting of a complex of food products or represented by their individual types, which have a specific effect on increasing adaptive capabilities of a person to physical and neuro-emotional load" [28].

Both according to the International Olympic Committee and to the wording of CU TR 027/2011 [28], food products for nutrition of athletes may contain additional biologically active components. At the same time, the level of receipt of evidence-based

Food product category	Distinctive features
Functional food products	They are additionally enriched with macronutrients (proteins, fats, carbohydrates) or micronutrients (vitamins, minerals, etc.)
Prepared food for diet of athletes	They provide the absorption of nutrients in a more convenient form than conventional products or are convenient for use during training (drinks, gels, bars, etc.)
Selected Nutrients	Food components presented in isolated or concentrated form (protein isolates and concentrates, etc.)
Multi-component food products	They have a specific purpose due to a specific combination of nutrients (for building muscle mass, post-workout complexes, etc.)

Table 3.
Groups of food products recommended by the International Olympic Committee for nutrition of athletes [26].

Nutrient group	Strength of evidence	Examples of nutrients
A	The effectiveness of application for specific situations in sports is justified by methods of evidence-based medicine.	Caffeine, β-alanine, nitrates, sodium bicarbonate, glycerin, creatine, multivitamin complexes, vitamin D, iron, calcium, zinc, probiotics.
B	New scientific data were obtained that require further research with the participation of athletes. The use by individual athletes is acceptable under supervision by scientific clinical studies. Some nutrients in this group are included in it due to the experience of their traditional use.	Polyphenols, vitamin C, collagen, chondroitin sulfate, glucosamine sulfate, carnitine, fish oil, curcumin, N-acetylcysteine.
C	Scientific evidence is lacking or has not demonstrated a positive effect on athletic performance.	Branched-chain amino acids (BCAAs), leucine, tyrosine, vitamin E, α-lipoic acid, magnesium, prebiotics, phosphates, β-hydroxy-β-methyl butyrate.
D	They are prohibited or likely to contain substances which could be a reason of a positive doping test.	Stimulants (ephedrine, strychnine, sibutramine, methylhexanamine, 1,3-dimethylbutylamine and other herbal stimulants), selective androgen receptor modulators (andarine, ostarine, ligandol), metabolic modulators (GW1516 (cardarine)).

Table 4.
Groups of biologically active components, depending on the effectiveness of use in sports [26].

materials serves as the basis for determining the effectiveness of specialized food products and/or dietary supplements for athletes. Depending on the results of assessing the effectiveness of the component in the composition of specialized food products and/or dietary supplements, obtained in accordance with the requirements of evidence-based medicine, all biologically active components are divided into groups A, B, C, and D [20], as shown in **Table 4**.

The meta-analysis of scientific publications presented in the Journal of the Sports Nutrition International Society [26] supported the semantic content of biologically active components of groups A and B, but as opposed to the International Olympic Committee classification, combined groups of components C and D into one category: "there is nearly no evidence of effectiveness and/or safety". Consequently, complete unity in the terminology and the classification of specialized food products and/or dietary supplements for athletes has not yet been achieved in the international format.

In the Russian Federation, the state standard has been in force since 2018, which formulates the basic terms used in the field of sports nutrition [29]. In accordance with this document, specialized food products acquire certain characteristics and can be recommended for use for certain purposes and in specific phases of the sports macrocycle, depending on the nutrient composition: the predominance of proteins, carbohydrates or other ingredients [30]. The characteristic features of the macronutrient composition of specialized food products are shown in **Table 5**.

The same document provides concepts of the dietary features of athletes during different periods of the sports macrocycle (**Table 6**).

All specialized food products produced and sold on the territory of the EAEU must undergo a conformity assessment procedure in the form of state registration [28]. The terms formulated in the regulatory documents regarding specialized food products for athletes impose special requirements not only on the procedure for confirming the product's compliance with the declared properties, but also on production processes, raw materials, and technology of these products.

For specialists producing specialized food products, knowledge of current legislative information contributes to the competent selection of raw materials and functional food ingredients, and also serves as a guarantee for the production of high-quality products. Ultimately, following the requirements of regulatory documentation protects manufacturers from unwanted claims from consumers.

Athletes, when choosing a specialized food products, can derive great benefit from regulatory documents, focusing on the list of functional food ingredients allowed in them.

Food products	Purpose
High protein supplement	To control muscle and fat mass of the body, as well as increase speed and strength indicators
Protein-carbohydrates supplement	To increase absolute and relative indicators of the athlete's muscle mass and restore the body's energy resources
Carbohydrate-protein supplement	To contribute to the rapid restoration of the body's energy resources and the increase of absolute and relative indicators of body's muscle mass
High carbohydrate supplement	To replenish the body's energy resources
Carbohydrate-mineral drinks	To maintain the body's water-electrolytic balance
Isotonic drinks	To maintain fluid and mineral balance in the body
Hypotonic drinks	To replace losses of fluid and minerals in the body quickly
Dietary supplements	To activate metabolic processes, to increase adaptive potential and/or functional activity of individual organs and systems of the athlete's body

Table 5.
Classification of specialized food products for athletes depending on macronutrient composition [29].

Period of the sports macrocycle	Dietary features
Preparative (basic)	Diet aimed at the perception of intense physical and psycho-emotional loads, maximizing general and special performance, reducing the impact of unfavorable factors of the training process on the functional activity of organs and systems of the body, helping to maintain muscle mass indicators at an optimal level without reducing endurance, coordination, and speed-strength qualities.
Pre-competition	Diet that contributes to bringing sports form up to the maximum level, improving the athlete's technical capabilities, and increasing speed-strength qualities and endurance.
Competitive	Diet that allows maximizing the athlete's capabilities, supporting and contributing to the formation of peak supercompensation, maintaining high performance, carrying out timely replenishment of the energy resources of the athlete's body.
Restorative	Diet that replenishes the body's energy resources and promotes the removal of metabolic products from the athlete's body, as well as general recovery, rehabilitation and stress relief.
Before training	The use of specialized food products in the diet of athletes in addition to the basic food intake, aimed at mobilizing the body's physical strength before physical activity.
During training	The use of specialized food products in the diet of athletes in addition to the basic food intake, aimed at maintaining physical strength during physical activity.
After training	The use of specialized food products in the diet of athletes in addition to the basic food intake, aimed at restoring the body's physical strength after physical activity.

Table 6.
Diet of athletes depending on physiological needs [29].

4. Technological aspects of nutrition for athletes

In modern technologies used in the production of sports food products there are several aspects that could be distinguished.

First of all, according to the analysis of the range of food products for athletes, it has been found out that dry mixtures prevail in all categories of these food products. Even in the sections "Drinks", most of the products are dry concentrates. Most often, such products are presented as dry powder or granular mixtures.

The use of dry products is very convenient in sports from the standpoint of transportation, storage outside the refrigerator, creation of some supplies for the time of moving, competitions and sports training camps. However, reconstitution of dry products requires liquids that must be purchased separately and also transported, therefore, the volume of products transported by the consumer will not decrease significantly, but the cost of the finished product will ultimately increase.

To reconstitute dry products, most manufacturers recommend using not only water, but also juices and skim milk, which have their own set of macronutrients, this, accordingly, affects the food and energy value of the product reconstituted from a dry mixture. It is usually not taken into account by the consumer. For example, **Figure 4** shows how the nutrient ratio in a serving of a protein mixture for sports nutrition changes when dissolved it in water, skim milk or juice.

The diagram shows that when the protein mixture is dissolved in both milk and juice, the carbohydrate content increases several times, but athletes may not pay attention to this, or make a mistake in recalculating the nutritional value of the finished product.

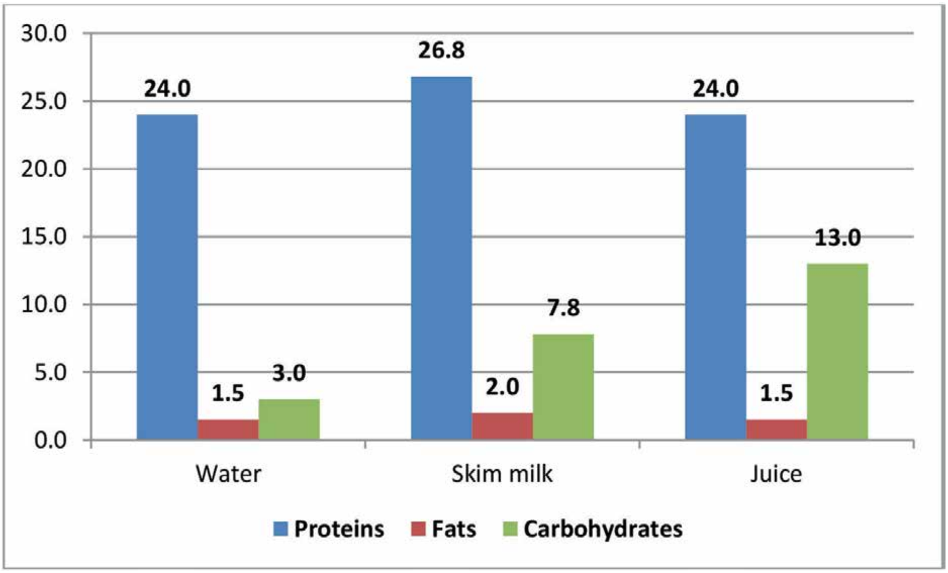

Figure 4.
Change in food value of dry mixture for diet of athletes with different methods of preparation.

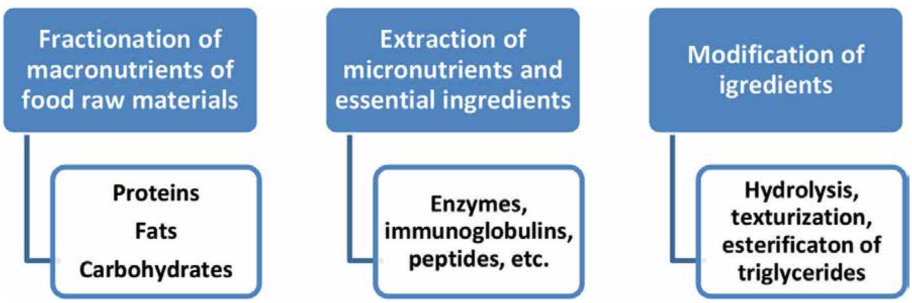

Figure 5.
The most important directions in SPP technology for athletes.

The study of specialized food products for athletes, presented in retail chains, regarding the raw materials used confirms that all raw materials components of the food products have been subjected to processing with varying degrees of technological impact before being combined into the mixture (**Figure 5**).

The most common technological technique is the fractionation of macronutrients of food raw materials into separate components: protein, lipid, and carbohydrate ones, which are ultimately aimed at developing food products with a similar profile. In this case, the degree of fractionation varies according to the depth of separation: extraction of whole macronutrients or separation of constituents. For example, among specialized food products of protein and carbohydrate profiles, there are mixtures that contain skim milk, milk protein concentrates, plant-based proteins, various types of vegetable oils, starch, and dietary fiber of various origins.

Upon deeper processing of macronutrients, their further fractionation is achieved, for example, separating whey proteins from casein, polysaccharides from mono- and disaccharides or extracting lecithin from soy or eggs, etc. with the use of high-tech innovative technologies. In particular, when processing dairy raw materials, membrane separation methods such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis are widely used.

Modern technologies make it possible to extract micronutrients and minor ingredients from food raw materials. For example, to preserve the native properties of biologically active components of dairy raw materials, such as enzymes, immunoglobulins, peptides, etc., fine physicochemical and biochemical separation methods are used, which include chromatography, gel filtration and other methods. Despite the innovativeness and progressiveness of such developments, their industrial application is still poorly scaled due to imperfections in technology, low efficiency of processes, and high cost of finished products. Consequently, in most multicomponent mixtures for athletes, which are prepared from dry ingredients, vitamins, mineral elements, redox enzymes, immunoglobulins, peptides and other biologically active substances are included in the mixtures as added ingredients, what increases the cost of the finished product significantly.

A common technique in specialized food products technology for athletes is the use of modified ingredients. In particular, biopolymer hydrolysis technologies are common for further processing of extracted macronutrients. Hydrolytic processing methods are used for proteins, carbohydrates and lipids, both of animal and plant origin. Another option for modification of proteins, especially plant proteins, is texturing of different types. Also among specialized food products for athletes there are examples in which the lipid component is subjected to interesterification or hydrogenation.

According to the market review, dry concentrates of milk protein and their modified forms are very popular in sports food products. For example, in protein complexes the total share of milk proteins reaches 75–90% of the total mass of the product. In a series of specialized food products for nutrition of athletes, developed at the Federal State Budgetary Institution of Science the Federal Research Center for Nutrition and Biotechnology, dry concentrates and isolates of milk proteins and whey proteins are used.

The predominant ingredient in powder mixtures across all sports food product categories is simply whey powder or skim milk powder. These types of dairy raw materials have a pleasant neutral taste, a color from white to cream-light and can be successfully combined with both sweet and spicy ingredients. Both powdered milk and dry milk processing products are high-quality products with high food and biological value, what determines their inclusion in the composition of specialized food products for athletes.

Most food products for athletes include ingredients of other origins in addition to whey powder or skim milk powder, such as egg whites, soy, collagen from various sources and other food ingredients.

Figure 6 shows the proportion of specialized food products for athletes which contain certain types of milk proteins.

The enumerated ingredients of raw milk perform several functions simultaneously in the specialized food products for athletes. Firstly, powdered milk raw materials increase the total dry matter content in food products significantly and provide high food value. Secondly, it improves the biological value due to the unique combination of essential amino acids remarkably. Finally, milk proteins have a whole range of technologically important properties: they are surfactants, can cause gel formation of food systems and stabilization of emulsions, provide emulsification and foaming during whipping.

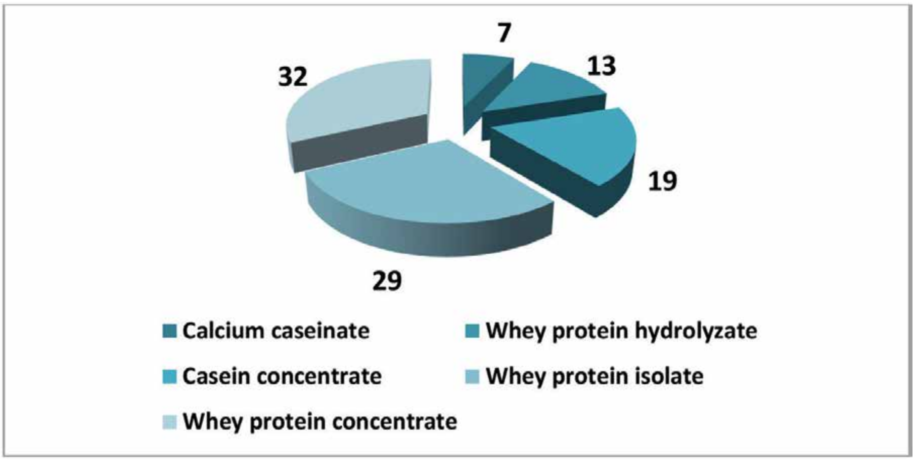

Figure 6.
Equity proportion of specialized food products for athletes containing various milk proteins, %.

According to the analysis of the composition of more than 100 types of specialized food products for athletes, the predominant technological solution by the production of such food products is the formation of multicomponent mixtures.

To form a certain direction in the specialized food products, the necessary functional nutrition ingredients are usually introduced into the initial raw materials.

The analysis of the composition of specialized food products produced for athletes showed that almost every second such food product contains vitamin and mineral supplements or dietary fibers, or the two of them at the same time. An idea of the number of specialized food products for athletes enriched with various functional nutrition ingredients is given in **Figure 7**.

The functional properties of dietary fibers come to the fact that they stimulate the growth of normal microflora of the large intestine and affect the processes of

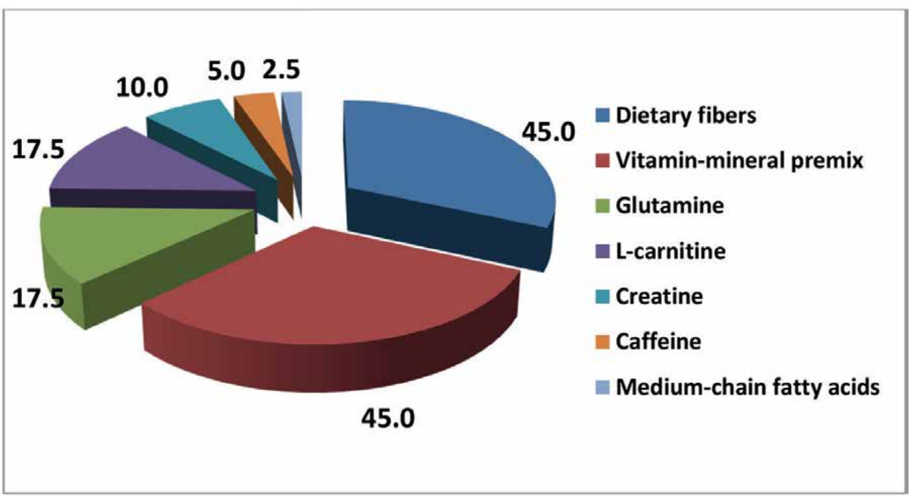

Figure 7.
Equity proportion of specialized food products for athletes with the corresponding functional nutrition ingredients, %.

absorption, microbiocinosis and evacuation of food significantly, that is, they exhibit the typical prebiotic properties. However, as indicated in the International Olympic Committee materials (**Table 4**), no data have been obtained confirming the positive effects of prebiotics on sports performance [26].

On the contrary, there are far fewer examples of probiotic food for athletes, although convincing scientific evidence has been obtained for probiotics on the effectiveness of their use in specific sports situations [26].

Among the functional nutrition ingredients for which a positive correlation with increased physical activity has been confirmed, caffeine and creatine are allowed in the Russian Federation. Caffeine has been proven to be effective for both long-term endurance exercise and short-term intense exercise. As can be seen in **Figure 6**, caffeine is present in 5% of the specialized food products.

One of the popular supplements positioning food products for athletes as food products for restoring, fat burning, weight loss, and as energy products is carnitine. Carnitine is also included in dry mixtures, gels, drinks, and bars, although proof of the effectiveness of this ingredient in specialized food products requires further research with the participation of athletes.

5. Conclusion

To optimize the nutrition of athletes, the consolidation of specialists in the field of medicine, legal regulation and production technology is necessary. Creating a methodology for commodity evaluation and classification of sports nutrition products with increased adaptive efficiency and the ability to regulate the intended purpose is an urgent task in the technology and merchandising of such products.

For biomedical specialists, the creation of a system of biomarkers that reflect the interconnection of nutrition with the criteria of productivity, health and recovery of the body remains relevant. Based on these studies, it is necessary to develop individual recommendations for adjusting the diets of individual athletes or groups of athletes. As a bank of such data is formed in the near future, personalization of the diet in accordance with the individual metabolic and genetic profile of the athlete is quite possible.

To fill personalized diets, it is necessary to develop individual technologies for sports nutrition products. When creating SPP, not only the scientific justification for the choice of biologically active substances, but also the principle of "do no harm" is relevant. The introduction of PPI with proven effectiveness should not exceed physiologically active quantities and worsen the consumer and functional-technological properties of the SPP.

When developing a specialized food product, not only the scientific justification for the choice of biologically active substances, but also the principle of "Do no harm!" is relevant. The introduction of functional nutrition ingredients with proven effectiveness should not exceed physiologically active quantities and worsen the consumer and functional-technological properties of the specialized food products.

All specialized food product and/or dietary supplements must be purchased only if there is information and state registration of these products in the Unified Register of the EAEU, in order to eliminate the risk of the product containing substances included in the World Anti-Doping Agency Prohibited List.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 2

Computer Simulation of Mechanisms to Reduce the Metabolic Costs of Running While Taking into Account the Individual Characteristics of the Athlete

Mikhail Shestakov and Alexander Korchagin

Abstract

Previous research demonstrates the relationship between the biomechanical characteristics of running and running economics (RE). An increase in results in cycle-based sports is connected with the improvement of motion biomechanics tailored for individual athletes. The purpose of the chapter is to conduct a computer simulation of the use of biomechanical mechanisms of the lower limb muscles during running, leading to a decrease in metabolic costs. Eight biathletes took part in the experiments: all from the top 30 world ratings at the time of the study. For experiments, we used a Qualisys motion capture system, a power plate (Tredmetrix) mounted on a treadmill, a Biodex-3 complex, and a Metamax-3 gas analyzer (Cortex). OpenSim software allows modeling based on collected experimental data. This study describes the methodology of an individual approach to the process of training elite-level athletes based on computer modeling. In particular, we studied the possibility of reducing metabolic costs when working above the anaerobic limit, that is, similar to the actual competitive speed for biathlon and cross-country skiing. The results of the model experiment clearly demonstrated that one of the potential ways to reduce metabolic costs during running is the individualization of the use of biomechanical mechanisms for performing repulsion in a running step.

Keywords: energy consumption, running, forward dynamics simulation, motor control, OpenSim

1. Introduction

Constant improvement in achievements in sport drives the necessity to search for new ways of increasing efficiency. There are on-going discussions on how to improve the way the world's top athletes perform in cyclic sports, including athletic running.

Running economy (RE) is typically defined as the amount of energy used to run at a certain speed without reaching maximum capacity. It is measured by observing the oxygen consumption and the Respiratory Exchange Ratio in a steady-state.

It is becoming increasingly clear that aerobic capacity training is not the only means of improving endurance performance [1]. The performed study demonstrates the relationship between the biomechanical characteristics of a run and its RE [2–6]. An increase in results in cycle-based sports is connected with the improvement of motion biomechanics tailored for individual athletes.

First of all, the training process personalization (or individualization) is based on understanding and using athlete's individual technique for performing the "main competitive exercise"—in our case, it is running. The individual technique is largely dependent on the architectonics of athlete's muscle groups and their interaction during motion.

Many researchers emphasize on the connection between lowering the energy consumption for COM (Center of Mass) movement and lowering the metabolic cost of muscles in lower limbs [7–10]. Another important mechanism that allows lowering the running metabolic cost is the use of elastic-viscous properties of muscles and the ability to store the elastic strain energy (ESE) in specific cases [11–14].

The analysis of elite-level athletes' movement specialties is possible by using an individual approach. The athletes have very different anthropometry and physical abilities (including force characteristics). Each sportsman has his/her own style of movement based on years and years of training. The research question should provide recommendations for a specific athlete, as it is almost near to impossible experimentally study the differences between elite-level athletes. This is largely due to the lack of option to have a statistically controlled environment: well performing athletes and those who are not doing well, different classification groups of athletes, the impact of different training methods used by different groups, etc.

But to some extent, these questions can be answered using individual computer modeling. In this case, the search for the most efficient "style" or technique is performed using multiple simulations on the same model with different control parameters that affect the end result.

OpenSim software [15] allows running simulation based on experimental (recorded) data and modeling the change of the running style while changing key influencing factors for the selected athlete. As a result, there is a way to quantify and analyze the differences in various running options for a specific athlete.

The purpose of the chapter is to conduct a computer simulation of the use of biomechanical mechanisms of the lower limb muscles during running, leading to a decrease in metabolic costs. It is assumed that a decrease in metabolic costs can occur due to the optimization of muscle activity over time.

This study is aimed to provide usable results which can be embedded in the training process of professional athletes. Most training programs for sportsmen include strength exercises, but for top level athletes these need to be proven effective given their individual features and characteristics. The results of this research allow the development of individual training plans, including force-based training aimed at specific muscle groups in order to "correct" the running style for lower energy consumption.

2. Methods

To solve the goal set in the work, eight male athletes were selected from the athletes of the national teams of Russia in biathlon (age 25 $\pm$ 3.4 years; height

1.82 ± 3.8; weight (76 ± 4.1 kg). The athletes are in the top-30 of world ratings at the moment of the study.

To control the training process in the biathlon national teams of Russia, athletes are tested before each stage of sports training. Testing involves running a test with incremental velocity to determine the aerobic and anaerobic limits of the studied athletes, as well as estimating the maximal oxygen consumption VO_2max metric using Metamax-3 (Cortex, Germany) gas analyzer system. The recorded parameters were used to calculate the rates of O_2 consumption and CO_2 excretion, respiratory quotient, ventilation equivalents of O_2 consumption and CO_2 excretion. These indicators were calculated automatically by the program included in the "Metamax-3". The same program was used to determine the level of the anaerobic threshold using the V-slope method [16].

For the experimental part of the study we used a motion capture system involving 18 high-speed Oqus 3+ cameras (Qualisys, Sweden)) with the frame rate of 400 frames per second. The running exercise was performed on a treadmill-mounted force plate (Tredmetrix, USA). The data obtained from the force platform made it possible to obtain indicators of the longitudinal and vertical reaction of the ground reaction, as a resultant vector, as well as the coordinates of its application [13]. Cameras and force plate sensors were synchronized using a specific adapter. A total of 54 reflecting markers (1 cm in diameter) were mounted on the study subjects according to **Figure 1**. Athletes were also tested using force-study complex Biodex 3 (Biodex, USA). The strength indicators (peak torque) of athletes were assessed during flexion-extension of the knee joint in the isokinetic mode at low speed (60 deg./s) according to the method [17]. In this study, subjects were running at speeds of 3 m/s and 5.1 m/s, respectively. The sequence of testing athletes was carried out as follows. After a standard warm-up lasting 5–8 minutes, the athletes tested their strength capabilities. Flexion-extension test in the knee joint was performed five times with each leg for each movement, in accordance. After that, 8–10 minutes were allotted for attaching

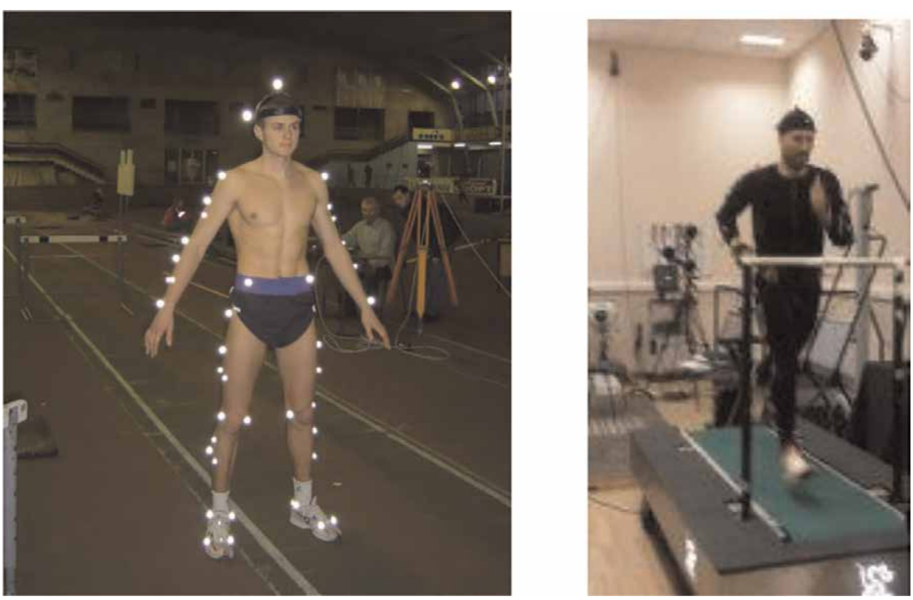

Figure 1.
Placement of the markers on the subject and the procedure for carrying out the test.

markers to the body of athletes for shooting and a gas analyzer. Then the athlete performed a warm-up run at an arbitrary speed for 3–5 minutes on the treadmill. When ready, the athlete ran at a speed of 3 m/s. After the athlete reached his individual aerobic threshold, kinetic and kinematic data were recorded for 10 s. Subsequently, the speed of the treadmill increased to 5.1 m/s. After 10 s after obtaining the values of the anaerobic threshold according to the gas analyzer “Metamax-3”, kinetic and kinematic data were recorded for 10 s.

With respect to the first method of increasing repulsive power, it is known that the pre-stretch of the muscle-tendon complex (MTC) enhances its subsequent contraction. It is manifested in various locomotions [11, 18–20]. Thus, they can increase or decrease muscle stiffness [14, 21–23]. Accordingly, it becomes possible to use the mechanism of elastic deformation in the muscles. Such a mechanism is sometimes called a “catapult” [24].

The second way to increase the power of a take-off is based on energy transfer through biarticular muscles. This process involves processes which occur in the musculotendinous unit (MTU) and is supported by the fact that the powerful monoarticular gluteus muscles, mainly the gluteus maximus (GM), play a significant role in hip extension, thus increasing hip joint angle. The energy transfer from GM to the knee joint occurs via the biarticular RF muscle. This muscle produces the greatest power output when contracting slowly and working in nearly isometric conditions. Additionally, the knee joint is extended by RF and a collection of monoarticular m.vastus (VA) muscles [25]. The triceps muscle of the calf is the primary muscle involved in this movement. It works in conjunction with the gastrocnemius muscle (GA) to transfer energy and create a reinforcing contraction. This is known as the “Energy Transfer Model” and is described in detail in the study “Knee Extension and Plantar Flexion: Energy Transfer Model” [19].

Athletes were divided into two groups in accordance with the use of two different mechanisms of muscle work during repulsion in a running step. Athletes’ data and parameters can be found in **Table 1**.

According to available studies, it is assumed that an athlete uses only one type of mechanism in different locomotion [13, 14], which determines the individuality of the technique for performing competitive exercises.

2.1 Data processing approach

Kinematic and dynamic calculations were conducted using the full-body model proposed in the Hamner and Delp paper [1]. This simulation enabled a deeper understanding of the body’s behavior with regards to the kinematic and dynamic calculations, and provided a more comprehensive evaluation of the motion. We used a three-dimensional musculoskeletal model with 29 degrees of freedom, 92 lower extremity and torso muscles, and arms driven by torque actuators, which has been used

Group	Height, m	Weight, kg	VO_2 max	Strength of knee flexion in the isokinetic mode with 60 degrees/s/kg
Group A (n = 4)	1.83 ± 3.4	82.3 ± 2.1	71.9 ± 4.3	2.7 ± 0.8
Group B (n = 4)	1.81 ± 4.1	71.7 ± 1.8	74.6 ± 3.5	2.0 ± 0.6

Table 1.
Key characteristics of studied athletes.

previously to study how each muscle contributes to accelerating the body's center of mass during running [1, 26]. In order to perform the analysis of metabolic costs during the running experiment a group of key muscles was selected: PSO (psoas), GMAX (superior, middle, and inferior gluteus maximus), BF (biceps femoris long head), SEM (semimembranosus and semitendinosus), RF (rectus femoris), VAS (vastus medialis), GAS (lateral compartments of gastrocnemius), SOL (soleus) and TIB (tibialis anterior). We first simulated five running cycles for each subject at each speed, following the methods described by Hamner and Delp [1]. The running cycle has two phases: the stance, or support phase and the flight phase (transfer of the fly leg). The stance phase is the push of the foot, the first contact of the foot with the ground. The beginning and end of the support phase in the running cycle was carried out according to the appearance and disappearance, respectively, of the vertical force according to the power platforms of the treadmill verification of the model we built for each athlete was carried out by comparison with identical models of athletes [1] located in the repository https://github.com/modenaxe/awesome-biomechanics#-running-running

The flow chart of the organization of research and model experiments is presented in **Figure 2**. Our process of simulation started by adjusting the measurements of the generic musculoskeletal model to fit the body proportions of each of our subjects, accomplished by using the OpenSim Scale Tool. Additionally, we also modified the maximal isometric strength of the muscles by using a regression equation based on the mass and height of each subject [27].

In order to calculate the joint angles at each time in the model, the "inverse kinematics" tool in OpenSim was used. The marker locations on the model were then optimized to match the trajectories of the corresponding markers measured on the subject, so the sum of the squared distances between the two marker sets was minimized, resulting in the optimal set of joint kinematics. The "inverse dynamics" tool in OpenSim was used to determine the net joint moments. The ground reaction forces were applied to the feet of the model, and the equations of motion were solved to calculate the joint moments. The "static optimization" tool in OpenSim was then used to calculate the net joint moments. This procedure was used to solve a minimization problem, the aim of which was to reduce the sum of the squares of all muscle activations, that is, to reduce total muscle stress. Constraints were applied to the

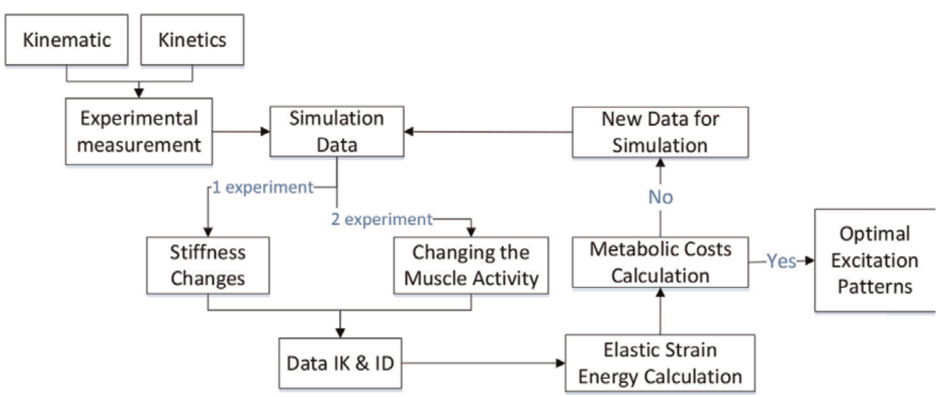

Figure 2.
Flow chart summarizing computational and experimental approaches for evaluating the energetics of locomotion.

optimization solution, which needed to fit the force-length-velocity surface of each muscle.

Each muscle produces mechanical power by multiplying the musculotendon force and the musculotendon velocity. The mechanical work is found by calculating the area beneath the power-time curve. Concentric contractions signify the energy generated by the muscle (positive work), while eccentric contractions represent the energy consumed (negative work).

The quantification of lower-limb muscle function was accomplished by computing each muscle's contribution to the ground reaction force and lower-limb joint accelerations derived from the experiment. This was achieved using the "pseudo-inverse induced acceleration analysis" and a custom plugin from OpenSim (available at h ttps://simtk.org/home/tims_plugins).

The isolated muscle force was applied to the model one at a time. This force was then transmitted to all of the body segments, causing: (1) a ground reaction force at the foot; and (2) angular accelerations in all body joints. This technique for computing the muscle's contributions to ground reaction forces and lower-limb joint accelerations has already been validated using running data .

We used OpenSim's Computed Muscle Control (CMC) Tool [28] to generate muscle-driven motions based on the recorded experiments, with the single adjusted model and the adjusted kinematics. CMC calculates the muscle stimulation required to generate the perceived running motion, while decreasing the total of squared muscle activations at standard intervals in the motion. Precisely, the objective function J of CMC consists of an effort term J_{effort} and a term associated with modeling and measurement mistake J_{error}:

$$J = J_{\text{effort}} + J_{\text{error}}, \tag{1}$$

$$J_{\text{effort}} = \sum_{i \in M} a_i^2, \tag{2}$$

$$J_{\text{error}} = \sum_{i \in R} \left(\frac{f_i}{w_{f,i}} \right)^2. \tag{3}$$

The effort term (Eq. (2)) depends only on the activation of the corresponding muscle group. Eq. (3) penalizes the force or moment f delivered by the set of reserve and residual actuators R, in accordance with [28]. Reserve actuators supply minor joint moments to make up for unmodeled passive structures (such as ligaments) and potential muscle weakness, while residual actuators apply any residual forces. The weighting factor $w_{f,i}$ is adjusted to make the reserves and residuals much more expensive to use in comparison to the muscles; in OpenSim, this factor is referred to as the actuators' optimal force property.

2.2 Elastic strain energy (ESE) calculation

During the analysis we attempted to calculate the possible amount of storing and utilizing the elastic strain energy (ESE) according to the methodology suggested by Prilutsky et al. [13, 14].

Mechanical energy can be transferred between the joints of the leg in five main ways (**Table 2**).

Five major pathways for energy transfer are listed in **Table 2** [13].

No.	$P_j(t)^*$	$P_j^c(t)$	$\sum_j P^m(t)$	The rate and direction of energy transmission through the two-joint muscles	The roles of the muscles that serve the jth joint
1	>0	>0	≥0	To the jth joint at a rate of $\lvert P_j(t)\rvert$ from the side of the (j − l)th and/or (j + I)th joints	Generate energy at a rate of $\lvert P_j^c(t)\rvert - \lvert Pj(t)\rvert$
2	<0	≥0	>0	From the jth joint at a rate of -$P_j(t)\rvert$ to the (j − 1)th and/or (j + 1)th joints	Generate energy at a rate of $\lvert P_j^c(t)\rvert + \lvert Pj(t)\rvert$
3	>0	≤0	<0	To the jth joint at a rate of $\lvert P_j(t)\rvert$ from the side of the (j − 1)th and/or (j + 1)th joints	Absorb energy at a rate of -[$\lvert P_j^c(t)\rvert + \lvert Pj(t)\rvert$]
4	<0	<0	≤0	From the jth joint at a rate of —$\lvert P_j(t)\rvert$to the Cj − 1)th and/or (j + 1)th joints	Absorb energy at a rate of -[$\lvert P_j^c(t)\rvert$- $\lvert Pj(t)\rvert$]
5	=0	≥0, <0	≥0, <0	(a) Energy is not transferred through two-joint muscles. (b) Energy is delivered to the jth joint at a rate of $\lvert Pj(t)\rvert$ [e.g., from the side of the (j + 1)th joint] and transferred from it at a rate of -$\lvert Pj(t)\rvert$ [e.g., to the (j − l)th joint]	Generate energy at a rate of $\lvert P_j^c(t)\rvert$ or absorb energy at a rate of -$\lvert Pj(t)\rvert$

At any given time t, Pj(t) is the energy transferred between two-joint muscles at the jth joint. The power developed by the joint moment at the jth joint is $P_j^c(t)$, while $\sum_j P^m(t)$ is the sum of the powers developed by all the muscles serving the jth joint.

