Applied Mathematics and Computation 262 (2015) 178–186

Contents lists available at ScienceDirect

Applied Mathematics and Computation

journal homepage: www.elsevier.com/locate/amc

Computational intelligence in sports: Challenges and opportunities within a new research domain

Iztok Fister Jr.[a,*], Karin Ljubič[b], Ponnuthurai Nagaratnam Suganthan[c], Matjaž Perc[d,e,f], Iztok Fister[a]

[a] Faculty of Electrical Engineering and Computer Science, University of Maribor, Smetanova 17, 2000 Maribor, Slovenia
[b] Faculty of Medicine, University of Maribor, Taborska 8, 2000 Maribor, Slovenia
[c] School of Electrical and Electronic Engineering, Nanyang Technological University, 639798, Singapore
[d] Department of Physics, Faculty of Sciences, King Abdulaziz University, Jeddah, Saudi Arabia
[e] Faculty of Natural Sciences and Mathematics, University of Maribor, Koroška cesta 160, SI-2000 Maribor, Slovenia
[f] CAMTP – Center for Applied Mathematics and Theoretical Physics, University of Maribor, Krekova 2, SI-2000 Maribor, Slovenia

ARTICLE INFO

Keywords:
Computational intelligence
Optimization
Swarm intelligence
Sports science
Triathlon
Cycling

ABSTRACT

Computational intelligence is a branch of artificial intelligence that comprises algorithms inspired by nature. The common characteristics of all these algorithms is their collective intelligence and adaptability to a changing environment. Due to their efficiency and simplicity, these algorithms have been employed for problem solving across social and natural sciences. The aim of this paper is to demonstrate that nature-inspired algorithms are also useful within the domain of sport, in particular for obtaining safe and effective training plans targeting various aspects of performance. We outline the benefits and opportunities of applying computational intelligence in sports, and we also comment on the pitfalls and challenges for the future development of this emerging research domain.

1. Introduction

Computational intelligence (CI) represents algorithms for solving real-world problems somewhat intelligently as similar problems are solved by natural systems. However, while intelligence by humans refers to a mental adaptation to new circumstances [18], artificial intelligence is based on an intelligent algorithm's capability of adapting to changing environment.

This class of CI algorithms encompasses algorithms like artificial neural networks (ANN), evolutionary algorithms (EA), swarm intelligence (SI), artificial immune systems (AIS) and fuzzy systems (FS). A commonality of all these algorithms is that the principles for their operations are borrowed from natural systems. For instance, the inspiration for artificial neural networks (ANN) is the human brain [19]. Evolutionary algorithms (EA) are inspired by the Darwinian struggle for existence, where only the fittest individuals can survive in nature [3,5,7]. The swarm intelligence (SI) based algorithms mimic the behavior of social living insects (e.g., ants, bees, termites) and animals (e.g., birds, dolphins, bats) [2]. Artificial immune systems (AIS) are based on natural immune systems (NIS), which are characterized by an amazing pattern matching ability [13]. Fuzzy systems use an approximate reasoning in place of exact reasoning and this incorporates a certain degree of uncertainty during a reasoning process.

* Corresponding author.
E-mail addresses: iztok.fister1@um.si (I. Fister Jr.), karin.ljubicc@gmail.com (K. Ljubič), epnsugan@ntu.edu.sg (P.N. Suganthan), matjaz.perc@um.si (M. Perc), iztok.fister@um.si (I. Fister).

http://dx.doi.org/10.1016/j.amc.2015.04.004
0096-3003/

The purpose of this paper is to initiate the new research domain of applying the CI algorithms in sports. To date, these algorithms have been mainly applied to the domain of sports' training, especially in endurance sports' disciplines [20] like triathlons and marathons. Here, we would like to classify the performed work within the context of sports' training theory. Those areas of sports' training should be searched for that have been left uncovered in previous research studies. Finally, an integration of the results obtained for different areas of sports' training should enable the creation of an artificial personal trainer. This could be helpful for athletes who cannot afford coaches because of the high cost. Although the first steps in this direction have been made for individual sports, it is also possible to upgrade the acquired knowledge with expert knowledge of coaches for team sports. Thus, the universal or specialized artificial personal trainer for all sports' disciplines should be gained.

The structure of this paper is as follows. Section 2 introduces the basic theory of sports' training. Section 3 proposes a programming model of sports' training. In Section 4, the existing applications that are arisen within this domain are reviewed. Section 5 proposes the possible directions for future work, while a summary of the performed work is presented in Section 6.

2. Background information

CI algorithms in sports can primarily be used in different phases of training especially because of the huge amount of data produced by various devices during tracking the sports activities. Typically, the sports' training sessions are planned, analyzed and monitored by coaches. Obviously, coaches have a great influence on the quality of training as well as on the achieved results of trainees in competitions. The main tasks of an effective coach are [22]:

- to establish trust in a relation with his/her trainees,
- to manage the person (trainee) to become a personality,
- not to hurt trainees either physically or psychologically.

In order to harness the best abilities, the coach needs a knowledge from broad areas, like anatomy, physiology, biomechanics, psychology, sociology, and didactics. Obviously, sports' training is a very complex task.

