Scientific and Social Research, 2025, Volume 7, Issue 2
https://ojs.bbwpublisher.com/index.php/SSR
Online ISSN: 2981-9946
Print ISSN: 2661-4332

Research Status and Hotspots of Movement Economy: A Visual Analysis based on VOSviewer

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Abstract: *Objective*: The more economical the energy consumption of the human body during exercise, the better the exercise effect, that is, the higher the movement economy (ME). This study applied VOSviewer to conduct a visual analysis of the research hotspots and trends of ME in recent years, with the aim to reveal the pattern and possible mechanism of energy metabolism during exercise. *Method*: This study screened 3149 relevant papers in the Web of Science Core Collection database before June 30, 2022, and used the VOSviewer for bibliometric and visual analyses. The extracted data included publication journals, countries, high-frequency keywords, etc. *Result*: The results showed that the United States had the largest number of papers in the field of ME. Medicine and Science in Sports and Exercise was the journal with the most publications and citations. Scholar Andrew M. Jones exhibited great influence in this field. The research on ME presented interdisciplinary characteristics, mainly focusing on five hotspots, including nutrition and metabolism related to exercise energy consumption, biomechanical factors affecting ME, physiological performance, the impact of special environment on ME, and exercise injury and recovery related to ME. *Conclusion*: The visual study of the movement economy is of great significance to the improvement of the rationality of sports technology. The analysis results provide a novel perspective for researchers to perform related research in the future and also confer a reference for finding potential collaborators and research cooperation institutions.

Keywords: Movement economy; Running economy; Energy consume; Visualization analysis; VOSviewer

Online publication: March 10, 2025

1. Introduction

Generally, the more reasonable the use of physical strength, the more economical the energy consumption of the human body and the better the motion effects, that is, the higher the movement economy (ME). ME is known as an important determinant of aerobic exercise performance [1]. ME has acquired increasing attention in endurance sports events (such as long-distance running, triathlon, and swimming) and mixed sports (such as football and basketball), and has been accepted as a pivotal indicator for predicting sports performance by athletes and coaches [2]. ME is typically defined as the energy/oxygen cost for a given submaximal-intensity exercise [3–4]. Since direct measurement of ME is difficult, ME is traditionally measured as the submaximal oxygen uptake (VO_2) at a given running velocity. Hence, ME is also often referred to as running economy (RE). This study applied VOSviewer to conduct visual analysis on the research hotspots and trends of ME in recent years, with the aim to reveal the law and possible mechanism of energy metabolism during exercise, thereby conferring a deeper and richer understanding of the scientific nature of sports training and national fitness.

2. Materials and methods

2.1. Data sources

Based on the Web of Science Core Collection database and visualization software VOSviewer, this study focused on the highly cited papers and hot papers in the field of ME research and performed visual analysis on the research hotspots of ME in recent years by using bibliometrics. The relevant papers were extracted from the Web of Science Core Collection and the search terms were set as follows: "Movement Economy", "Energy Consume", "Oxygen Consume", and "Running Economy", taking OR as the connecting word and connecting "Exercise" with AND. The final retrieval execution time was 30th June 2022. The selected literature types were "Articles" and "Review Articles." The main discipline categories selected were "Sports Science" and "Physiology." After screening, a total of 3149 valid papers were finally obtained.

2.2. Data processing

The papers retrieved from the Web of Science Core Collection database were exported in the format of "Full Records and Cited References" with tab separators, and then, the data were imported into the VOSviewer software for keyword co-occurrence analysis and co-citation analysis. Thereafter, the keywords of different clusters were exported to Excel. The synonyms, singular and plural numbers, and abbreviations of the keywords were merged to ensure the accuracy of the clustering analysis results. For example, the keywords "Oxygen cost", "O_2 uptake kinetics", and "O_2 cost" were replaced with "Aerobic performance".