Table 2.
Variations of mechanical energy exchange between the two-joint muscles [13].

2.3 Metabolic costs calculation

To evaluate metabolic energy consumption from the simulations, we used a modified version of the metabolic model developed by Umberger et al. [29] and Verkhoshansky and Verkhoshansky [30]. This model was implemented in OpenSim v3.3 using the Umberger2010MuscleMetabolicsProbe.

In accordance with the calculation method, we added up the energy consumption rate of all muscles, as well as a basal rate (1.2 W/kg) [31], then incorporated the total rate in the running cycle and divided by the length of time the athlete's supporting leg was on the support. This process was used to estimate the running cycle. To calculate the average whole body metabolic rate for simulations obtained from the trials, we took the mean of the instantaneous whole-body rate over half a running cycle. To evaluate the influence of this approximation on our results, we also computed an average rate for five evenly distributed half-running cycles across the available data. We observed that there was a negligible distinction between using the mean of those five average rates and using a solitary half- running cycle.

2.4 Leg stiffness calculation

Calculation of leg stiffness (K_{leg}), which is given by the ratio of the maximum vertical ground reaction force normalized to body weight, $F_{\max}$, to the variation in leg length during stance phase, normalized to leg length at foot contact, l_0:

$$K_{\text{leg}} = \frac{F_{\max}}{(l_o - l_{\min})/l_o},$$

where l_{min} is the minimum leg length during stance phase of the running cycle, l_0—leg length at rest, F_{max}—peak vertical ground reaction force. Leg length was estimated as the distance between the center-of-pressure [32] and the center of the pelvis in a model constructed from the musculoskeletal model described by Delp et al. [33].

2.5 Ethical approval

The study was approved by the Local Human Research Ethics Committee (Protocol #2/21 LHREC VNIIFK), and all participants provided their written informed consent before testing. Every human testing procedure followed complied with the rules stated in the Declaration of Helsinki.

3. Results

3.1 Characteristics of the running step of the subjects

The data in **Figure 3** show the difference in the manifestation of the joint power of the lower limb during the stance phase in a running step at a speed of 3 m/s for groups A and B, which can characterize the individual style of the running technique. The calculation of the joint power was carried out according to the described algorithm [13], summing the power produced by each muscle in the model serving the corresponding joint (the sign of the direction is taken into account),

Table 3 and **Figures 4** and **5** outline the kinematic, dynamic and energy data observed for the two groups for the speeds of 5.1 and 3 m/s.

Figures 4 and **5** show data characterizing the metabolic power of the main muscles involved in the running step for different running speeds. Расчет metabolic power consumed for muscles in the model was carried out by Umberger et al. [29] and Verkhoshansky and Verkhoshansky [30] with some modifications [10].

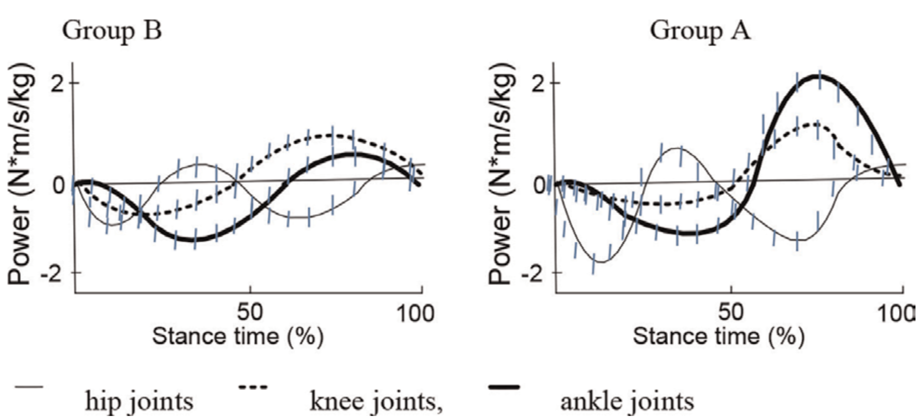

Figure 3.
Patterns of joint power for the ankle, knee, and hip joints during the ground contact phase in running 3 m/s.

Subject/ speed		Peak moment, N m/kg	Peak power, N m/s/kg	Stiffness	Energy transfer from hip to knee, %	Energy transfer from knee to ankle, %	Summary metabolic power consumed, W/kg
Group A	5 m/s	1.72	0.304	13.1	0.52	1.19	9.76
	3 m/s	0.63	0.790	14.1	1.28	1.58	8.76
Group B	5 m/s	1.52	0.44	12.5	2.41	0.58	9.75
	3 m/s	1.32	0.28	9.8	5.5	0.5	4.77

Table 3.
Initial experimental data.

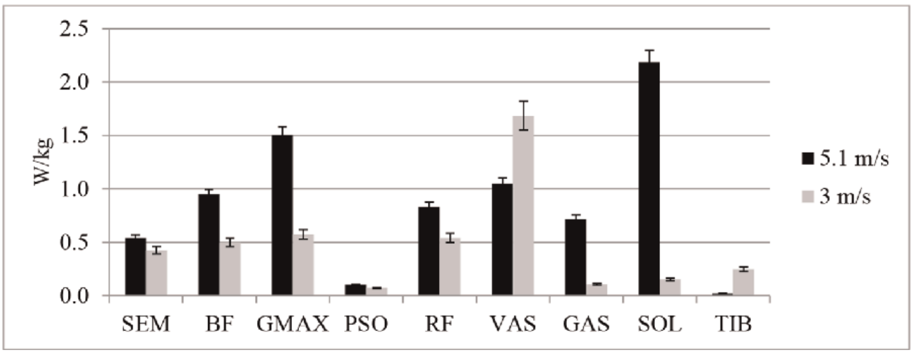

Figure 4.
Comparison of metabolic power consumed (W/kg) for running at 3 and 5.1 m/s (group A) (by Umberger et al. [29, 30] with some modifications [10]).

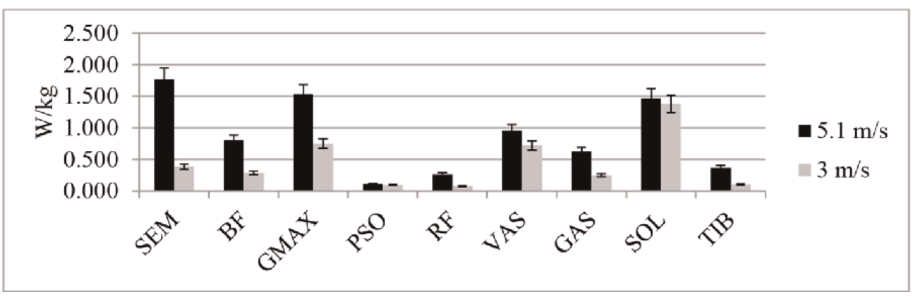

Figure 5.
Comparison of metabolic power consumed (W/kg) for running at 3 and 5.1 m/s (group B) (by Umberger et al. [29] and Verkhoshansky and Verkhoshansky [30] with some modifications [10]).

3.2 Modeling the change in running technique by modifying the stiffness

From the practical point of view, for the purposes of improvement the running technique and control, one of the key parameters K_{leg} is the amplitude of knee flexion during the stance phase of a running step. This was achieved by increasing or decreasing the l_0.

To conduct the modeling in this case, we made an assumption of stiffness changing to have an effect on RE. For that purpose, the studied models were changed by increasing or decreasing the leg stiffness by 5% driven by changing the knee angles.

The results in **Table 4** demonstrate that increasing stiffness by decreasing the knee angle amplitude for the subjects from group A leads to elevated impact of elastic energy when transferring energy from hip to knee (15%) and from knee to ankle (6.6%). Similar result is observed when decreasing the stiffness—the corresponding changes are 10.4% and 3.3%, respectively.

Figures 6 and **7** show changes in the metabolic power of the muscles in the running step with increasing and decreasing stiffness of the leg according to the results of computer simulation.

3.3 Changing the muscle activity while running toward reducing metabolic costs

In accordance with conducted analysis of experimental data, the second part of the study was targeted for individual editing of muscle excitation patterns for muscles in the lower limbs. This is achieved by using a specific OpenSim tool—Excitation Editor. This is a mandatory step when modeling using the Forward Dynamics approach [15, 33].

For the model experiment, one athlete from each group was selected: the subject SA from group A, the subject PD from group B.

For the PD subject (**Figure 8**), the muscle activation change was aimed toward a sequential involvement of joints while push-off: first, the hip flexion started, and only later—the knee flexion.

Making changes to the muscle activity patterns (**Figures 8** and **9**) leads to changes in the results of output indicators (**Table 5**). An increase in muscle coactivation in an SA athlete leads to an increase in the stiffness of the supporting leg by 1.5%. At the same time, an increase in leg stiffness reduces the value of torque and maximum power by 5.3 and 3.3%, respectively. Also, the SA athlete has reduced energy transfer between joints by 7.7% from hip to knee and by 5.3% from knee to ankle. A different situation is observed in the PD athlete, in whom conditions were created in the model to increase the time of work of the biarticular muscles. As a result of such changes, in the PD

		Maximum moment, N m/kg	Maximum power, N m/s/kg	Stiffness	Energy transfer from hip to knee, %	Energy transfer from knee to ankle, %	Summary metabolic power consumed, W/kg
Group A	Stiffness increased	1.39	2.0	13.8	0.61	1.23	9.74
	Stiffness decreased	1.59	1.50	12.45	0.58	1.26	9.79
Group B	Stiffness increased	2.15	0.49	13.2	3.18	0.59	9.09
	Stiffness decreased	2.36	0.38	11.85	2.50	0.60	9.82

Table 4.
Modeling data obtained by increasing or decreasing leg stiffness.

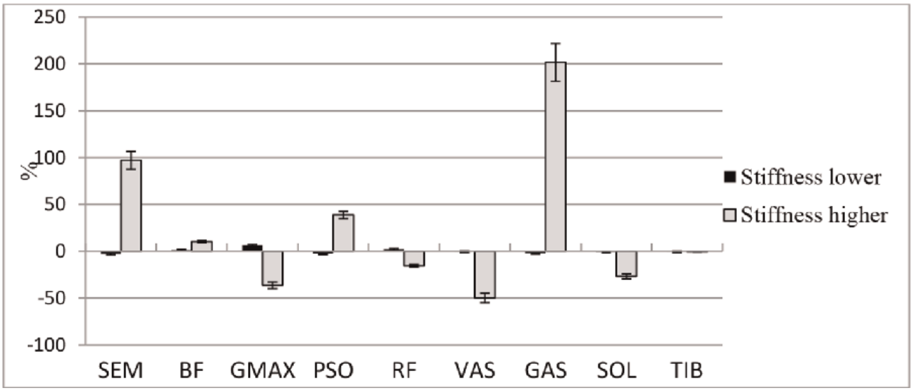

Figure 6.
The difference (in %) between the values of consumed metabolic power of muscles during the simulation of the stiffness of the supporting leg in group A athletes. Stiffness lower—reduction in leg stiffness by 5%, Stiffness higher—increase in leg stiffness by 5%.

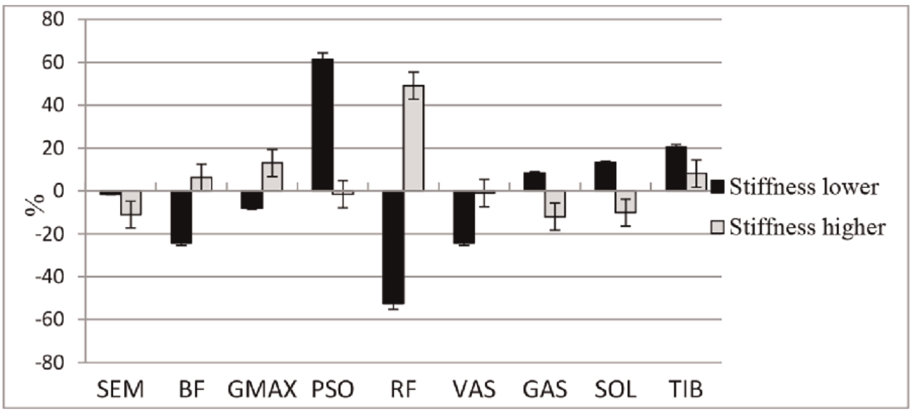

Figure 7.
The difference (in %) between the values of consumed metabolic power of muscles during the simulation of the stiffness of the supporting leg in group B athletes. Stiffness lower—reduction in leg stiffness by 5%, Stiffness higher—increase in leg stiffness by 5%.

athlete, the stiffness of the muscles of the supporting leg, in contrast to the SA athlete, decreases by 2.4%. Accordingly, there is an increase in both torque and maximum power by 6.2% and 4.4%, respectively. Noteworthy is the increase in ESE between the joints by 67.2% from hip to knee and by 81.9% from knee to ankle. Such a relationship in running between leg stiffness, moment of force and power is noted by other authors [24]. Despite the opposite changes in the output data of both athletes, the total metabolic costs are reduced in the SA athlete by 9.3% and by 5.5% in the PD athlete.

4. Discussion

Experimental laboratory testing of athletes revealed the features of the running step technique, dividing them into groups A and B (**Figure 3**). The difference in running technique is based on the results of earlier studies [13, 14, 25, 34].

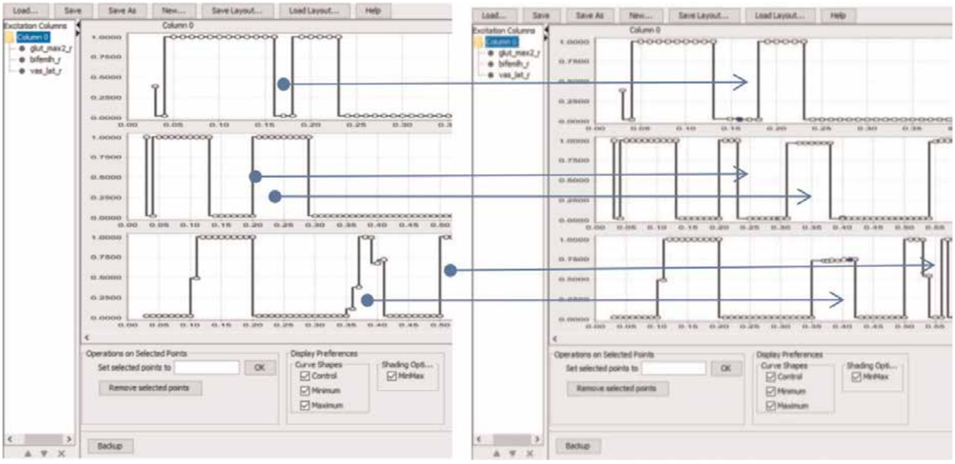

Figure 8.
Example of excitation editor for PD subject from group B. Muscles top to bottom—BF (biceps femoris long head), RF (rectus femoris), VAS (vastus medialis); on the left—simulating muscle activity before making changes; on the right—simulation of muscle activity after making changes. Arrows show changes in muscle activity.

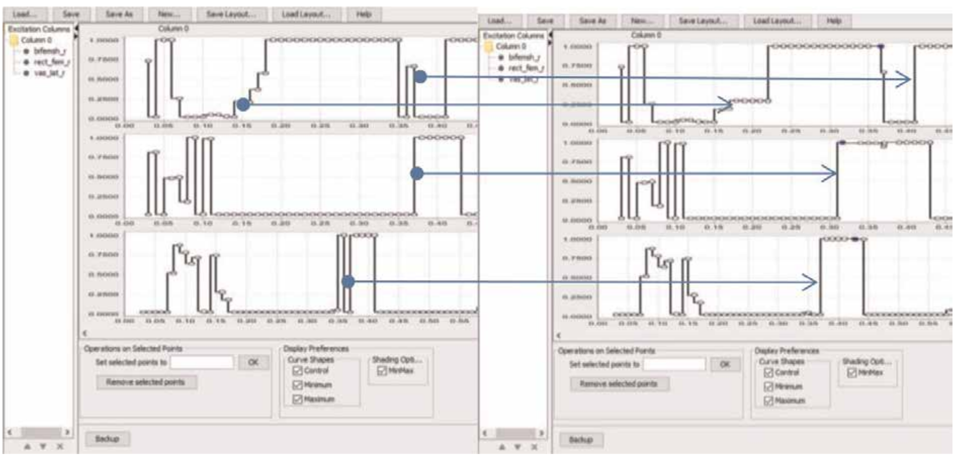

Figure 9.
Example of excitation editor for SA subject from group A. Muscles top to bottom—BF, RF, VAS; on the left—simulating muscle activity before making changes; on the right—simulation of muscle activity after making changes. Arrows show changes in muscle activity.

Athletes in group A in running use the "catapult" mechanism, in which the transfer of energy between the joints is carried out with the help of biarticular muscles. When performing repulsion while running, athletes of group B use the effect of accumulation and release of elastic deformation energy.

The data in **Table 3** show that group A during the 5.1 m/s run had low peak power (the sum of hip, knee and ankle joint powers of the leg that contacts with the surface) while having a high peak moment in the same group of joints. For the 3 m/s run the same subject demonstrates high aggregated joint moment, while the aggregated power is significantly decreasing. Both speeds have similar muscle metabolic costs and stiffness.

		Maximum moment, N m/kg	Maximum power, N m/s/kg	Stiffness	Energy transfer from hip to knee, %	Energy transfer from knee to ankle, %	Summary metabolic power consumed, W/kg
SA	Before (original)	1.72	0.304	13.1	0.52	1.19	9.76
	Modeled (changed)	1.63	0.291	13.3	0.48	1.23	8.86
PD	Before (original)	1.52	0.44	12.5	2.41	0.58	9.75
	Modeled (changed)	1.62	0.46	12.2	7.34	4.78	8.24

Table 5.
Modeling data obtained when increasing or decreasing the leg stiffness for subject.

These data suggest a significant change of running style for the two speeds. Subject from group A has strong isometric force capabilities for the knee muscles (**Table 1**). For the lower speed the subject uses his force abilities and demonstrates high stiffness of the leg touching the surface. The stiffness is driven by the large amounts of work performed by the muscles on the back side of the leg—SEM, BF, GMAX and SOL (**Figure 3**). The subject, however, does not use elastic strain energy. The muscle usage drives high metabolic costs and is linked to the usage of "catapult" mechanism. The "catapult" is explained by the energy transfer via bi-articular muscles. Strong monoarticular gluteus muscles, in particular, m. gluteus maximus (GMAX), play a major role in hop extension. Power from GMAX is transferred to a knee joint via a bi-articular m. rectus femoris (RF); knee joint extension is performed by RF and a group of monoarticular m. vastus (VAS). Extension in a knee joint causes plantar flexion in an ankle joint due to energy transfer via m. gastrocnemius (GAS), thus contributing to contraction of a triceps muscle of calf. This mechanism was described in few studies devoted to examination of biomechanics of running, hopping and vertical jumps [13, 14, 25, 35, 36].

In contrast to the 3 m/s run, while running at 5.1 m/s the subject does not use the "catapult" mechanism, and the excentric mode work is largely performed by the thigh de-flexion muscles (VAS). The GAS and SOL muscles are almost not used in the movement due to their low metabolic outputs (**Figure 2**), i.e. the "force" push-off option is used.

Compared to group A, for group B we have observed lower peak joint moments and peak powers, as well as lower stiffness while running. However, the usage % of ESE is much higher (**Table 2**), especially for running at the speed of 3 m/s. This leads to lower metabolic costs at the speed of 3 m/s. At the same time, for the 5.1 m/s experiment, the 2-time decrease of ESE usage leads to almost 2-time increase in the metabolic costs. Group B, compared to group A, does not change the technique from one speed to another, which is proven by the same muscle usage (**Figure 3**). ESE usage decrease for 5 m/s can be explained by elevated work of the hamstrings (SEM, BF and GMAX), which is connected to lower power capacity of the subject (**Table 3**). Push-off is performed by lowering the muscle contraction rate, but this leads to increase of the leg stiffness, which, in result, leads to increased metabolic costs.

It is worth mentioning that ESE transfer from joint to joint is achieved using a different mechanism: the mechanism of energy transfer by bi-articular muscles.

The mechanism of energy transfer starts working when a bi-articular muscle is operating in concentric regime. However, when it operates in an almost isometric regime (i.e. very low speed of contraction), it can develop a greater force [25]. Furthermore, bi-articular muscles help involve monoarticular muscles into performing in the optimal way in order to achieve the most effective energy usage [37].

This metric can be used to estimate the stiffness of the leg. Intuition tells us that vertical fluctuations have negative effect on energy economy. Dalleau et al. [34], Arampatzis et al. [18] emphasized the importance of neuro-muscular factors and demonstrated that RE depends on the leg stiffness, with higher stiffness leading to better RE. Similarly, Williams and Cavana [38] have shown the tendency (albeit, small) toward smaller vertical fluctuations and better RE.

However, we do not observe a decrease in total muscle metabolic costs, since in absolute values the changes are too small. For running exercise, the change of the stiffness is connected with the increase of required power through increasing the work of two-joint GAS muscle (**Figure 5**). Presumably, the same fact for lower stiffness can be explained by larger preemptive flexion of muscles in the amortization phase.

For subjects from group B, when we increase stiffness the sum join moment is also increased because of significant bump (24.2%) in ESE component. This model behavior leads to a significant decrease in the overall metabolic cost (7.7%). If we lower the stiffness the metabolic cost is highly increased, because in this case we have to stress the muscles that de-flex knee and hip joints (RF) and additional use the hip flexion muscles (PSO)—see **Figure 6**.

The stiffness change modeling demonstrated that the metabolic cost impact of these changes is heavily dependent on subject's individual characteristics. For the subjects from group A, who is better strength capacity and uses the "catapult" energy transfer approach, it is very difficult to change and adapt the running technique. This leads to extra metabolic costs. The subjects from group B, changing the technique leads to a better energy economy.

A forward dynamics (FD) simulation is the integration of the differential equations that define the dynamic behavior of a musculoskeletal model with revised (modified) muscle activation data for predetermined time intervals. In contrast to inverse dynamics, where the motion of the model was known and the forces and torques responsible for the motion were required, FD is a mathematical model that outlines how coordinates and their velocities change due to the application of forces and torques (moments). The modeling for this part of the experiment was performed only for the running speeds of 5.1 m/s aimed to lower the total metabolic cost.

For the two studied cases, the following assumptions were used. For the SA subject (**Figure 7**), the introduced muscle changes were aimed to increase the leg stiffness by co-activation of "antagonist" muscles when transferring from the concentric muscle regime to eccentric muscle regime.

Calculations for individual muscles demonstrated that the most drastic drop in metabolic cost for SA subject is concentrated in the muscles responsible for body stabilization—PSO, SEM. For PD subject, the calculations outlined that the highest metabolic cost reduction is linked to RF and VAS muscles. This can be explained by the fact that the modeling muscle activation was aimed to decrease the impact of antagonist muscles.

The technology is based on using a regulated testing procedure aimed to discover individual characteristics of an athlete, not only of his/her technique, but also of the related physiological functional systems abilities. Then we use computer modeling with pre-selected criteria for motion optimization in order to achieve the best result.

This data allows us to select the options, training method aimed to correct specific areas. During this time the target (end) result is known, which makes it a more structured approach.

Limitations that exist in this study should be noted. Firstly, in a computer simulation experiment, one successful option for calculating the direct dynamics, found by manual selection, is presented. Secondly, we must take into account that the above statements can only be extrapolated to performing cyclic running exercises on a flat surface. At the same time, the biathlon tracks pass through rough terrain. The model presents only a limited number of skeletal muscles and their characteristics of contractile behavior. Potential differences in the functioning of the fast and slow muscle fibers of the contracting muscle are not taken into account. However, the present model can also form the basis of a more complex model, which includes the behavior of other physiological systems (cardiovascular, respiratory). Thus, it can be used to study the contribution to which the variability in the behavior of these systems introduces certain limitations in the use of biomechanical mechanisms to save metabolic costs in running. Future studies can use the developed methodology in this study to determine the individual characteristics of the - locomotion technique and use this information to develop special strength and - coordination programs to improve athletic performance and reduce the risk of injuries.

5. Conclusion

Despite the limitations of our work, we believe that two important conclusions can be drawn from this study. First, it is defined that top-class athletes in cyclic endurance disciplines tend to use various biomechanical mechanisms for performing movements. Despite the fundamental difference in the organization of these mechanisms, they can equally be used to reduce metabolic costs.

Our second finding is that our model of muscle energy expenditure provides greater insight than simpler measures based solely on raw instrumental data on muscle activation (electromyography data) or measurements of mechanical joint power and/or the Center of Mass from tensometry data. Computer models of muscle energy allow us to study energy consumption with unprecedented accuracy, complementing the indirect calorimetric measurements obtained experimentally at the whole body level.

This research shows that modern hardware and the modern computer technologies can be used to enable 'pin-point' engineering approach for training purposes, including constructing highly accurate forecasts for each athlete depending on the suggested training activities—ultimately leading to greater results in professional sport.

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Chapter 3

Conditioning Strategy for Previous Injured Players

Tomonori Kawai

Abstract

Football players are prone to sports injuries such as ankle sprain, groin pain, ACL injury, and so on. Muscle strain injury also frequently occurs in football games or practice. As previous studies show, previously injured players have altered muscle and neural functions as well as tissue properties associated with muscle strain injury. They have altered vibration sense, tissue stiffness, and increases in micro-muscle damage. However, training load or conditioning programs are provided the same as those for uninjured players in most cases. In this chapter, the conditioning strategies for players who have previous muscle injuries will be suggested according to the phenomenon after muscle strain injury.

Keywords: muscle strain, conditioning, sensory, monitoring, training load

1. Introduction

Musculoskeletal injuries have occurred in over 30% of all players in the major professional football leagues. Furthermore, injured players lost almost 1/4 of total time due to injury in a season. Overall incidence is 8.1 injuries in 1000 hours of exposure; training-related incidence is 3.7 injuries in 1000 hours; and match-related incidence is 36 injuries in 1000 hours. Incidence rates are higher in lower extremity injuries compared with other regions [1].

Among the lower extremity injuries, hamstring strain is the most common injury, followed by groin injuries, ankle sprain, and ligamentous injuries of the knee [2].

Most studies of epidemiology are investigated in European league players with limited studies in other professional leagues such as Arian, American, or African leagues. Since body composition varies in races and affects injury ratio, more comprehensive regional studies are required [3].

Injuries have negative impacts both financially and physically on teams and players, and they, of course, decrease team success. The loss of the players due to injury is important for the team because of the limited funds or resources. An injury will lead to neuromuscular alteration and increase the risk of developing osteoarthritis later in an athlete's career depending on the rehabilitation [4]. Therefore, injury prevention is a key factor to sustain the productivity of the team and a player's performance [5].

In the last decade, a large number of studies related to injury prevention have been released in football. Literally, the study shows that the injury prevention program such as "The 11+" from FIFA has been recently implemented for professional, amateur, or youth football teams [6]. Nowadays, a lot of injury prevention techniques have been introduced; some examples are as follows.

- Eccentric strength exercise prescription tends to decrease recurrent hamstrings' muscle strain [5].

- Core stability exercise intervention may decrease the rate of back and lower extremity injury [7].

- Balance training, especially a soccer-specific balance training implementation, could reduce hamstring injury and tendinopathy [8].

- Stretching is still suggested pre- and post-training. Even though stretching does not significantly reduce injury rate, it may slightly reduce the injury rate [9].

- GPS monitoring and increase in training and gameplay intensity could predict soft tissue injuries [10].

However, here is a question: "Is Injury prevention actually possible for all players?" Even though some injury prevention programs seem to be effective, the recurrent ratio of muscle strain has not decreased [11].

At that point, injury prevention has been controversial, and football-related injuries may be inevitable. It is suggested that more reliable and valid studies in epidemiology or statistics will be necessary. Plus, it needs to be investigated for preventive programs or devices, for example, medical screenings, warming up, protective equipment, training programs, stretching methods, or team education [12].

Furthermore, in order to make an effective injury prevention program in some factors, the program should be modified or personalized.

One of the factors as to why all "effective" injury prevention programs do not work may be their behavioral aspects.

Any kind of program can be ineffective without the player's active involvement. There have been a few studies related to injury prevention as a social and behavioral science [13]. The main theories are the Theory of Planned Behavior and the Self-Determination Theory [14]. The examination of injury prevention is utilized to integrate two theories, and it can positively predict intentions of injury prevention [15]. Behavioral factors should be considered in order to take injury prevention programs into effect.

The second factor is multicomponent injury prevention intervention.

Since only one injury prevention program may not be enough to reduce injuries, it has been suggested that injury prevention programs should combine two or more programs.

For example, stretching exercises and movement screening, which are part of the suggested programming, may not reduce injury incidence [9].

"Nothing is perfect." Like Nordic hamstring exercise, which is one of the most reliable injury prevention exercises for hamstring muscle strain, but this exercise cannot perfectly prevent injury. Medical or conditioning staff in sports teams should not focus on only a single component of injury prevention intervention.

Another factor can be that previous injury history will influence effective programming. The recurrent injury rate in football has been high. Recurrent injury incidence is higher within two months after returning to training. These results are considered a premature return to play "too much too soon." There is still a lack of evidence-based criteria for a safe return to play; therefore, the true reason for recurrent injury has been unknown [1]. Even so, a previous history of injury is considered a strong predictor of recurrent injury, such as hamstring strain injury, and it leads to some functional alterations such as neuromuscular function, sensory function, or tissue stiffness [16, 17].

To take into consideration these results, the players who have a previous history of muscle injury may receive different feedback from the players who do not have a history of injury. Moreover, players who have a previous history of muscle injury tend to have a raised urine titin fragment value compared to healthy players on the same training load condition. A fragile titin filament can lead to less resistance during muscle activity [18]. It may alter neuromuscular activities and lead to neuromuscular fatigue [19].

As excessive fatigue is associated with performance failure, decision-making ability, coordination and neuromuscular control with an overwhelming training load, and management of fatigue are important factors in preventing injury [20].

In the recent decade, the concept of workload management, in other words, "load/capacity" management, has appeared and been applied to the sports field.

Training workload is measured as a prescribed external training load, such as physical work, combined with internal training load such as physiological or perceptual response.

The concept of workload measurement has been controversial. It is suggested that there are further reliable parameters because of their inconsistent values; therefore, more individualized consideration will be required [21].

This chapter includes a proposal of reconsidering internal workload and conditioning strategy, especially for those players who have had a previous muscle injury, because previous injury may affect internal workload value.

2. Conditioning strategy

2.1 Workload

Workload measurement and training-load monitoring have been a part of standard conditioning methods in football teams. According to some studies [22, 23], they may reduce the injury ratio.

The concept of workload first appeared in the 1970s, and it proposes that the performance of an athlete in response to training can be estimated from the difference between fatigue and fitness, called the Fitness–Fatigue Model [24]. To strike an appropriate balance between the positive side, fitness, and negative side, fatigue, the ideal training stimulus does not exceed the capacity of training load.

The concept of ACWR is based on the Fitness–Fatigue Model, introduced in 2016.

ACWR attempts conditioning management, performance development, and injury prevention by the relationship between acute and chronic workload data. Inadequate training-load management and prescription is one of the risk factors for injury [20]. The key of ACWR application in the sports field should be comparing the acute training load to the chronic training load, which provides the feature of the conditioning. If the acute training load is low, it means less fatigue, and if the chronic training load is high, it means fit. As a result, athletes should be prepared to train or compete in this condition.

The optimal ACWR is in the range from 0.80 to 1.30, called the sweet spot, which is the lowest relative injury risk. When ACWR is too low (less than 0.80), it means under-training and a higher relative injury risk. When ACWR is too high (1.50 or more), called the danger zone, it is the highest relative injury risk [25] (**Figure 1**).

Both too low and too high ACWR may be necessary to manage the training load. The value of ACWR varies from sports to sports, such as Australian football, cricket, rugby, and soccer [26].

In fact, evidence shows that the lowest relative injury risk in the “sweet spot” can be between 1.00 and 1.25 in professional soccer; on the other hand, the sweet spot is 0.85 to 1.35 in rugby league [27].

Thus, when utilizing the ACWR concept, it should be a sports-specific or individualized monitoring protocol.

The ACWR is generally calculated by external training load and internal training load. External load is an objective measurement, that is, the external stimulus exposed to the athletes. External load commonly includes total distance, number of sprints, body load, or weight lifted. Recently, global positioning system (GPS) has been utilized for monitoring external loads.

Internal load is both an objective and subjective measurement, which is the individual’s physiological and/or psychological response to external loads. Internal load basically includes ratings of perceived exertion (RPE) applied as session ratings of perceived exertion (sRPE), heart rate, blood lactate concentrations, or creatine kinase measurement [28]. Most internal load measurements include RPE. RPE is a subjective measure of how hard an athlete feels during physical activity. The first appearance of RPE was created by Swedish psychologist Gunnar Borg as the RPE/Borg scale. The

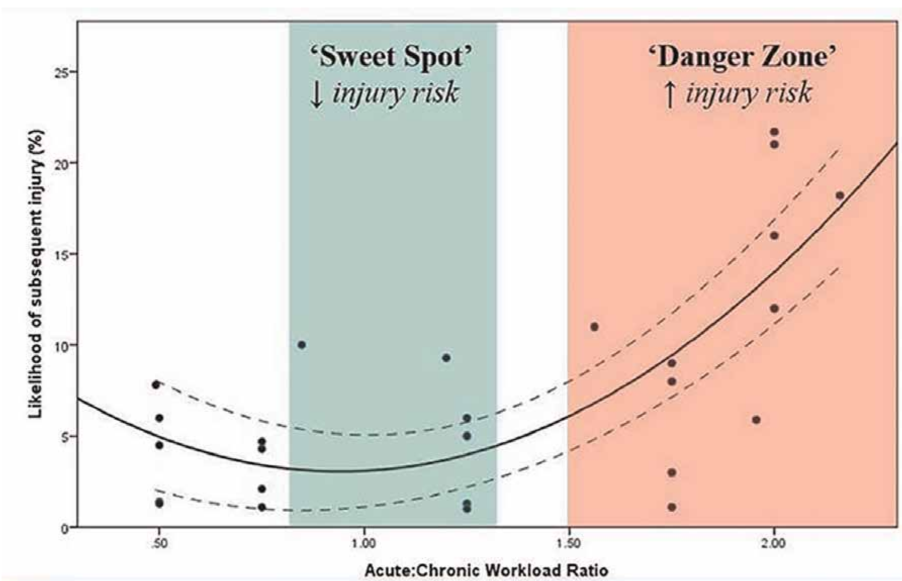

Figure 1.
If ACWR is above 1.5 “danger zone”, there is a significantly increased risk of injury within 1–4 weeks after rapidly increasing training load [25].

original Borg scale rates an athlete's level of exertion on a scale from 6 to 20, with 6 being "very light" and 20 indicating "very difficult". If the 6–20 rating was multiplied by 10. Borg also added a 10-point scale (Borg CR10 scale) that is utilized in medical or psychological fields in addition to the sports field. In an actual sports setting, athletes subjectively provide a 0–10, −100, or 6–20 rating on the intensity of the training session, and the intensity of the session is multiplied by the session. The unit of training load for RPE is calculated by the multiplication of training intensity and the length of training.

Training Load (AU) = RPEX session duration (min).

Example: 60 min training with RPE of 7 (very hard) = 420 AU.

Generally speaking, the range of training load is between 300 and 500 AU for lower intensity training and between 700 and 1000 AU for higher intensity training.

The acute workload is performed daily or weekly, but it is typically performed in one week. The chronic workload is calculated as 4 weeks' accumulation divided by 4.

Example: week 1 = 420+ week 2 = 720+ week 3 = 480+ week 4 = 640/4 weeks = 565AU.

To calculate ACWR, an acute workload of 420 AU is simply divided by a chronic workload of 565 AU, providing an ACWR of 0.74(420/565 = 0.74). Well-known research suggests that if an ACWR is between 0.8 and 1.3, it is called the "sweet spot" for less injury risk; however, if an ACWR is above 1.5, it is called the "danger zone" for highest injury risk. In addition, if an ACWR below 0.8, it also increases the injury risk due to under-training [25]. Therefore, by following the suggestion, the example athlete could increase injury risk by under-training.

Communication between athletes and coaches with personal oral and/or written feedback is important for identifying potential issues with motivation, stress, fatigue, and training. Behavioral aspects should be taken into consideration as crucial information in order to avoid motivational problems.

Models for ACWR calculation:

- The Rolling Average Model
- The Exponentially Weighted Moving Average Model

The Rolling Average Model

In the Rolling Averages Model, ACWR is calculated by dividing the acute workload by the chronic workload. Each workload in an acute and chronic period should be equal; therefore, all workloads in a given time period are seen as equivalent. If the chronic workload is greater than the acute workload, ACWR is lower. On the contrary, if the acute workload is greater than the chronic workload, ACWR is higher. The problem of this model is that it cannot accurately represent variations in the way loads accumulate.

The Exponentially Weighted Moving Average (EWMA) Model is calculated as below. EWMA (t) $= a^* x(\mathrm{t}) + (1 - a)^*$ EWMA(t-1).

EWMA (t) = moving average at time.

a = degree of mixing parameter value between 0 and 1.

$x(t)$ = value of signal x at time.

EWMA describes the decaying nature of fitness because it emphasizes the most recent workload. It is considered as a variation in the manner in which loads are accumulated [29].

Even though both models show a high ACWR indicating increasing injury risk, the EWMA model is more sensitive to detect the injury risk due to the decaying nature of fitness [30].

Since ACWR measurements are popular in sprint sports such as football, running distance and number of sprints using GPS are mostly used for training-load measurement. However, other useful measures should be considered depending on the sports. For example, shoulder or elbow torques have been utilized in baseball.

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Moreover, if the team could have any adequate equipment for the examination of neuromuscular fatigue and recovery, for example, countermovement jump, exercise velocity, or musculoskeletal tests, those assessments would be useful for neuromuscular recovery and injury prevention.