The purpose of sports' training is to achieve maximal performance from an athlete or a team within selected sports' disciplines. Sports performance in selected sports discipline is evaluated with the achieved results of trainees by considering rules known in advance. The efficiency of an athlete is an ability to achieve targeted performances repeatedly. The sports' performance of athlete depends on the following types of sports' training (Fig. 1) [22]:

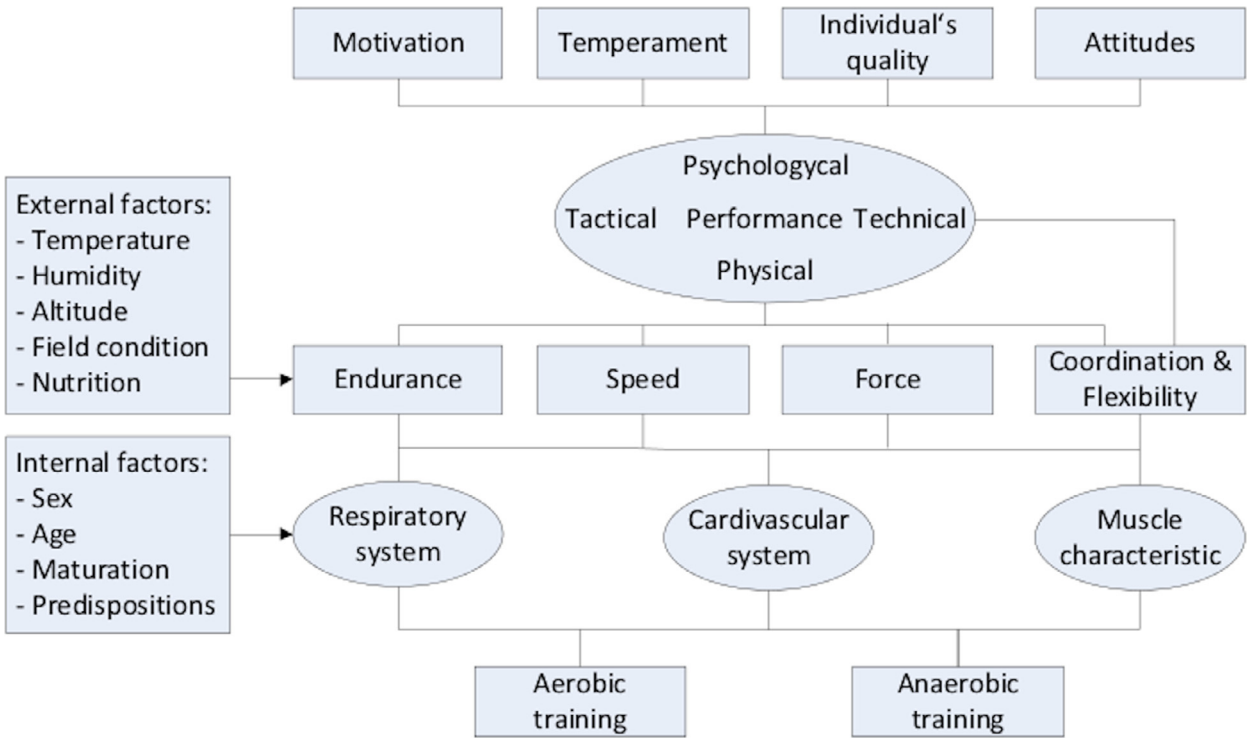

Fig. 1. Key components of sports' training. The core of tactical, psychological, technical and physical skills branches out as depicted schematically to determine the overall performance of the athlete.

- physical,
- technical,
- tactical,
- psychological.

Physical training is oriented towards improving an athlete's motor abilities. These abilities refer to the athlete's characteristics, like endurance, speed, force, coordination and flexibility. Interestingly, specific sports' disciplines demand specific abilities. For instance, marathon athletes primarily need endurance, while a sprinter running 100 meters, requires speed. Reasonable sports' training sessions must be adopted by coaches for each of that sports' disciplines. Technical training focuses on acquiring sports skills through motor learning. These skills are more important in team sports, since coordination and flexibility are of paramount importance. Tactical training is grounded on the studies of different strategies, which lead to victory. Psychological training gives priorities to exercises for improving the athlete's personality. Here, personal characteristics, like motivation, temperament, individual's qualities and attitude are taken into account.

In general, sports' training is devoted to improving the performance of athlete's psycho-physical abilities. From the physical point of view, a performance in a selected sport discipline is based on the characteristics of athlete's respiratory and cardiovascular systems as well as muscles. Genetic factors determine all the mentioned elements which can also be improved by training. Additionally, the training process depends on so-called internal and external factors. Internal factors include an athlete's sex, age, maturity and predispositions, while external factors cover temperature, humidity, altitude, field conditions and nutrition.

During an activity, an athlete's body draws energy by breaking down glycogen and converting it to sugar. When this chemical reaction in the muscles is performed with the presence of oxygen, the process is aerobic. In this case, carbon dioxide and water result as by-products. Both these chemical compounds are easily discharged by breathing. On the other hand, anaerobic process produces energy without the presence of oxygen. Normally, this arises when the intensity of a workout increases above the so-called aerobic threshold. Thus, a lactic acid is generated as a by-product of this chemical reaction. Unfortunately, this by-product causes extreme fatigue and is more difficult to remove from the muscles.