3. Result

3.1. Annual publication and co-citation analysis

The number of published and cited foreign papers in the field of ME increased year by year (**Figure 1**). The number of publications reached the highest of 239 in 2019, and the cited frequency reached the highest of 11794 in 2021. The average cited frequency of each paper was 32.87. As of June 30, 2022, a total of 3149 valid papers were retrieved, including 2880 research articles (91.46%) and 269 review articles (8.48%). The ranking of highly cited articles is shown in **Table 1**. Through co-citation analysis, it was found that there were a large number of high-quality studies on ME in the 1980s. In the early years, the research on ME mainly focused on running performance. The most frequently cited paper was Running Economy and Distance Running Performance of Highly Trained Athletes published in Medicine and Science in Sports and Exercise in 1980 by American scholars Douglas L. Conley and Gary S. Krahenbuhl, which was cited 232 times, mainly discussing the relationship between RE and running performance of well-trained long-distance runners. In the past decade, the research focus on ME has gradually diversified, and many studies have begun to explore the relationship between nutrition diet, energy metabolism, and ME. Among all researchers, Jones Andrew M. had great influence in this field, with 24 relevant studies and 1820 citations.

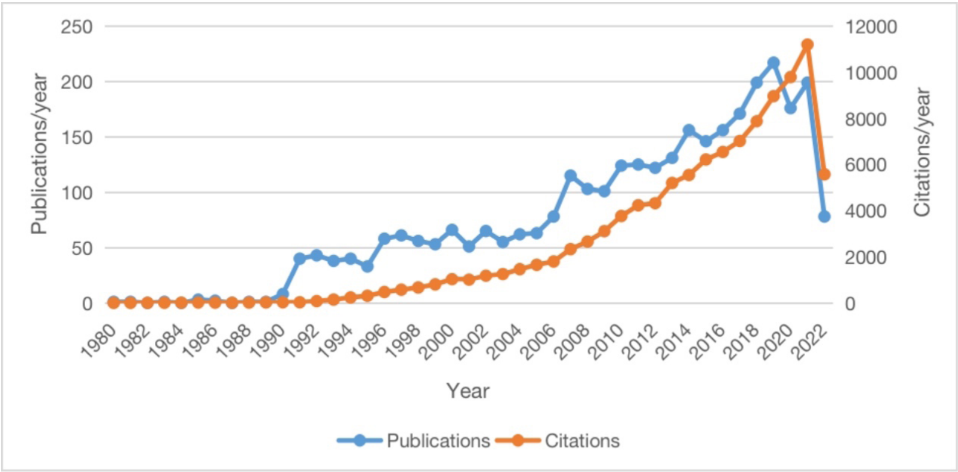

Figure 1. Publication and citation of papers on the movement economy

Table 1. Highly cited papers on the movement economy

Title	Country	Year	Author	Journal	Citation
Running economy and distance running performance of highly trained athletes	America	1980	Douglas L. Conley and Gary S. Krahenbuh	Medicine And Science in Sports and Exercise	232
Factors affecting the running economy in trained distance runners	Australia	2004	Philo U. Saunders, David B. Pyne,	Sports Med	230
Relationship between distance running mechanics, running economy, and performance	America	1987	Keithr. Williams and Peter R. Cavanagh	American Physiological Society	162
Psychophysical bases of perceived exertion	Sweden	1982	Gunnar A.V. Borg	Medicine And Science in Sports and Exercise	145
The effect of stride length variation on oxygen uptake during distance running	America	1982	Peter R. Cavanagh and Keith R. Williams	Medicine And Science in Sports and Exercise	113
Relationship between distance running mechanics, running economy, and performance	America	1987	Keithr. Williams and Peter R. Cavanagh	American Physiological Society	107

3.2. Analysis of country/region and affiliated institution

In the VOSviewer software, the screening threshold of the number of country publications was set to 5 times. Cluster analysis showed that 83 countries had published papers on ME, and only 50 countries reached the set threshold (**Figure 2**). The country with the largest number of papers was the United States (1036, 32.90%) (**Table 2**), and these studies mainly came from the economically developed regions in Europe and America. China had 62 published papers (1.97%) and only ranked 17th in the number of research results. The publication institutions were mainly various universities (**Figure 3**, **Table 3**), such as the Australian Institute of Sport, University of Copenhagen, Loughborough University, University of Granada, and McMaster University. The number of papers and citations on ME in Europe and the United States was much higher than that in other regions, and researchers from different countries cooperated with each other, showing the characteristics of cluster distribution with the United States as the center.