2.2 Problem of the workload measurement

There are some issues with the ACWR monitoring and application for the actual sports field. The data for training load must be accurate and reliable in order to measure precise ACWR. However, Gabbett et al. pointed out mathematical errors of accumulation for ACWR data. If ACWR is 0.5–1.0, the midpoint of 0.75 is used as the ACWR score. As the endpoint is 0.5–2.0, any score below or above it is treated as 0.5 or 2.0 [31]. Furthermore, ACWR measurements are not enough for injury prevention because ACWR is a measurement for training load but not mechanical load for tissue damage. Plus, old injuries affect mechanical load and consequently increase tissue damage [32]. Therefore, the individual characteristics of each athlete, such as age, physical capacity, and injury history, should be taken into account when determining the training load in order to determine the training outcome. This is especially true for individual information about muscle injury history; it is linked to fatigue; therefore, it affects RPE as an internal load [33].

2.3 Consider previous injury

It is well-known that previous muscle injury history is the greatest risk factor for reinjury. Even though the relationship has not been clear, there are some alterations after muscle injury [34].

2.3.1 Neuromuscular inhibition

Due to scar tissue formation after muscle injury, it leads to the development of maladaptation including eccentric hamstring weakness, selective hamstring atrophy, and shifts in the knee flexor torque-joint angle relationship [35].

2.3.2 Muscle weakness

Previously injured players had muscle weakness on injured limbs. Besides, if the injured leg was nondominant, the dominant leg was much stronger before injury. That compensation will lead to improper sports performance [36].

2.3.3 Nerve conductivity

Athletes who had previous hamstring muscle strain had lower sciatic nerve conduction velocity. It may be due to damage in nerve tissue and the myelin sheath and/or axonal thinning. Because eccentric contraction during sprinting and sudden acceleration are incidences of muscle strain injury, alteration of sciatic nerve conductivity will affect the mechanism of muscle strain injury [37].

2.3.4 Decreased sensory function and increased tissue stiffness

The study shows that athletes who had previous muscle strain had decreased sensory input such as vibration sense in the injured area. Additionally, they had increased tissue stiffness [17]. This tissue stiffness is most likely from the stiffness of fascia, which contains viscoelastic ground substances [38]. Stiffer tissue affects the sliding system of the connective tissue, and it is important to sustain optimal tissue stiffness by tissue hydration [39]. Fascia contains abundant nerve receptors, free and encapsulated nerve endings such as Pacinian corpuscles, and Ruffini endings, which respond to mechanical forces [40]. Previous injury causes some damage in the fascia as well as muscle [41]. Stiffer tissue will change its mechanical properties and affect the sensory sensation through nerve receptors. Incorrect sensory feedback by nerve receptors alters muscle activation patterns and movement execution [42]. Therefore, these changes may lead to compensatory movement during sports activity.

2.3.5 Increased muscle damage

The study shows that larger urine titin fragment values are observed in previously injured football players after training compared to uninjured players [43].

Titin is a mechanical protein in muscle cells that has the function of stabilizing the filaments, preventing overstretching of the sarcomere, and recoiling the sarcomere as a spring effect [44]. Since the function is related to the mechanism of muscle strain injury that is mainly caused by eccentric contraction during lengthening of the muscle fiber, it is considered to have an important role in muscle strain injury. Chronic musculoskeletal injury will change structurally or physiologically as a response to the adaptation of neurophysiological processes. Fragile titin filament may lead to less resistance during lengthened activation of contracted muscle. As a result of this phenomenon, neuromuscular activity is altered in previously injured players.

In addition, the kinematic change from the micro damage will lead to fatigue response to muscle activities. This means that previously injured players experience more fatigue in response to training or games than uninjured players. Therefore, team staff should be careful to manage their training response more than uninjured players.

2.4 Reconsider internal load calculation for previously injured players

Currently, the internal load mostly counts for RPE, heart rate, and heart rate variability. Nowadays, football has become a more explosive sport, requiring more running distance and a greater number of sprints compared to the last several decades. Thus, heart rate might be a useful measure for internal load. However, from the point of injury prevention, most injuries are musculoskeletal injuries rather than cardiovascular problems. In this respect, heart rate may not be the right measurement for internal load in football [45]. In addition, the activity of muscles and tendons, power output, and force sustention during a football game or training can be a part of the aspects of the load in RPE score.

Therefore, RPE is a better representative measure of the internal load in order to prevent injury as well as evaluate the performance [46].

RPE is a very simple and feasible way to subjectively assess how hard an athlete feels to gauge the training and game intensity in the actual sports situation.

Previously injured players tend to have high micro-muscle fiber damage and may feel more fatigued compared to uninjured players. They have more muscle fiber damage, mostly within a day, and they may react more sensitively following the training [47]. Therefore, previously injured players may require daily training-load monitoring rather than weekly monitoring.

Body awareness is the key to know how previous injury affects RPE.

Body awareness is how conscious and connected to the body, the awareness of the position and movement, or feeling of body parts is.

As abovementioned problems with previous injuries, previously injured players tend to alter their proprioceptive function. Thus, they may feel an awkward sensation of their movements. Another expression of body awareness is "interoceptive awareness". Interoceptive awareness is the conscious awareness of internal physiological states. Interoception is described as a physiological sensation such as touching, joint motion, or vasomotor reaction.

Interoception has become a popular concept in health-care professions, especially those who follow the subject of fascia, because the sensory receptors of interoception are mainly free nerve endings, and these are seen in fascial tissues.

Such free nerve endings are unmyelinated sensory nerve endings, and they transmit to the insular cortex and not to the somatosensory cortex, which is considered as the proprioceptive center [48].

Interoceptive sensations produce feelings that are not only sensory but also affective and motivating and are related to sustaining homeostasis. They are linked to behavioral motivations that are necessary for maintaining the physiological integrity of the human body. In competitive sports, athletes should be encouraged to focus on the task of identifying primary internal sensations of tiredness as RPE. In particular, previously injured players tend to damage micro-muscle fibers more compared to uninjured players, as mentioned before [43]. Such players tend to express higher sRPE depending on the condition of the injured area.

An internal sensation may be only part of the interoceptive sensations. Internal perception is sometimes almost entirely focused on proprioceptive refinement. Recent research has shown that interoceptive sensation is sensitive to pleasant touch [49].

When the nerve receptors in fascial tissues are stimulated, they provide sensory feedback such as tissue stretching, vibration, or light touch to the brain, and this information will be integrated for the movement and achieve neuromuscular control. It has been demonstrated that if athletes change the sensory input from the tissue, they will exhibit movement changes during sports activities. Because previously injured players could impair their sensory feedback, assessment of the sensory information could be a useful tool for interoceptive sensation of previously injured players.

Previously injured players tend to have stiffer tissue around their injured tissue [38]. The stiffness is mostly affected by the viscoelastic ground substances [50]. Stiffer viscoelastic properties may affect the sliding movement of connective tissues and change the biomechanics of the soft tissues by force transmission of FTs when the tissue is stretched [51]. Therefore, feeling the stretching on the stiff tissue can be an assessment tip for previously injured players.

Optimally, the sensory function should be evaluated by a somatosensory evoked potential test (SEP), and stiffness should be evaluated by an examination device such as elastography or soft tissue stiffness meter. However, it takes time and costs; therefore, it is not realistic to apply to actual sports-team management. In addition, the overwhelming data can be the pitfall of the ACWR calculation. The team staff finds it hard to manipulate mountains of data.

Taking the abovementioned factors that can alter proprioceptive and interoceptive feedback integration, I would like to suggest the following two internal load measurements for previously injured players (**Figure 2**).

Subjective scale for feeling

1. Sensory

As athletes monitor their RPE, previously injured players monitor "how they feel" on their injured area. The simplest and feasible way is touching their injured area. The less the feeling, the more is the altering in their sensory input (**Figure 3**).

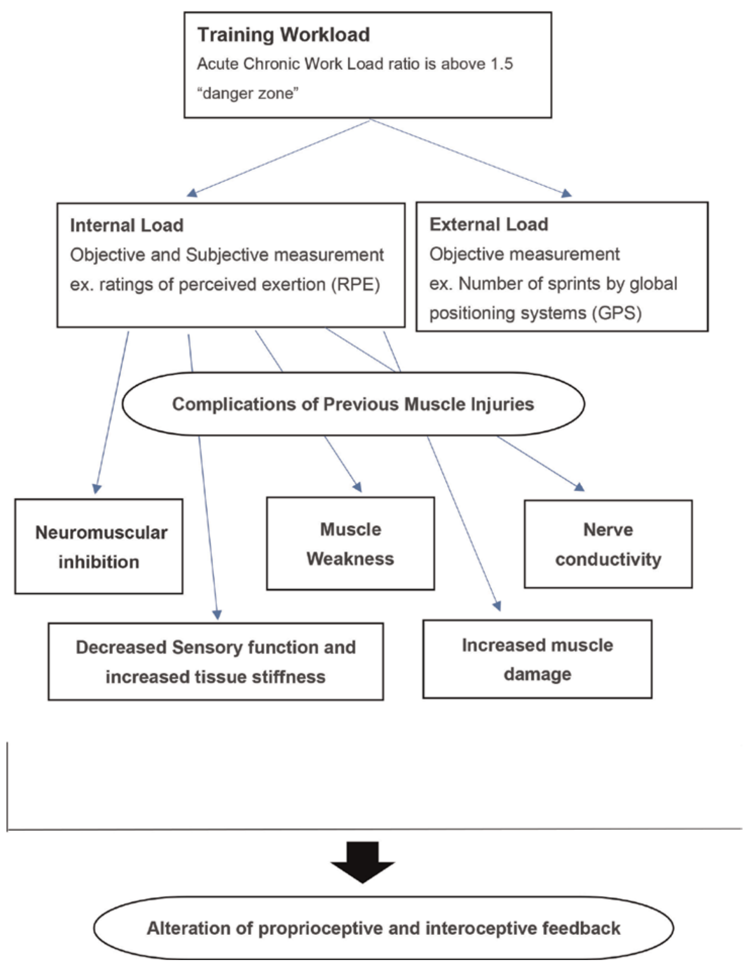

Figure 2.
Flowchart of alterations due to previous muscle injury.

Figure 3.
Athletes put their hand or a cotton pad to the injured area and scale "how they feel?" from 1 to 10.

1. Stretching.

Same as monitoring sensory, monitoring "how they feel" with stretching as a function of injured muscle. The less the feeling, the more is the altering in their sensory input (**Figure 4**).

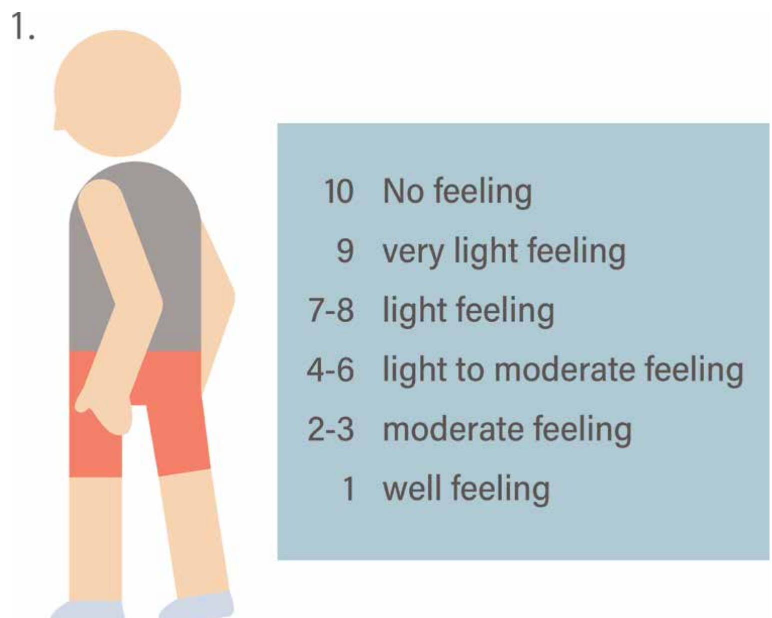

Figure 4.
Athletes stretch a muscle of their injured area and scale "how they feel?" from 1 to 10.

3. Discussion and conclusion

Management of the training load is considered one of the most recognized and useful tools for sports-team conditioning. Actually, it has been considered as an injury prevention method in current studies. However, current monitoring methods may require some improvement; for example, they should be more individualized.

Oftentimes, each athlete is suffering from other difficulties rather than sports activities and external stressors; for example, friendship relationships, financial difficulties, family-related psychological stress, fatigue, sleep quality, or lack of motivation [52].

Furthermore, current analysis has been more focused on external load and ratio, but internal load, especially for previously injured players, tends to be high and alters their subjective feeling in response to the training.

The monitoring should be simplified in order to easily apply to teams. However, to maximize compliance, the monitoring has to be adjusted individually for optimal conditioning.

The goal of conditioning is to optimize the performance of the athlete and minimize the risk of injury. Each athlete has a different reaction following the training. Physical Stress Theory describes this as "changes in the relative level of physical stress cause a predictable adaptive response in all biological tissues." That means the body adapts and reacts to a given stimulus, and mechanical stress levels change in response to the amount of that stimulus. They alter sensory function and increase muscle fiber damage associated with fatigue, which causes their biological adaptation to mechanical stimulus to differ from that of uninjured players.

Previous muscle injury is the strongest risk factor for football injury and causes some changes.

When muscle strain injury occurs in fascial tissues that contain abundant proprioceptive receptors, there are two possible alterations. First, it can be damage of the loose component that affects the sliding system between different layers. Another one is the damage of the fibrous component that affects the capacity of loading transmission [53]. Furthermore, accompanied with damage to proprioceptive receptors, it can be alteration of the collagen fiber composition, a transformation of fibroblasts into myofibroblasts, or changes in ground substance [54]. This consequently changes some problems after suffering from muscle strain injury. Athletes with changed tissue stiffness and sensory input may change their body awareness, coordination of movement, and muscle activation patterns and achieve neuromuscular control [53, 54], resulting in incorrect movements during sports.

These alterations can lead to a possibly increased risk of a subsequent sport injury. Moreover, because previously injured players have more muscle fiber damage associated with the training, they may feel more fatigued, which is one of the internal risk factors of muscle injury.

The definition of conditioning is "the process of training to become physically fit by a regimen of exercise, diet, and rest."

Training load is currently calculated by mostly combining external load such as GPS and internal training load such as RPE. However, because previously injured players are more likely to have a different internal load compared to uninjured players and since their feelings of being "physically fit" and recovery from "rest" can be different from those of uninjured players, their conditioning strategy will be more individualized and specific.

Therefore, I strongly suggest that previously injured players should “never ignore their body sign” and monitor their sensory function as a simple and feasible way in order to sustain their optimum condition.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 4

Development of Quantitative Movement Analysis Software Specifically for Boxing Competitions

Kouichi Nakamura and Takayuki Kodama

Abstract

Boxing is the ultimate contact sport in which the objective is to knock down an opponent by striking the opponent in the head and abdomen with knuckle punches while wearing minimal protective gear. Sports trauma and injury surveys of professional and amateur boxers in Japan and overseas have reported athletes suffering not only from orthopaedic disorders, such as lacerations and fractures, but also from acute subdural haematomas after knockouts and even chronic traumatic encephalopathy after retiring from boxing. Efforts have been made to improve boxing safety by improving the protective equipment and revising competition rules. However, the nature of the sport has not allowed significant results to be achieved. The primary prevention of trauma and injury during boxing involves avoiding attacks by an opponent. This chapter focuses on the performance of boxing from a scientific perspective, mainly the improvement of defensive techniques, and examines the usefulness of quantitative motion analysis software developed specifically for boxing. The fusion of boxing and technology is a step towards the construction of a new support system for the primary prevention of sports injuries and its potential has been explored.

Keywords: boxing, analysis software, performance, injury prevention, technical assistance

1. Introduction

Boxing is a contact sport in which fighters strike each other directly with their fists on the head, face, and abdomen. Amateur boxers, such as those competing in the Olympic Games, wear headgear and are judged based on the number of clean punches they land on their opponents, whereas professional boxers wear no protective gear other than a mouth guard and are judged based on the damage or knockout they inflict on their opponents. In general, professional boxers are paid by their gyms through the sale and purchase of tickets, endorsement fees from sponsors' names and logos on their outfits, and fight money given by the promoter, whether the fighter wins or loses. In the modern era, athletes' livelihoods are supported by pay-per-view

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viewership. Top athletes have an increasing number of sponsors and additional sources of income, such as endorsements, television appearances, joint product development with companies, book sales, and speaking engagements. According to a 2015 Forbes article, the top-earning celebrity in the world, with an annual income of $300 million, was Pro Bobo, ranking first on the list of the world's highest-earning celebrities. Topping the list of the world's highest-earning celebrities, with an annual income of USD 300 million, was Floyd Mayweather Jr. The fact that Floyd Mayweather Jr. was able to take first place ahead of football, which is said to have the world's largest athlete population, musicians supported by passionate fans, and holiday stars strutting down the red carpets, shows the potential of boxing as a professional sport. The fact that Floyd Mayweather Jr. was ranked number one ahead of the musicians and the holiday stars strutting down the red carpet shows the potential of boxing as a professional sport.

Despite its glamourous world, boxing, due to its sporting characteristics, causes a high incidence of sports injuries and disorders. In a trauma and injury survey involving amateur boxing, orthopaedic conditions, such as lacerations and fractures and cranial nerve conditions, such as acute subdural haematoma were frequently observed, and fatal accidents caused by these conditions have been reported [1]. Although improvements have been made with respect to the protective equipment and the rules of sports have been reviewed, it is difficult to say that the number of traumatic injuries and disabilities has decreased [2, 3]. The primary prevention of trauma and injury during boxing involves avoiding attacks by an opponent. This requires improving defensive techniques to avoid being attacked by the opponent and simultaneously improving offensive techniques to increase the rate of hitting the opponent, which is a strategy to prevent trauma and injury by ending the fight early. Boxers, who are often forced to lose weight as a fight approach, are trained based on nutritional and training science. However, it remains to be seen whether technical strategies in boxing offences and defence have been addressed from a scientific perspective.

This chapter begins with an overview of the origins of boxing in order to understand the sport. Next, the current status of sports-related disorders in boxing and the mental characteristics of boxers are summarised. Therefore, this chapter explores the possibilities of merging sports and technology by presenting findings from the development and operation of quantitative motion analysis software, specifically for boxing.

2. Origins of the sport of boxing

2.1 Ancient Olympics and fist-fighting

The origins of boxing are unclear; however, there is evidence of boxing-like games (fisticuffs) in Egyptian and Mesopotamian civilisations as early as 3000 BC, as evidenced by murals and vases. Boxer figures, thought to date from 1600 BC to 1200 BC or earlier, have also been found throughout the Mediterranean. However, it is from the ancient Greek period that continuity with modern boxing was most likely established. The earliest record of a fistfight for a prize is found in Homer's heroic epic poem The Iliad (c. 750 BC), which dates back to ancient Greeks [4]. The image of two fighters, cloth wrapped around their waists and a cowhide wrapped around their fists, fist-to-fist, is preserved in a mural in Akrotiri, Santorini, in the northern part of Greek Crete. The city state of Polis was born in Greece in the 8th century BC, when Homer's heroic epic was written. Agriculture and herding were carried out by slaves, whereas the aristocracy and wealthy citizens participated in sports. For ancient Greeks, it was of utmost importance that various religious rites of the ancient world be performed according to their traditions. During rites and festivals, athletic competitions were often organised, such as funeral games, the most important of which were the Ancient Olympics. The most important of these was the Olympic Games, held as a festival in Olympia in the domain of the god Zeus. The first games were held in 776 BC, and the compilation of records of the Ancient Olympic champions began around 400 BC. Although there is some dispute as to whether this is an accurate account of what happened approximately 300 years before the compilation began, it seems certain that the games were held every four years without interruption for at least 1000 years, from 6th century BC to 4th century AD [5]. Pugilism was introduced in the 23rd century (688 BC) and was a popular sport. Socrates, a famous philosopher, was a fist-fighting enthusiast person who travelled from Athens to Olympia for three days and three nights to watch the games.

2.2 Rules of fistfighting

The exact rules for fisticuffs at that time were not known; however, analogies can be drawn from vase paintings, murals, dictionaries, and descriptions in the literature. These rules are significantly different from those of modern boxing. First, the shape of the playing field was unknown; however, no ropes were used to divide it. There was no class system based on weights or other criteria. The match combinations were also determined by lot. Once a match began, the fighters were required to stay close to each other and fight without resting. The referees used ladders and stick-like devices to encourage fighters to hit each other in close proximity. Referees would sometimes hit fighters who clinched, as clinching was forbidden. There was no round system or time limit; however, the referees allowed fighters to take breaks during a bout if they agreed. Forbidden were holds, blows to the groin, etc., which are common in wrestling [6]. Victory or defeat was decided by one side holding up one or two fingers to signal surrender or by the other side fainting; there were no draws or judges' scores.

2.3 Changes in fittings in fistfighting

The only fastening device was a cord wrapped around the fist. In 5th century BC, athletes began to use soft cowhide cords, called himantes to secure their wrists and fingers and wrap around their arms. However, the himantes were complicated and time-consuming to wind; therefore, a ready-made fastening device was developed in the form of a coiled leather cord. The "sharp strap" (oxeis himantes) was the first official boxing glove in history. The fingers were held in place using hard leather straps and the inside was made of wool to protect the hand. This type of equipment was used until the end of the 2nd century during the Roman period [7]. This was followed by the infamous caestus, which was reinforced with iron and lead. Reinforced with iron and lead, it was not as much a glove as a weapon in itself (**Figure 1**). Changes in the first attachment also changed the fisticuffs. In the early days, when soft leather straps were used, contestants competed with agile offensive and defensive techniques. However, when 'sharp straps' were introduced, the damage caused by a single strike shifted the movement to a defensive focus. Later, when the caestus was introduced, the game became a bloody and destructive spectacle and a contest of facial and physical destruction.

Figure 1.
Originally, the himantes was a thin leather strap wrapped around the wrist to secure the finger joints (two left), evolving into a glove in the 4th century (two middle) and a kaestus (two right) reinforced with iron or lead in the Roman period [Andronikos M, 1981].

2.4 End of the ancient Olympic games and the codification of fist-fighting rules

The end of fistfighting in antiquity is said to be due to the total ban on pagan rituals issued by Theodosius I as a result of the nationalisation of Christianity in Rome; however, the last recorded tournament was the 291st in 385 AD. At this time, fist fights were held along with wrestling, pankration, and athletics [8]. In other words, it can be said with certainty that fisticuffs were held during the ancient Olympic Games for more than thousand years. The first codification of the rules of fistfighting was in 1743 and is known as the "Broughton Rules" [2]. The round ended when the opponent was down. The interval between the rounds was 30 s [4]. Striking at a downed opponent or grabbing the opponent from the waist down, such as the thighs and buttocks, was prohibited [5]. No decision can be made until the second referee declares a defeat. (vi) Regardless of the prior arrangement between individuals, the winner received two-thirds of the prize money, which was distributed on stage. (vii) To avoid disputes, two judges are selected from the audience and their decisions are absolute [9]. This earliest codified rule, which led to the current boxing rules, was established to minimise interference with spectators and guarantee the fairness of betting. Betting was the mainstay of entertainment and for betting to be fair, the fights themselves had to be fair. This was the reason for the codification and disclosure of the rules, and the spirit of fair play was also emphasised for betting. The London Prize Ring Rules, which came into force in the following century, stipulated that all bets were to be stopped if the match was not settled [10]. The rules were laid down with wagering in mind, and the subsequent introduction of three weight classes - lightweight, middleweight, and heavyweight - was also because it was more interesting as a betting game.

2.5 From prize-fighting to glove boxing

The decline in prize-fights, in which fighters fought with their bare hands, was a major factor in boxing. In 1841, the Fist Fighting Club was formed in London, an elegant association of patrons that provided facilities for prize-fights, developed a bounty system, tightened rules, and banished the practice of cheating. Because of their efforts, prize-fights enjoyed their heyday. Throughout the 19th century, the crackdown on prize-fights was tightened in three stages: first, as a threat to public safety and society; second, from the moral point of view of cruelty; and finally, as a threat to the lives and health of those involved. Prize fights were popular until then because the nobility and gentry were patrons of the fights; however, the endless number of betting-related illegalities led to a loss of confidence in the fairness of the fights, and they stopped being patrons [11]. It was natural that the decline began as soon as this happened, and prize fights disappeared from this stage in the late 19th century. However, for boxing to exist, prize fighting had to decline. The history of boxing divides the period from the 17th century to the 1860s as the era of bare-knuckle fighting and the period after that as the era of glove boxing, called sparring. When learning kung-fu in classes as a 'noble art of self-defence', the practice of kung-fu was referred to as sparring. The ability to expand sparring enthusiasm by selling safe gloves became the foundation of modern boxing, and the decline of prize fighting was the tailwind of the era of glove boxing.

2.6 Development of glove boxing

In the 1860s, sparring was introduced into physical education in public schools and rose to the status of a youth discipline. It was precisely during this period that sparring rules were codified as competition, and the era of glove boxing can be said to have begun in 1867 with the 'Queensbury Rules'. The rules have the following characteristics: (1) the prohibition of wrestling acts, such as grabbing and throwing; (2) the introduction of a round system with each round lasting three minutes and an interval of one minute; (3) the introduction of a ten-count after a down; (4) wearing gloves; and (5) wearing shoes without non-slip soles [12]. In the tournament, there were three weight classes–lightweight, middleweight, and heavyweight–and points were awarded in three three-minute rounds. A modern boxing framework has already been implemented using these rules. In the UK, the Amateur Boxing Association was formed in 1880 and grew into a national governing body that overtook the Queensbury Rules. Simultaneously, the establishment of the Queensbury Rules, where time is clearly defined, can be regarded as the establishment of boxing as a modern sport.

2.7 From fisticuffs to modern boxing as a competition

Historically, Britain, the founder of industrial capitalism, developed into a world empire in the 17th century, controlling the seven seas, and had colonies all over the world. In colonies with no stable legal system, confrontations through fistfighting were sometimes used as a means of adjudication. Therefore, being a master of fencing was also useful in demonstrating one's superiority as a ruler. In medieval Europe, fencing skills were a mark of nobility; similarly, in the colonies of the United States, Canada, and Australia, fisticuffs were a mark of dignity for the conquerors [11]. In the 19th century, therefore, in these New World countries, pugilism based on the Broughton and London Prize Ring Rules spread widely. While prizefighting began to decline in the United Kingdom, the United States became the home of prizefighting and boxing from the 1860s onwards. Boxing spread from the USA to the rest of the world as popular culture and was internationalised. The influence of mass media and visual entertainment, such as newspapers, television, and films, played a major role in this worldview, in which people of all birth and upbringing can become successful with a single fist. As boxing became popular in several countries, its popularity became immense among men and women of all ages.

In modern professional boxing, men are divided into 17 weight classes and women into 18 classes to eliminate unfairness due to weight differences and ensure the safety of boxers. Ranks were also defined according to the boxing results, and the number of rounds was accordingly limited. The weight of the gloves differs according to rank, and fighters must wear bandages to protect their fists, mouth guards to protect their teeth and oral cavity, and foul cups to protect their lower abdomen. Weigh-ins are now conducted the day before the competition, and some organisations stipulate a range of recovery increases after the weigh-in. Efforts are being made to protect the fairness of the competition and the health and lives of the fighters from all aspects, such as thorough rule meetings attended by judges and both sides, the introduction of a standing-down system, the right to stop fights by the ringside doctor, and doping tests. Although the environment surrounding boxing has changed over time, the only thing that is common to both the era of firefighting and the current transformation of boxing into a sport is that the pride and prestige of each country are at stake and fights attract the hearts of numerous people.

3. Sports disorders in boxing

Sports include professional sports, amateur sports as a competition, and sports as a hobby, recreation, health promotion, or exercise therapy, and sports can be said to be one of the most popular forms of activity among people to this day. However, sports injuries caused by various factors are an unavoidable problem in all sports and must be resolved, although the degree of injury varies. Boxing is one of the contact sports with the highest incidence of trauma and disability [13]. Trauma and injury investigations targeting boxing athletes have been conducted in the USA [1, 14, 15], Australia [16, 17], the UK [18], and other countries, focusing on the occurrence of head injuries. In Japan, investigations on head injuries and disorders have been conducted in professional and amateur boxers, as well as investigations on oral trauma, trauma to the hand and face, which are direct sites of attack, and disorders of the trunk and lower limbs [19–22]. These results show that several sports injuries and disorders are common during boxing, including concussion, intracranial haemorrhage, facial lacerations, retinal detachment, orbital floor fractures, nasal bone fractures, rib fractures, organ injuries, and back pain [1, 19, 23–25]. In this section, sports disorders observed to occur in boxing are discussed.

3.1 Acute subdural haematoma

Acute subdural haematoma (ASH) is a major cause of boxing-related fatalities. As a basic reference for the occurrence of ASH, during the 23-year period from 1978 to 2000, 45 cases of ASH in official matches (31,808 fights in total) were recognised by the Japan Boxing Commission (JBC), of which 15 were fatal. The ASH rate was 0.14% per match, almost twice that of other countries, and the probability of death was 0.24 per 1000 athletes. ASH was not necessarily more common in heavyweight or inexperienced fighters; however, it was more common in flyweights and super flyweights, more common in 10-round fights (JBC-certified A class), and less common in 4-round fights (JBC-certified C class). Furthermore, ASH was found to be more common in fights lost by knockout and occurred significantly in the latter part of the fight. In comparison with other sports, the fatal accident probabilities in jockeying, hang gliding, and college football in the USA were reported to be 12.8, 5.1, and 0.3 per 1000, respectively, indicating that professional boxing does not have a particularly high fatal accident rate. However, they may include causes other than ASH. In addition, boxing is the only sport in which the goal is to knock out an opponent with a direct blow to the head, which is undeniably different from other sports in which accidental injuries occur. In American football, a representative contact sport in which players collide violently with each other, a number of fatal accidents occurred in 1970, which became a social problem. This shows the recommendation of the medical doctors' efforts, as well as the fact that direct blows to the head were dangerous. In Japan, efforts have been made to avoid the occurrence of ASH in professional and amateur boxing [26]. Specifically, efforts have been made to establish a backup system for specialised medical facilities that are relatively close to the fight venue, abolish scheduled 15-round fights, conduct weigh-ins on the day before the fight, and educate boxing professionals by doctors on health management and accident cases. Since 1983, major organisations worldwide have changed from 15-round systems to 12-round systems. The move to avoid ASH was accelerated as much as possible.

Although the impact strength of the punch itself is a factor in the occurrence of ASH, as it often occurs in the second half of the match, fatigue or a mild concussion state may cause a decrease in the muscle tone of the neck muscle group, contributing to the acceleration of the head caused by the blow. Moreover, owing to the unique strategy of boxing, few athletes tend to hydrate adequately during matches, which may lead to excessive dehydration and may be a factor in the development of ASH. Therefore, regardless of previous medical efforts, boxing should be recognised as a sport in which ASH may occur. Earlier stoppage of fights and hydration within acceptable limits are recommended for fights scheduled for longer rounds.

3.2 Concussion

Although sports-related neurological trauma tends to focus on severe cases, sending patients with impaired consciousness and neurological symptoms to the emergency department immediately after injury is not controversial, and the treatment plan and prognosis do not change significantly regardless of the injury mechanism. In fact, seemingly minor 'concussions' can be considered a major problem [27, 28]. In boxing, high-intensity, practical sparring is often included in the training menu as official fights approach. Professional boxers, like amateur boxers, spar with headgear, to prevent trauma. Although headgear is effective in preventing skin lacerations and fractures, it cannot be said to play a role in preventing damage to the cranial nerves, that is concussion. This is supported by the fact that concussion-related injuries have been observed in sparring sessions and official amateur fights, even when headgear is worn. Some concussions diagnosed on the training ground or in the competition are later found to be haemorrhages or cerebral contusions after a medical examination, and even specialists find it difficult to distinguish between these immediately after onset [29]. In a survey of 632 professional boxers on the effects of punching, what 'works' for the athlete was concussion-related accounted for more than 90% of the cases [26]. The specific punches that led to this were said to be straight punches to the jaw; however, in reality, they were more often hook punches that rotated the head to the jaw or side of the head. This may be related to the report by Gennareli [30] stating that diffuse injuries, as typified by concussions, are highly correlated with impacts that have a relatively long impact time and produce a rotational acceleration of the head.

In a large-scale survey in Japan, approximately 30% of boxers who had experienced a knockout experienced memory impairment, and approximately 80% had symptoms associated with post-concussion syndrome, such as headache, nausea, vomiting, tinnitus, and dizziness post-fight [26]. Notably, even in players who were knocked out, symptoms, such as headache and other symptoms often abated within a week. However, a problem arises in relation to the second impact syndrome [31, 32], which describes the possibility of more severe brain tissue damage if the player suffers another blow to the head in the presence of concussion-related symptoms, albeit transient. This condition occurs in boxing, football, and other sports, in which head trauma causes diffuse brain swelling and other severe disorders during concussion, resulting in a poor prognosis. In addition, when the symptoms of concussion persist for approximately three months, it is encompassed by the concept of post-concussion syndrome [33], and although its pathogenesis is unknown [34], it must be borne in mind that it can also lead to chronic brain injury with higher brain dysfunction and other complications. Therefore, in the daily healthcare of boxers, it is essential to avoid blows to the head or to seek medical attention during periods of post-concussion syndrome, as has been suggested in other countries.

Currently, guidelines for staged returns to competition after concussion have been proposed [35, 36]. The JBC extended the suspension period for knockout boxers from 45 to 60 days; however, concussions can still occur in daily practice. However, concussions can occur in daily practice because of the competitive nature of boxing. Therefore, it is necessary to take adequate measures against concussions by selecting sparring partners according to physique and experience, reviewing the number of rounds and interval times of sparring, providing hydration to prevent dehydration and maintain performance. Additionally, it is essential to undertake adequate measures against concussions usingconcussion recognition tool 5 (CRT5) and periodic head computed tomography (CT) and magnetic resonance imaging (MRI) examinations at medical institutions.

4. Boxing and technology

4.1 Acquiring the correct form for first-time learners

Information technology has been widely introduced in sports training in baseball, football, and tennis [37, 38]. Notably, virtual reality (VR) and augmented reality (AR) technologies, used for image training and feedback through visualisation have been introduced. Systems have also been proposed the use of skeletal information to learn the correct form in golf and dance [39–41]. Learning form is an important aspect of learning in several sports [42]. The same applies to boxing, in which the correct punching form is first taught by an instructor. However, there are cases in which direct instruction is difficult because of a lack of instructors in rural areas or boxing gyms in some areas. In such cases, when beginners in boxing competitions practice on their own, they may refer to videos or instructional books; however, there is no correct feedback from the learner; thus, there is a possibility that they may learn incorrect forms.

With the increase in health consciousness in the recent years, gamification has attracted attention in the field of fitness, and various digital contents based on boxing have been released. While there are several reviews on the effects of exercise in enabling effective interval training, the system does not require a correct punching form as long as the direction of the punch is consistent to a certain extent. Even if boxing training is for fitness purposes, training with the correct punching form reduces the burden on the body while increasing the exercise effect and preventing injuries. In other words, the benefits of acquiring the correct punching form are significant, even if not for competitive purposes. Till date, to establish a teaching method for beginners, there have been reports verifying the movements of experienced and inexperienced players from biomechanical elements using electromyography and floor reaction force measurements, as well as attempting to determine the indicators of correct form from the pelvis rotation angle, rotation angle speed, and rotation time using a three-dimensional movement analysis system [43, 44]. However, it has been difficult to utilise these methods as general teaching methods because of the time factor in analysis, cost of equipment for analysis devices, and practical movement guidance. Against this background, the integration of boxing and technology is at a stage of rapid development with the need for technological applications that make full use of VR and AR systems, making it easy to obtain appropriate feedback information on an individual basis.

4.2 The birth of quantitative movement analysis software specifically for boxing competitions

VR and AR systems are effective technological techniques for beginners to acquire correct form; however, boxing itself is an interpersonal sport in which fists exchange in front of each other to knock each other out. This requires skill in both attack and defence, as well as strong mental strength to overcome anxiety and fear. Therefore, before introducing scientific innovations in offence and defence, we will first discuss the psychological characteristics of boxers.

To achieve the best results and records in sporting situations, it is essential to optimise psychological conditioning prior to competition and technical and physical training [45]. Therefore, understanding the psychological state of athletes prior to competition is considered one of the preparatory steps to achieve the desired results [46]. Boxing is a life-threatening sport, as boxing causes orthopaedic disorders (**Figure 2**) as well as brain disorders such as punch-drink syndrome [27]. Although boxers are often featured for their extremely trimmed, refined bodies, as in other sports, they are a sport that emphasises the importance of physical and mental balance. This is because it requires a high level of emotional intelligence [47], including feelings, coping, and adaptation to changing conditions. There are numerous reports on competition anxiety in athletes [48–51]. When looking at mental characteristics from the perspective of both competition anxiety and emotional intelligence, boxers tended to have higher competition anxiety than general reference values.

Figure 2.
Typical examples of sports injuries (orthopaedic conditions) from boxing, from left to right: Eyelid laceration, nasal bone fracture, boxer's fracture (second middle phalanx fracture).

Furthermore, by examining mental characteristics using the Emotional Intelligence Scale (a psychological test to assess emotional intelligence), it has been suggested that competition characteristics lead to differences in the corresponding domains in emotional intelligence. This is connected to the needs of the athletes, and in boxing, where the athletes are prone to mental instability, advice and guidance in the areas of "interpersonal response" and "situational response" are effective. In addition, the manner in which the athlete is approached must be considered, depending on whether the recipient is male or female [52, 53]. Regarding the differences in effective voice-overs according to sex, for example, male players tend to have a result-oriented mindset and, therefore, prefer simple, theoretical voice-overs that are directly related to winning or losing, whereas female players tend to focus on the process leading up to the result and sympathetic voice-overs that are more in tune with their emotions at the time are more effective. In contrast, female athletes tend to focus more on the process leading to the outcome, and sympathetic voice-overs that are more in tune with their emotions at the time are more effective.