In order to improve the abilities of both types of metabolism (e.g., aerobic and anaerobic) in an athlete, aerobic and anaerobic training sessions must be conducted. As a matter of fact, the intensity of the aerobic training cannot exceed the aerobic threshold. This threshold denotes a level of workout intensity. It is a line above which the anaerobic metabolism becomes a significant part of energy production [14]. On the other hand, the intensity of the aerobic training does not exceed the anaerobic threshold. This refers to a level of workout where the building of lactic acids in muscles is faster than can be discharged away. Interval training includes exchanging the high intensity workout (anaerobic phase) followed by low intensity workout (aerobic phase) and therefore covers both types of training. Typically, this training process is repeated by athletes many times. However, coaches must also keep account about over-training an athlete during training. Over-training arises when the further training load starts too early and the athlete's body has not recovered in time.

3. Computational intelligence in sport

Recently, applications of CI algorithms in sport have become more widespread within domain of sports' training. Obviously, sport training is a complex task that takes care regarding to athlete's psycho-physical performances on the one hand, and helps to improve the athlete's technical-tactical performances on the other. Sports' training is planned by a coach and adapted on the basis of analyzed data obtained during the training sessions. In this overview study, a step further is performed because it proposes an artificial personal trainer resembling real coaches consisting of the characteristic CI applications from this domain. To date, athletes depend on various trainers who take care of their progress, prescribe plans for their sports' training sessions, advise about nutrition and recovery from injuries arisen during sports' activities. On the other hand, these trainers are typically busy especially if they are highly reputable.

A programming model of the artificial personal trainer is illustrated in Fig. 2. Millions of people worldwide could use this effective and cheap solution that is suitable for leading various athletes during a training period. Although this study presents an introduction for initiating this research domain, we trust that a big step towards popularizing CI in sports' domain will be made.

The model in Fig. 2 consists of the following components:

- Identifying long-term objectives: Long-term objectives represent a training strategy. Usually, a particular competition for which an athlete is preparing, belongs to the training objective. In line with this, an off-line planning of the training sessions needs to be performed by the model [11]. This planning depends on the awareness of external factors, i.e., temperature, humidity, altitude, nutrition, and field conditions as well as internal factors like sex, age, maturity, and predispositions of an athlete. As a matter of fact, the plan can consist of various types of training sessions like endurance, speed, force and coordination. For instance, the first three types of training sessions are important for triathlon athletes.
- Identifying short-term objectives: Short-term objectives represent a training tactic. In line with this, an on-line planning of training sessions is considered where the corresponding training session is proposed regarding the factors, like weather, nutrition and athlete's feelings. However, it is adapted in accordance with the training strategy. Here, different types of training sessions can be proposed, i.e., aerobic, anaerobic or interval.
- Measuring the training intensity: The measuring is typically performed with applications for tracking sports' activities running on the mobile devices (e.g., Garmin Forerunner). Data about sports' activities are collated within XML datasets.
- Data analysis: This component is divided into:

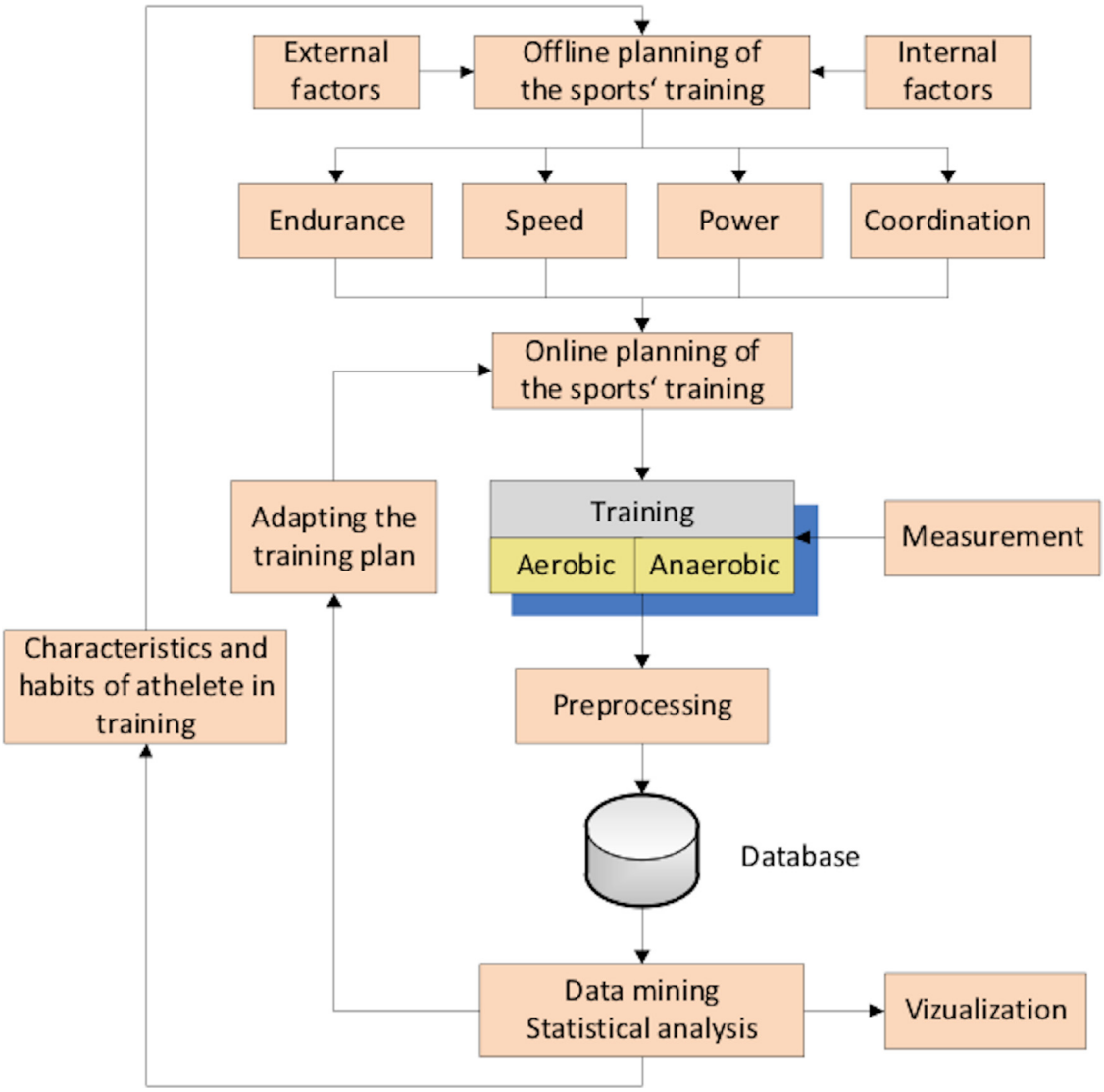

Fig. 2. A programming model of sports' training. Here the physical aspects of performance are at the heart of the model.

- data preprocessing,
- data processing,
- data visualization.

Aim of data preprocessing is filtering information from the XML datasets and storing them within a database. Data processing encompasses the usages of different computer methods on training databases, like data mining and statistical analysis. The results of data analysis are visualized to enable athletes to present additional, mostly hidden, information about training sessions, like familiarization with their habits during training activities, identification of relations between various types of trainings, influences of sleepwear or nutrition on athletes' readiness.

The components of data analysis represent an entry point for decision making that affects both the strategic and tactical planning of sports' sessions. In the remainder of the paper, the mentioned components are presented in more detail.

3.1. Data preprocessing

Data for analyzing the sports activities are accumulated by sports trackers (on smartphones) or sport watches. These mobile devices are worn by athletes during the sports' training and are capable of indicating internal factors like heart-rate, or external factors like distance, duration and altitude. The measuring of distance is performed by global positioning system (GPS) receivers. They use a system of four or more GPS satellites moving around the Earth in circulated orbit for determining the exact position

of the GPS receiver anywhere on the Earth. The accuracy of the GPS system is up to 3 meters for commercial use and provides the sufficient reliability necessary in the sports.

Sports trackers save data about sports activities in the training center XML (TCX) files. Interestingly, the trackers identify detailed measures about the time-stamp, the latitude (in degrees), the longitude (in degrees), the altitude (in meters), the distance from the last measured position (in meters), the heart-rate (in beats/minute) and the speed (in meters/second) during each tracking interval (also track-point) which lasts a few seconds. The cumulative data referring to the whole activity are summarized according to each measure.

Each track-point identifies an athlete's performance over second intervals. As a result, a huge amount of data are produced during the sports activity. On the other hand, the number of TCX files increases quickly because an athlete in training can produce two or even more TCX files daily. This is especially true for multi-sport training sessions (e.g., triathlon). More than 500 TCX files can be produced by multi-sport athletes per year. All these data must be stored within a database in order to be used for further analysis.

3.2. Data processing

The rapid development of web computing today has resulted in huge amounts of data remaining unexplored in databases [15]. At the same time, the computational power and computer science methods have grown exponentially. Data mining deals with the problem of revealing information hidden in data. It is a multidisciplinary domain and draws inspirations from mathematics, statistics, computer science, physics, engineering and other natural as well as social sciences. However, this domain has mainly been influenced by (a) statistics using the statistical methods and data visualization; (b) artificial intelligence applying the machine learning [16] as well as computational intelligence methods [6]; (c) and database systems [8] providing methods for storing a huge amount of data and retrieving them from big data warehouses.

Two types of applications have emerged within this domain:

- predictive: Using a part of the variables in the databases in order to predict the values of one or more variables in the future. This task falls into classification or regression.
- descriptive: Identifying the patterns for describing data stored in the databases and visualizing the data in a way that can be easily understood by the users. This task falls into clustering, association rule mining and sequential pattern discovering.

Recently, data mining methods have attained a matured phase. The traditional data mining methods were developed and verified by solving real-world problems. Searching for a new solution, this domain also began to focus on solutions from other domains. This paper is dedicated to the applications of CI methods within the data mining referring to a sports' domain.

3.3. Data visualization

Humans are in essence visual beings. Therefore, visual information tells more than alphanumerical data alone. How to represent mined knowledge in large database graphically is thus especially important for a database designer. In line with this, numerous graphical techniques have been developed which enable us to represent raw data in charts, bars, pie charts or even in histograms. Using these techniques important trends and correlations within a database can be discovered, and conveyed visually [1].

The selection of appropriate visualization techniques depends on the application type. Usually, these techniques can be divided into query independent and query dependent. The former visualize datasets directly, i.e., without any assertion, while the latter according to a query specified by a user.

A novel visualization technique using glyphs [4,17,21] can be used for illustrating sequential patterns or time sequences within big datasets. Glyphs are graphical entities which convey one or more data values via attributes like shape, size, color and position. The geometric projection techniques [1], on the other hand, search for a convenient projection of data in multiple dimensions.

4. Existing applications within the sports domain

This section briefly overviews existing applications proposed within the sports domain. It does not review only applications of computational intelligence in sport but also other applications from this broad spectra of a research area. Combining different solutions may advance the development of more efficient artificial sports trainers. According to the issues they cover the existing applications are divided into three types: managing the sports training, sports training and the pervasive computing and other applications in sport. In the remainder of the paper, these types of applications are reviewed in detail.