The influence of mental characteristics and vocalisation on boxers was introduced; however, the root of competition anxiety is not anxiety about being hit by an opponent and suffering trauma or disability, but anxiety about losing a match and the future after losing. These factors have a significant influence on the boxers' competition anxiety. We believe that these factors have a significant impact on boxers' competitive anxiety. If this is the case, how one can scientifically work on strategies to win can be one of the factors in eliminating anxiety and bringing one closer to achieving the best performance. Training science is utilised to improve physical function, and strategies to maximise the effects of training are derived from nutritional science. There arises a question of how key offensive and defensive boxing techniques are tackled. In general, apart from physical training, boxers improve their offensive and defensive boxing skills through shadow boxing, sandbagging, mitting, and sparring. Once an opponent has been decided upon, the boxer and coach review the footage of previous fights to identify weaknesses and develop a strategy. However, the question remains as to whether this strategy is scientific. In many cases, strategies are constructed based on the senses of the players and coaches by repeatedly checking parts of the footage. This was probably because no analysis software was specifically designed for boxing. Therefore, we have spent two years developing a quantitative movement analysis software specifically for boxing, with the aim of preventing sports injuries and improving offensive and defensive performance.

4.3 Features of quantitative movement analysis software specific to boxing competitions

What does it take to develop the boxing strategy? It begins with an accurate understanding of one's own characteristics as a boxer and those of one's opponents. To achieve this, we built a system in which past match footage and current sparring footage were imported into a quantitative movement analysis software, and the following items were extracted as a result of the extraction of analysis points and quantitative analysis (**Figure 3**).

(i) Number of attacks (total number and changes over time in each round)

(ii) Hits (total number of rounds)

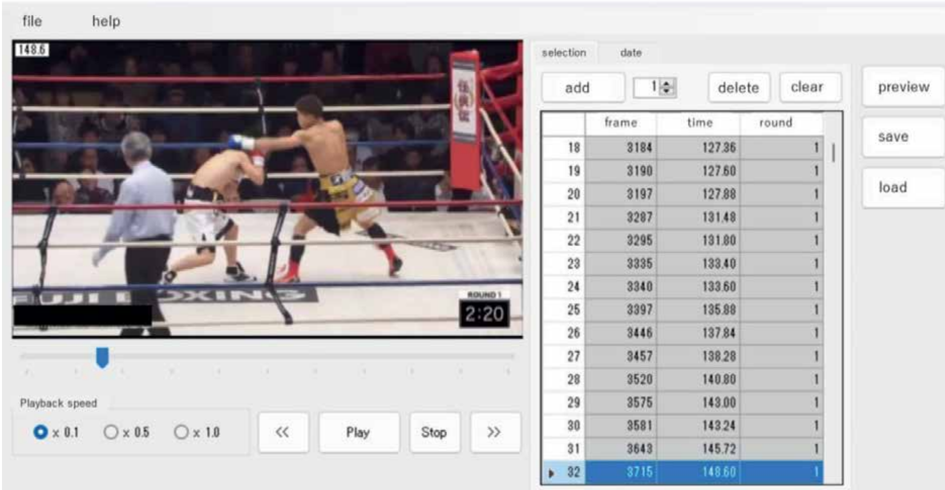

Figure 3.
*Boxing-specific quantitative movement analysis software.**
**This software is designed to analyse athletic performance quantitatively by importing match footage into the software, extracting analysis points along the time axis, and selecting and inputting information such as the type of attack, type of defence, attacking area, and presence or absence of hits.*

(iii) Attack trends (types of single shots and combination patterns).

(iv) The type of attack (single or combination pattern types) that inflicted a hit.

(v) Attack sites (total number of rounds).

(vi) Number of bullets (total and round)

(vii) Types of attacks (single-shot and combination pattern types).

(viii) Trends in defence (choice of defence methods for single and combined types).

Points (i)–(v) clearly indicate the points that need to be strengthened from an offensive aspect. In (i), it is possible to ascertain the degree of aggressiveness throughout the match and whether the player was in control of the match. In addition, because the number of attacks accumulates every 60 s in each round, it is possible to grasp the relationship with the stamina within a round and throughout the match. In (ii), the accuracy of the attacks can be determined using step (iii), the attack pattern can be objectively understood. This is useful for correcting the ratio of single shots and combinations and the bias of combination patterns. (iv) It helps to check the accuracy of specific types of attacks. For example, in combination patterns, it is possible to determine the number and types of attacks that increase the hit rate. In (v), it is useful to determine the attack ratio between the head and abdomen to correct for the bias towards the attacking part.

Points (vi) to (viii) clarify the points that must be strengthened on the defensive side of the game. In (vi), the definition of "bullet" is a strike by an opponent to an unguarded part of the face or body. The overall defensive technique can be explored by understanding the rate of being hit by bullets throughout the match and the rate of being hit by bullets in each round. At point (vii), it is possible to determine the specific type of attack that results from being hit by the bullets. It is possible to clarify the relationship between the attack trajectory and the rate of being hit in the single and combination patterns. (viii) It provides an opportunity to review whether a defensive selection is appropriate for each attack by an opponent. In other words, it is useful for correcting the tendency or habit of being hit by a certain stance or the same defensive choice in a certain attack or combination pattern.

We believe that using this system [54] to analyse yourself and your opponents will help you build more scientifically based strategies, reduce competition anxiety, reduce sports injuries and disorders, and get closer to achieving the best performance.

5. Examples of the operation of boxing-specific quantitative movement analysis software

Herein, we present our efforts to improve competitive performance, mainly in defensive techniques, using boxing-specific quantitative movement analysis software.

5.1 Experiments

Efforts to prevent trauma and injury in boxing, as in other sports, began with the recognition of the importance of warming up and cooling down and have continued to the present day through repeated improvements in equipment, such as gloves, headgear, and mouthguards, and revisions to the rules of sports. In amateur boxing, the International Amateur Boxing Association revised its rules, and since the 1984 Los Angeles Olympic Games, Olympic-style boxing has been practiced using a points system without the aim of knocking out fighters. Most injuries occur in high school and university students. In particular, medical staff are required to propose and implement methods to scientifically and comprehensively prevent traumatic injuries and disorders from various perspectives, not only from the viewpoint of treatment, but also from returning to competition.

Therefore, this study developed a quantitative movement analysis software specifically for boxing competitions and focused on the changes in the rate of bullet hits throughout the match, positioning it as a basic study for the primary prevention of sports injuries.

5.1.1 Methods

5.1.1.1 Subjects

The subjects were active boxers (male, 12 subjects) with JBC-accredited professional boxing qualifications, mean age: 22.8 ± 4.3 years, and 4.2 ± 2.1 years (mean ± standard deviation) of competitive experience.

5.1.1.2 Experimental procedure

Based on the analysis software, six subjects were randomly assigned to the task condition (task group) and six to the control condition (control group).

All subjects were quantitatively analysed using analysis software on the video footage of their first match after the start of the study to extract the subject's overall shot rate for the match as a baseline evaluation measure. Subsequently, the subject group was given feedback on the analysis results to the trainers and players, and was subjected to a training program based on the analysis results for approximately three months until the next match, whereas the control group was not given the analysis results and was subjected to normal practice until the next match. Finally, the video footage of the second match after the start of the study was analysed in the same manner as that of the first match, and the overall rate of bullet hits was compared and verified between the groups before and after the intervention (**Figure 4**).

Motion analysis software was developed specifically for boxing competitions to enable the quantitative evaluation of offensive and defensive performances. Specifically, the software was programmed to extract analysis points in the offence and defence based on match footage and to quantitatively analyse the choice of defence method for each type of attack, the attacking area, whether or not the fighter was hit, the number of hits, and the hit rate (**Figure 3**). These can be analysed over time in each round and output as a competition performance evaluation table so that players and trainers can easily understand the analysis results.

5.1.1.3 Statistical processing

Statistical analysis was performed using the bullet coverage rate for the entire match. A repeated-measures analysis of variance was conducted on the change in the bullet rate, with the measurement condition (first match × second match) and task condition (task group × control group) as the two factors, and the Bonferroni method was used for multiple comparisons. The statistical analysis software was SPSS25.0. J for Windows, and the significance level was set at 5%.

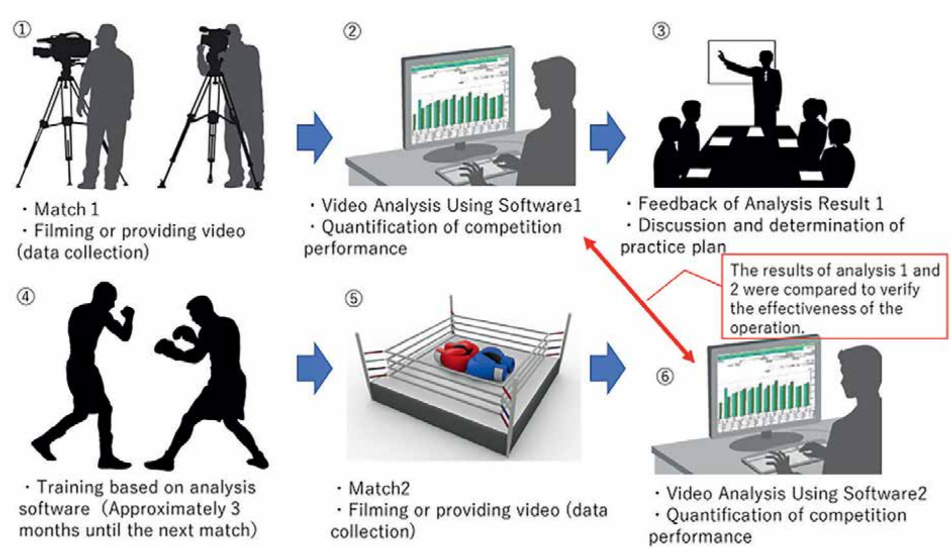

Figure 4.
Experimental methodology flow using boxing-specific quantitative movement analysis software.

5.1.2 Results

The results of a comparison of the overall match exposure rate between "with/without analysis software" and "measurement period" showed no main effect for "with/without analysis software" [F (0.267), P = 0.5924] and a main effect for "measurement period" [F (3.682), P = 0.02]. There was no interaction between factors [F (0.363), P = 0.8577]. The results of the multiple comparison test in the 'measurement period' showed that the FTS group had a significantly lower rate of exposure after the intervention compared to before (P < 0.05). No significant differences were found between the pre- and post-intervention comparisons in the control group (P > 0.05).

5.1.3 Considerations

This study was positioned as basic research on the primary prevention of sports injuries in boxing; quantitative movement analysis software specific to boxing competitions was developed, and changes in the rate of exposure to bullets were verified from its operation.

The task group showed a significantly lower rate of bullet hits throughout the match after intervention. However, there was no significant change in the control group in the pre- and post-intervention comparisons. The reason for the low rate of hits in the entire match after the introduction of the analysis software was that the players themselves were able to quantitatively analyse the types of attacks in which they were hit, the combination patterns in which they were prone to being hit, and the types of defence they chose against each type of attack in which they were prone to being hit and to use this information as a numerical value and reference for the analysis of the game. It can be inferred that the players were able to implement a cautionary strategy based on an image of movement by looking back at numerical and visual images and that they were able to conduct training to efficiently improve their defensive skills until the next game based on the results of the analysis. As background, Sakamoto et al. [55] reported that combining observations of behaviour and images when performing motor imagery facilitated corticospinal tract excitability better than manipulations performed alone. Sakuraba et al. [56] also reported that appropriate attentional strategies based on individual-specific motor imagery can improve performance during motor learning tasks. In the present study, we did not add assessment items to the motor imagery; therefore, we were unable to observe the neurophysiological aspects of these changes. However, because the players and coaches were able to logically reflect on the match while receiving match footage, analysis materials, and feedback from the analysts, it is possible that during the feedback, the excitability of the corticospinal tracts was enhanced and motor-related areas, such as the supplementary motor cortex, were activated. Therefore, the task group also contributed to the construction and reproduction of motor images, such as the trajectories of the attacks that were being hit, the types of attacks, and the corresponding defence choices, which could have been reflected from a scientific perspective in the understanding and efforts of tailor-made countermeasure programs based on analysis software.

This study explored the possibility of primary prevention of sports injuries in boxing from a technological perspective using the index of the rate of bullet wounds in the entire match. Boxing is a sport in which the attack sites are limited to the head and abdomen, and as a result, brain damage tends to accumulate more than in other martial arts such as karate and kickboxing [57, 58]. Reducing the rate of exposure is directly related to reducing the risk of brain damage. It may also have the potential to preserve the lives of athletes and reduce the risk of chronic traumatic encephalopathy, a condition known as punch-drunk syndrome, in post-athletic lives.

In the future, neurophysiological evaluations during feedback using analysis software will be added, and the relevance of sex differences, age, competition history, and competition anxiety will be examined from various perspectives. We also aim to introduce programming techniques to improve the accuracy of the analysis and develop a technology that enables timely feedback of the analysis results during the competition interval.

Finally, we strongly believe in the potential of the fusion of sports and technology to brighten the future of athletes and will continue to explore this.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 5

ECG in Athletes

Yeltay Rakhmanov, Bauyrzhan Toktarbay, Zaukiya Khamitova and Alessandro Salustri

Abstract

Athletes require careful evaluation by specialized physicians to obtain eligibility for sport. In this context, electrocardiogram can be helpful to recognize patterns associated with heart disease that put the athletes at high risk of sudden cardiac death and may interdict participation in sports. On the other hand, adaptation to exercise may induce structural remodeling of the cardiac structures that results into electrocardiographic changes that are not associated with an increased risk of adverse events during exercise. Clearly, a correct interpretation of a resting 12-lead electrocardiogram is essential to differentiate athletes at risk of sudden cardiac death who must be prohibited from agonistic sports from those with physiologic changes who should be reassured and declared eligible for sport activities. Interpretation of the athlete's ECG has evolved over the past 15 years, and in this chapter, we provide a brief review of current evidence regarding the electrocardiographic findings considered normal and abnormal in athletes based on the latest international recommendations.

Keywords: ECG, athletes, physical training, endurance exercise, strength exercise

1. Introduction

Physical training in athletes may induce changes in the cardiac structure that can be detected by electrocardiography. Due to the relevant clinical impact, it is crucial to interpret electrocardiogram (ECG) in athletes accurately and to differentiate between physiological and pathological changes. In fact, misinterpretation can lead to costly diagnostic procedures and wrong disqualification from sports, with severe psychological and economic implications. Conversely, erroneous reporting of pathological changes as normal can be falsely reassuring for athletes, leading to potentially fatal consequences [1–8].

Interpretation of the athlete's ECG has evolved over the past 15 years, from the 2005 European Society of Cardiology (ESC) consensus [9], progressing to the ESC recommendations (2010) [10], the Seattle criteria (2013) [11], and the "refined" criteria (2014) [12]. After the first consensus statement by the ESC, ECGs were found abnormal in up to 50% of athletes, resulting in an unacceptable low specificity. Accordingly, the revised ESC criteria in 2010 divided ECG changes into training-related and training-unrelated. However, still black athletes had a significantly high number of false positive ECGs, and the Seattle criteria aimed to address the issue of ethnicity that was not accounted for in the previous recommendations. The evidence that some ECG changes in isolation assigned to the training-unrelated group may not be representative of pathology has led to the publication of the refined criteria that were later validated in large studies. Finally, in 2018 international recommendations for electrocardiographic interpretation in athletes have been published with additional refinements of the ECG abnormal patterns, which has led to a significant reduction in false positive and screening-associated costs [13].

In this chapter, we will summarize the ECG interpretation standards that classify the ECG findings and provide a clear guide to the proper evaluation of ECG abnormalities in athletes.

2. Methods

We have reviewed the recommendations from the international societies, with an emphasis on the latest one [13] that has refined the previous [9–12] and resulted in a decrease in false positive findings. Accordingly, the ECG findings in athletes were classified into normal, borderline, and abnormal (**Table 1**).

3. Normal ECG findings

3.1 Increased QRS voltage for LVH or RVH

Definitions (high-voltage QRS)

Left ventricular hypertrophy (LVH): SV1 + RV5 or RV6 >3.5 mV.

Right ventricular hypertrophy (RVH): RV1 + SV5 or SV6 >1.1 mV.

High-voltage QRS complexes are frequently found in ECG of athletes, and Sokolow–Lyon voltage criteria for LVH can be present in up to 50% of male athletes (**Figure 1**); however, without echocardiogram, this is not a reliable indicator of an increased thickness of the left ventricular wall. Signs of LVH are confirmed by echocardiogram only in 12% of the cases, and this prevalence is related to the type of sport activity, ranging from 29% in high cardiovascular demand sports (decathlon, cycling, and rowing), as compared to only 12.3% and 5.4% in sports with medium (swimming, rugby, and skating) or low (bowling and golf) cardiovascular demand, respectively.

The correlation between these ECG findings and echocardiographic measures of left ventricular wall thickness is low (10%-50% depending on the series), with the Sokolow–Lyon index being the best-correlated parameter in different publications [12]. Of note, in a study in 947 highly trained athletes, only 1.7% had wall thickness greater than or equal to 13 mm, compatible with the diagnosis of hypertrophic cardiomyopathy [14].

Evaluation

Isolated QRS voltage criteria for LVH do not necessarily indicate pathology in athletes. In fact, this pattern is quite common in athletes and is present in less than 2% of patients with hypertrophic cardiomyopathy (HCM) [15–21]. Furthermore, pathological LVH is usually accompanied by other ECG features such as T-wave inversion (TWI) in the inferior and lateral leads, pathological Q waves, and ST segment depression [12, 22]. In this regard, the high QRS voltages present alone, fulfilling the criteria for LVH in the absence of other ECG or clinical pathology, can be interpreted as normal and training-related changes in athletes, and there is no need for further evaluation.

Normal ECG findings
• Increased QRS voltage for left ventricular hypertrophy (LVH) or right ventricular hypertrophy (RVH)
• Early repolarization
• ST elevation followed by T-wave inversion V1-V4 in black athletes
• Juvenile ECG pattern (T-wave inversion V1-V3 age <16 years old)
• Sinus bradycardia or arrhythmia
• Ectopic atrial or junctional rhythm
• Incomplete right bundle branch block (RBBB)
• First-degree A-V block (P-R <400 ms)
• Second-degree A-V block Mobitz 1
Borderline ECG findings
• Left axis deviation
• Left atrial enlargement
• Right axis deviation
• Right atrial enlargement
• Complete RBBB
Abnormal ECG findings
• Abnormal T-wave inversion
• ST segment depression
• Pathologic Q waves
• Complete left bundle branch block (LBBB)
• Non-specific intraventricular conduction delay (QRS ≥140 ms duration)
• Ventricular pre-excitation
• Prolonged QT interval
• Short QT interval
• Brugada type 1 pattern
• Profound sinus bradycardia (<30 bpm)
• PR interval ≥400 ms
• Second-degree A-V block Mobitz 2
• Third-degree A-V block
• ≥2 premature ventricular contractions (PVC) per tracing
• Atrial tachyarrhythmias
• Ventricular arrhythmias (couplets, triplets, non-sustained ventricular tachycardia)

Table 1.
Classification of ECG findings in athletes based on international consensus standard (modified from Ref. [9]).

Voltage criteria for RVH are also common in athletes, with up to 13% of them meeting the Sokolow–Lyon index. However, when present in isolation, QRS voltages for RVH do not correlate with any underlying medical condition in athletes. It is similar to the voltage criteria for LVH and is considered a normal ECG finding in athletes. Therefore, isolated QRS voltage criteria suggest RVH does not require further evaluation.

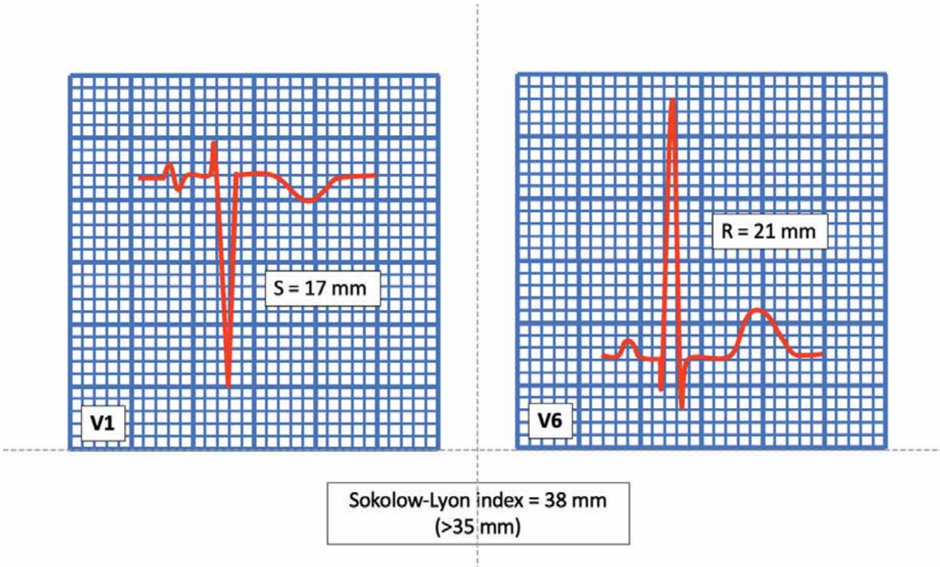

Figure 1.
Increased QRS voltage for LVH. Sokolow-Lyon index is the sum of the amplitude of S wave in V1 and the highest R wave in V5 or V6. In this example, the sum is 38 mm, suggesting the presence of LVH.

3.2 Early repolarization

Definition

Elevation of the QRS-ST junction (J-point) by at least 0.1 mV, which is often accompanied by a late QRS slurring or notching (J wave).

This condition is usually observed in the inferior and/or lateral leads and is commonly found in healthy populations, with a prevalence ranging from 2% to 44% (**Figure 2**).

It is more frequently observed in athletes, young individuals, males, and people of black ethnicity. Up to 45% of Caucasian athletes and 63%–91% of African-Caribbean descent athletes ("black athletes") exhibit early repolarization [13].

Studies in patients who have suffered from cardiac arrest or have had primary ventricular fibrillation (VF) suggest that there might be a link between early

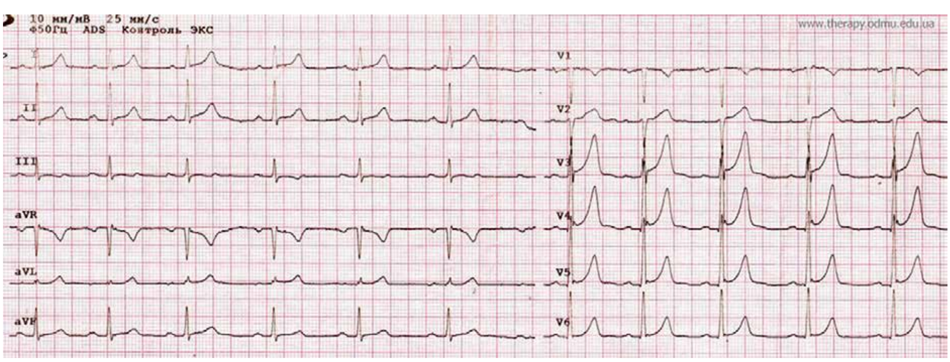

Figure 2.
Early repolarization pattern.

repolarization and the risk of VF [23, 24]. A study on middle-aged individuals has shown that those with an early repolarization pattern in the inferior leads, horizontal or descending ST segment after the J-point, have a significant risk of arrhythmic death. Meanwhile, a rapidly ascending ST segment – the dominant ST pattern in healthy athletes has a better positive [25, 26]. In some athletes, early repolarization is a dynamic process that is directly influenced by exercise training. This results in an increase in frequency of early repolarization patterns during times of peak fitness [24, 27, 28].

Evaluation

While further research is necessary to understand the pathophysiology and prognosis of early repolarization in professional athletes, currently, there is no evidence of the relationship between inferior early repolarization and sudden cardiac death in athletes. Therefore, isolated early repolarization in athletes can be considered a benign variant [29].

3.2.1 Repolarization findings in black athletes

Definition

Elevation of the J-point and convex ST segment elevation in the anterior leads (V1-V4), followed by TWI.

In the last decade, ethnicity has been considered as a significant determinant of cardiac adaptation to exercise in black athletes, demonstrating a higher prevalence of ECG anomalies, including repolarization changes. In over two-thirds of black athletes, the presence of ST-segment elevation and T-wave inversion (TWI) (in one-fourth of athletes) were noticed [17, 30–32].

A study involving African descent of 904 black male athletes demonstrated that 13% of them, in leads V1-V4, had isolated TWI compared to 4% of black sedentary controls [30]. The most anterior TWI was shown by J-point elevation and convex ST segment rise. However, the athletes with anterior TWI did not exhibit symptoms or signs of cardiomyopathy after a comprehensive assessment and a 5-year follow-up period. Quite the same findings in female and adolescent black athletes were reported by other researchers [30].

Evaluation

Therefore, TWI in leads V1-V4, when followed by J-point elevation and convex ST segment rise, should be considered part of the "black athlete's heart," and in the absence of other clinical or ECG features of cardiomyopathy, there is no need for further investigation.

3.3 Juvenile ECG pattern

Definition

T-wave inversion (TWI) or biphasic T-wave in two contiguous anterior leads (V1–V3) in individuals <16 years of age.

TWI in the area of anterior precordial leads may be interpreted as a normal age-related changes in athletes up to the age of 16 years. Studies evidence that in 10%-15% of white athletes aged 12 years, the juvenile pattern was present, but only 2.5% of athletes aged 14–15 years had juvenile ECG pattern [33–35]. The occurrence of anterior TWI beyond lead V2 in white athletes aged 16 years or younger who have completed puberty is rare, with only 0.1% of athletes showing this pattern.

Evaluation

Based on current evidence, in the absence of symptoms, signs, or a family history of cardiac disease, TWI in the anterior leads (V1–V3) in adolescent athletes younger than 16 years of age or prepubertal athletes does not require further evaluation [13, 35].

3.4 Physiological arrhythmias

Sinus arrhythmia is considered to be a physiological pattern in heart rate due to breathing. This variation is a normal condition and should not be mistaken for sick sinus syndrome or sinus node dysfunction. The P wave axis remains normal in the frontal plane, and the fluctuation in heart rate should resolve with the onset of exercise in sinus arrhythmia. Criteria for the evaluation of sinus node dysfunction are important because it can be identified by several distinctive features, such as absence of rhythmic changes in heart rate; sudden and sustained decreases or increases in heart rate; periods of sinus arrest or prolonged pauses; slowed acceleration or excessively rapid deceleration during exercise; and any association with clinical symptoms such as exercise intolerance, pre-syncope, and syncope.

A *junctional escape rhythm* might be registered when the QRS rate is faster than the resting P wave or sinus rate. This is typically connected with increased vagal tone. In a junctional escape rhythm, the R-R interval is regular, and unless the baseline QRS has a bundle branch block, the QRS complexes are narrow. Once physical activity starts, sinus rhythm should resume.

In an *ectopic atrial rhythm*, the morphology of P waves is different from that of the normal sinus P wave. These P waves are most easily observed when they are negative in the inferior leads (**Figure 3**). Sometimes, two different P wave patterns may be seen ("wandering atrial pacemaker"). In up to 8% of all athletes at rest, a junctional escape rhythm or wandering atrial pacemaker may be observed. Ectopic atrial rhythms happen due to a slower resting sinus rate caused by increased vagal tone in athletes. With the onset of physical activity, the sinus rhythm should resume.

First-degree AV block (**Figure 4**) and *Mobitz type I second-degree AV block* (**Figure 5**) are also considered normal in trained athletes.

4. Borderline ECG findings in athletes

Recent data suggests that some ECG findings which were previously considered abnormal, may be a normal variant or a result of physiological cardiac remodeling in athletes. Recent findings suggest that axis deviation, voltage criteria for atrial enlargement, and complete right bundle branch block (RBBB), are classified as "borderline" findings in athletes and do not typically indicate cardiac disease [13].

4.1 Axis deviation and voltage criteria for atrial enlargement

Definitions

Left axis deviation: −30 to −90°

Right axis deviation: >120°

Left atrial enlargement: Prolonged P wave duration of >120 ms in leads I or II with negative portion of the P-wave ≥1 mm in depth and ≥40 ms in duration in lead V1;

Right atrial enlargement: High-pointed P-wave ≥2.5 mm in II, III, or V1

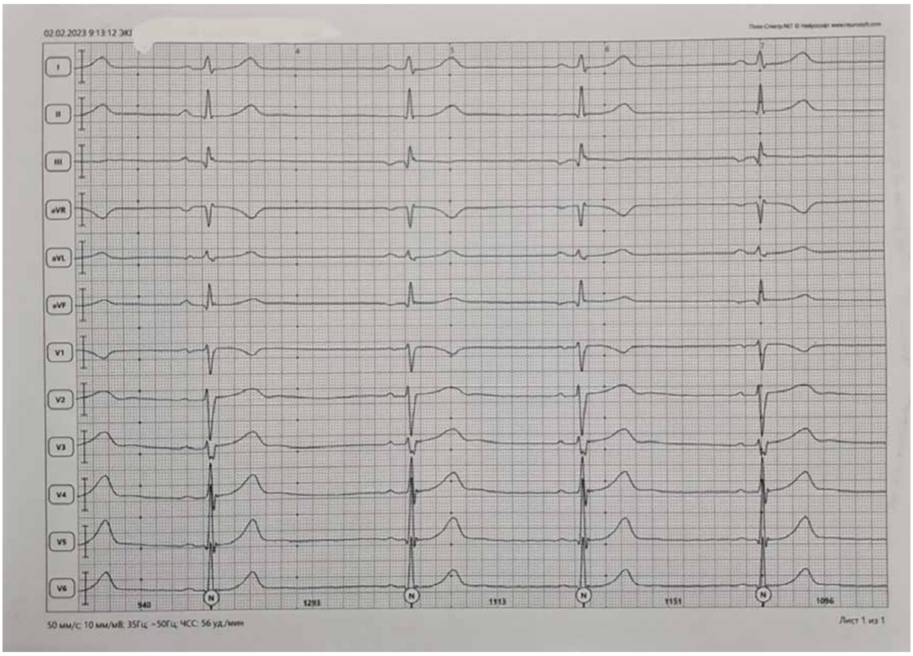

Figure 3.
ECG recording at 50 mm/s. Sinus bradycardia (56/min). The second, third, and fourth beats show inverted P waves in II, III, and aVF, indicating an ectopic atrial rhythm.

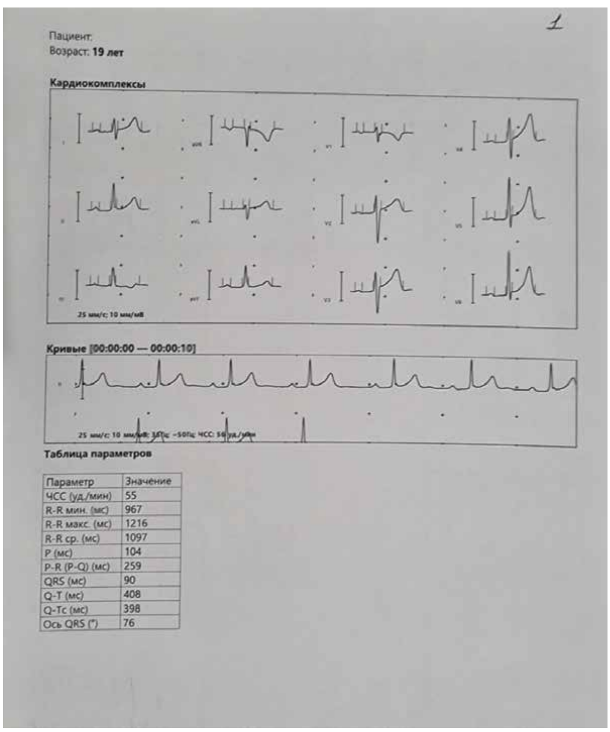

Figure 4.
ECG recording at 25 mm/s. Sinus bradycardia 55/min. P-R interval 0.26 s, indicating first-degree A-V block.

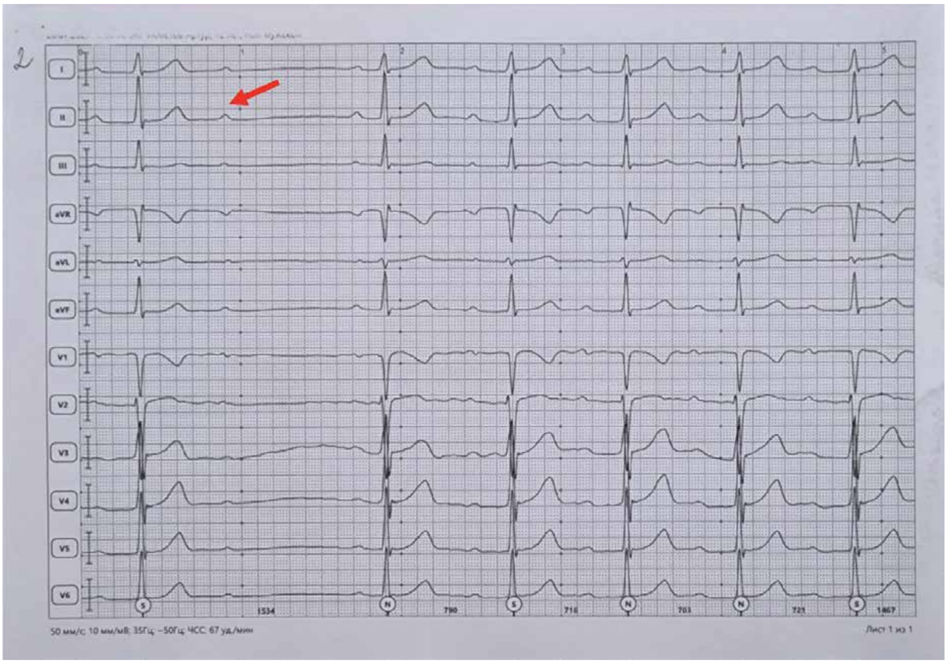

Figure 5.
ECG recording at 50 mm/s. P-R intervals are progressively increasing (from the second beat of the strip) until a P wave is blocked (arrow). This indicates a second-degree Mobitz 1 A-V block.

Researchers found that the Seattle criteria reduces the number of positive ECGs compared to the 2010 ESC criteria by at least 40% [17, 18, 36]. It also improves specificity without compromising sensitivity. However, more recent publications suggest that some ECG patterns classified as abnormal in athletes do not correlate with cardiac pathology [16]. These patterns include axis deviation and voltage criteria for atrial enlargement.

In a study of 2533 sportsmen aged 14–35 years and 9997 controls of analogous age, isolated right or left atrial enlargement and isolated right or left axis deviation accounted for 42.6% of all ECG findings [16]. Athletes had a slightly higher prevalence of these findings compared with controls (5.5% vs 4.4%; p=0.023). Athletes also showed a higher prevalence of left atrial enlargement and left axis deviation compared to controls (1.46% vs 0.96%; p=0.028% and 2.13% vs 1.37%; p=0.007, respectively), especially those who trained over 20 h per week. However, there were no significant differences in the prevalence of right atrial enlargement and right axis deviation between the groups (1.11% vs 1.10%; p=0.983% and 0.83% vs 0.92%; p=0.664, respectively) [13].

Athletes who have left axis deviation or left atrial enlargement have larger left ventricular and atrial dimensions compared to athletes with a normal ECG [16]. However, there are no evident differences in the number of athletes with cardiac dimensions exceeding predicted upper limits between the two groups. On the other hand, there are no differences in cardiac dimensions between athletes with right atrial enlargement or right axis deviation compared to athletes with normal/physiological ECG changes. Echo assessment of 579 athletes and controls with voltage criteria for atrial enlargement or isolated axis deviation failed to identify any abnormalities. Thus, the exclusion of axis deviation or atrial enlargement as an abnormal finding reduces the number of false positives from 13% to 7.5%. This improves the specificity of the screening (from 90% to 94%) with a marginal decrease in sensitivity (from 91% to 89.5%). Furthermore, a study of 508 university athletes in the US found that 49 (9.6%) had abnormal ECGs. However, subsequent echocardiography revealed that at least 29 of these athletes (59%) had either voltage criteria for left atrial enlargement alone or in combination with large QRS complexes [37]. These findings were consistent with athletic training and revealed no structural abnormalities in the heart.

Evaluation

Based on these findings, if an individual displays right axis deviation and right atrial enlargement either alone or in combination with other electrical markers of "athlete's heart," it is likely to be a normal variation (**Figure 6**).

However, if a person has left axis deviation and left atrial enlargement, it could indicate a relative increase in LV dimensions among some athletes (**Figure 7**).

4.2 Right bundle branch block (RBBB)

Definitions

Complete right bundle branch block: rSR' pattern in lead V1 and an S wave wider than R wave in lead I and V6 with QRS duration >120 ms.

Incomplete RBBB: rSR' pattern in lead V1 and a qRS pattern in lead V6 with QRS duration <120 ms.

While incomplete RBBB is common in young athletes (**Figure 8**), the clinical relevance of complete RBBB is still not well understood (**Figure 9**).

According to the 2010 ESC recommendations and the recent "refined" criteria, this particular ECG pattern is defined as abnormal, even though it is considered a normal finding in the Seattle criteria if the QRS duration is less than 140 ms. The prevalence of the complete RBBB among the general population is 1%, and among young adult athletes is 0.5% to 2.5%.

The United States researchers have reported that RBBB prevalence was 2.5% of 510 athletes [37]. The athletes with complete RBBB demonstrated lower right ventricular

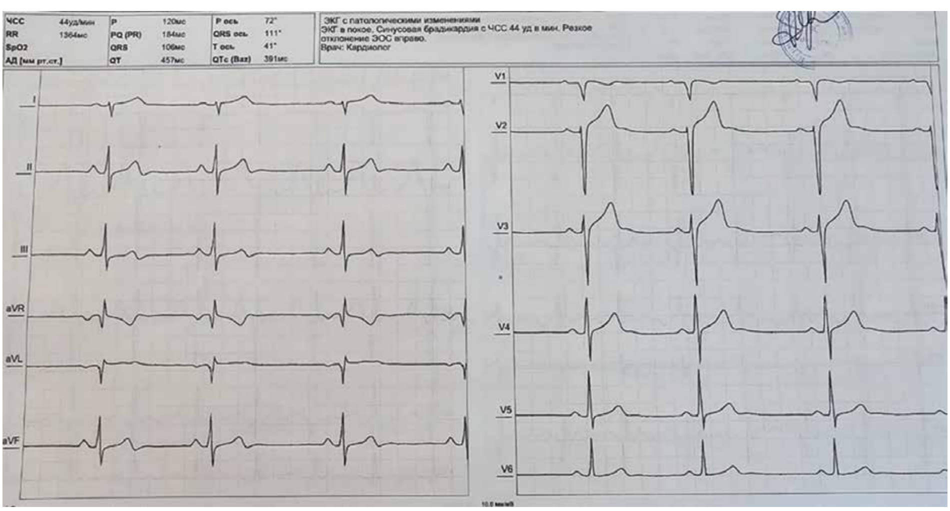

Figure 6.
ECG recording at 25 mm/s. Sinus bradycardia (44/min). QRS axis at 111° consistent with right axis deviation.

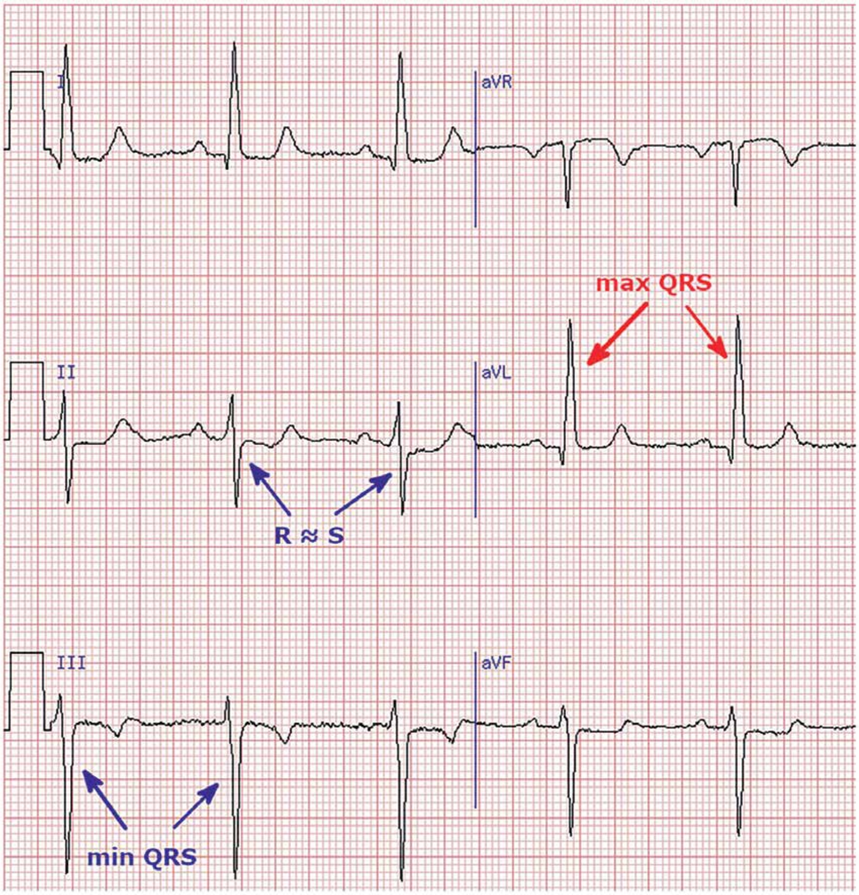

Figure 7.
Left axis deviation.

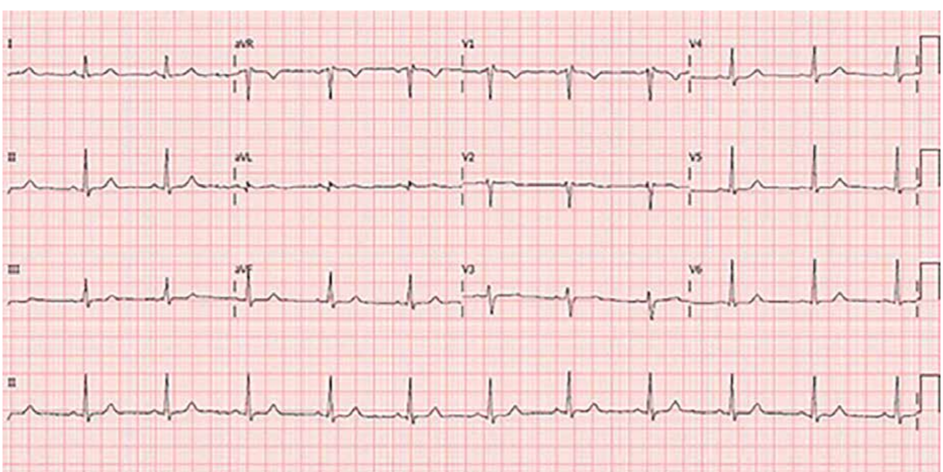

Figure 8.
ECG recording at 25 mm/s. Sinus rhythm 64/min. Normal A-V conduction. rSr' pattern with normal duration in V1-2, indicating incomplete RBBB.

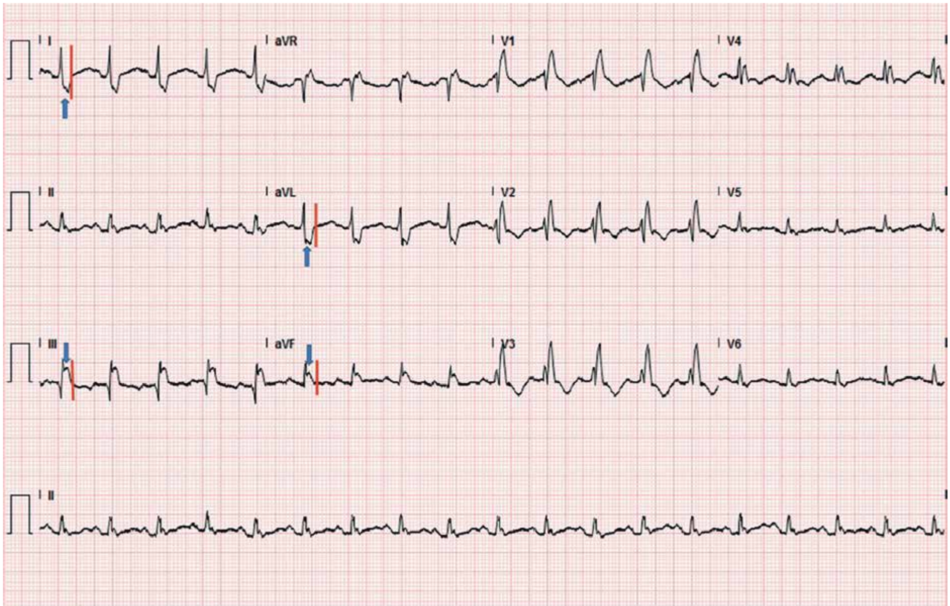

Figure 9.
ECG recorded during a treadmill test in an athlete. rSR' in V1-4 with wide complex, indicating complete RBBB.

ejection fraction and larger right ventricular dimensions and yet maintained a preserved fractional area change. However, none of the athletes with complete or incomplete RBBB showed any signs of structural heart disease. This ECG pattern may be due to the right ventricular adaptation to extreme exercise, indicating a spectrum of structural and physiological cardiac remodeling marked by right ventricular dilatation, resulting in QRS prolongation and a relative reduction in right ventricular systolic function at rest.

Evaluation

Based on the previous findings, some ECG changes in athletes, including left axis deviation, left atrial enlargement, right axis deviation, right atrial enlargement, and complete RBBB, can be considered borderline variants. If an athlete has any one of these conditions alone or in combination with other commonly seen electrical patterns in athletes, is not experiencing any symptoms, and has no family history of premature cardiac disease or sudden cardiac death (SCD), then there is no need for further assessment. However, if an athlete has more than one of these borderline conditions, then they fall under the abnormal category, and further investigation is necessary [13].

5. Abnormal ECG findings in athletes

5.1 Abnormal T-wave inversion

Definition

T-wave inversion >1 mm in depth from baseline in ≥2 adjacent leads, not including aVR, III, or V1.

T-wave inversion (TWI) in leads aVR, III and/or V1 are always considered normal. When TWI are present in other ECG leads, they may be associated with underlying structural heart disease. Except for TWI limited to leads V1–V4 in black athletes and leads V1–V3 in all athletes younger than 16 years, TWI ≥1 mm in depth in two or more contiguous leads in an anterior, lateral, inferolateral, or inferior territory is abnormal and requires further evaluation for underlying structural heart disease.

5.1.1 Anterior T-wave inversion

T-wave inversion in leads V1–V4 is present in 12% of black athletes and is usually preceded by J-point elevation and convex S-T segment elevation and can often return to normal with detraining [38]. T-wave inversion in anterior leads is also a normal finding in asymptomatic athletes aged <16 years [39]. Apart from these contexts, TWI beyond V2 should be further investigated to rule out an underlying arrhythmogenic right ventricular cardiomyopathy, in particular, if the J-point is not elevated and/or ST segment depression is present.

5.1.2 Lateral or inferolateral T-wave inversion

T-wave inversion in the lateral leads (I, aVL, and V5–V6) can be associated with cardiomyopathy and should always trigger further evaluation including cardiac MRI regardless of ethnicity. Cardiac MRI should be a standard part of the evaluation for ECG that is clearly abnormal and suggestive of apical hypertrophic cardiomyopathy, particularly ECG with profound (≥0.2 mV) TWI and ST segment depression in the lateral or inferolateral leads.

5.1.3 Inferior T-wave inversion

The clinical relevance of TWI in the inferior leads is not clear. Accordingly, when these abnormalities are present in an athlete's ECG, further investigations including echocardiography or cardiac MRI are recommended.

5.1.4 Biphasic T waves

Although there is no data on the clinical significance of biphasic T waves in athletes, it is recommended further evaluation of this ECG pattern when the negative part is ≥1 mm in depth in ≥2 leads [11].

5.2 S-T segment depression

Definition

≥1 mm in depth in ≥2 adjacent leads ST segment depressions are relatively uncommon in young athletes with normal heart sound and structurally normal hearts [25, 39, 40] and are not considered a feature of athletic training.

Evaluation

Any S-T depression in ≥2 leads is considered an abnormal finding and requires further investigation (echocardiography and/or cardiac MRI) to rule out underlying structural heart disease.

5.3 Pathological Q waves

Definition

Q/R ratio ≥0.25 or a duration ≥40 ms in ≥2 contiguous leads (except III and aVR).

Any initial negative deflection of the QRS complex is referred to as a Q wave, and they are associated with both physiological and pathological electrical activity of the ventricle, including cardiomyopathy, myocardial infarction, and conduction problems.

About 1%–2% of all athletes have been shown to have pathological Q waves, with these rates perhaps being greater in male and black athletes [12, 41]. Pathological Q waves in athletes were previously defined as >3 mm in depth or >40 ms in duration in ≥2 leads (apart from III and aVR) [42, 43]. However, the specificity of these criteria is not optimal, since skinny teenage athletes and trained athletes with physiological LVH may exhibit high-precordial voltages and deep lateral or inferior Q waves. Therefore, it has been suggested that the Q wave depth be normalized to the degree of the preceding R-wave voltage to decrease the rate of false positive rate without compromising the sensitivity for detecting cardiomyopathy [12]. Accordingly, the current definition of pathological Q waves in athletes includes a Q/R ratio ≥0.25 or a duration ≥40 ms in ≥2 contiguous leads (except III and aVR).

Asymmetric septal hypertrophy, a typical feature of HCM, can result in aberrant Q waves because of higher septal stresses, septal fibrosis, and asymmetric electrical activity. In 32% to 42% of individuals with HCM, pathological Q waves are among the most prevalent aberrant ECG abnormalities [22, 44].

Evaluation

The presence of pathological Q waves in two or more adjacent leads calls for further echocardiographic examination to rule out cardiomyopathy. In particular, athletes under the age of 30 should have their risk factors for coronary artery disease thoroughly assessed, since stress testing may be necessary in those athletes who have numerous risk factors for coronary artery disease or a history of myocardial infarction. No more testing is often required if the echocardiogram is normal and there are no other alarming clinical symptoms or ECG abnormalities. Additional assessment using cardiac MRI should be taken into consideration if abnormal Q waves are detected together with other ECG abnormalities, such as ST segment depression or TWI, or if there are any suspicious clinical signs [11].

5.4 Complete LBBB

Definition

QRS >0.12 s, predominantly negative QRS complex in lead V1 (QS or rS), and upright monophasic R wave in leads I and V6.

LBBB is present in <1 in 1000 athletes, whereas it is common in patients with ischemic heart disease or cardiomyopathy [45–47].

Evaluation

To rule out a serious cardiac condition, complete LBBB must thus always be regarded as an aberrant finding and subjected to a thorough investigation. Complete LBBB athletes need to have a comprehensive myocardial disease evaluation, which includes echocardiography and a cardiac MRI.

5.5 Profound non-specific intraventricular conduction delay (NIVCD)

Definition

Non-specific, QRS >0.12 s

Intraventricular conduction delay in athletes is likely caused by both enlarged myocardium and delayed conduction fibers brought on by neural impulses. While the precise threshold for further investigation in athletes with an NIVCD is still unknown, international recommendations suggest that any marked NIVCD in athletes >140 ms, regardless of QRS morphology, should be taken seriously and warrant further investigation.

Evaluation

No additional diagnostic testing is necessary in asymptomatic athletes with an isolated, NIVCD of <140 ms. Athletes with cardiovascular symptoms, a worrisome family history of sudden death, suspected cardiomyopathy, and an NIVCD 140 ms or in combination with additional ECG abnormalities need to be further assessed.

5.6 Ventricular pre-excitation

Definition

PR interval <0.12 s with a delta wave (slurred upstroke in the QRS complex).

Ventricular pre-excitation pattern is present in about 1/1000 to 4/1000 athletes (**Figure 10**) [36, 46, 48]. The clinical implication of pre-excitation is that athletes may be more susceptible to sudden cardiac death since ventricular fibrillation may happen in case of paroxysmal atrial fibrillation conducted through the fast accessory pathway.

Evaluation

Athletes with an isolated short PR interval without delta wave or wide QRS do not deserve additional evaluation. In contrast, asymptomatic athletes with a Wolff-Parkinson-White (WPW) pattern should be investigated for a low-risk or high-risk accessory pathway. In these athletes, an exercise stress test is the first non-invasive step for risk stratification, and it indicates a low-risk accessory route when there is a

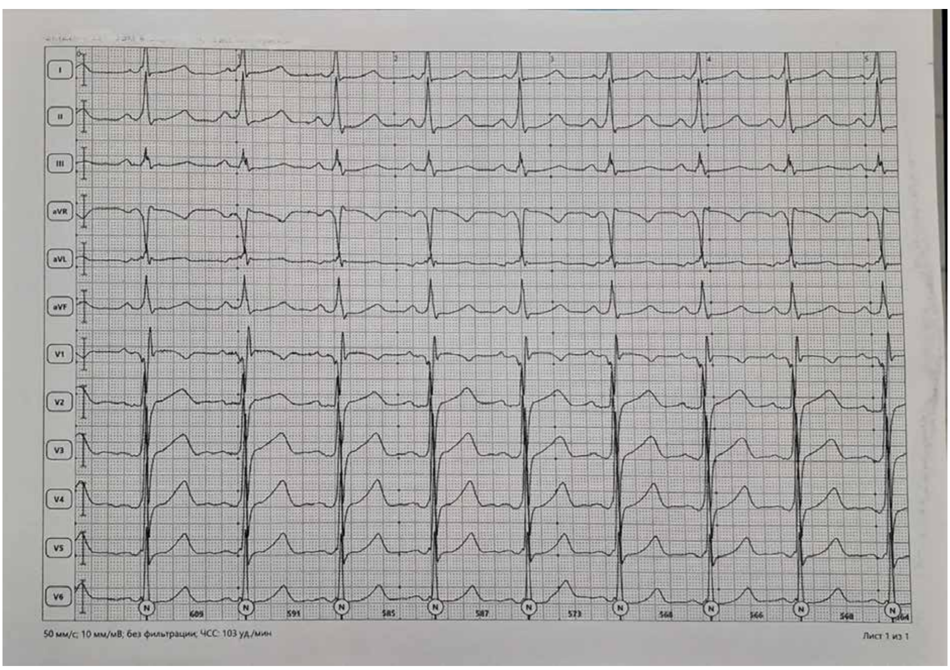

Figure 10.
ECG recording at 50 mm/s in a 24-year-old asymptomatic athlete. Sinus tachycardia 103/min. Short P-R interval with the slurring slow rise of the initial portion of the QRS (delta wave) indicating ventricular pre-excitation through an accessory pathway.

rapid, complete cessation of pre-excitation at increasing heart rates [49, 50]. A low-risk accessory pathway is also consistent with intermittent pre-excitation during sinus rhythm on a resting ECG, which may eliminate the requirement for additional tests [51].

If non-invasive testing is equivocal or unable to prove a low-risk accessory pathway, electrophysiology study should be performed to find the shortest pre-excited RR interval during an induced atrial fibrillation. A pre-excited RR interval of <250 ms (equal to a heart rate of 240/min) indicates a high-risk accessory pathway, and athletes should undergo radiofrequency ablation [50].

5.7 Q-T interval

5.7.1 Prolonged Q-T interval

Definition

QTc ≥0.47 s (males)

QTc ≥0.48 s (females)

QTc ≥0.50 s (unequivocal long QT syndrome (LQTS))

Congenital long QT syndrome (LQTS) is a potentially fatal syndrome characterized by genetically mediated ventricular arrhythmias (torsades de pointes or ventricular fibrillation) (**Figure 11**). The hallmark electrocardiographic feature is represented by marked QT prolongation due to loss-of-function mutations in the genes producing voltage-gated potassium channels, which control phase 3 repolarization.

The prevalence of this abnormality is around 1 in 2,000 individuals [52], and it may account for 25–40% of autopsy-negative sudden cardiac deaths [53].

Since the accuracy of computer-produced QT intervals corrected for heart rate (QTc) values range from 90% to 95%, accurate measurement and manual validation of the computer-derived QTc are essential. Six principles have been

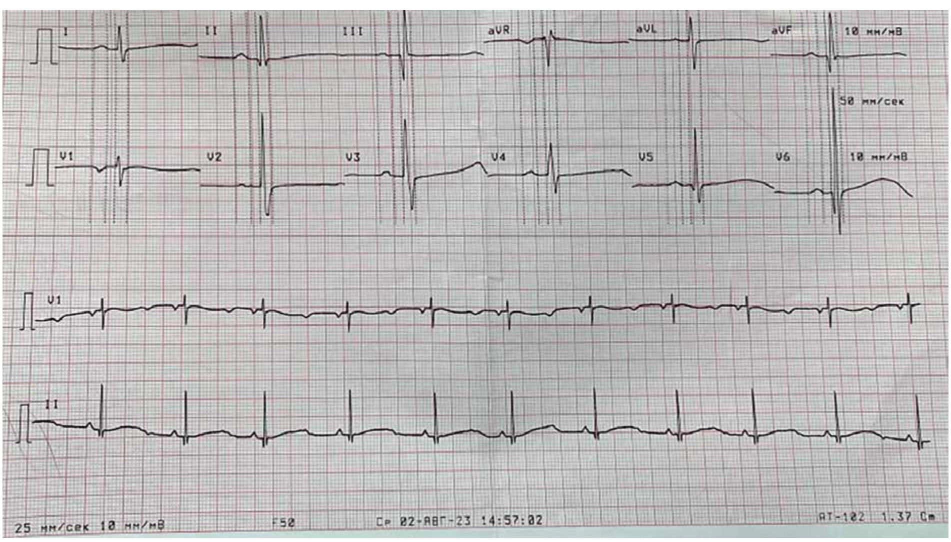

Figure 11.
ECG recording at 25 mm/s. Prolonged Q-T interval (560 ms).

suggested by Postma et al [54] in order to have an accurate assessment of the QTc; however, in clinical practice, we can compare the manually measured QTc in lead II and V5 with the one provided by the computer, which should provide a difference <10 ms.

5.7.2 Short QT interval

Definition

QTc ≤0.32 s

The prevalence of a short QT interval is 0.1%, according to data from over 18,000 asymptomatic young British people; hence, it is pragmatic to recommend that a cut-off value of 320 ms is abnormal. However, individuals with a short QT (<320 ms) did not experience any adverse events, syncope, or sudden death throughout a mean follow-up period of 5.3 years [55]. Thus, a short QT interval should be alarming only in the presence of clinical markers like syncope, premature atrial fibrillation, ventricular arrhythmias, or a pertinent family history.

Evaluation

A prolonged QTc needs additional evaluation. A family history of syncope and premature sudden death should be investigated. In the absence of symptoms or familial disease, a QTc <500 ms is unlikely to represent an LQTS, while a QTc ≥500 ms is highly suggestive of LQTS. If the personal or family history is positive, electrophysiology evaluation is recommended. If the personal/family history is negative, ECG should be repeated on a different day, and if the QTc is below the cut-off values, no additional tests are required.

5.8 Brugada type 1 pattern

Definition

High take-off and downsloping ST segment elevation in V1–V3.

Distinguishing the elevated ST segment characteristic of the Type 1 Brugada pattern from the upward-sloping ST elevation evident in early repolarization among athletes is imperative. In pursuit of this discrimination, the Corrado index emerges as a pertinent metric. This index entails the assessment of the ratio between the ST elevation at the onset of the ST segment/J-point (STJ) and that at 80 ms subsequent to the initiation of the ST segment (ST80). A Corrado index exceeding 1 signifies a predisposition toward a Type 1 Brugada pattern, whereas a ratio falling below 1 in the context of an athlete denotes the manifestation of an early repolarization pattern [56, 57].

Brugada syndrome is an inherited cardiac electrical disorder with an autosomal dominant mode of transmission and incomplete penetrance, with a prevalence ranging between 5 and 66 per 10,000 [58]. Brugada syndrome is projected to account for approximately 4% of total instances of sudden deaths within the general population and represents 5%-20% of cases involving sudden unexplained deaths with an anatomically normal heart upon postmortem examination [12]. The diagnostic criteria for Type 1 Brugada pattern, currently regarded as the exclusive diagnostic indicator, encompasses a coved rSr' pattern, ST elevation of ≥2 mm, and the inversion of the terminal segment of the T wave in leads V1, V2, and V3. Importantly, these manifestations are not associated with myocardial ischemia, electrolyte imbalances, or overt structural heart pathology [59, 60]. It predisposes to ventricular arrhythmias unrelated to structural heart diseases, and sudden cardiac death occurs more often during states of enhanced vagal tone.

Over the past 25 years, there has been prevalent interchangeability in both scholarly articles and clinical practice between the terms "Brugada type 1 ECG pattern" and "Brugada syndrome" [61]. Even the recent guidelines from the European Society of Cardiology (ESC) concerning the prevention of sudden cardiac death (SCD) equate the Brugada type 1 ECG pattern with Brugada syndrome, establishing the diagnosis of Brugada syndrome primarily based on ECG criteria. This semantic error has the deleterious consequence that any subject displaying a Brugada type 1 ECG pattern is considered to be at risk of SCD, regardless of symptomatic or asymptomatic arrhythmic presence or absence [62, 63].

Evaluation

The electrocardiographic pattern of Type 1 Brugada syndrome requires investigation, regardless of the presence or absence of clinical symptoms. When the ECG pattern is unclear, it is crucial to verify the accuracy of lead placement and perform a high-precordial lead ECG with V1 and V2 positioned in the second or third intercostal region during the repeat ECG. If the Type 1 pattern is identified on this high-precordial lead ECG, it is advisable to refer the patient to an electrophysiologist for further assessment. Careful consideration should be given to potential contributing factors that may accentuate a Brugada-like ECG pattern, such as elevated blood potassium levels, febrile states, medications with Na+ channel-blocking properties, and ensuring appropriate electrode positioning [13].

5.9 Profound sinus bradycardia/first-degree AV block

Definition

<30 bpm or sinus pauses ≥3 s.

Profound sinus bradycardia is characterized by a notable deceleration of the heart rate stemming from dysfunction within the sinoatrial (SA) node. This condition manifests as a heart rate dropping notably below 60 beats per minute, a distinguishing feature often observed in individuals with rigorous athletic training [16, 27]. However, if an athlete exhibits a resting heart rate ≤30 beats per minute or experiences a sinus pause lasting ≥3 s, a comprehensive assessment is warranted [11].

In athletes, there may exist a mild to moderate first-degree atrioventricular (AV) block, evidenced by a PR interval spanning 200–399 ms, attributable to heightened vagal tone [64]. A PR interval ≥400 ms represents a substantial prolongation and a thorough investigation to discern the presence of cardiac conduction anomalies is needed.

Evaluation

When faced with profound sinus bradycardia or a significantly prolonged PR interval, a thorough evaluation should encompass an assessment of the chronotropic response during mild aerobic activity, such as engaging in stationary running or stair climbing. Exercise testing proves valuable in this context, providing an objective evaluation of the PR interval and heart rate response to aerobic exertion. Should the heart rate demonstrate a proper increase, the PR interval normalize, and the athlete remain asymptomatic, further testing is generally unnecessary. Conversely, if the heart rate fails to rise appropriately or the PR interval does not shorten adequately during exertion, if the athlete experiences pre-syncope or syncope, or if the athlete has a family history of cardiac disease or sudden death, a more comprehensive evaluation is warranted. Depending on the specific clinical context, an echocardiogram or ambulatory ECG monitor may be deemed necessary for a thorough assessment [12, 13].

5.10 High-grade atrioventricular block

Definition

Second-degree AV block Mobitz type 2: Intermittently non-conducted P waves not preceded by PR prolongation and not followed by PR shortening.

Third-degree AV block: Complete heart block.

Mobitz type 2 second-degree AV block and third-degree AV block are consistently pathological and should be regarded as an abnormal finding in athletes. Complete heart block can sometimes be mistaken for AV dissociation without block, a circumstance wherein the junctional pacemaker operates at a faster pace than the sinus node, leading to a higher number of QRS complexes compared to P waves. AV dissociation without block represents an expression of autonomic discordance between AV and sinus nodal modulation, yet it is not indicative of pathology. Similar to other functional disturbances, conducting a minor exercise load alongside subsequent ECG recording will demonstrate a resolution of the ECG findings in AV dissociation [11].

Evaluation

Upon the detection of a high-grade AV block, a comprehensive evaluation is essential. This assessment generally incorporates an echocardiogram, prolonged ECG monitoring in everyday activities, and a stress ECG test. Interpretation of these findings guides the need for further investigations, which may encompass laboratory testing and cardiac MRI for a more in-depth assessment. It is imperative to refer the individual to an electrophysiologist for specialized evaluation and management, given the seriousness and potential implications of these cardiac conduction abnormalities [13].

5.11 Multiple premature ventricular contractions

Definition

≥2 per tracing.

The occurrence of multiple premature ventricular contractions (PVCs)– defined as two or more in an ECG strip – is infrequent and is observed in less than 1% of 12-lead electrocardiograms in athletes [36, 46] (**Figure 12**). Research studies, such as those conducted by Biffi and colleagues in 2002 and Verdile et al. in 2015, have indicated that PVCs often diminish during physical exertion or following periods of decreased physical activity [65, 66]. These studies shed light on the extended medical implications of frequent and intricate ventricular tachyarrhythmias observed in highly conditioned athletes, emphasizing the dynamics of these arrhythmias during varying activity levels and deconditioning phases.

Evaluation

Although multiple PVCs are generally benign, their presence can signify potential underlying heart disease [66]. Specifically, the identification of two or more PVCs within a 10-s trace, noted as couplets, triplets, or non-sustained ventricular tachycardia, is considered abnormal and necessitates a more thorough evaluation to rule out underlying structural cardiac abnormalities. At a minimum, individuals presenting with such PVC patterns should undergo an ambulatory Holter monitor, echocardiogram, and exercise stress test. With advancements in technology, the availability of modern, compact, leadless ambulatory recorders facilitates prolonged electrocardiographic monitoring, even during training and competition, enabling the exclusion of complex ventricular arrhythmias [11].

If both the Holter monitor and echocardiogram produce normal results and PVC decrease during exercise, typically, no further assessment is recommended for asymptomatic athletes. Existing research indicates that in competitive athletes with ≥2,000 PVCs per 24 h, about 30% manifested underlying structural heart disease, a notable contrast to the lower percentages of 3% and 0% observed in those with <2,000 and <100 PVCs per day, respectively [65]. Consequently, athletes presenting with ≥2,000 PVCs per 24 h, instances of non-sustained ventricular tachycardia, or an increasing ectopic burden during an incremental exercise test may necessitate additional evaluation. This could involve contrast-enhanced cardiac MRI and electrophysiology studies to more comprehensively assess the cardiac condition.

While some studies have indicated that a reduction in PVC burden with detraining suggests a favorable prognosis, this finding has not been universally corroborated. Therefore, employing detraining as a diagnostic or therapeutic measure is not currently recommended [13].

5.12 Atrial tachyarrhythmias

Definitions

Supraventricular tachycardia, atrioventricular nodal reentry tachycardia, atrial fibrillation, atrial flutter.

Supraventricular tachycardia (SVT), *atrial fibrillation*, and *atrial flutter* are infrequently observed in resting ECGs among athletes. The occurrence of these arrhythmias in young athletes during ECG screening is extremely low, amounting to only 6 cases out of 32,561 individuals [46]. Nevertheless, their presence is invariably regarded as abnormal and necessitates comprehensive further investigations.

Moreover, atrial tachyarrhythmias may be linked to other critical conditions, including LQTS, Wolff-Parkinson-White (WPW) syndrome, Brugada syndrome, and various cardiomyopathies, underlining the significance of thorough evaluation and assessment in such cases [67].

Evaluation

If a resting sinus tachycardia exceeding 120 beats per minute is observed, it is advisable to conduct a repeat ECG after a period of rest, considering recent exercise or anxiety as potential causative factors. Additionally, an exploration of other underlying etiologies is warranted, including fever, infection, dehydration, stimulant use, anemia, hyperthyroidism, or, albeit rare, underlying cardiac or pulmonary disease [62].

In cases of paroxysmal SVT, obtaining a repeat ECG during the non-SVT episode is advisable if feasible. If maneuvers like the Valsalva maneuver, carotid sinus massage, or the diving reflex are utilized to terminate the arrhythmia, obtaining a rhythm strip can offer insights into the mechanism of the SVT. Comprehensive evaluation should include an echocardiogram, ambulatory ECG monitoring, and an exercise treadmill test.

Upon the identification of atrial fibrillation or flutter, a comprehensive approach is crucial. Initiating an echocardiogram is essential to evaluate potential structural heart disease. Furthermore, adhering to standard guidelines and considering anticoagulation therapy is prudent. To ascertain the nature of the arrhythmia (paroxysmal or persistent) and ventricular rate variations throughout the day, an ambulatory ECG monitor should be utilized. A thorough family history evaluation may shed light on any potential underlying genetic predispositions. Depending on the findings from these assessments, additional diagnostic steps such as cardiac MRI, electrophysiology study with potential ablation, and/or genetic testing should be contemplated, aiming to tailor the management plan accordingly [12, 13].

Figure 12.
ECG recording at 25 mm/s. Monomorphic premature beats with wide morphology, indicating their ventricular origin.

5.13 Ventricular arrhythmias

Definitions

Couplets, triplets, non-sustained ventricular tachycardia.

The presence of ventricular couplets, triplets, and non-sustained ventricular tachycardia always necessitates thorough investigation due to their potential to indicate underlying cardiac pathology or act as precursors to sustained ventricular tachycardia, a condition that may result in sudden cardiac death [68].

Evaluation

In the presence of ventricular arrhythmias, a comprehensive evaluation is imperative. This should encompass a thorough review of the individual's family medical history, an echocardiogram to assess for potential structural heart disease, and a cardiac MRI to investigate the possibility of arrhythmogenic right ventricular cardiomyopathy or other types of cardiomyopathies. Additionally, utilizing an ambulatory ECG monitor and conducting an exercise ECG test are crucial components of the assessment process.

Based on the outcomes of these initial evaluations, further investigations may be warranted, including the possibility of an electrophysiology study or genetic testing. These steps aim to provide a comprehensive understanding of the condition, allowing for appropriate management and intervention strategies [12, 13].

6. Discussion and conclusions

Interpretation of the athletes' ECG is of paramount importance to differentiate between physiological and pathological changes. Clearly, too strict ECG criteria will result in false positive findings and wrong disqualification of athletes from sports, while pathological changes considered normal could be falsely reassuring for athletes, which may result in potentially dramatic events. Over the last decades, the classification of the different ECG patterns has been refined with the introduction of training-related patterns and changes due to ethnicity, which has resulted in a consistent reduction of false positive findings without an increased risk of cardiac events.

The 2018 international recommendations for electrocardiographic interpretation in athletes [13] represent a useful guide for physicians who are involved in the evaluation of athletes. Following these recommendations facilitates the assessment of athletes and the decision in terms of fitness for sport while identifying those subjects which can be at risk of fatal cardiac events.

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Chapter 6

Lactate: Anaerobic Threshold and New Discoveries

Jonathan Fusi, Giorgia Scarfò and Ferdinando Franzoni

Abstract

Since its discovery, the lactate molecule has always aroused interest and curiosity in academia. Over the years and scientific discoveries, lactate has only been approached in human physiology as a waste product of anaerobic metabolism. To better understand lactate, researchers have also identified and devised the concept of the anaerobic threshold. However, lactate is rediscovering a new life, as it also appears to be a metabolite of the aerobic system. In addition, it also appears to have a decisive role in neuroplasticity, as well as first and second messenger activity. The aim of the understanding is to deal with an examination of lactate from its beginnings up to the most recent discoveries, passing from the concept of the anaerobic threshold.

Keywords: lactate, anaerobic metabolism, physical activity, anaerobic threshold, metabolism, BDNF

1. Introduction

This chapter aims to reassess the role of lactate in physical exercise.

Within the chapter, we will analyse the historical controversy surrounding lactate, seen in the early days only as a waste metabolite produced in the absence or reduction of oxygen, to the present day, where lactate plays an active role in determining performance improvement.

There will be a focus on the concept of the anaerobic threshold and how it is modulated by exercise.

The term lactate is almost always associated with anaerobic metabolism, but as we will see in this chapter, new scientific evidence is finding that lactate can also be associated with aerobic metabolism [1].

The goal of the metabolic system during exercise is to maintain a constant ATP concentration so that the effort can continue over time. In order to achieve this, the human body has three types of metabolism at its disposal: phosphocreatine system (alactacidic anaerobic), aerobic and lactacidic anaerobic [2]. These three systems alternate with each other in relation to the duration and intensity of exercise in order to sustain the demand for ATP in the unit of time. In biochemical terms, we could call these metabolisms oxidative (O_2-dependent) and substrate phosphorylation (O_2-non-dependent). When physical activity is below 75% of VO_2max, the predominant metabolism is oxidative; for parameters above 75% of VO_2max, the metabolic activity of the skeletal muscle is supported by the anaerobic system with a high production of lactate [3]. Lactate, once produced, can be used as an energy substrate or transported to adjacent muscle fibres via lactate shuttles [4, 5]. Due to these characteristics in various metabolisms, lactate is also defined as a possible link between the glycolytic pathway and oxidative metabolism [6].

In this chapter, we will therefore illustrate how lactate once produced, can be a decisive substrate in energy production and not merely a product of fatigue induction. In addition, we will highlight developments in studies on the anaerobic threshold and how its correct interpretation can influence sports performance.

2. A brief history of lactate

The lactate molecule was first discovered in 1780 by the Swedish scholar Scheele (1742–1786) in sour milk, but it was only later, around the early 1800s, that we were able to observe the relationship between lactate and skeletal muscle [7]. This was made possible by the study conducted by Berzelius (1779–1784), in which the researcher observed how the amount of lactate was proportional to the effort exerted by skeletal muscle [8]. Through the work of many researchers, it has been possible to distinguish muscle lactate from milk lactate. Indeed, muscle lactate is described with the l(+)-lactate isoform, in contrast to that produced by microorganisms described with the d(−)-lactate isoform or a racemic mixture of d(−) and l(+) [9].

At the same time, in 1861, Louis Pasteur (a French chemist and microbiologist) noted how the presence of oxygen-induced more yeast growth than its absence per gram of sugar. Later, it was found that in yeast, there was a decrease in sugar consumption in relation to the amount of oxygen, with a simultaneous decrease in alcohol produced [10, 11]. This phenomenon was also demonstrated in muscle. Less lactate production was found under aerobic conditions than in the absence of oxygen, this condition was termed the "Pasteur effect" [12].

Continuing down the path through history, in 1890, it was shown that the interruption of oxygen supply to muscles in mammals and birds induced an increase in lactate concentration [13]. Following this, A.V. Hill, Long and Lupton [14, 15] and Krogh and Lindhard established the increase in blood lactate concentration in humans following intense exercise [16].

Early researchers believed that lactate formation was necessarily an anaerobic process. In fact, it was assumed that oxygen would play a role in "burning" the lactate produced during activity and where this was not possible, the [La-] would increase. One of the most active researchers in the early 1900s on Jervell [17]. In his studies in which he investigated the concentration of lactic acid, he came to the conclusion that the increase or decrease in lactate was closely related to the presence or absence of oxygen. The real application in understanding lactate in sports we owe to the studies done by Owlen, Wasserman and Kinderman. These researchers, along with many others, have helped us both to understand the next step, namely the interaction between the physiology of lactate metabolism under stress and to and cardiopulmonary response (VCO_2/VO_2) [18]. This interaction gave rise to the concept of the anaerobic threshold.