4.1. Managing the sports training

CI algorithms have been applied for solving optimization, modeling and simulation problems in mathematics, physics, economy, medicine, engineering, as well as biology and ecology. Recently, this methodology has also been applied for solving problems within sports' domains. The main characteristics of the mobile tracking devices are for producing huge amounts of data in the form of TCX files, which can be saved within a database. These data identify an athlete's performance over a few

Table 1
Managing the sports training.

Application	Reference
Analyzing of performances in sports	[40]
Rapid feedback systems	[31]
Adaptive systems in sport	[29]
Modeling of training loads	[51]
Automatic physical effort plan generation	[36]
Sport training modelling	[42]
Recruitment process for sport swimming	[50]
Complex systems in sport	[34]
Automatic evaluation of exercises	[43]
Training optimization	[61]
Sport training support	[35,37]
Method and system of delivering an interactive and dynamic multi-sport training program	[59]
Performance evaluation	[46]

Table 2
Sports training and pervasive computing.

Application	Reference
A server-based mobile coaching system	[33]
Wearable system for fitness training	[38]
A mobile health application for dietary evaluation	[52]
Motivation	[28,62]
Fitness companion demonstrator	[55]
Running performance	[56]
Exercise repetition detection	[48]
Motion rehabilitation training system	[54]
Filtering fitness trail content	[39]
Physical activity support	[27,57]
Music synchronizer	[41]

seconds' interval, named track-points but are too complex to be analyzed by coaches manually. Therefore, first CI algorithms for mining such data have emerged that can plan and predict the number of sports' training sessions, detect the phenomenon of over-training, and even advise a nutrition during endurance competitions. The paper of Fister et al. [10] dealt with the problem of how to exploit data obtained from sports watches in TCX format. Here, data mining methods are proposed for helping athletes analyze their training sessions, predicting their further training activities or giving advice about nutrition. Later, Fister et al. [11] proposed the bat algorithm for planning the number of sports sessions according to reliable data acquired from sports watches. On the other hand, the authors in [44] showed the potential of artificial intelligence techniques in sports using the example of weight training. The same authors also proposed the fuzzy logic approach for the evaluation of strength training exercises [45]. Skiba [53] presented a system and method for computing athletic performance. Other very interesting and suitable work is presented in Table 1.

4.2. Sports training and pervasive computing

The expansion of mobile and pervasive computing has led to the developments of many different approaches and mobile applications which help athletes during training. This area is very extensive and therefore it is impossible to review all the work within this domain. There exists a bunch of applications for monitoring sporting activities, for predicting proper food, for helping people lose weight and even for encouraging people to practise sport. On the other hand, a number of academic papers have arisen over the past years. The more interesting and useful papers are presented in Table 2. Further, a comprehensive survey about the influence of ubiquitous computing in sports is presented in [30].

4.3. Other applications in sport

Some papers in the literature are special and therefore cannot be classified within any of the mentioned categories. Therefore, these are collated and presented in Table 3.

5. Future ideas and opportunities for research

The above brief review of CI methods proves that this methodology can be successfully applied for solving problems within sport domain. Recently, we have witnessed the significant progress of mobile devices. Modern mobile devices have been supplemented with sensors that are also capable of identifying the following indicators of training readiness: lactate, oxygen

Table 3
Other research and applications in sports domain.

Application	Reference
Stability analysis of motion patterns in biathlon shooting	[32]
Jump detection	[49]
Nonlinear fuzzy control of human heart rate	[47]
Ambient intelligence systems for personalized sport training	[60]
Peloton phase oscillations	[58]
Problem of nutrition during sport competitions	[9]
Avoiding over-training	[12]

consumption and respiratory exchange ratio (RER). In the past, these measures could only be measured in the ambulance. Moreover, power-meters have been developed especially for cycle training, where the consumed power is measured by trainees during the training session. Measuring all these indicators will produce additional data and open new possibilities for using data mining methods for the planning of future training sessions.

The basic point of most research studies in sports today is data mining. However, the traditional data mining methods are insufficient for confronting the complex problems within this domain. Therefore, CI data mining methods [24–26] can successfully supplement the traditional methods. Undoubtedly, using CI algorithms will be increased within all sports domains in the future. The final goal of using the CI algorithms in sports is the development of an artificial personal trainer that should replace coaches in all areas of athlete's training. An artificial trainer would provide all the services of a human coach and would be cheaper. This is especially important for amateur athletes whose counts have increased due to emergence of multi-disciplinary sports like triathlon, where amateur athletes compete with the professionals in the same event at the same time.

For implementation, the following features must be incorporated within data analysis component of artificial personal trainer:

- clustering,
- classification,
- sequential pattern mining,
- association rule mining.

Clustering is the technique of grouping several objects into groups of similar attributes in order to simplify large, complex sets [1]. For instance, selection of TCX files according to the duration or intensity of an activity is the problem that is suitable for solution by clustering methods. Sequential pattern mining algorithms search for patterns to detect trends in sequential data. The task of association rule mining is to find hidden if-then rules within the dataset containing unrelated attributes [1]. The sequential pattern mining is useful for detecting trends during an athlete's training period, while the association rules are appropriate for identifying the habits of athletes in training.

This trainer should be capable of adapting suitable training sessions according to the results achieved at the last training sessions. In line with this, the artificial personal trainer should be able to determine the proper type of training sessions at the right time. However, there are also many other possibilities beyond the development and design of an artificial personal trainer, where CI algorithms should also be applied in:

- Optimization of sports' equipment like bike frames, wetsuits and helmets: EAs and SI-based algorithms are suitable for the optimization of sport equipment. For instance, road bikers need specific bikes that can be adjusted using CI algorithms.
- Optimization of different player positions on the field in team sport: Here, a task of CI algorithm is to determine which position in the field is the more suitable for a specific player.
- Detection of doping in sport: Doping can easily be detected by an artificial personal trainer from historical files about sports activities using data mining algorithms.
- Training course generation: Choosing a proper course for training is still a very hard task for athletes. Why not develop a CI algorithm for generating a full training course by specifying some requirements and constraints?
- Predictions of overall times in different competitions: Based on results from previous training sessions and using the personal history of an athlete, the CI algorithm can predict an overall time before competition takes place.
- Detection of an athlete's crisis during endurance competitions: Almost every athlete encounters a crisis during an endurance race. Using the sequential pattern mining, the artificial personal trainer can find conditions where an athlete usually falls into a crisis, how long it is, and how to minimize this phenomenon by an athlete.
- Virtual simulations may also predict the behavior of our opponents: In other words, currently it is easy to fetch historical data of athletes during the years from the Internet that also enables us to analyze the data of our opponents. From these data, the CI algorithm can mine characteristics of our opponents, and searches for their potential weaknesses that can be used against them.
- Avoiding pains and over-training: Using the data mining methods, this is an easy task that may prevent a trainee from overdoing sports' training.

6. Conclusion

The purpose of this paper was to open the new research domain of CI in sports and thereby encourage researchers especially from the CI domain to investigate those research problems in sports which have not been sufficiently investigated. In line with this, papers were assembled and classified according to the subject they covered. It has been shown, there are a few papers covering this domain, while the majority of these deal with problems tackling the sports' training. Therefore, the concepts of sports' training have been given a closer look in order to better illustrate the issues within this domain. Accordingly, the analyzed papers are divided into sub-areas comprising the long-term and short-term objectives, measurement and data analysis. As it can be seen, almost all issues have been yet tackled by the observed papers.

The results of the performed analysis showed a necessity for developing an artificial personal trainer with the following features:

- to generate a plan for proper training sessions according to an agreed training strategy,
- to adapt the training plan according to current external and internal factors,
- to measure indicators of an athlete's readiness during the training sessions from different sources like heart-rate, lactate, RER and power-meter,
- to analyze the huge data produced by mobile tracking devices during training sessions.

Although the first steps in this direction have yet to be successfully performed especially in individual sports' disciplines, a lot of work would be needed to also spread the usability of the proposed artificial personal trainer to team sports. However, swarm intelligence algorithms seem to be more more suitable for collective sports, where the interplay among many cooperative agents mights lead to more sophisticated behaviors and unexpected outcomes might arguably be obtained.

Acknowledgment

Authors are very thankful to Dr. Samo Rauter from Faculty of Sport at the University of Ljubljana. Special thanks also go to reviewers for their constructive and very helpful suggestions.

Appendix A. Sport activities dataset

There is also a lack of datasets of sport activities which were created by sport trackers for data analysis and data mining purposes. Recently, one comprehensive dataset [23] was released and covers nine persons. It covers all of their training and its speciality is that their entire seasons are visible. Therefore, it might enable researchers to use it for serious research. Data are obtained from Strava and Garmin Connect profiles. Formats are GPX and TCX, which is basically XML. The following features: GPS location of training with elevation, duration, distance, heart-rate, calories should be extracted from data.

Appendix B. Call for sport activities data for research

Since, research into sport activities files created by sport watches and smart phones is very new and research databases are very poor, we would like to ask everyone who is able to donate the sport activity files of athletes. It is recommended that athletes donate their whole seasons. In order to obtain very special results from research, consecutive activities are suggested for use. However, every athlete who donates must be informed about such research method and he/she has to have a guarantee that no one should use his/her data for their own comparisons or espionage. It is because of such problems, a lot of athletes are afraid about providing their activities for research.