As we will see in the following paragraphs, to say today that "lactate is produced in the absence of oxygen" is an inaccuracy as lactate is a metabolite that is constantly formed during exercise and only under certain conditions, unrelated to the absence of oxygen, does it increase in muscle and blood.

3. Metabolism during exercise

The main objective of muscle tissue during exercise is to defend the ATP concentration, even when the demand for ATP is very high. Within muscle, ATP concentration is between 20 and 27 mmol/kg of dry muscle and could be totally consumed during very high-intensity activity within 15 seconds [19, 20]. In order to maintain a constant ATP concentration, metabolism has three possible solutions at its disposal:

- Phosphocreatine (PCR) system
- Aerobic metabolism
- Anaerobic metabolism [3]

These metabolisms work so well that in the course of a sprinting activity, or in several sprint repetitions, there is only a decrease of between 20 and 40% compared to the resting condition [2].

These metabolisms are activated simultaneously in order to maintain a constant ATP concentration in the unit of time.

3.1 Phosphocreatine (PCr) system (anaerobic alactacid metabolism)

The phosphocreatine system is also referred to as the alactacid anaerobic system as it is oxygen-independent without lactate production. Through the activity of the enzyme creatine kinase, ATP is recharged from ADP by the release of a phosphate group from phosphocreatine. Not only that, in the course of this (reversible) reaction, a proton (H^+) is consumed, which is essential for keeping the cellular pH under control [3].

$$\mathrm{ADP + PCr + H+ \leftrightarrow ATP + Cr}$$

The concentration of creatine in dry muscle is between 75 and 90 mmol/kg and is essential for maintaining ATP concentration during high-intensity exercise.

The PCr system is the fastest metabolism to activate and has a shorter half-life than the other two, around 10–15 seconds [3]. Note that the restoration of consumed PCr is very rapid at rest. In fact, phosphocreatine can be resentitised due to the reverse reaction involving ATP. The store of PCr is concluded in approximately 60–90s, thus making it ready to be reused [19].

From the dual role played by ATP in terms of both energetics and restoring, it is possible to imagine and understand how the three metabolisms must necessarily work as a unicum so that the ATP concentration remains constant in the unit of time.

3.2 Aerobic metabolism

The term aerobic metabolism is used to classify those oxygen-dependent metabolic reactions. These reactions have both carbohydrates (1) and lipids (2) as energy substrates. Both energy substrates play a key role in muscular metabolism under stress, as already characterised by Christensen's [21] very early studies. The reference metabolic pathways of the aerobic system are, therefore, the glycolytic pathway and the beta-oxidation of fatty acids [22].

Glycolytic pathway:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36 \text{ or } 37 \text{ ATP}$$

Beta-oxidation pathway:

$$C_{16}H_{32}O_2 + 23O_2 \rightarrow 16CO_2 + 16H_2O + 130 \text{ ATP}$$

First of all, it is good to note that from the above reactions, it is possible to derive a parameter that will also be very useful in the analysis of lactate and anaerobic threshold, namely the respiratory quotient (RER). This represents a molar ratio between the CO_2 produced and the O_2 consumed. With a value of RER = 1, we will define the utilisation of carbohydrates for energy, with a value of 0.7, we will define fatty acids [3]. The value of RER is very important during the cardiopulmonary exercise test; in fact, during the test, we will observe the change from values of 0.7 and 0.8 to values of 1.0 and higher. When this happens, it means that we are in a condition of using carbohydrates for energy which will correspond to the anaerobic threshold (we will see this concept later).

The glycolytic pathway is a process in which glucose is converted into two smaller molecules: pyruvate. Subsequently, the two pyruvate molecules enter the tricarboxylic acid (TCA) cycle after conversion to acetyl-CoA and are oxidised into CO_2 + H_2O. Within the TCA cycle, acetyl-CoA binds to an oxaloacetate molecule, and following a series of transformations, 3 NADH, 1 FADH2 and 1 ATP molecule are produced. The two enzyme cofactors produced (NADH and FADH2) then serve as electron transporters within the electron transport chain located on the mitochondrial matrix, with the ultimate goal being the production of energy in the form of ATP [23].

In contrast, the lipolytic pathway involves the breakdown of triglycerides into glycerol and fatty acids. Fatty acids enter the mitochondrial matrix via carnitine transporters (CPT1-CPT2) and undergo beta-oxidation. At the end of this process, acetyl-CoA molecules are also formed, which subsequently enter the TCA cycle [24].

3.3 Anaerobic metabolism and lactate production

The process of energy formation using the lactacid anaerobic pathway is characterised by the glycolysis and glycogenolysis pathway with the final formation of lactate.

From the reference reaction, it can be seen that one molecule of glycogen is required to produce two molecules of lactate with the formation of three molecules of ATP:

$$\text{Glycogen} + 3\,\text{ADP} + 3\text{Pi} \leftrightarrow 2\,\text{lactate}^- + 3\text{ATP} + 2\text{H}^+$$

Immediately noticeable is the release of $2H^+$ ions; indeed, the increase in their concentration, in association also with the increase in lactate anion is associated with an inability of the muscle to sustain contraction due to the inability to produce ATP [25]. How both lactate and H^+ ions are handled and buffered by muscle metabolism will be discussed later.

The enzymes involved in these two reactions (anaerobic glycolysis and glycogenolysis) are phosphofructokinase (PFK), glycogen phosphorylase (PHOS), and lactate dehydrogenase (LDH). The ability of these two metabolic pathways to generate ATP during exercise is approximately four times greater than that of the PCr system [26]. In reactions of anaerobic metabolism, lactate is the final product of the reaction. As we have previously seen, lactate has, since its discovery, been associated with the concept of fatigue as described by Hogan et al. [27]. Indeed, it is now safe to assume that lactate is the real link between aerobic and anaerobic metabolism [1] and that it is not just a product for muscle fatigue but can be a valuable metabolic resource, if not "an universal" resource as reported by Rabinowitz et al. [28].

Before going any further, it is good to provide that lactic acid, which is formed by anaerobic glycolysis or glycogenolysis, has a dissociation constant (pKa) of 3.8. This characteristic means that at physiological pH (~7) it is in the form of lactate anion (La–) [29]. This consideration is very important because from now on, whenever the concept of lactate is introduced, we will refer to the anionic form (La-).

Lactate produced by the glycolytic pathway is obtained by reducing pyruvate. Pyruvate is the end product of the glycolytic pathway, but when the rate of pyruvate production is such that it cannot follow the concentration gradient that would lead it into the mitochondrion, lactate dehydrogenase (LDH) converts it into lactate [30]. On the other hand, glycogenolysis involves the formation of 6-p glucose from glycogen. The 6-P glucose immediately enters the anaerobic glycolytic pathway and the formation of lactate also occurs [3].

It should be emphasised that lactate production is always active but with low activity for physical activity below 50 per cent of maximum oxygen consumption (VO_2max) [22]. In fact, for intensity values between 0 and 70%VO_2max there is a decreasing utilisation of lipids and therefore of the aerobic pathway (glycolysis and beta-oxidation), with an increase in the utilisation of anabolic substrates (anaerobic glycolysis and glycogenolysis). Above the 70% value and even higher values, there is a sudden increase in the utilisation of carbohydrates as the sole source of energy in the form of anaerobic metabolism, with clear and high lactate production [22].

This ability of lactate to allow shifts between the various metabolisms during physical activity is referred to as metabolic flexibility [31, 32]. It would, therefore, seem that the lactate that is produced in the course of normal physiological functions, but even more so during physical activity, can act as a real link between the various metabolisms, leading to an activation of some metabolic pathways and an inhibition of others [33].

Analysing the role of lactate in this respect, we can divide the activity of this molecule within human metabolism into three categories:

As an energy source [34, 35];

In terms of energy source, the study carried out by Hui et al. [35] shows a very interesting key. In fact, in their mouse model, the authors, through the infusion of 13C-labelled lactate, were able to ascertain that it is one of the main fuels in the tricarboxylic acid cycle (TCA). Not only that, at the tissue level (excluding the brain), lactate is found to be more valuable than glucose as a fuel for TCA. This scientific evidence m0ight therefore suggest that despite what has always been assumed, lactate may be a more universal energy fuel than glucose [28]. Conversely, we might speculate on the concept of glucose as an ad hoc energy substrate for the brain and that the plurality of lactate interactions means that the share of glucose can be saved for the brain.

The major gluconeogenic precursor [36, 37];

As reported by Jenssen et al. [38] and later confirmed by Gerich et al. [39], lactate is the major gluconeogenic precursor. This is described through the well-known "Cori cycle." This metabolic pathway interconnects the muscle with the liver and enables blood glucose to be sustained by using lactate conversion as the first substrate to induce gluconeogenesis [38, 40].

Signal molecule with autocrine, paracrine and endocrine activities, in the latter characteristic, lactate would act with hormone-like functions [41, 42].

The characteristic of the lactate molecule to act as a signal molecule is very important as it can act both as a first and second messenger in relation to the metabolic state, energy demands and adaptations induced by physical activity.

Lactate can perform its action as a "lactormone" through the use of transporters called monocarboxylate transporter isoforms (MCT) [43] (shuttle theory of lactate) that allow its cell-cell, tissue-tissue, organ-organ interaction [44]. As described by Brooks [45], lactate is able to modulate the utilisation of glucose and fatty acids as the primary energy source. Down-regulation of fatty acid utilisation is possible through lactate binding to G-protein receptors (GPR81). This interaction, which occurs in adipocytes, causes an inhibition of the lipolytic pathway [46]. In addition to the modulation of energy substrates, lactate studies would also seem to confirm a role for lactate in modulating gene expression, such as that of its MCT receptors [42]. In a study by Hashimoto et al. [42], incubation with 20 mM lactate was found to induce gene activation with an increase in peroxisome proliferator-activated receptor γ coactivator-1α (PGC1α) expression. This response is very interesting and also sheds fundamental light on the interaction between lactate and aerobic metabolism. In fact, PGC1α is the promoter of mitochondrial biogenesis, and we know how an increased number of mitochondria leads to an improved aerobic response with an increase in VO_2max [47]. Backing up these considerations are numerous studies in which it is observed that any type of physical activity is capable of increasing the number of mitochondria. The various types of physical activity also include high-intensity interval training (HIIT), probably the type of exercise that, due to its fluctuations in terms of VO_2max (<70% and >90% VO_2max) and thus metabolism, is able to produce the greatest amount of lactate [48, 49].

3.4 Shuttle theory of lactate

As described above, the lactate produced is capable of exerting a hormonal function, resulting in its activity as a "lactormone" [45].

Garcia et al. [43] highlighted how lactate is capable of triggering a gene response, with the ultimate goal being the production of its own transporters: the monocarboxylate transporter isoforms (MCT). These transporters have the task of enabling the movement of lactate, according to a concentration gradient, between cell to cell, tissue to tissue, and organ to organ [45].

MCTs belong to the solute transporter family 16 (SLC16) gene and are characterised by a symport, in which lactate and 1 proton are co-transported, and has a stereoselectivity, in fact, it can transport the L-lactate isoform but not D-lactate [50]. In addition, they can transport many other substrates such as pyruvate, short-chain fatty acids (acetate, propionate, butyrate), and ketone bodies (acetoacetate and β-hydroxybutyrate) [51]. As many as 14 MCTs are highlighted in the scientific literature. Each one is well localised in cells, fibres, tissues, and organs in a highly tissue- and transport-kinetic-specific manner [43, 52, 53]. On the plasma (sarcolemmal) membranes of skeletal muscle, there are MCT1 and MCT4 transporters [45]. MCT1 appears to be more highly expressed in high aerobic muscle fibres, whereas MCT4 does not appear to correlate with muscle fibre type [54]. These differentiations, however, highlight a ubiquitous role for lactate, emphasising its interaction with other organs and its activity as a "lactormone."

Studies have related the amount of lactate transporters to the degree and type of physical activity [55–57]. As reported by Thomas et al. [57], constant low-intensity exercise causes an acute increase in MCT in humans. In sedentary subjects, increases in MCT1 and MCT4 were observed 2–6 days after a 5–6 h cycling training session at 60% of VO_2 max in untrained humans [58]. During 16 hours of heavy, intermittent cycling exercise (6 minutes of exercise at 90% VO_2 max per hour for 16 h) in untrained subjects, a rapid increase in MCT4 content (24%) was reported, with no change in MCT1 [58].

In contrast, however, no increases in MCT4 and MCT1 were found in moderately trained endurance runners subjected to a time-to-fatigue test performed at 110% VO_2 max [59] lasting 2 h. This is probably induced by the fact that in sedentary subjects, the acute response is more rapid and significant than in moderately trained subjects.

The increase in lactate transporters is most evident when athletes and moderately active subjects are compared. Indeed, Thomas et al. observed a higher amount of MCT in endurance athletes than in less active subjects [60].

The role of the lactate transporters located at the muscle level is to decrease its concentration in the muscle fibres that are producing it. In this way, the fibre that is working can release both lactate and H^+ ions and thus maintain its activity. The efflux would take place in the extracellular fluid adjacent to the fibre. Conversely, thanks to another MCT transporter, an adjacent fibre can utilise the lactate and by introducing it into the mitochondrial level can reoxidise it, thus supporting mitochondrial respiration. This scenario was called the intracellular lactate shuttle hypothesis [61].

When the "intracellular lactate shuttle hypothesis" was postulated by Brooks et al. [62], it was not unanimously accepted by the scientific world due to the difficulty of demonstration [63, 64]. Through numerous subsequent studies, researchers have come to postulate the presence of the Mitochondrial Lactate Oxidation Complex (mLOC) capable of utilising lactate for aerobic purposes [65]. This is possible because mLOC is characterised by a lactate transporter (MCT), its membrane chaperone basigin (BSG or CD147), LDH and cytochrome oxidase (COx) [66]. In addition to the lactate transporter, at the mitochondrial level, the pyruvate transporter (mPC) could also be identified through laboratory analysis [65]. This discovery makes the concept that lactate is reoxidised at the mitochondrial level even more plausible.

Questions still remain as to the location of mPC, as there are many conflicting studies [67–71]. Further studies are therefore needed to better describe the lactate and pyruvate complexes; what is certain is the presence of mechanisms at the level of the mitochondrial reticulum to oxidise both lactate and pyruvate.

4. Lactate and muscular fatigue

The term muscle fatigue identifies a decrease in muscle strength to complete an action under constant load [72].

Muscle fatigue can have two components and undergo specific physiological responses depending on the component involved. The two components are central and peripheral fatigue. Central fatigue involves the central nervous system, with the alpha-motoneuron, the spinal cord. Conversely, peripheral fatigue is at the muscular level [73].

In terms of muscle fatigue, we can identify temporary and chronic muscle fatigue.

During physical activity, in relation to the amount and type of effort required, there is a more or less marked production of lactate. The greater the production of lactate, the more rapidly the phenomenon of muscle fatigue may arise in the absence of adequate buffering systems or sufficient lactate transporters to discharge lactate. Not only that, the theory of acidosis-induced muscle fatigue postulates that the phenomenon of fatigue begins to occur due to the concentration of H^+ ions, resulting in decrease in cellular pH [74]. The decrease in pH is accompanied by the exercise-induced increase in lattemia.

Subsequently, however, further and more in-depth studies [65] showed that it could not be lactate accumulation or a decrease in pH alone that induces muscle fatigue, but rather a combination of acidosis, phosphate ion accumulation and low Ca^{2+} [75] interaction with the theory of thread sliding, thus altering muscle contraction.

From a review of the literature, it would appear that the concomitant increase in lactate and decrease in muscle pH lead to metabolic and acid/base imbalance, resulting in the cessation of muscular contraction [76].

4.1 The definition of the anaerobic threshold

Lactate has a very dynamic metabolism during physical activity. In fact, it can undergo rapid changes in concentration both at the muscle level and in the bloodstream, depending on the type and duration of the effort. For example, during high-intensity exercise, lactate concentrations of 40 mmol/L and 25 mmol/L can be found in muscle fibres and the bloodstream, respectively [77].

The ability of the human metabolism under stress to be able to switch between aerobic and anaerobic metabolism with high lactate production has been widely discussed throughout history [18], since as we shall see, the ability to anticipate or stay longer at the anaerobic threshold could represent a fundamental turning point in performance prediction.

The concept of the anaerobic threshold closest to what we have today was postulated by Owles in 1930. In his study, he observed how the lactate concentration increased above a certain level during physical activity, calling this point: Owles' point [78].

This evidence proved to be very useful and differed from previous authors in that, whereas previously an increase in lactate was observed in conditions of oxygen absence, with Owles, the decrease in the binding of CO_2 by haemoglobin also began to be related to the increase in lactate concentration. This consideration laid the foundations for future studies and especially for what we might consider the study par excellence on the concept of the anaerobic threshold (AT): that set out by Wasserman and McIlroy [79]. In fact, in his postulate in the early 1960s, they highlighted the terminology of anaerobic threshold by merging the aspect of increased lactate concentration with the physiological response. This was possible because the buffering of lactate by bicarbonate would produce an excess of CO_2, so by analysing respiratory volumes (VCO_2 and VO_2) it would be possible to identify the anaerobic threshold [80]. The innovation proposed by Wasserman and later developed by the same, involved a direct interaction between respiratory physiology and lactate biochemistry (breath-by-breath), whereas Hollmann, Kindermann, Keul focused exclusively on lactate concentration [18]. This test is called cardiopulmonary exercise testing (CPET). By relating the cardiopulmonary response to lactate biochemistry, it is therefore possible to indicate that the anaerobic threshold is that point on the graph where the amount of VCO_2 exceeds the amount of VO_2, thus leading to a decrease in available oxygen. In this condition, there is a high accumulation of lactate in the muscles and arteries, resulting in the anaerobic threshold condition [22]. The other fundamental characteristic for understanding the physiology of lactate under stress and its possible application in sports is the evaluation of the heart rate under stress. In fact, by cross-referencing the data of the VCO_2/VO_2 ratio and the curve that is created during exertion, it is possible to identify the metabolic shifting between the aerobic system and the lactacid anaerobic (AT) system at what power is established and at what heart rate. This concept is very important because it then defines a cardiac threshold value below which we are fairly sure we can work with a predominant aerobic metabolism and above which the anaerobic metabolism has predominance [22]. Without forgetting, however, that both metabolisms work in the first and second case; they just do not take absolute precedence.

Based on many studies and scientific evidence, many synonyms of anaerobic threshold have been described [80–82]. In fact, according to studies and various degrees of interpretation, two phenomena can be defined as anaerobic threshold or aerobic lactate threshold or "onset of blood lactate accumulation" (OBLA). These definitions refer to a point in the course of exercise at which metabolic shifting occurs, but this may not be definitive, in fact according to Kindermann et al. [81], the point that Wasserman identifies as the anaerobic threshold may actually be the maximum point of utilisation of the aerobic system. The second phenomenon refers to a moment when, during exertion, the accumulation of lactate is unavoidable. This condition is described by the term maximal lactate steady state (MLSS) [83].

In relation to the above, training can interfere with the former phenomenon as opposed to the latter. In fact, thanks to the increase in MCTs and PCr stores and the ability to buffer both H^+ ion and lactate, typical of muscular adaptation to exercise, it will be possible to modulate either anaerobic threshold entry or cause MLSS to occur with much delay.

The differentiations between OBLA and MLSS seem like abstract concepts; in reality, they have a real application. Indeed, in a recent study [84], a double anaerobic threshold was observed in healthy subjects. The authors evaluated cardiopulmonary exercise tests performed over the previous 9 years. They found that 11% of the subjects evaluated had a double anaerobic threshold. The presence of the double anaerobic threshold did not lead to a differentiation in terms of CPET; however, subjects with the double threshold had lower VCO_2 production, resulting in a lower respiratory exchange ratio. The authors suggest that subjects with a double anaerobic threshold actually had an earlier onset of anaerobic threshold entry but were able to remain in this state for longer than other subjects until inexorable lactate production occurred.

However, it is important to remember, as by the authors' own admission, the lactate concentration was not measured, so it might make the study not very precise.

4.2 Anaerobic threshold as predictor of performance

Based on what has been described, an active role in the prediction of performance could be assumed to be played by the anaerobic threshold. Again, as in others previously described, the literature data is conflicting and confusing [83, 84].

Haverty et al. pointed out that in runners, maximum oxygen consumption (VO_2max) is not a reliable predictor of performance, but VO2 value at MLSS speed, on the other hand, has a fundamental weight in understanding performance [85].

A similar concept was also highlighted by the work of Gregory et al. [86]. The author's aim was to use cardiopulmonary exercise testing and anaerobic threshold analysis to describe the best type of training for cross-country mountain bikers. The data again showed that VO_2max should not be the focus of the training, but rather power at the lactate threshold, and VO_2 at the lactate threshold.

Ji et al. [87] through their study were able to observe how the anaerobic lactate threshold could be used to predict performance during a race. Although the data provided by the authors are very interesting, the sample size suggests that a much larger study would be needed to better understand the use of this parameter.

This consideration comes in the face of many contradictory studies on the true use of the anaerobic threshold as a predictor of performance [82]. Major contradictions also lie in the fact that the cardio-metabolic response may be sport-specific and that it may therefore be difficult to use only one absolute parameter to understand and anticipate performance [88].

The anaerobic threshold, like any other physiological parameter, can be trained, but unlike the other parameters, where even low to moderate intensity can induce an improvement, the anaerobic threshold needs high-intensity exercise to be improved [89].

From this point of view, high-intensity interval training is an excellent method for improving the utilisation of lactate for energy purposes and thus staying much more in that shadow zone between OBLA and MLSS [90].

5. Discussion and future prospective for lactate

Some 150 years have passed since the discovery of lactate, and even today, there are still considerable doubts and misunderstandings as to the real role of this molecule in the human body.

In fact, at first, it was assumed that lactate was only a waste product of metabolism and that during physical exertion, together with the concomitant release of H^+ ions, it caused muscle fatigue.

We now know with certainty that lactate is produced approximately 65% by glucose metabolism and 16–20% by alanine metabolism [51]. Its production occurs at a low intensity during normal physiological functions but can abruptly increase in relation to an increased energy demand in a short unit of time. Once lactate is produced, it can undergo detoxification processes (e.g. Cori cycle), buffering, or via specific transporters (MCTS and SMCT), it can pass from the muscle fibre that is producing it to an adjacent one that is not "working." This characteristic is very important as it has led to the hypothesis, and then to the demonstration, of the presence of a mitochondrial complex capable of reoxidising lactate so that it can be reused for energy purposes.

Moreover, the role of lactate has recently been rehabilitated, making it a true messenger, with hormonal activity, capable of interacting with other tissues and organs by determining gene suppression or activation. In addition, lactate can also modulate neurotrophic factors such as brain-derived neurotrophic factor (BDNF) [91].

This new observation opens the door to a new lactate frontier.

From a biochemical point of view, lactate can cross the blood-brain barrier [92] reaching neurons via MCTs [93, 94]. In this case, the main player is MCT 2 [95], whereas MCT 4 is only expressed in astrocytes [96]. As lactate can be used for energetic purposes, the transport of lactate from astrocytes to neurons plays a crucial role in memory formation [97, 98] and thus could be a link between exercise and neuroplasticity [92]. Indeed, exercise can increase levels of BDNF and insulin-like growth factor 1 (IGF-1) [91] and vascular endothelial growth factor (VEGF) [99].

In contrast, according to Yang et al. [100], lactate could promote neuroplasticity by enhancing NMDA glutamate receptor activity in neurons.

Morland et al. evaluated the role of hydroxycarboxylic acid receptor 1 (HCAR1) on increase VEGF expression and angiogenesis, activated by lactate binding. In this study, the authors observed a direct interaction between a molecule released from muscle during physical activity such as lactate and the central nervous system in a murine model [101]. To achieve this result, the authors divided the animals into three groups: High-intensity interval exercise 5 days weekly for 7 weeks of treadmill training, a group treated with sodium L-lactate injections and a control group with saline injections. The use of sodium L-lactate resulted in an increase in lactate concentration like that obtained with physical activity. The results showed that both the rats treated with training and those with sodium L-lactate expressed an increase in VEGFA in the brain. These data underline the direct relationship between increased blood lactate related to physical activity and increased brain neurotrophic factor.

In a recent work [102], the possible metabolic and biochemical link between physical activity, increased lactate and improved neuronal plasticity and memory was investigated.

In the mouse model proposed by El Hayek et al. [102], it was shown that lactate produced during regular physical activity can induce not only increased BDNF expression but also the NAD + -dependent histone deacetylase SIRT1. The increase in SIRT1 expression could also lead to an increase in antioxidant defences [103] in the brain, posing a possible further explanation for the improvement in neuronal plasticity.

6. Conclusions

Over the years, since its discovery, lactate has always been compared to the phenomenon of muscle fatigue and as a waste product of metabolism. The study of the possible role of lactate in muscle fatigue has led to the discovery and development of the concept of anaerobic threshold to the present day.

With the succession of studies, the role of lactate has been rehabilitated, in fact, it can be a first fuel during physical activity, and its formation prevents the accumulation of pyruvate. Not only that, more and more recent studies have also identified signalling roles. In fact, in physiological conditions or induced by physical activity, it can act either as a first signalling, for example with hormonal activity (lacthormone) or act as a second messenger. Not only that, by means of specific interactions, it would seem implicated with angiogenesis and the increase of the neurotrophic and plastic factors at the brain level. Such interactions always seem to be dependent on an active role of exercise.

Based on this latest scientific evidence, it is legitimate to hypothesise motor programmes designed to increase lactate concentration in a controlled manner to exploit the “lactormone”” capacity, especially in the brain in the most severe physiopathological conditions. More scientific evidence will certainly be needed both to redefine the concept of the anaerobic threshold and the role of lactate in human physiology.

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Conflict of interest

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Chapter 7

Sport Analytics: Graduating from Alchemy

Charles Mountifield

Abstract

Sport analytics allows sport teams and organizations to improve performance and associated business decisions. There is an increasing demand for sport analytics, in part connected to the emergence of Big Data, resulting in a new discipline in the sport industry. Business models related to sport analytics offer the opportunity to analyze the performance of athletes, teams, clubs, and sport organizations. The burgeoning yet competitive objectives based on sport analytics explain, to a degree, why it is rare to find algorithms, predictive models, and other statistical methods and analyses being carried out in the public domain. This chapter first outlines topical views of the developing field of sport analytics that suggest that its application is based on organizational self-interest, resulting in a degree of obfuscation that may limit the pursuit of knowledge. Countering these opinions, however, is evidence pointing to sport analytics becoming more mainstream and a domain of shared knowledge. The chapter provides a non-exhaustive literature review, including sections addressing statistical elements, performance optimization, theoretical frameworks, and the application of sport analytics, followed by some overall observations. Within that context, recent developments in the sport industry demonstrate that sport analytics is more than alchemy.

Keywords: alchemy, analytics, business, science, sport

1. Introduction

Described as the analysis and modeling of sporting performance and achievement [1] and a data-driven approach to the business of sport [2, 3], the application of statistical methods within sport facilitates improved athletic performance for athletes and teams, ultimately leading to success for sport organizations. Globally, the sport analytics market was valued at circa USD 3 billion in 2022 and is projected to be worth USD 22 billion by 2030 [4]. With the advent of the age of Big Data [5] in sport – viz., the application of massive datasets to identify patterns – sport analytics has evolved into a legitimate division of the sport industry [1]. The application of Big Data is affecting the sport industry multi-dimensionally [6, 7] and profoundly impacting the administration of aspects of professional sport [2]. By applying comprehensive datasets and facilitating probability over prediction, sport analytics impacts on-field sporting action and, in turn, the management of sport organizations [8–10].

From the perspective of sport organizations - and their athletes and teams - sport analytics includes statistical methods and quantitative models, and visualization surrounding these methods and models to improve performance. In short, applying mathematical and statistical principles in sport can enhance athletic performance and create a competitive advantage [11]. Sport analytics is applied in a structured manner, backed by research findings, and relies upon contributions from both the computer science and sport science field, along with statistics and engineering [12]. Despite the immense growth of sport analytics in becoming a part of mainstream sport, however, some critics challenge such a general viewpoint. For example, Szymanski [13] contends that "much of the work in sport analytics seems to possess the same traits as alchemy - secretiveness and obscurantism" (p. 60), thus relegating the discipline from an integral part of the mainstream sport industry. There are references to a lack of scholarly analysis relating to the theoretical application of Big Data and associated social, legal, and ethical concerns [14], the imbalance between elite sport organizations and comparatively poorly resourced sport organizations, including women's sport [15, 16], and the overall objectives of sport organizations turning to sport analytics to gain a competitive advantage [13, 17] and improve business performance based on corporate objectives [18–20].

With the above in mind, the objective herein is to challenge such notions and show that sport analytics is now an essential functional and operational aspect for teams, clubs, and sport organizations [10, 19]. While it is not suggested that secrecy is not uncommon, particularly concerning the pursuit of competitive advantage, there is sufficient literature to demonstrate that the increasing importance of the discipline outweighs the concerns about the nature of sport analytics or suggestions that the field is not integral to the sport industry. On a non-exhaustive basis, this chapter provides some background and a literature review that forms a platform for some general observations for future research.

2. Background

Sport analytics has a rich history of applying prognostic statistical methods based on past performance and forecasting future performance [21, 22]. Used to measure the competitive advantage of teams, coaches, and individual participants, sport analytics represents a valuable tool for informing sporting decisions [10, 23]. Historically, sport analytics was primarily characterized by the video recording of competition or training sessions and the creation of video highlights that athletes and coaches would review pre-and post-match. More recent examples include the interpretation of external load profiles [24], the analysis of acute chronic workload ratios [25], the use of GPS competition data to create and analyze training drills [26], and the application of data to analyze the impact of substitutes in team competition [27]. Within such context, sport analytics applies to team sports such as football, cricket, rugby, athletics, basketball, golf, and niche or indoor sports such as hockey, chess, table tennis, and martial arts. Sha et al. [28] point out that analytics in professional sport has seen histrionic growth in the past decade due to technological advances observed during this period.

As the practice of sport analytics continues to develop and to attract sport scientists who increasingly rely on the predictive nature of the discipline, opinions are divided on the relevance of sport analytics [1]. While sport analytics offers an avenue to predict future performance and make informed decisions to facilitate competitive advantage predict [1, 29–31], skeptics have labeled sport analytics alchemy [13] and a discipline that comes with a degree of notoriety [32]. Amidst the apparent growth of sport analytics as a prophetic discipline in sport, opinions regarding sport analytics' ineffectiveness are evident. For one, Szymanski [13] claims that much of the work in sport analytics is motivated by the need "to influence coaches and gain influence" (p. 61), which discourages honesty in sport, thus hindering the true spirit of sportsmanship in turn. There are opinions of those involved directly with sport, such as athletes and sports writers, who claim analytics is ruining sport [33, 34] and also an unsettling general debate about the position of sport analytics in mainstream sport [11, 32, 35, 36].

Further, despite the evident disruption of sport analytics due to technological advances, questions remain about whether sport analytics has reached a level of maturity, understanding and recognition within the sport industry [8, 37]. Cynics contend that sport analytics is yet to become a mainstream division of sport [13], that its application is inconsistent across various sports [38] and that it comes with risks and ethical concerns attached [14, 16, 39]. Some risks of Big Data in sport include athlete data and the control over their data, the accuracy of data, user privacy, and the interpretation of data, leading to concerns that the advances in sport research may be impacted by ethical considerations [39]. In some cases, concerns have been raised about mistrust amongst athletes about increasingly detailed data collection and who owns and controls the data [40]. Further, it is argued that the objective of teams to look for every competitive advantage means collecting data from as many sources as possible, which leads to ethical questions about what data may be forthcoming, including sensitive medical data relating to athletes or through hereditary issues, even their extended family [16]. Overall, scholarly discussion on literature that analyses the application of Big Data to test theory and answer research questions is limited [14], and there are suggestions that a collective fascination with sport analytics obscures the complex nature of organizational objectives to gain a competitive advantage and adds to inequalities in sport [15].

Notably, when considering the predictive nature of sport analytics, Hatfield et al. [23] adds that prognostic statistical methods are a matter of chance. The application of analytics in sport may not provide a reliable relationship between past performance and future performance or measure the competitive advantage for sport teams or participants; thus, there is a risk of ill-informed sport-related decisions. The alchemic aspect of a predictive application to sport is founded on the argument that the analytics involved in competition, team, or athlete analysis thrive on odds versus probability. From a business perspective, Szymanski [13] adds that organizational self-interest and the pursuit of competitive advantages limit the growth of knowledge, observing that "however much like alchemy, sport analytics is characterized by opacity and secrecy, and outside of baseball, evidence of success that would meet the usual scientific criteria is limited" [p. 57]. Corporate objectives for sport organizations may be founded initially on on-field success, but it is the advent of analytics linked to, for example, improved marketing functions and sponsorship processes that mean sport organizations benefit from an increasing array of commercial opportunities through data analysis [18–20, 41, 42].

Yet, in contrast, the discipline's importance continues to grow with a rise in its use by sport organizations [17, 43]. Therefore, coupled with earlier successes, advanced automated data collection processes, and increased computational power, sport analytics has evolved into a significant division in the sport industry. From simple projections of performance and predictions for future competition, the use of sport analytics has grown over time, allowing for helpful insight into athlete and team achievement [10, 28]. Many advocates of sport analytics argue that it represents a straightforward way to improve athlete and team performance, particularly from a competitive perspective. There are examples of such applications in rugby [44], cricket [45], NFL (or American Football) [46], and soccer [7, 47, 48] where there are cases that demonstrate that sport analytics aids in the tracking live sport performance, perfecting athletic movement, and virtually eliminating injuries [49]. Further, there are instances where sport analytics is applied to an athlete's health and the probability of an injury which enhances the general performance of a sport organization [23, 50]. Finally, there have even been suggestions in soccer that teams have won league titles with the aid of sport analytics [51].

Numerous platforms, including websites, television channels, and other digital avenues, are dedicated solely to sport analytics [45]. Increasingly, sport analytics is a more structured field, and research findings support the increasing levels of application of complex data within sport organizations. According to Steinberg [52], referring to sport in North America, "today, every major professional sport team either has an analytics department or an analytics expert on staff" [para. 3]. Further, data-driven decision-making means sport analytics is now a significant focus for the entrepreneurial space in the sport industry [53, 54]. Whether sport analytics is a science or a pseudoscience, however, the ultimate standard of the discipline is the capacity to predict with significant statistical accuracy [1, 29–31]. Accordingly, it is necessary to delve into a discussion supported by literature outlining the position of sport analytics in mainstream sport and whether it is now a science rather than alchemy.

3. Literature review

This review explores examples of literature on sport analytics to demonstrate if the discipline has become mainstream while simultaneously opposing the view that it is alchemy. In particular, predictive statistical methods, or forecasting [55], are evaluated to find a reliable relationship between past performance and future performance and to see if that renders sport analytics as science or alchemy. The review also examines the functions of sport analytics and its role in aiding the competitive advantage of sport organizations and the relationship with interconnected organizations, employees, and fans, that collectively help drive performance and profitability [56]. The key sections address statistical elements, performance optimization, theoretical frameworks, and the application of sport analytics.

3.1 Statistical elements

Studies confirm that sport analytics is a progressive discipline with immense growth potential [17]. The field continues to explore new ways to incorporate statistical methods for improving predictive accuracy [10]. Kapadia et al. [45] recognize the practice noting that "sport analytics is a promising research field which involves deriving valuable information about the game, based on past games played, or even games in progress" [p. 2]. Such a position implies that using statistical methods to evaluate and improve an athlete's or team's performance to assist stakeholders in managing an athlete's health (e.g., the probability of injury) gives sport analytics significant legitimacy. Sport analytics derives significantly from mathematical and scientific methods [48]. The idea that it is alchemy – "characterized as the fruitless attempt to turn straw into gold" [13] – is far from reality. Groll et al. [57] proposed that the scientific application in the analytical process should qualify the discipline as a science. Furthermore, within the discipline of sport analytics and the development of technology, the domain provides evidence of engagement between various people ranging from analysts, presenters, sport betting sites, and companies together with their employees and fans [17, 56, 58].

Some studies observe that sport enthusiasts, participants, and fans use information derived from sport analytics to better understand a team's performance with sufficient accuracy [59, 60]. With technology taking center stage, it is evident that sport analytics incorporates multiple technological applications to improve its statistical precision [6, 58]. According to Cortsen and Rascher [18], predictive analytics has been used successfully in many other sectors of the economy to foster commercial progress while, at the same time, improving business performance [3]. Such situations affirm the position of predictive analytics, thus, the potential for sport analytics to make accurate predictions.

Applying analytical methods to Big Data and combining them with predictive algorithms yields superior performance in sport and other industries [61]. For example, Szymanski [13] points out that sport analytics is characterized by Big Data, advanced statistical methods, and complexity, illustrating how sport analytics combines with technology to improve accuracy, efficiency, and interactivity. Goes et al. [48] contend that sports analytics involves using Big Data that requires complex statistical synthesis to harness its potential. Szymanski [13] notes that Big Data is revolutionizing several aspects of sport, based in part on increasing levels of accessibility with "the development of open-source software platforms such as Python and R, together with the increased availability of sport data online" [p. 60]. This revolution includes various applications, from genomics research to business [62, 63]. In business, companies can track a customer's purchases, forecast the product they are likely to purchase and then present them with the opportunity to make such a purchase [20]. Accordingly, this development indicates that using Big Data in professional sport offers the potential for a competitive advantage that will appeal to every sport organization.

There are examples of sport organizations creating brand value and obtaining a competitive advantage in sponsorship and purchase predictions [41] and clubs and teams that gain a competitive advantage in the field of play [1]. Coupled with the recent advances in computational power, Big Data has paved the way for sport analytics to become mainstream. This development partly relates to the fact that sport organizations are moving beyond low-level intervention-based observational data [64] to predict performance as increasingly complex data becomes available, permitting more refined analysis [7]. For example, in statistical analyses of soccer, game logs – files of soccer matches – are "obtained through next-generation tracking technologies and physiological training data collected through novel miniature sensor technologies have become available for research" [7]. By encoding game logs, there is the potential to predict when an opponent will perform strategic actions like pass prediction [65].