References

[1] A.R.R. Alazmi, A.A.R. Alazmi, Data mining and visualization of large databases, Int. J. Comput. Sci. Secur. 6 (5) (2012) 295–314.
[2] C. Blum, D. Merkle, Swarm Intelligence, Natural Computing Series, Springer Verlag, Berlin, 2008.
[3] X. Chen, Y.-S. Ong, M.-H. Lim, K.C. Tan, A multi-facet survey on memetic computation, IEEE Trans. Evol. Comput. 15 (5) (2011) 591–607.
[4] D.H.S. Chung, P.A. Legg, M.L. Parry, R. Bown, I.W. Griffiths, R.S. Laramee, M. Chen, Glyph sorting: Interactive visualization for multi-dimensional data, Inform. Visual. 14 (2015) 76–90.
[5] S. Das, P.N. Suganthan, Differential evolution: A survey of the state-of-the-art, Evol. Comput. IEEE Trans. 15 (1) (2011) 4–31.
[6] R.C. Eberhart, Computational Intelligence: Concepts to Implementations, Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 2007.
[7] A.E. Eiben, J.E. Smith, Introduction to Evolutionary Computing, Natural Computing Series, Springer Verlag, Berlin, 2003.
[8] R.A. Elmasri, S.B. Navathe, Fundamentals of Database Systems, third ed., Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 1999.
[9] I. Fister, D. Fister, K. Ljubic, Y. Zhuang, S. Fong, Towards automatic food prediction during endurance sport competitions, in: Proceedings of the 2014 International Conference on Soft Computing & Machine Intelligence, IEEE Computer Society Press, 2014, pp. 6–10.
[10] I. Fister Jr., D. Fister, I. Fister, S. Fong, Data mining in sporting activities created by sports trackers, Comput. Bus. Intell. (ISCBI), 2013 Int. Symp., August 2013, pp. 88–91.
[11] I. Fister, S. Rauter, X.-S. Yang, K. Ljubič, I. Fister Jr., Planning the sports training sessions with the bat algorithm, Neurocomputing Part B 149 (0) (2015) 993–1002.
[12] I. Fister Jr., G. Hrovat, I. Fister, S. Rauter, Am I Overtraining? A Novel Data Mining Approach for Avoiding Overtraining, in: Proceedings of the 2014 1st Student Computer Science Research Conference, Primorska Press, 2014, pp. 45–52.
[13] S. Forrest, A.S. Perelson, L. Allen, R. Cherukuri, Self-nonself Discrimination in a Computer, in: Proceedings of the 1994 IEEE Symposium on Research in Security and Privacy, IEEE Computer Society Press, 1994, pp. 202–212.
[14] J. Gaudette, The Ultimate Marathon ebook. December 2014,