Mumcu and Fried [66] point out that sport administrators can use sport analytics datasets to identify patterns suggestive of an athlete's or team's competitive advantage. For instance, some analysts have demonstrated that athletes consistently display the same reactions in competitions, meaning sport organizations can gauge an athlete's resilience in certain circumstances [67]. By providing interactive prediction through situational analysis [28], sport analytics offers an off-field element linked to commerce and organizational profitability [56]. For example, some athletes are valued for endurance, some for speed, and others for style, skill, and how they blend in a team setup. Hence, sport analytics goes beyond predicting outcomes, as Szymanski [13] suggests, because it also includes using various metrics to evaluate talent, build teams and accelerate engagement with fans, which has a significant commercial element [17, 56, 68]. In other words, the statistical elements associated with this technique apply to both on-field and off-field simulations.

Kostakis et al. [69] refer to the application of scientific methods in data mining and the use of algorithms that makes sport analytics a mainstream sport division. Numerical algorithms and machine learning reduce the margin of error, thus increasing the accuracy and efficiency of sport analytics [45, 70]. According to Singh [17], such technology supports the business aspect of sport and allows organizations to "capture and collect data on games, bidding, bookmaker odds, playing styles, scores, and many other sport attributes" [p. 64]. Thus, using mathematical methodologies coupled with different prognostic statistical methods provides reliable relationships between past and future performance, further qualifying sport analytics as a science. While Szymanski [13] argues that "much of the work in sport analytics seems to possess the same traits as alchemy" [p 60], the continuous application of sport analytics and its ability to derive accurate outcomes overtime outweighs the general view that it is secretive and obscurant.

Finally, sport analytics has developed to become an integral part of the mainstream sport, evidenced in part by what has been referred to as the 'Moneyball moment' [13, 71], a story from American baseball involving the novel application of data analytics to gain a competitive advantage. Developments since the Moneyball moment have resulted in various sports applying algorithms to guide business decisions for athlete assessment [72] and team success [51]. These advances include the entrepreneurial application of sport analytics, witnessing millions worldwide participating in statistics-based imaginary sport leagues such as Fantasy Football [68]. Thus an approach to the business and marketing of sport, based on the application of data, is potentially of immense value [3, 17], and in this context, the disciplines' validity warrants acknowledgement.

3.2 Performance optimization

It is essential to note that sport is a highly competitive and performance-oriented engagement. According to Hatfield et al. [23], sport analytics' essence is to optimize performance, as participation in any sport equally needs a performance-based strategy. Hence, sport analytics provide relevant statistical measurements to improve a team's performance and examine sport participants' athletic capacity [73], the probability of incurring an injury [23, 49], and its impact on the team; sport analytics makes the approach sport management intelligent [13]. Since sport is a viable business and one of the leading occupations, sport analytics' role enables teams to perform at the peak from a managerial perspective [3].

In advanced sport management, sport analytics involves profound elements of human kinetics, performance psychology, cognitive-motor, exercise psychology, sport analysis, and performance history. An important aspect of sport analytics is psychophysiological monitoring, which is used to obtain "a better understanding of the processes underlying athletic performance and to improve it" [74]. Therefore, sport analytics cynics may have more to lose from failing to recognize the essential analytics function in planning for better team and individual athlete performance [73]. That being the case, what becomes paramount is sport analytics' capacity to predict with substantial accuracy [1, 29–31].

As an organizational objective, superior performance in sport is characterized by better decision-making informed by consistent practice, having the right resources, and the best coaching. While some instances may require coaches, athletes, or teams to explore their intuition, it does not mean, as Szymanski [13] suggests, "that almost all-important insights from science can be explained intuitively" [p. 60]. For example, Szymanski [13] highlights the importance of Big Data in business decisions, including predicting consumer behavior. Hence, all-important insights heavily rely on "the science of recognizing patterns on a grand scale" [13]. As such, all-important decisions today rely on data patterns rather than intuition.

In elite sport, high-performance sport managers regularly explore and analyze data patterns in the past to improve future athlete performance [73]. Doing so demonstrates that prioritizing statistics as part of professional decision-making is gaining widespread acceptance [52]. Various sport stakeholders use sport analytics for multiple purposes, such as improving the business' bottom line – "the pursuit of profit" [13] – but coaches, athletes, or teams need the information to optimize performance. For instance, the data derived from the analysis can create profiles for athletes and their teams which may act as a point of reference for past, present, and future performance [17]. Thus, any professional sport team, coach, or athlete that does not use the insights derived from sport analytics fails to exploit the competitive advantage effectively.

Apart from the athlete and team, sport analytics evaluation includes creating a team's strategy and managing competition. Part of this involves the financial aspect of sportsmanship, driving customer engagement, and augmenting back-office intelligence. Statistical modeling has become an integral aspect of business [9], spreading into other essential business functions such as marketing, administration, member retention, and expanding partnerships [42, 66]. For instance, since most sport now depends on sport analytics insights, sport organizations can attach the correct value to a team, the athletes, or even leagues or tournaments [73]. The same information is used in ticket pricing, identifying, and signing new athletes, and attracting partners and opportunities for investment. Consequently, the position and function of sport analytics depend on various stakeholders' ability to put the information gained into meaningful use with sufficient accuracy [1]. An example of the meaningful use of sport analytics occurs when different sport platforms such as websites, television programs, and digital avenues adopt the science to advance commercial aspects of sport.

Coupled with the growth of the computational capacity of the most advanced computer systems, the development of open-source software platforms and the availability of sport data, sport analytics is increasingly part of the contemporary mainstream sport culture [75]. At the organizational level, some activities related to sport analytics include recording matches and training sessions, analyzing each athlete's movement in the team context, delivering feedback, and updating databases for further analyses [76]. Such processes are typical of any business seeking to optimize its market performance, usually coined market research and analysis. Therefore, sport now involves using analytical tools to reduce risks and identify the best in a pool of talent, thus ensuring that every decision offers value to a sport organization [10, 77, 78].

Finally, sport organizations are increasingly aware of integrity issues relating to sport analytics combined with their business objectives. Critics dismiss sport analytics labelling as a practice motivated by the need to influence coaches and gain influence over competitions and teams, discouraging sporting integrity and thus hindering the true spirit of sportsmanship. While some ethical concerns are tied to sport analytics [16, 39], there is the need to appreciate it as an insightful professional tool rather than dismissing it based on its negative aspects, a characteristic synonymous with most innovations. Alamar [79] notes that "as data becomes more accessible, decision-makers have found clearer insight into their organizations and the nature of the decisions they face through the use of metrics that did not exist even a few years ago" (p. 65). Within that context, data collected through the sport analytics process is subject to legislation, including, for example, the Privacy Act 1988 (Privacy Act) in Australia and international legislation such as SOC 2 (Service Organization Control Type 2) cybersecurity compliance frameworks designed to ensure that third-party service providers (e.g., sport data analytics companies) store and process sensitive data in a secure manner [80].

3.3 Theoretical frameworks

Any form of statistical synthesis requires the qualitative aspects of analysis to foster understanding and comprehensive application [81]. The qualitative aspects of sport analytics explore theoretical frameworks to make sense of the complexity involved in Big Data analysis to derive value [1]. Thus, theory becomes an essential part of scientific investigation, which helps solve complex questions regarding sport analytics' history and whether it has a place in mainstream sport. There are suggestions that "research in sport analytics avoids theorizing" [13], yet studies discussed herein are evidence of the research efforts associated with sport analytics. Hayduk [3] argues that sport analytics continues to attract sport enthusiasts and stakeholders who rely on the analytical nature of the practice based on existing theoretical concepts from different disciplines.

Goes et al. [48] contend that "contributions from the domain of sport science and the domain of computer science are typically characterized by distinctly different research paradigms" (p. 2). Specifically, sports science often involves deductive reasoning to form hypotheses and experimental design studies. For example, teams are complex dynamical systems, and as such, a hypothesis concerning group or individual behavior is illuminated based on theoretical perspectives such as deductive reasoning [82, 83]. On the other hand, the computer science domain utilizes a very different research paradigm than the sport science domain. Gudmundsson and Horton [84] maintain that computer science involves the theoretical underpinnings of information retrieval and advanced analysis, thus realizing high levels of complex and large data representations. Therefore, combining the domains points to science in practice and counters any notion of a lack of theoretical application in sport analytics. Regardless of the theoretical frameworks used to justify sport analytics, the ultimate benchmark of sport analytics is the capacity to predict [1, 29–31].

The predictive analysis involved in sport analytics is characteristic of 'complex systems theory' – which exploits scientific methodologies such as computational modeling and simulation to understand or predict social issues [85]. Typically, a complex system is a structure made up of multiple components that how they interact [86]. On that basis, McCarthy et al. [87] suggested that it can be challenging to understand sport analytics' complex nature. Accordingly, it is conceivable that an aversion to the mathematical application may lead to the rejection of statistical methods used in sport analytics based on the issue of chance. Such dismissal rests on the fact that chance may not provide a reliable relationship between past and future performance [88, 89]. Further, chance may not measure the competitive advantage of sport teams or participants in a complex system. Such systems are fundamentally challenging to model owing to multiple interdependencies, competitive relationships, and other types of interactions between some of their parts or between a given system and the environment in which it exists [90].

Exploring the discipline's theoretical aspects and statistical elements is essential to generate a balanced understanding of the application of sport analytics [91]. Some skepticism about crucial components of sport analytics arises from the still-developing links with performance history, cognitive motor skills, performance psychology, and human kinetics [12, 92, 93]. Further, the attribution of doubt is limited to understanding exercise psychology, the ability to analyze Big Data, and the complexities of sport analysis in a statistical manner [94]. Since aspects of the fundamentals of sport analytics may appear unrelated, the interconnections that are difficult to trace have become one of the grounds for discharging sport analytics as a legitimate area of the sport industry [13]. Therefore, the discussion about the position of sport analytics in mainstream sport and whether it is a science or alchemy should consider the link between the theoretical and statistical aspects of predictive analytics [13]. There is a need to improve the illustrative relationship between the qualitative vis-a-vis the quantitative elements of sport analytics to foster a balanced understanding of its application as a tangible division of sport [95, 96].

3.4 Application of sport analytics

To ascertain the position of sport analytics as a legitimate branch of sport, it is crucial to assess multiple sources of information ranging from analytics provided by in-house departments of sporting divisions to evidence from sport analytics companies and organizations that sell sport data. Further, there is a need to arrive at evidence-based conclusions against the ongoing discussions regarding the position of sport analytics as a mainstream sporting practice and whether it is a science or alchemy. Companies such as WyScout, Opta, FiveThirtyEight, Sportradar, and Diamond Kinetics sell sport data based on statistics relating to playing styles, bookmaker odds, competitions, and results [17, 55]. Several platforms, such as websites, television channels, and digital avenues, are dedicated solely to analyzing competitions and teams or athlete performance [45]. According to companies such as WyScout, the information derived from sport analytics readily applies to the actual management of teams and clubs with high accuracy.

Organizations like WyScout sell sport data and provide information used in several fields by various sport stakeholders, including analysts, presenters, and fans. Some companies provide real-time information about competitions and teams to manage and commercialize fan expectations and experiences before and during competition [56]. Such predictions are possible due to the data supplied through aspects of sport analytics [97]. Data that companies provide include seasonal datasets and historical data. Within that context, betting on the performance of individuals or teams, or the outcome of competitions, is evidence of the commercial application of sport analytics. Indeed, sport betting is an emerging trend in sport analytics [98] and demonstrates that data-driven decision-making is not only a reserve for high-profile sport management as sport fans benefit from applying sport analytics to inform betting strategies [53].

More evidence about the application of sport analytics in sport management derives from companies that provide analytics data and platforms to help organizations improve performance. Professional sport purchases such data and platforms because they offer valuable insights into, or management of, coaching processes and teams and athletes. Some of the most recognized companies in this category include Covatic, Edj Analytics, AISpotter, Fusion, Catapult, EDGE10, Sportradar, MacVar, and StatsBomb. The information derived from such companies is based on technology that synthesizes information – a data-driven ecosystem [99] – about athletes and competitions. Capturing athletes' past and present performance is critical for planning future competitions. Armed with such information, it becomes possible to attach value to sport teams, athletes, or events. For example, some athletes are valued for endurance, some for speed, style, skill, and how they blend in a team setup.

Further, technology provided by analytics companies has been assimilated into sport analytics to improve accuracy, efficiency, interactivity, and team performance [100]. For instance, a company such MacVar exploits simulated fields that clone positions of athletes wearing smart jerseys in a match with finite levels of accuracy to analyze athlete movement [101]. Athlete profiles and team performances have become leading sources of information for coaches and sport managers. Various sport stakeholders use sport analytics for various purposes, but coaches, athletes, or teams need the information to optimize performance. Sport analytics provides details such as the position of a ball, work rate, fatigue, the time of a specific action, and the results of such action. Software firms such as Coach Paint, Dartfish, and Sportscode, coupled with third-party data and statistics companies such as Opta, have made it possible to collect, retrieve, code, capture and analyze essential data points efficiently and effectively for real-life applications. Applying statistics as part of professional decision-making is gaining wide acceptance as a mainstream activity [102], no less so in sport due to sport analytics' numerical value [6].

From a sport organization perspective, many teams also have internal analytics departments that provide data to inform decision-making. In-house analytics departments offer greater precision than data derived from sport analytics companies [103]. Amidst considerable reliance on sport analytics supported by Big Data, some teams find it helpful to set up internal sport analytics departments that enable them to own such vital information. The internal departments use technologically supported models and software to break down complex data matrices [1]. In-house data analysis is often more precise and tailored – the information is more contextual [104]. Football clubs, Australian Football League clubs, and American baseball teams value the sport analytics resource and continuously invest in internal analytics departments. This development has created roles such as tactical analyst, technical scout, scouting analyst, training analyst, goalkeeper analyst, and research analyst, individuals increasingly viewed as sport scientists [105]. Sport organizations are investing significant resources towards building these departments that strictly focus on robust metric and statistic systems, and analysts are increasingly valuable recruits for such structures [106]. Therefore, sport analytics is an increasingly crucial scientific venture supporting team and club performance within that context.

Finally, the application of sport data serves other purposes as data analytics companies seek to monetize data for commercial reasons. Some examples of data produced relate to digital media consumption needs, sport writers, teams, and leagues

[100]. Sport organizations can use data that tracks online sentiment and behavior [54], which gives rise to a new and advanced approach to customer relationship management [107]. Further, from the perspective of selling to fans away from competition, data available through sport analytics enables the creation of gaming models prevalent in games such as Fantasy Football [100]. The variety of applications demonstrates multiple creative ways in which sport analytics is applied [100]. Analytics companies recognize sport as a serious business that can inform strategic management and intelligent planning from a data perspective [3]. As most sport teams and clubs continue to put information derived from sport analytics into meaningful use, sport analytics' position as a mainstream factor becomes more challenging to deny.

4. Observations

Various authors opine that sport analytics is yet to reach a level of maturity, understanding and recognition within the sport industry [8, 37], is yet to become mainstream, appears secretive and obscure, and is characterized as alchemy [13]. Other authors suggest the relevance and value of sport analytics is questionable [1], and there is unsettling debate about the position of sport analytics in mainstream sport [11, 32, 35, 36]. There are suggestions that the application of sport analytics is inconsistent across various sports [38], and it comes with risks and ethical concerns attached [14, 16, 39], and that the development of the field adds to inequalities in sport [15].

Nevertheless, based on the recent advances in sport and computer science, Big Data and the capacity to analyze data, there is robust evidence that sport analytics is meaningful, impactful, and widely applied to great effect in the sport industry. Further, numerous developments in science and technology related to sport analytics assist with organizational decisions, from a team or athlete performance basis to strategic planning and management. Such developments are based on sophisticated data collection methods, storage, analysis, and the meaningful presentation of these data. With the growing impact of Big Data in sport, analytical skills have improved and become paramount to and synonymous with the sport industry, especially considering the large amount of data handled, disseminated, and analyzed to generate valuable insights. Evidence that significant insights have developed to improve team, athlete, and club performance is portrayed in several examples featured herein.

While there are situations where statistical methods and algorithms used to forecast performance might be closely guarded details for a sport organization, it is essential to remember that the discipline was developed specifically to help such organizations drive team efficiencies in addition to revenue and profit generation [108]. Where profit – the bottom-line – is involved, it is impossible to perform these analyses in public, let alone share the models and algorithms used in the analyses. In so doing, there would be a threat to the competitive edge of analytics firms, clubs, and sport organizations. The increased exposure and use of sport analytics in sport, however, indicates how data analytics has been transformed into a mainstream component of the sport industry. Analytical tools and the availability of Big Data have improved sport organizations' ability to evaluate team performance and identify both team and individual strengths and weaknesses. An examination of the role of data analytics in sport points clearly to the discipline being a science, and, in this respect, the argument that sport analytics is notorious or alchemy is flawed.

5. Future direction

Whilst not obfuscation, protecting one's competitive edge is logical. In assessing the development of sport analytics, however, there is a sufficiently robust platform that demonstrates those involved in the discipline are directly or indirectly adding to knowledge. Although sport analytics research is in a nascent stage [17], an increasing body of research is available to assess how data-driven analytical methods influence sport [2, 14, 109]. Quantifying such a situation – and challenging any notion that sport analytics lags in the shadows of alchemy – is an area for future research. Such research might include gaining insight into the burgeoning data analytics organizations providing data and platforms for professional sport teams, the success of sport teams as they rely increasingly on sport analytics, and the impact of sport analytics on individual athletic performance. Although there will always be organizations that seek to limit knowledge sharing to protect their competitive advantage, the cumulative impact of sport analytics in mainstream sport, as evidenced herein, means future research has abundant data to apply to the science of sport analytics. Indeed, analysis of large datasets will provide a more comprehensive understanding of ever-changing phenomena [14], increase knowledge in sport science, inform competitive strategies, and facilitate innovative research [110].

6. Conclusion

In conclusion, the increasing demand for sport analytics is primarily because of the available data (i.e., Big Data), which has increased exponentially over the last decade. The radical advances in information technology increased computing power, the amount and frequency of data collected, and reduced storage space costs are more far-reaching today compared to some years hence. Sport analytics has become a new discipline in the sport industry, enabling a new level of efficiency and competitive advantage [52]. Most business models related to this field aim to improve the performance of individual athletes, teams, clubs, and sport organizations while at the same time helping achieve corporate objectives, particularly the bottom line. Therefore, the profitability aspect, like in any other business, makes it challenging to find sport analytics companies or sport organizations benefiting from the data output of said companies, readily sharing their algorithms and predictive models. While this may limit the pursuit of knowledge in one aspect of sport, it does not demonstrably impact the potential for datasets to be used in a more open, beneficial way for sport science. More importantly, it does not suggest that alchemic traits of notoriety, opacity, and secrecy characterize sport analytics.

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Chapter 8

Talent in Top-Flight Football: Concept, Recruitment and Predictive Models for Identification

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Abstract

Addressing the importance of understanding the concept of talent in football and how the lack of conceptual clarity can lead to biases and flaws in recruitment practices. The identification and development of talent are fundamental for talent management in high-performance football. We seek to reflect on the complexity and dynamics of this process, in order to contribute to the development of objective and predictive models for identifying talented young people in sports, using multi-sited ethnography. Talent detection can be influenced by factors beyond the technical and mental skills of young players, such as height and hand size. The club's culture and the availability of financial resources are also important for the development of talented young footballers. Sports organizations are adopting an interdisciplinary model to minimize process failures. The detection and development of talent in football involve many factors beyond the technical and mental abilities of young people, and the definition of talent is a subjective and sometimes empty concept, which makes identifying talent even more challenging.

Keywords: talent management, football, skills, athletes, multi-sited ethnography

1. Introduction

The search for talented young people capable of becoming high-performance soccer players is a topic that has attracted the attention of many researchers. However, the precise definition of what constitutes a "talent" in childhood or youth has proven to be an increasingly complex and ambiguous challenge [1]. The lack of objective criteria for identifying these athletes has compromised the selection process carried out by professionals in the world of soccer.

Adamsen [2] points out that the concept of talent is an imprecise construction, an empty signifier. To overcome this ambiguity, it is necessary to create objective and predictive models for identifying soccer talent, taking into account which factors and attributes are relevant for future sporting success. This incessant search for young people with different profiles and potential, able to stand out from the rest and generate profits for the clubs in their talent management processes, has been the subject of great interest and research.

Over the years, the term "talent" has been used in the football world to describe players with exceptional ability. However, research carried out so far has been unable to define precisely what a talent is, demonstrating the complexity and ambiguity of this concept within the sport sciences.

This chapter is the result of an ethnographic research carried out between 2018 and 2021 in southern Brazil, analyzing the process of young aspiring soccer players and entrepreneurs. Our objective is to highlight the flaws in the identification and development of "talents" in the base categories, considering the very ambiguity of the term. To this end, we present empirical examples that show the conceptual fragility of talent management, which encompasses the identification and development of potential [2]. Based on our ethnographic research, we seek to reflect on the complexity and dynamics of this process and contribute to the development of objective and predictive models for identifying talented young people in sports.

2. Methodology

In this chapter, we present a multi-sited ethnography [3], which currently demarcates a large part of ethnographic studies, insofar as few researchers are restricted to a place or a community in their research. Multi-sited ethnography is not limited to the field, but the whole research process itself, the way to record what was noticed, at the time of data analysis, is to accompany all the interweaving of information and perceptions, the "following the threads" , adjusting the look to each specific situation, its particularities, and how each one ends up leaving its mark on the others. Through a process of adjustment, of reorganization of the events narrated by the interlocutor and reassembled by the researcher, the narrative gains meaning. To enrich the debate on the subject, we also used the concept of semiotic anthropology [2], which makes it possible to understand the symbolic load of certain terms with greater precision and depth, giving meaning to all the baggage that a given word carries in a group or specific field.

3. First approximations

During the ethnographic investigation that we carried out in the youth football categories [4], we faced a significant challenge: conceptualizing the term "talent". During the study, we noticed that this term was often used ambiguously and that its meaning was difficult to define clearly and objectively. To overcome this difficulty, we held several conversations with football professionals, family members and fans involved in the process to obtain different perspectives and understandings about the expression in question.

In order to deepen our analysis and establish a more horizontal communication, we decided to study the language in depth, through semiotic anthropology [2], which allowed us to understand that the expression "talent" had a symbolic meaning that was not easily definable. We realized, then, that this expression was an empty signifier, a term that, although frequently used, did not have a precise definition, being in football something complex and multifaceted, and that its definition can vary according to the context in which it is used. In addition, the study of language and anthropological semiotics provided us with a greater understanding of the use of signs and meanings in the world of football and other areas of social life. It is also important to take into account your origin and linguistic nuances. According to Adamsen [2], the word talent has its roots in Latin and was originally a unit of measurement of weight and currency used in the Roman Empire. Later, the word began to be used in the artistic context to describe natural skills and aptitudes that allowed the creation of masterpieces. Over time, the concept of talent expanded to other contexts, including sports, business and education to refer to skills and aptitudes that allow success in different areas.

The indiscriminate use of the term "talent" leads to an arbitrary and subjective understanding of the concept, which makes talent management dysfunctional and undermines selection systems [2]. Still according to the author, the word "talent" presents a polysemy of meanings, ideas and references that are not easily defined, and its understanding depends on a discursive relationship. This is corroborated by the observations of Lewis and Heckman [5], which point to imprecision and lack of clarity in the definitions of the term. Several authors add that talent is not a directly observed concept, but rather inferred, which contributes to its imprecision and the existence of more than 100 different definitions for the term [6]. In other words, although the word exists, its meaning is not clear, which raises an ontological problem that questions the very existence of talent in today's world.

Currently, the concept of talent has expanded to include a set of skills developed and improved over time. Talent is often associated with success in different areas of life such as sports, arts and business. This semantic evolution reflects the constant transformation of language and culture, as well as the different ways of understanding and valuing human capacity throughout history. According to several authors, a term with an indefinable meaning is one that has a multiplicity of meanings, each one applicable only to a particular world [7, 8].

Authors claim that talent is associated with a conception of success already achieved through conquests, and no longer with a starting point [9], which highlights the difficulty of defining it. It is important, therefore, that talent management consider these multiple dimensions of talent to identify and develop potential talent and avoid subjective biases in selection. Football talent is the result of a broad domain of the set of general motor skills, psychological attributes and cognitive components potentiated at high values [6].

The ambiguity of the term is evident, as it can refer both to a person's attitude or ability and a talented performance, a behavior that goes beyond the ordinary [10].

A clear and consistent understanding of the concept of "talent" is essential for organizations to manage their human resources effectively and achieve success and market competitiveness. For a comprehensive and precise definition of the concept of talent, it is necessary to avoid simplistic approaches that could limit or underestimate its complexity. A narrow or vague definition could fail to consider important aspects of talent, such as its development and the influence of external factors. In addition, the dichotomous perspective that talent is innate or artificial can be problematic, as talent is the result of the interaction between biological, environmental and cultural factors [11]. Therefore, a robust definition of talent must account for these complexities and nuances, recognizing that talent is a combination of skills, knowledge, experience and opportunities, which can be developed and improved over time.

4. Talent management

For this research, we adopted sports talent management as the process of identifying, attracting, developing and retaining athletes with special skills and competencies in a given sport, seeking to maximize the potential of footballers and teams, with the scope of sporting and financial success.

Talent management is a practice that is increasingly present in modern organizations, which seek to identify, attract, develop and retain individuals with special skills and competencies that are valuable to the company. Several studies [12–15] point out that talent management is an essential strategy for organizational success.

In a certain study [16], talent management can be defined as "a way of identifying, organizing and managing the innate talents and acquired skills of people, teams and/or organizations". However, it is important to emphasize that the consideration of an individual as a talent depends on the organizational context in which the person is inserted. In an organization, an employee may be considered a talent for having skills that other employees do not have, but in another organization, that same person may not be considered a talent, since there are employees with superior skills [17].

5. The identification

Football is a world-popular sport that relies heavily on talented players to maintain its spectacular appeal [18]. Without these players, the sport would not be as attractive to fans and therefore would not have the same financial impact. That's why clubs are investing more and more money in training talented youngsters through the youth ranks.

There is an informal collaborative network available to these entities, in addition to their own observers, who carry out this process, known as garimpo. The practice consists of recognizing, throughout the country, minors who demonstrate good sports potential and who can compose their base teams.

In Brazil, most talent identification and recruitment methods occur in the popular and middle classes [18–20]. This may be due to the fact that these social strata are more exposed to the eyes of technical analysts since boys from higher castes generally do not play in fields or terrains that are accessible and easy to maneuver by agents. In addition, there is the widespread idea that the lowest strata have the most talented people.

Another notion in relation to the identification process in the most deprived places is presented in the following study [21], where the researchers attribute this phenomenon to the dream of economic and social growth of disadvantaged young people, who see in football a chance for work and enrichment, but there is a context to be analyzed, as many of these children have the dream of becoming a player not only because they have a talent, but also due to different conditions, such as: financial difficulties, family pressure, housing, unemployment, low education, violence, among others [22, 23].

It is not always a simple task to spot potential talent. To a large extent, the difficulty lies in the interpretation process by the professionals involved [24]. Normally, the technical observers of clubs—people in charge of watching games, in different locations to try to identify players with the potential to become professionals—are former players who played in the entity itself, who do not have scientific knowledge or adequate training. Therefore, the detection and selection of talents for football is often based solely on experience and also on intuition [25].

With regard to the identification of talents in football, perhaps this is the element that presents the least standardized criteria. The methodological choices are more defined by the traditions and cultures of the clubs than by determining scientific criteria. Traditions end up determining which types of talent are recruited and regionalities help define which talent is being sought. Therefore, based on a definition of what is valued, sought after and needed, scouts go to the field to observe and select players. Although there is no clear standardization in Brazilian football, the most used components in the analysis and selection of talents are: anthropometric measurements, physical, technical-motor skills, tactical learning capacity, performance readiness, social and emotional factors [26].

At this point, we find one of the main obstacles in identifying talent in football. To better understand this theme, we can use the study by Pelegrini and collaborators [27], in which a total of 7500 children of both sexes, aged between 7 and 10 years old, were evaluated. The vast majority of these children, 96%, did not reach satisfactory levels of physical and motor fitness consistent with their age.

The study carried out by Luguetti and Böhme [28], with 3145 boys and girls between 7 and 16 years old, aimed to measure physical fitness indicators related to health and sport. In general, the results were greater than 50% of classification as "poor". Along the same lines, the study by Seibel, Torres and Ignácio [29], when evaluating 54 children between 7 and 10 years of age, found that the vast majority did not reach the levels considered ideal in the aptitude and sporting potential scales, evidencing the low index of physical and motor development of students.

The questions, therefore, dwell on how to identify whether that boy who is running after the ball has the talent to become a soccer player, can he be transformed into a soccer player? Is that easy dribbling applied to the opponent a virtue, a product of a gift, or is it more like the rival's fragility? These are questions that a good coach must ask himself at all times. Well, there is no way to obtain these answers in a first analysis. This quality needs to be put to the test. And the ideal place is in the training centers. However, this generates a higher cost for the club. In this way, the observer needs to further refine his talent in detecting in order to generate less expenses for his association.

Discovering whether a boy has the talent to become a star or a star without much effort would be the glory of many pickups. While that does not happen, the way is to bet on the process of mistakes and successes. The detection of potential talent is certainly at the forefront of the training structure. After all, for the production of the final artifact, it is necessary to have the human body of the young man. Therefore, there is no way to develop the training process without the appropriate raw material. In this sense, the material must be identified so that this development produces interesting sporting and, consequently, economic results.

In a tangle of subjectivations, the search for objective aspects in this field becomes the biggest challenge. In this sense, the problem of talent selection lies in the definition of exact criteria that allow a premature and safe prognosis of performance capacity [30]. Without setting parameters for profiles of characteristics and skills differentiated on the playing field, the work of detecting talent would be limited to mining for jewels and approaching training centers.

Some studies, such as Monteiro [25], point to the possibility of scrutinizing the body of talent through the evaluation of physical characteristics, technical and tactical skills and behavior on the field to help in the constitution of a primary concept to lead them to spaces formative. Many believe that talent is a social construction, coated with football capital. Along the same lines, another study explains that sports talent is related to the development process, which involves genetic and environmental components, and their interaction [30]. A talented athlete is one who has above-average skills in a specific group, identified through skills already developed in a particular sporting environment [19].

According to another study, sports talent is a process that depends on the temporal relationships between genetic dispositions, age, performance requirements and training yield and psychological qualities, conceived from structures of anatomical and physiological characteristics, capacities and other qualities of personality, with a high probability of reaching a high sporting level through training [31]. It is concluded that the concept of talent permeates a hybrid of genetic potential related to inherited psychomotor skills combined with motor development in favorable environmental and social conditions and that the innate, rare, unique and exclusive bodily predisposition of each player whose talent is fundamental. For sporting success. Furthermore, talent as reification, as the materialization of the gift, makes it become something concrete [32].

Young people selected for training can be chosen through technical evaluations carried out by professionals, but there are other ways of accessing training centers, such as football schools, videos of highlights, selections and direct indications for tests in the main team [33]. However, none of these forms guarantee success in talent detection, since the notion of talent is polyhedral and has many specificities to be considered.

6. The formation

Taking into account that the talented player is a social construction, shaped by different hands, bets and intentions, which equip him with adequate football capital, the frequent failures in producing promising players at the base who do not make it to the first team can be attributed either to detection and selection regarding formation [18]. According to a study, those who meet certain requirements in the child (under-15) and youth (under-17) categories are not always the ones who stand out in the higher categories and even in the professional [19]. According to the author, this is quite common in youth teams, as the concept of talent often focuses only on maturation and does not take into account specific skills related to soccer. Thus, what is very common are exceptional athletes in the base categories that do not correspond to expectations in professional athletes. In view of this, the question arises: the high investments in the base categories are aimed at supplying the main team and selling or forming winning base teams, promoting their young coaches or even supporting bets—since football is a collective sport? For such a complex question, there is no simple answer. We will not get these answers easily if we do not delve into the formative complexities and take into account each sporting context. The idea is to shed light on these uncertainties so that they are duly considered on how the training of young talents has developed over the years in Brazil.

In identification, objectively determining the existence of talent destined for soccer becomes challenging while the biological maturation process is not closed [34]. Because there is always doubt about the residual to be developed by teachers of the basic categories. As a means of illustrating, we will bring two cases of young people of similar ages who participated in youth categories in Porto Alegre[1] [4]. Aspiring footballers were in the process of becoming goalkeepers. The two started their journeys very early. When they got close to 14 and 15 years old, the technical ability attribute became insufficient. Although the two had prestigious performances in the initial categories, stature came to be fundamentally considered by talent developers. The two young men were not the tallest in their groups, but they were recognized for their

[1] One trained in a club considered big and the other in a medium club in relation to the gaucho context.

technical and mental abilities. Thus, one of them, from a more economically affluent family, had a medical intervention with the use of hormones to enhance his growth in height; while the other was only dismissed because of the scientific-biological probability of exceeding 1.80 meters being very low. The importance of physical appearance in the world of football, especially for goalkeepers, can lead to extreme solutions. Although height appears to be an advantage in some positions, it is not the only determining factor for success in football. There are many examples of goalkeepers who stood out in the sport thanks to their technical ability, agility, speed and tactical intelligence, such as the Mexican Guilhermo Ochoa, the Englishman Jordan Pickford, and the Swiss Yann Sommer[2].

In Boehl's research [4], a young man, after being identified as a possible talent by an observer of a big club in Porto Alegre, due to his stature and technical ability [11], was integrated into the youth team of the club. However, another attribute, the palmar dimension, emerged and the smaller diameter of the young man's hand became an obstacle to his permanence in the development team. Despite the young man's talent having been well evaluated by field professionals, such as coach Bernardo, who claimed to be a great admirer of the young athlete's potential [4], his career withdrawal was justified by the size of his hand. In this sense, Brazil is a notable barn of talent for football [18], but many talents do not reach their full development for several reasons.

Possibly, height, as a symbolic component, as the training process progresses, may be the first attribute to be considered for certain positions in football. In other sporting cultures, however, this factor may not carry the same symbolic weight. Despite this, common sense has shown a certain globalization in this preference, which can transform the connotative talent, since it remains a vague concept in the face of subjectivities [2].

Young people who are selected to be trained are usually chosen through the technical evaluation of professionals, but there are other ways of accessing training centers, such as football schools, videos of highlights, selections and direct indications for tests in the main team [33]. However, none of these forms guarantee success in talent detection, since the notion of talent is polyhedral and has many specificities to be considered.

To interpret a talent, as this continues to be refined in the youth categories [18], it is necessary to take into account the football context of the sports association, that is, to know the culture of the club, before analyzing the characteristics of the player. There are assumptions that guide the search for talent, taking into account the physical, cognitive and anthropometric aspects that are relevant in certain situations. When you have access to training centers, it is often more grounded with family commitment, which has social and economic conditions—here it could be understood as some of the important components for the formation of football capital—which spare no efforts to ensure that their offspring is receiving training, than with the entry of young people who carry elements that suggest they have greater aptitude. It may appear that the young people who are attending the training spaces would not be the ones with the most sporting skills, that is, the most gift, but the ones who are more persistent or who have more ballast, in this case economic and/or family support.

[2] Size does not matter: "short" World Cup goalkeepers inspire Rodrigo Viana, available in: https://ge.globo.com/sp/tem-esporte/futebol/times/sao-bento/noticia/tamanho-nao-e-documento-goleiros-baixos-da-copa-inspiram-rodrigo-viana.ghtml.

During the training process, it is important to note that places in the best centers are limited, which means that not all talents will be selected, even if this is not a reflection of their abilities. In addition, for those seeking opportunities in more distant centers, it is necessary to invest in financial resources to travel there, which can prevent talented young people from having their skills recognized and developed. These young people can be excluded from the improvement process, which results in stagnation and loss of potential. Exposure to about five thousand hours of specialized training, fundamental for the formation of talent, is crucial and the lack of it can harm the development of a future star [18]. Excluding these youngsters from the improvement process could prevent Brazil from producing its best players and achieving significant results in the future. As the high-performance training process is long, continuous and interdependent, the late detection of talent can limit the time available for the maximum development of motor skills [24].

To avoid failures in the evaluation processes in the detection and selection of talents, as well as during the training stage, sports organizations have been abandoning empirical standards and adopting more interdisciplinary models, which integrate several scientific areas, such as physiology, nutrition and psychology, with the objective of improving the performance of athletes and teams [35]. However, the adoption of scientific discourse is not enough if conservative sponsorship practices continue to be maintained.

Off-field behavior is considered by managers and coaches to be a key factor in choosing players, often above technical, physical or psychomotor skills [36]. This shows that sports training is influenced by off-field factors, which can be decisive for the continuity of athletes in the process. Therefore, a more comprehensive view is necessary, which considers not only physical aspects but also behavioral, psychological and social aspects.

With regard to biological and bone maturation, there are several strategies available to verify whether a player's chronological age matches his biological age. Talent selection occurs in a period of the inconstancy of the variables that make up performance, and early maturation may provide some advantages in relation to physical strength [37]. However, the selection of players based only on height and physical development can cause those with more advanced technical, tactical and psychological skills to be neglected at the expense of taller and stronger ones, which can harm the training process and, consequently, the discovery of talents.

It is important to remember that early maturation can provide a momentary advantage in terms of strength, but that does not mean these players are better at every aspect of the game. Furthermore, the weaker players can end up being disadvantaged, as they are often passed over by the stronger ones, who are routinely used by coaches. It is essential to have a broader vision in the detection and selection of talents, taking into account not only the physical aspects but also the technical, tactical and psychological skills of the players. Only in this way will it be possible to avoid the loss of many talents and ensure that technical quality is valued in the training process.

The complexity of information to be verified is immense. What is sought here is to show that selection is often based on elements that do not match the promotion of talent. In reality, directors are more focused in the titles of the competitions than in the development of talents. Therefore, the clubs use more "mature" boys to reinforce their teams to win youth championship titles—the media controversially agrees with this, because sometimes they criticize, without any theoretical support, the formation of athletes and sometimes they demonize teams and technicians that lost the competition. When they understand that the main actor is the player, not the coach, not the team, they will learn about training in football.