[15] F. Gorunescu, Intelligent systems reference library, Data Mining: Concepts, Models and Techniques, Springer, Berlin, Hiedelberg, 2011.
[16] R. Kovahi, F. Provost, Glossary of terms, Mach. Learn. 1 (30) (1998) 271–274.
[17] H. Müller, R. Reihs, K. Zatloukal, A. Holzinger, Analysis of biomedical data with multilevel glyphs, BMC Bioinform. 15 (6) (2014) S5 Suppl.
[18] J. Piaget, The Psychology of Intelligence. Routledge Classics, 2001.
[19] S. Russell, P. Norvig, Artificial Intelligence: A Modern Approach, Prentice Hall, New Jersey, 2009.
[20] C.A. Rüst, M.A. Zingg, T. Rosemann, B. Knechtle, Will the age of peak ultra-marathon performance increase with increasing race duration? BMC Sports Sci. Med. Rehabil. 6 (1) (2014) 36.
[21] M.O. Ward, A taxonomy of glyph placement strategies for multidimensional data visualization, Inf. Vis. 1 (3–4) (2002) 194–210.
[22] D. Zahradnik, P. Korvas, The Introduction into Sports Training. Masaryk University, Brno, 2012.
[23] S. Rauter, I. Fister Jr., I. Fister, A Collection of Sport Activity Files for Data Analysis and Data Mining, Technical report 0201, University of Ljubljana and University of Maribor, 2015.
[24] B. Alatas, E. Akin, Rough particle swarm optimization and its applications in data mining, Soft Comput. 12 (12) (2008) 1205–1218.
[25] C. Grosan, A. Abraham, M. Chis, Swarm Intelligence in Data Mining, Springer, 2015.
[26] K.E. Heraguemi, N. Kamel, H. Drias, Association rule mining based on bat algorithm, in: Bio-Inspired Computing-Theories and Applications, Springer, 2014, pp. 182–186.
[27] A. Ahtinen, M. Isomursu, S. Ramiah, J. Blom, Advise, acknowledge, grow and engage: Design principles for a mobile wellness application to support physical activity, Int. J. Mobile Human Comput. Interact. (IJMHCI) 5 (4) (2013) 20–55.
[28] S.M. Arteaga, M. Kudeki, A. Woodworth, S. Kurniawan, Mobile system to motivate teenagers' physical activity, in: Proceedings of the 9th International Conference on Interaction Design and Children, ACM, 2010, pp. 1–10.
[29] A. Baca, Adaptive systems in sports, Social Networks and the Economics of Sports, Springer, 2014, pp. 115–124.
[30] A. Baca, P. Dabnichki, M. Heller, P. Kornfeind, Ubiquitous computing in sports: a review and analysis, J. Sports Sci. 27 (12) (2009) 1335–1346.
[31] A. Baca, P. Kornfeind, Rapid feedback systems for elite sports training, Pervasive Comput. IEEE 5 (4) (2006) 70–76.
[32] A. Baca, P. Kornfeind, Stability analysis of motion patterns in biathlon shooting, Hum. Mov. Sci. 31 (2) (2012) 295–302.
[33] A. Baca, P. Kornfeind, E. Preuschl, S. Bichler, M. Tampier, H. Novatchkov, A server-based mobile coaching system, Sensors 10 (12) (2010) 10640–10662.
[34] N. Balague, C. Torrents, R. Hristovski, K. Davids, D. Araújo, Overview of complex systems in sport, J. Syst. Sci. Complex. 26 (1) (2013) 4–13.
[35] K. Brzostowski, J. Drapała, G. Dziedzic, J. Świątek, Algorithm to plan athletes prolonged training based on model of physiological response, in: Intelligent Information and Database Systems, Springer, 2015, pp. 273–283.
[36] K. Brzostowski, J. Drapała, A. Grzech, P. Świątek, Adaptive decision support system for automatic physical effort plan generationdata-driven approach, Cybernet. Syst. 44 (2–3) (2013) 204–221.
[37] K. Brzostowski, J. Drapała, J. Świątek, Application of nonlinear state estimation methods for sport training support, in: Intelligent Information and Database Systems, Springer, 2014, pp. 513–521.
[38] F. Buttussi, L. Chittaro, Mopet: A context-aware and user-adaptive wearable system for fitness training, Artif. Intell. Med. 42 (2) (2008) 153–163.
[39] F. Buttussi, L. Chittaro, D. Nadalutti, Filtering fitness trail content generated by mobile users, in: User Modeling, Adaptation, and Personalization, Springer, 2009, pp. 441–446.
[40] P. Jürgen, B. Arnold, Application of neural networks to analyze performance in sports, in: Proceedings of the 8th Annual Congress of the European College of Sport Science, Salzburg: ECSS, vol. 342, 2003.
[41] T. Kitahara, S. Hokari, T. Nagayasu, Music synchronizer with runners pace for supporting steady pace jogging, in: HCI International 2014-Posters Extended Abstracts, Springer, 2014, pp. 343–348.
[42] E. Me, O. Unold, Machine learning approach to model sport training, Comput. Hum. Behav. 27 (5) (2011) 1499–1506.
[43] H. Novatchkov, A. Baca, Machine learning methods for the automatic evaluation of exercises on sensor-equipped weight training machines, Proc. Eng. 34 (2012) 562–567.
[44] H. Novatchkov, A. Baca, Artificial intelligence in sports on the example of weight training, J. Sports Sci. Med. 12 (1) (2013) 27.
[45] H. Novatchkov, A. Baca, Fuzzy logic in sports: a review and an illustrative case study in the field of strength training, Int. J. Comput. Appl. 71 (6) (2013) 8–14.
[46] G. Owusu, Ai and computer-based methods in performance evaluation of sporting feats: an overview, Artif. Intell. Rev. 27 (1) (2007) 57–70.
[47] A. Patrascu, M. Patrascu, I. Hantiu, Nonlinear fuzzy control of human heart rate during aerobic endurance training with respect to significant model variations, in: System Theory, Control and Computing (ICSTCC), 2014 18th International Conference, October 2014, pp. 311–316.
[48] I. Pernek, K.A. Hummel, P. Kokol, Exercise repetition detection for resistance training based on smartphones, Personal Ubiquitous Comput. 17 (4) (2013) 771–782.
[49] C.L. Roberts-Thomson, A.M. Lokshin, V.A. Kuzkin, Jump detection using fuzzy logic, in: Computational Intelligence for Engineering Solutions (CIES), 2014 IEEE Symposium on, IEEE, 2014, pp. 125–131.
[50] R. Roczniok, I. Rygula, A. Kwasniewska, The use of Kohonen's neural networks in the recruitment process for sport swimming, J. Hum. Kinet. 17 (2007) 75.
[51] I. Rygula, Artificial neural networks as a tool of modeling of training loads, in: Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the, IEEE, 2006, pp. 2985–2988.
[52] B.M. Silva, I.M. Lopes, J.J. Rodrigues, P. Ray, Sapofitness: A mobile health application for dietary evaluation, in: e-Health Networking Applications and Services (Healthcom), 2011, 13th IEEE International Conference on, IEEE, 2011, pp. 375–380.
[53] P. Skiba, System and method for computing athletic performance, US Patent 8,533,001.2013.
[54] G. Spina, G. Huang, A. Vaes, M. Spruit, O. Amft, Copdtrainer: a smartphone-based motion rehabilitation training system with real-time acoustic feedback, in: Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing, ACM, 2013, pp. 597–606.
[55] O. Ståhl, B. Gambäck, M. Turunen, J. Hakulinen, A mobile health and fitness companion demonstrator, in: Proceedings of the 12th Conference of the European Chapter of the Association for Computational Linguistics: Demonstrations Session, Assoc. Computat. Linguist., 2009, pp. 65–68.
[56] C. Strohrmann, H. Harms, G. Troster, What do sensors know about your running performance? in: Wearable Computers (ISWC), 2011, 15th Annual International Symposium on, IEEE, 2011, pp. 101–104.
[57] P. Świątek, P. Klukowski, K. Brzostowski, J. Drapała, Wearable smart system for physical activity support, in: Advanced Techniques for Knowledge Engineering and Innovative Applications, Springer, 2013, pp. 291–304.
[58] H. Trenchard, Peloton phase oscillations, Chaos, Solitons & Fract. 56 (2013) 194–201.
[59] R.J. Urbanowski, S.E. Leckie, L.S. Pasin, S.S.Q. Whitfield, Method and system of delivering an interactive and dynamic multi-sport training program, US Patent App. 13/411,437, 2012.
[60] J. Vales-Alonso, P. López-Matencio, F. J. Gonzalez-Castaño, H. Navarro-Hellín, P.J. Baños-Guirao, F.J. Pérez-Martínez, R.P. Martínez-Álvarez, D. González-Jiménez, F. Gil-Castiñeira, R. Duro-Fernández, Ambient intelligence systems for personalized sport training, Sensors 10 (3) (2010) 2359–2385.
[61] M.E. van der Zande, J.Van Der Loo, S. Kalisvaart, System for training optimisation, US Patent 8,348,809, 2013.
[62] G. Wijnalda, S. Pauws, F. Vignoli, H. Stuckenschmidt, A personalized music system for motivation in sport performance, IEEE Pervasive Comput. 4 (3) (2005) 26–32.