In the selection and development of football talents, it is important to consider the specific skills of the sport, that is, the technical and tactical qualities that a football player must possess [38]. Often, the concept of talent is based only on maturation, without taking into account the essential skills for football. If young people need years of training and education to develop their footballing capital, it is crucial that exposure time is adequate for those who have the potential to become professionals, not just those who receive prestige for winning an under-12 championship, for example. It is important to remember that teachers who are dismissed at the door of the under-14 s due to their advanced maturation stage may have given little value to technical and tactical skills. If there is not a complete incorporation of football capital in the aspirant, which includes theoretical and practical knowledge about football, as well as a strategy to transform the football gift into a profession, the desired excellence will not be achieved, despite the investment and dedicated efforts.

7. "Killing a lion a Day"

The empirical field of research addresses the expression "killing a lion a day", which metaphorically means facing major challenges and overcoming obstacles daily, in a persevering and determined way [4]. Just as killing a lion is a difficult task that requires courage, facing and solving complex and difficult problems also requires willpower and persistence. This expression is often used to describe the work or study routine of someone who faces many daily challenges and needs to stay motivated to overcome them.

In the case of talent development in football, it is not an easy task to get into training centers. This requires many strategies, as well as having some potential to consider. The door is narrow, and only the most talented, distinguished, or sponsored have access to it. Although the difficulty in reaching this goal can be compared to passing the medical entrance exam at a prestigious university, for example, the problem is not in overcoming this step. Unlike entering university, where most freshmen complete their course, the football player in training never knows what the future holds [4]. Competition for places in the youth teams is extremely fierce, and every week new tests appear, representing a potential threat to those who are already there and do not have a better footballing capital.

Thus, team coaches usually advise young players to do their best in training, following the football saying "kill a lion a day", so that they are not surprised with bad news. However, little is said about the process of "discarding" players in the base categories, which is still surrounded by uncertainties. Science has been more interested in understanding detection, selection, and training procedures than dismissals. Some primary causes can explain the dismissal of athletes in training, but it would be naive to list them without an adequate context and scientific deepening.

While a player's talent is the most valuable resource in football, there is a huge disparity in power in the development process. According to Pelé Law n° 9.615 of March 24, 1998, youth contracts can be terminated unilaterally, without the obligation to pay any compensation to the young player. However, if the initiative comes from the athlete, he must compensate his "trainer". With the legislation in their favor, clubs recruit and dismiss young talents without the slightest embarrassment. This situation leaves the player in a position of emotional vulnerability, which prevents him from fully developing, as he is always subject to being discarded. It is like he has to "kill a lion a day". The athlete is considered as something easily replaced, and that can be exchanged at any time for another more talented or with greater potential, not giving much importance to the individual [39].

In the collective imagination, soccer players emerge from poverty and financial despair, and soccer in Brazil offers them a chance for social and financial ascension. Clubs use this dream for their own ends, often making the only option to get out of poverty to be a footballer. However, this means that players are subjected to all sorts of abuse and manipulation by the clubs that control them. In case of failure, these "jewels" can be easily discarded by clubs that only seek victory and profit, often ignoring their basic rights [18]. This results in a lack of proper stoning and often trauma for players who are poorly formed or poorly selected and are discarded. In addition, a football career often competes with school training, which can lead to problems in the future for those who were unable to complete their education [39].

Football clubs use different methods to release young players. Some prefer to communicate the decision in person in a meeting with parents or legal representatives, while others opt for a phone call or publication of lists with the names of players who will remain. Before digital technology, the list was posted in the locker room, now it is published by apps. Some clubs strive to relocate the released player to less prestigious partner clubs, while others do not care about the fate of the player who lent them some symbolic capital for a period [4]. It is possible that, depending on the process, some talent is wasted and is no longer incorporated into the Brazilian football training system. The "discarded" player needs to persist in his dream and look for a club suited to his gift/talent, usually with the help of specialists, friends or former colleagues [18].

Big clubs often select players based on stature and physical development rather than technical, tactical and psychological skills, which can lead to the exclusion of players with later development. However, early maturation does not mean that a player is better at all aspects of the game. It is important to consider football-specific skills when selecting and developing talent, ensuring exposure time is adequate for players with the potential to become professionals. The complete incorporation of football capital is crucial to achieving excellence, including theoretical and practical knowledge about football, as well as a strategy to transform football gift into a profession.

8. Discussion and conclusions

The lack of understanding about the concept of talent in the world of football, which leads to biases and flaws in recruitment practices, making talent management dysfunctional. The research highlights that the identification of talents in football is a complex process that involves not only the technical evaluation but also the culture of the club, the relevant physical, cognitive and anthropometric valences, in addition to the availability of financial resources. It is important that sports organizations adopt an interdisciplinary model that integrates different scientific areas that support the performance of athletes. However, the lack of conceptual clarity in talent management needs to be addressed to make it more effective.

The main objectives of talent management in football are to identify, attract, develop and retain individuals with special skills and competencies that are of great value to the organization. Although talent management involves several steps, talent identification and development are considered the most important factors. Therefore, attention should be focused on these aspects to get an effective talent management system. Investing in youth teams may aim to form winning teams, supply the main team or support bets, but it is important to take into account the complexity of the process of training young players and the particularities of each sporting context.

The text highlights the importance of understanding the concept of talent before discussing it, and the lack of conceptual clarity must be addressed to make talent management more effective. The detection and development of talent in football involve many factors beyond the technical and mental abilities of young players, and the definition of talent is a subjective and sometimes empty concept, which makes identifying talented young people even more challenging. It is important to adopt a scientific and interdisciplinary discourse to minimize failures in talent development processes, but conservative sponsorship practices still persist and can prevent talented young people from having their skills recognized and developed.

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Chapter 9

Utilizing Blockchain Technology in the Realm of Sports Medicine

Thomas Wojda, Carlie Hoffman and Mateusz Plaza

Abstract

Blockchain, or distributed ledger technology (DLT), originally devised for cryptocurrencies, notably Bitcoin, has garnered widespread interest for its capacity to transform data administration, enhance transparency, and fortify security across diverse sectors. Its progressive assimilation into Sports Medicine has surfaced as a compelling realm of exploration. This book chapter delves into extant research and advancements regarding the integration of distributed ledger technology in Sports Medicine, elucidating potential advantages and obstacles. By scrutinizing the multifaceted applications of distributed ledger technology, this review underscores its promise in revolutionizing aspects of data management within the domain while acknowledging the inherent challenges that necessitate further consideration.

Keywords: blockchain, distributed ledger technology, machine learning, Sports Medicine, sports health, management, injuries

1. Introduction

Blockchain, characterized as a decentralized ledger, monitors transaction entries concurrently across multiple computers via a cooperative network. It is built upon a type of distributed database technology that securely and permanently stores transactions, ensuring their resistance to tampering. A blockchain is an evolving series of interconnected records, referred to as blocks. Every block includes encrypted hashes preceding the previously linked unit, accompanied by a chronological notation and specifics related to the exchange. Blockchain technology primarily consists of a digital ledger encoding transactions as blocks, stored in an open and decentralized manner. Information is dispersed among autonomous nodes that authenticate it without dependence on a central authority. Essential elements are present within this framework **Figure 1** [1]. Key characteristics of blockchain technology are found in **Figure 2** [2, 3]. Blockchain systems differ based on user access and information visibility, encompassing public, private, consortium, and hybrid categories, each with unique traits found in **Figure 3** [4].

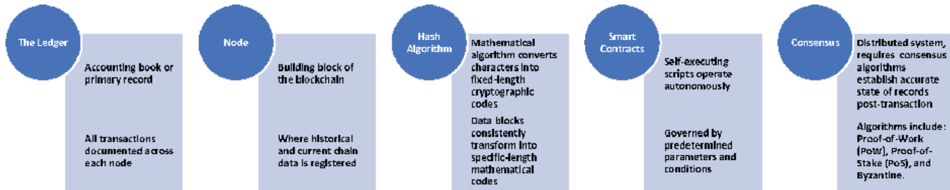

Figure 1.
Essential elements of distributed ledger technology.

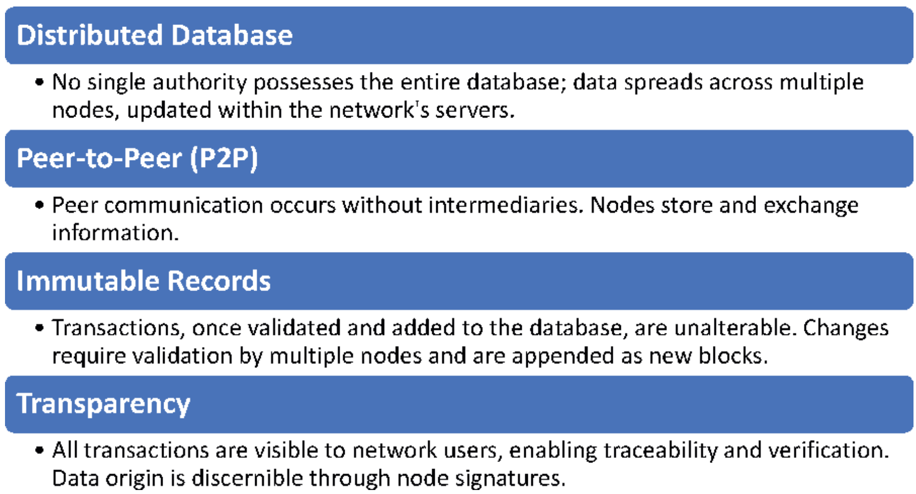

Figure 2.
Key characteristics of blockchain technology.

2. Methodology

We conducted online searches using Google Scholar and PubMed using key terms such as "Blockchain," "Distributed Ledger Technology," "Machine Learning," "Sports Medicine," "Sports" "Health," "Management," and "Injuries." We also identified additional sources by examining references in the primary studies. After reviewing the literature, all pertinent authors collaborated to create a comprehensive outline for the research manuscript applying blockchain in healthcare, specifically the discipline of Sports Medicine, classified based on various use cases. These utilization scenarios include electronic medical records (EMR), sports supply chain management (SCM), injury monitoring and prevention, and personal health information (PHI). The writers also explore the practicality of these blockchain solutions and their technological constraints. In addition, this chapter highlights fundamental obstacles and distinct possibilities for exploration in implementing blockchain technology in Sports Medicine. It identifies lessons learned from existing studies and suggests future research directions in this domain.

Studies that did not relate to the previously mentioned topics were not considered. The manuscript provided here showcases different applications of blockchain technology that are currently active or in development. A single evaluator (T.W) reviewed the titles and summaries of the articles. Full manuscripts were reviewed and included by two authors.

Figure 3.
Unique traits of blockchain.

3. Enhancing medical records management in Sports Medicine

3.1 Challenges in managing electronic medical records (EMR)

Health system databases are often proprietary, exclusively accessible, and demonstrate limited interoperability [5]. In certain instances, patients and doctors might experience restricted external entry to health records. Lack of data sharing among healthcare providers may lead to outdated patient information when patients are treated by different providers [6]. Another concern arises from the possible presence of duplicate health records within institutions, caused by uncertainties or repetitions in patient names [5, 7]. Also, increasing volume of health data and managing this information requires addressing issues like data standardization, storage capacity, location, security, and efficient data filtering and analysis [7].

The obstacles to increased standardization and EMR interoperability include concerns about the sensitive nature of health records and the complexities in managing ownership and access for both owners and users [8, 9]. Users have reservations about disclosing their data, concerned about the storage location and the entities that could get to it [10]. Healthcare providers also raise worries about overseeing and verifying records as patients have ownership and control over their own records [5]. Because of the considerable expenses involved in sustaining data centers, numerous services have transitioned to external providers utilizing cloud computing infrastructures [8]. Nevertheless, this shift gives rise to apprehensions regarding access control, security vulnerabilities, legal considerations, and the possibility of data loss, all of which could have adverse effects on the storage of health information in cloud environments [11].

3.2 Securing health information via blockchain

DLT integration in managing medical records offers solutions for data security, transparency, interoperability, and patient control. By addressing existing challenges in sharing, accessing, and managing health data, these applications pave the way for a more efficient and secure healthcare ecosystem.

One such implementation is MedRec, employing a non-hierarchical methodology to oversee approval, access rights, as well as data transfer among participants [12]. Using the Ethereum platform, MedRec empowers patients with control over who accesses their healthcare information. FHIRChain (Fast Health Interoperability Records + Blockchain) stands as an additional blockchain-driven application merging EMRs [13]. Constructed upon the Ethereum platform, FHIRChain concentrates on overseeing healthcare record administration, delivering remedies attuned to Office of the National Coordinator for Health Information Technology (ONC) stipulations. This application aims to enhance data sharing and interoperability in the healthcare sector.

Medshare addresses collaboration challenges in sharing medical data between cloud services while safeguarding the privacy of private data [14]. This Ethereum-based application offers solutions for data provenance, auditing, and control within cloud repositories, ensuring secure and controlled sharing of medical data. Additional EMR applications based on blockchain technology encompass MedBlock and BlocHIE [15, 16]. MedBlock, a system for documented information, arranges patient data into blocks linked to particular healthcare providers or departments. In contrast, BlocHIE introduces a healthcare framework merging off-chain storage with on-chain validation. This methodology upholds a hashed representation of external records on the blockchain, enhancing equity and efficiency through inventive transaction packaging algorithms.

Ancile, another blockchain-based framework, leverages employing Ethereum smart contracts to realize data confidentiality, safeguarding, access management, and the harmonization of EMR data [17]. This framework addresses critical concerns in the management of sensitive medical information. OmniPHR, an expansive framework, establishes a harmonized, accessible perspective of personal health records (PHR) through a distributed model [18]. By employing a flexible, interoperative, and expandable framework, omniPHR ensures seamless access to PHR data through a routing overlay network.

3.3 Benefits of decentralized medical records

A variety of academic research collectively underline blockchain technology's versatility and potential in healthcare. Addressing pivotal concerns encompassing data security, transparency, and patient autonomy, blockchain stands poised to reshape medical records management, ushering in more streamlined and secure healthcare systems. Zyskind and Nathan explore blockchain's effectiveness in access control and secure data storage [19]. Their study highlights how strong access controls in DLT safeguard sensitive medical records, allowing exclusive access and modifications by authorized personnel. Azaria et al. present a DLT system, which ensures EMRs remain secure and accessible only to authorized parties [20]. Fan et al.'s energy-efficient information management proposal addresses energy consumption concerns by refining consensus mechanisms, reducing energy usage while efficiently managing patient data—showcasing sustainable blockchain solutions in healthcare [15]. Zhou et al.'s research introduces a health insurance DLT repository leveraging Shamir's secret sharing, a cryptographic technique, to bolster security and confidentiality [21]. This method fortifies sensitive insurance data, permitting access and utilization solely by authorized entities. Xia et al.'s data sharing framework, underpinned by blockchain, tackles challenges associated with confidential medical information sharing in cloud environments. Their solution harmonizes data privacy and security with controlled sharing among large-scale data entities, facilitating collaboration without compromising data integrity [14]. In a patient-centric paradigm, Li et al.'s framework accentuates user rights for records contained within reliable platforms [22]. Employing attribute-based encryption (ABE), which allows data encryption and accessibility based on specific attributes or traits, empowers self-governance of information sharing while upholding privacy and security. Guo et al.'s work concentrates on patient privacy and EMR validity within a blockchain milieu [23]. Their application of ABE may preserve EMR credibility and safeguarding patient confidentiality.

3.4 Case studies of blockchain-based medical record systems in Sports Medicine

DLT stands to reshape athlete care and management, bolstering data security, accessibility, and collaboration. This potential can be realized by adapting insights from the above referenced case studies and models to achieve these advancements.

Zyskind et al.'s emphasis on access control and secure data storage can safeguard athletes' sensitive health data [19]. Employing blockchain's encryption and permission-based access ensures that only authorized individuals, such as medical staff and coaches, can access specific information based on their roles. This dual action promotes privacy and facilitates collaboration. The decentralized record management system conceptualized by Azaria et al. seamlessly aligns with the management of athletes' EMRs [20]. Storing athlete health records, diagnostics, treatments, and recovery plans on a blockchain ensures data integrity and facilitates collaboration among sports medical professionals. Authorized parties can securely access and update information, promoting efficient care.

Fan et al.'s energy-efficient blockchain information management system can effectively monitor athletes' health metrics and training progress. Real-time data collection and analysis provide insights into performance and well-being. By optimizing consensus mechanisms, blockchain operations can be energy-efficient, ensuring sustainable application in Sports Medicine. A DLT driven medical insurance repository, utilizing extended Shamir's secret sharing, can adeptly manage athletes' insurance-related information (Zhou et al.). This encompasses coverage for injuries, rehabilitation costs, and medical expenses related to sports. Blockchain's distributed nature ensures security and accessibility for sensitive insurance data.

By incorporating blockchain technology, athlete care can undergo a transformative evolution. Secure, transparent, and collaborative platforms for managing health data, injury history, treatment plans, insurance coverage, and more can be established. This adoption promises informed decisions, improved care outcomes, and overall enhanced well-being for athletes.

4. Facilitating anti-doping efforts

4.1 Overview of anti-doping practices in Sports Medicine

Anti-doping (AD) practices in Sports Medicine encompass a range of strategies aimed at ensuring fair competition and safeguarding the well-being of sports participants. These practices involve identification, prevention, and screening for performance-enhancing drug use in sports. A key component includes implementation of strict drug testing protocols. Athletes are regularly tested for prohibited substances, and rigorous laboratory analysis is conducted to detect doping agents. Additionally, therapeutic use exemptions (TUE) allow athletes with legitimate medical needs to use certain prohibited substances under specific conditions. Anti-doping practices play a crucial role in maintaining integrity and promoting clean sports, fostering a level playing field for all participants. The World Anti-Doping Agency (WADA) spearheads international performance augmentation deterrence efforts. Numerous other parties abide by WADA's rules and conditions. WADA has authority over the Anti-Doping Administration & Management System (ADAMS), an online integrated repository for tamper-control practices, accessible to various concerned parties [24]. ADAMS distills confidential doping information that includes location, reports, TUEs, blood work, rule violations, and other communications [25]. The Athlete Biological Passport (ABP), an AD monitoring program detects banned materials through blood and urine analysis [26]. Fluctuations in markers are identified, which indicate a possible doping infraction.

4.2 Current challenges in anti-doping efforts

Current difficulties in AD efforts pose ongoing obstacles to fair sports. Constant adaptation of detection techniques is required due to new performance-enhancing substances and underground markets. Complexities surrounding therapeutic use exemptions and balancing athlete health with regulations present ongoing problems. Despite efforts, doubts persist about the effectiveness of anti-doping, as few cases are caught compared to widespread suspicion. Some individuals still cheat and evade detection, risking shame, despite the commitment to a drug-free environment [24, 27]. From a technical standpoint WADA's anti-doping management faces challenges, including sharing medical records, maintaining medication records, and banning harmful drugs. An incident involving withheld test results raised concerns about potential doping violations and investigation obstacles [24]. Data handling in ADAMS, controlled solely by WADA, raises conflict of interest and cybersecurity worries, leading to athlete information leaks from cyber-attacks. Non-digitalized processes for critical procedures like doping control sample collection create opportunities for manipulation and cheating without traces, as exemplified in the 2014 Sochi Winter Olympics [24]. Privacy risks arise from privileged access to confidential files, and requesting special permission for medication exposes identities to various system users. Implementing digital technologies can improve data protection and address these issues, enhancing the integrity and effectiveness of anti-doping efforts [24, 25, 28, 29].

4.3 Utilizing blockchain for transparent and tamper-proof drug testing

The utilization of DLT offers a robust solution to address challenges related to drug testing, counterfeit medications, and regulatory compliance. By providing transparency, traceability, and immutability, DLT has the potential to transform drug testing processes into secure and tamper-proof endeavors.

Modum.io AG, an emerging company utilizing blockchain to attain material constancy, ensuring adherent quality control temperature prerequisites, Modum.io AG utilizes blockchain to create public accessibility to temperature records during the transportation of pharmaceutical products [30]. This approach guarantees that the temperature conditions for these products are accurately recorded and cannot be tampered with, thereby enhancing the integrity of drug testing protocols.

The issue of counterfeit drugs is also effectively addressed through blockchain technology. Various authors propose safe, unchangeable, and trackable medical supply chains facilitated by DLT [28, 30, 31]. By utilizing this advancement, organizations can establish a transparent system where the origin and movement of drugs can be tracked at every stage, mitigating the risk of counterfeit medications entering the market. Jamil et al.'s research tackles problems associated with drug standardization and counterfeits [32]. The authors highlight the challenges in detecting falsified drugs and propose a blockchain-based solution. By leveraging blockchain's transparency and immutability, this approach enables the detection of counterfeit drugs within the supply chain, ensuring patient safety.

4.4 Examples of blockchain applications in anti-doping initiatives

In the future DLT may address pressing issues in AD efforts within the sports industry. Now research delves into the conceptual framework of using blockchain to enhance doping control applications in sports. In the proposed conceptual approach, blockchain acts as a distributed and unalterable ledger that records every step of the anti-doping process, from sample collection to testing to result verification [24]. By integrating blockchain into anti-doping initiatives, the study envisions a comprehensive and tamper-proof system that streamlines the collection, testing, and verification of samples. Athletes' data, test results, and related information can be stored securely, ensuring that the anti-doping process remains transparent, fair, and free from manipulation.

5. Ensuring supply chain integrity

5.1 Importance of supply chain management (SCM) in sport

SCM wields a central function in sport, streamlining the flow of resources, equipment, and vital medical supplies essential for athlete care and performance optimization. In this dynamic realm prioritizing athletes' health, a well-functioning SCM system is paramount. The comprehensive SCM approach encompasses procurement, distribution, and oversight of medical equipment, diagnostics, pharmaceuticals, and rehabilitation products. Swift access to top-tier supplies is fundamental for precise diagnoses, effective treatment, and efficient recovery protocols. From averting injuries to post-injury rehabilitation, appropriate resource availability significantly influences athletes' journeys. SCM bolsters athlete safety by ensuring the credibility and purity of medical supplies, crucial in anti-doping endeavors to thwart counterfeit or prohibited substances. Transparent, traceable supply chains amplify trust in product quality and origins, upholding ethical benchmarks. An effective SCM system curbs waste, optimizes resource allocation, and reduces disruptions caused by supply shortages. In sport, where prompt interventions are vital, this efficiency substantially impacts athletes' recovery progress. Essentially, SCM safeguards athlete health, elevates performance, and maintains ethical standards, facilitating uninterrupted access to crucial medical resources and contributing ultimately to athletes' overall triumph and well-being.

5.2 Counterfeit drugs and equipment in sport

Sport faces significant challenges due to counterfeit drugs and equipment, posing risks to athletes' health, fair competition, and the integrity of the sporting ecosystem. Illicit activities involving fake substances and gear encompass production, distribution, and use, impacting sports at various levels. Counterfeit pharmaceuticals, including steroids and stimulants, risk athletes' health by offering inconsistent quality. Such actions compromise fairness and athletes' well-being, undermining sportsmanship. Fake sports equipment, from attire to technology, endangers athletes who unknowingly purchase subpar gear. Exploiting reputable brands erodes trust and leads to injuries. These issues tarnish sports integrity and discourage clean competition. Combatting this requires strict regulations, transparent supply chains, and innovative technologies like blockchain for authentication. These measures ensure athletes' safety and the authenticity of their resources, upholding the true spirit of sports.

5.3 Leveraging blockchain for traceability and authenticity verification

The exemplars mentioned below exhibit the significant role of DLT in ensuring traceability and authenticity verification within the pharmaceutical and healthcare sectors. The utilization of blockchain for these purposes brings about a transformation in how critical information is managed and shared.

MedicalChain introduces a smart healthcare ecosystem that utilizes blockchain to ensuretraceability and immutability through smart contracts [32]. By implementing smart contracts, MedicalChain offers patients a restricted timeframe for EMR usage, enabling secure sharing of medical data between doctors, pharmacies, insurers, and even research institutions. This approach ensures the authenticity of medical data while promoting patient-centric care. MeFy's subscription-based model utilizes blockchain to offer secure and authentic medical tests [33]. The integration of the MeMe Edge apparatus guarantees the credibility of conducted tests, while the use of artificial intelligence (AI) generated autoprescriptions enhances patient care. MediBloc focuses on creating a private information habitat for involved stakeholders, leveraging DLT to streamline data ownership and sharing [32]. This approach enhances the transparency and accessibility of medical data, enabling efficient communication and collaboration among stakeholders.

5.4 Real-world examples of blockchain implementation in sports supply chains

Although there are many real-world and academic proposals regarding DLT and SCM, there remains a dearth of information in relation to its applicability in Sports Medicine. Nevertheless, one article focuses on enhancing delivery in the realm of athletics through DLT [34]. The inefficiencies arising from inadequate stakeholder management within the sports SCM are addressed using a combination of AI and fuzzy comprehensive appraisal (FCA) algorithm. FCA is a decision-making approach that establishes a comprehensive set of evaluation factors, forming the basis for assessing risks. Experts carry out fuzzy evaluations on each individual factor, contributing to the creation of an evaluation matrix. Incorporating AI technology, an information mining system is developed for SCM vulnerability control. This system creates coherent hierarchical connections between indicators and regulations, leading to systematic standardization of SCM and associated guidelines. It serves as a unified platform for surveillance and trend assessment. Subsequently, this approach is utilized to assess SCM vulnerability in sport. The outcomes of this thorough risk assessment are examined, uncovering uniform evaluation cues in sports SCM.

The study's findings hold practical significance for those involved in Sports Medicine, offering guidance for refining management strategies, and enhancing organizations competitiveness. Moreover, the study elucidates the hazards and results linked in sports SCM, adding to scholarly comprehension, and pushing forward the concepts pertaining to its restructuring and progress. The implementation of DLT could further contribute to transparency, reliability, and traceability of Sports Medicine SCM. By securely recording and sharing information among stakeholders, blockchain could streamline verification processes, improve data management, and elevate overall transparency within Sports Medicine SCM.

6. Improving athlete performance and injuries management

6.1 Introduction to athlete performance tracking and injury management

Performance tracking and injury management are vital in optimizing athletic performance and ensuring athlete well-being. Tracking metrics like speed, endurance, and strength aid progress assessment and program customization. Injury management involves prevention, diagnosis, treatment, and rehabilitation, enhancing performance and reducing injury risks. Proactive measures and timely interventions promote long-term athletic success.

The conventional system for managing and monitoring athlete injuries relies heavily on manual records maintained by team medical staff, lacking the ability to intelligently analyze the gathered information. This renders the system of limited practical relevance. Moreover, the data storage in the traditional system is insecure. Several studies have focused on analyzing athlete movements and types of injuries to improve injury recovery and prevention. For example, Guo et al. examines the impact of fatigue in player movements with its impact on knee joints [23]. Other researchers oversaw sequence of injuries experienced by high school football athletes and aided in their quick recovery based on past injury experiences [35]. Tee et al. emphasized the importance of supervising and analyzing the entire sports process to prevent injuries and identify their causes promptly [36]. Kerr monitored sports injuries in American high school football for a decade, gathering valuable data for effective injury treatment and recovery [37].

While these studies have helped in understanding and improving injury recovery, the current systems lack intelligent technology for smart data collection and processing of athlete injury information. Incorporating advanced analytical and data processing capabilities into the injury management and monitoring system could substantially augment the comprehension of injury origins, leading to more effective injury recovery and prevention strategies for athletes.

6.2 Blockchain-enabled performance monitoring systems

Innovative strategies are emerging that leverage electronic devices for data collection. DLT and the Internet of Things (IoT), which pertains to an interlinked web of tangible items and gadgets capable of communicating, gathering, and trading information through cyberspace, may seamlessly integrate to gather crucial body-related information from athletes, presenting a comprehensive approach to enhancing performance and health management.

Wearable devices equipped with acceleration sensors, such as the ADXL345 three-axis acceleration sensor, offer continuous monitoring of athletes' movements [38]. This real-time data acquisition during training sessions and competitions yields invaluable insights into the intensity and patterns of their physical activities, enabling a deeper understanding of their performance dynamics. Another avenue explored involves embedding integrated sensors in fitness equipment [39]. Armbands housing acceleration sensors, temperature sensors, and heart rate monitors hold immense potential for Sports Medicine applications. Working in tandem, these sensors capture data on movement, body temperature, and heart rate throughout workout sessions. This data aggregation contributes to assessing exercise intensity, energy expenditure, and physiological responses, offering a holistic view of athletes' well-being.

The integration of data transmission techniques, such as Wi-Fi, Bluetooth, and ZigBee, further enriches this landscape [40, 41]. Through wireless connectivity, real-time monitoring of athletes' performance and health indicators becomes feasible. This seamless link provides coaches and medical professionals with immediate feedback, facilitating prompt adjustments to training routines and recovery strategies to maximize efficacy. Acceleration data seamlessly integrated with physiological indicators emerges as a pivotal approach. Combining metrics from acceleration sensors with temperature and heart rate data results in a comprehensive assessment of exercise intensity [42]. This holistic perspective enables a precise evaluation of athletes' exertion levels and potential fatigue during training, consequently contributing significantly to injury prevention and performance optimization.

The fusion of IoT and DLT introduces a transformative paradigm for sports fitness management. In the context of Sports Medicine, this concept establishes a secure and transparent platform dedicated to collecting, storing, and analyzing athletes' movement and health data. IoT devices continuously gather data, which is securely stored and processed within a blockchain framework. This immutable ledger records athletes' activities and health metrics, furnishing medical professionals and coaches with invaluable insights for tracking progress and making well-informed decisions.

6.3 Examples of blockchain applications for athlete performance and injuries management

Injuries stand as the foremost prevalent factor influencing a player's performance, a scenario diametrically opposed to their aspirations. Comprehensive insights into the genesis of athlete injuries and optimal methods of recuperating from sports-related setbacks are constantly being scrutinized. Nevertheless, the conventional paradigm governing the management and oversight of athlete injuries is inherently fraught with vulnerabilities concerning data retention, yet more crucially, it lacks the cognitive prowess to dissect the amassed data. In the backdrop of the ceaseless evolution of blockchain and machine learning (ML) domains, the tenets of DLT have been harnessed to gather, stockpile, refine, uncover, and visualize the unbroken gamut of data regarding football players' injuries. In tandem, ML has been harnessed to deliver astute remedies for the convalescence of football players from their injuries. For example, a comparative analysis was drawn between the holistic management and monitoring scheme for athlete ailments via DLT and ML, with an archetypal scheme of managing and overseeing such injuries in the football milieu [35]. The experimental findings underscored that the mean autonomous processing capacity of this technology, which reached an impressive 70%, in stark contrast to a conventional system, pegged at 50%. The assimilation of DLT and ML into this thorough supervision and oversight system for athlete injuries emerges as a potent catalyst in substantively heightening the system's autonomous processing acumen, which may play a role in future Sports Medicine athlete injury and performance management.

7. Ensuring data privacy and consent

7.1 Importance of data privacy in Sports Medicine

Data privacy is of paramount importance in Sports Medicine for several critical reasons. Firstly, the field involves sensitive health data collection, encompassing athletes' medical histories, injuries, treatment plans, and genetic details, necessitating protection to maintain confidentiality and trust. Secondly, adherence to legal frameworks like HIPAA is essential to prevent legal repercussions and uphold the credibility of medical professionals and sports institutions. Athletes rely on healthcare providers to safeguard their health information, breaches of which can lead to withheld data and strained doctor-patient relationships. Leaked data jeopardizes reputations, invites legal liabilities, and compromises fair competition by enabling unfair advantages. Data privacy also supports medical research by providing confidential data access for advancements in athlete well-being and injury prevention. It addresses discrimination concerns, cybersecurity risks, and ethical obligations. Ultimately, data privacy preserves athletes' health information, sustains trust, adheres to regulations, and maintains sports integrity, fostering research progress while mitigating legal, ethical, and reputational challenges.

7.2 Blockchain-incorporated remedies for safeguarded and agreement-guided data exchange

Each of the case studies provided presents a different approach to utilizing blockchain technology for secure and consent-driven data sharing. These solutions address the challenges of maintaining privacy, data integrity, and controlled access to sensitive athlete health data.

To enhance the security of sensitive health records stored on various platforms, the Modified Blowfish Algorithm may be employed [43]. This algorithm encrypts medical records, treatment histories, and treatment plans, effectively preserving data privacy and preventing unauthorized access. The CF Model emphasizes security [44]. By combining a wearable health system with cloud server distribution, sensitive medical information can be securely stored. The model's security protocols, including Confidentiality, Integrity, Availability (CIA), and adherence to HIPAA rules, provide comprehensive protection for athletes' information. Microsoft's HealthVault addresses security, privacy, and interoperability concerns specific to patient needs [45]. By customizing the platform, health data can be managed securely, enabling efficient data sharing while maintaining privacy. The healthTicket model's focus on ubiquitous access to personal health records via mobile devices and web applications is valuable [46]. By integrating security mechanisms like ciphertext-policy attribute-based encryption (CP-ABE), stakeholders can securely enter health data on-the-go, especially when dealing with sensitive health information. The implementation of a distributed accountability mechanism in cloud-based data sharing, as proposed by Sundareswaran et al., enables collaborators to monitor data access [47]. This transparency builds trust and enhances security by ensuring that only authorized personnel interact with health records. Incorporating a blockchain-based decentralized monitoring infrastructure, such as DRAMS, could prove invaluable because this system detects policy violations in access control, ensuring data integrity and reducing unauthorized access risks by decentralizing the monitoring process [48]. The ChainAnchor system's anonymous yet verifiable identity approach can safeguard health data while maintaining identity confidentiality [49]. This becomes crucial when sharing sensitive health information while preserving personal privacy.

7.3 Case studies demonstrating blockchain's role in data privacy in Sports Medicine

As sports activities increase, safeguarding athletes' health information has become a critical concern. Nonetheless, owing to the distinct attributes of the information and the constraints of conventional security paradigms, guaranteeing the confidentiality of athlete health data presents a multifaceted predicament. Liu et al. focuses on quantitatively assessing exercise volume and level through the accumulation of health and physical activity information from athletes and highlights DLT-driven data privacy functions in Sports Medicine [50].

In this scenario, blockchain technology is employed to address key objectives, including the assurance, distribution, tracking, and reliability of the system safeguarding and assembling athletes' health data. The primary focus of the study centers around the development of a Machine Learning and Blockchain-based Athlete Health Information Protection System (MLB-AHIPS), which helps clean and process health data, ensuring accurate recognition and secure management of sportspersons' physical well-being data.

The platform employs a feature-dependent access control system, facilitating flexible and detailed entry to athlete health information. This access control framework ensures that only authorized parties can interact with specific components of the data. To safeguard the data's integrity and invulnerability, the health details are housed within a blockchain framework. This blockchain-based storage is further fortified by utilizing smart contracts, which enhance the security and tamper-proof nature of the stored health data. Simulation results showcase the efficacy of the proposed MLB-AHIPS. It achieves notable outcomes, including a 97.8% precision rate, 98.3% protection proportion, 97.1% effectiveness index, 98.9% expandability factor, and a 97.2% query response time. These achievements are in comparison to other existing approaches. This demonstrates the robustness of the blockchain-based solution in safeguarding athlete health information while ensuring accurate data processing, secure access, scalability, and high levels of data protection.

8. Future directions and challenges

8.1 Discussion

DLT holds the capacity to drastically transform Sports Medicine, reshaping EMR management, athlete safety, and service transactions. Through a tamper-proof repository, athlete health records can be securely managed, facilitating secure data sharing between medical professionals and athletes. Smart contracts ensure that data sharing is consent-driven, granting athletes control over their personal health information. Furthermore, blockchain can contribute significantly to verifying supplement authenticity, enhancing athlete safety, and bolstering anti-doping efforts. Additionally, the introduction of blockchain-based tokens and marketplaces could usher in a new era of secure transactions for sports-related services, thereby marking a significant advancement within the sports industry.

8.2 Challenges and future research

However, the implementation of blockchain technology faces technical and practical challenges. Scalability issues must be addressed when handling substantial volumes of data efficiently. Striking the right balance between data privacy and transparency is essential, as well as integrating different blockchain platforms with existing systems. Navigating regulatory compliance and legal considerations is paramount. Moreover, overcoming the challenge of educating stakeholders and addressing resistance to change is crucial to enhancing DLT capacity in Sports Medicine. Collaborative efforts and standardization initiatives are vital for the widespread adoption of blockchain within Sports Medicine. Through industry-wide collaboration, stakeholders can collectively confront challenges, share insights, and drive innovative solutions. Standardization ensures interoperability and robust data security, fostering trust and transparency within the ecosystem. The widespread integration of blockchain could lead to enhanced data privacy, improved healthcare outcomes, and transformative advancements in the Sports Medicine field.

Ethical considerations and potential risks associated with blockchain's implementation are of paramount importance. Striking a delicate equilibrium between data privacy and transparency is a fundamental ethical concern, necessitating the protection of informed consent and athlete data control. Mitigating potential risks, such as vulnerabilities in smart contracts and over-reliance on untested platforms, demands the implementation of stringent security measures. By addressing these challenges, responsible and ethically sound blockchain implementation can be ensured within Sports Medicine.

8.3 Conclusion

In conclusion, DLT may revolutionize Sports Medicine by offering transformative applications. From secure health record management to enhancing athlete safety and enabling secure transactions, blockchain introduces unprecedented opportunities to the sports industry. Although challenges exist, fostering collaboration, standardization, and ethical considerations will be pivotal in harnessing blockchain's potential for elevating athlete care and propelling the progress of Sports Medicine. As blockchain technology matures, its seamless integration into Sports Medicine is poised to gather momentum, providing heightened efficiency, trust, and automation. Further research is imperative to address technical intricacies, ensure interoperability, and tackle scalability concerns. The outlook for blockchain within Sports Medicine holds promise and excitement for transformative advancements.

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