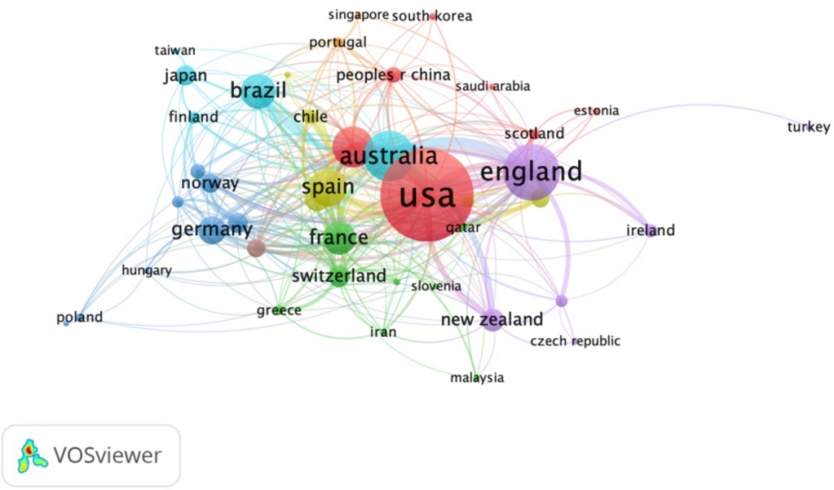

Figure 2. Country distribution of hot research in VOSviewer

Table 2. Ranking of country publications on movement economy

Rank	Countries	Documents	Citations
1	America	1036	36896
2	England	442	16449
3	Australia	341	10980
4	Canada	272	8514
5	France	198	7160
6	Spanish	184	4686
7	Chile	167	1953
8	Germany	132	3422
9	Italy	131	5539
10	Netherlands	100	2620

Table 3. Ranking of organizations on movement economy

Rank	Organizations	Documents	Citations
1	Norwegian University of Science and Technology	39	5049
2	Australian Institute of Sport	58	2666
3	University of Copenhagen	47	2445
4	University of Colorado	39	2354
5	University of Exeter	27	2131
6	University of Rome Tor Vergata	9	2121
7	University of Jyvaskyla	39	1990
8	University of Connecticut	21	1964
9	Liverpool John Moores University	39	1866
10	RMIT University	15	1860

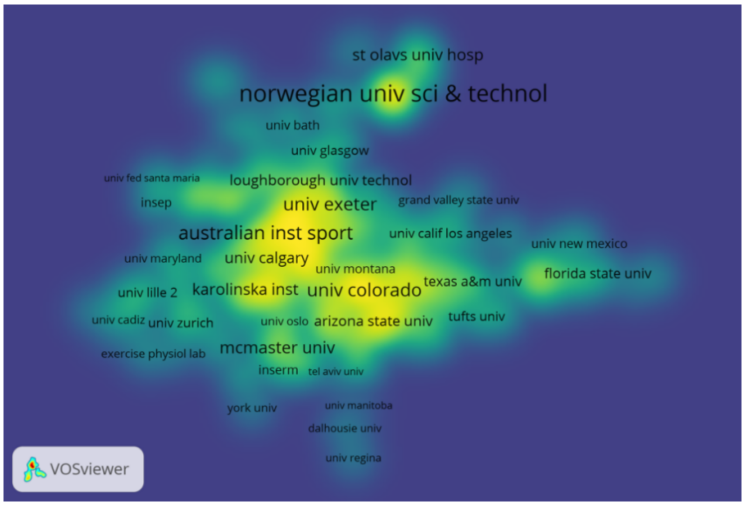

Figure 3. Institution distribution of hot research in VOSviewer

3.3. Analysis of publications

Based on the VOSviewer analysis of the publication sources of relevant literature, the top 10 journals with the most published literature in the field of ME are shown in **Table 4**. The Medicine and Science in Sports and Exercise had published the largest number of papers in the field of ME, with a total of 350 papers (8.45%). ME-related papers were mainly published in the journals of physiology, sports science, and nutrition under the medical category.

Table 4. Ranking of publications on movement economy

Publication Titles	Record Count	Percentage
Medicine and Science on Sports and Exercise	350	11.15%
Journal of Strength and Conditioning Research	212	6.75%
European Journal of Applied Physiology	161	5.13%
Journal of Applied Physiology	137	4.36%
International Journal of Sport Nutrition and Exercise Metabolism	130	4.14%
Journal of Sports Sciences	123	3.92%
International Journal of Sports Medicine	112	3.57%
Applied Physiology Nutrition and Metabolism	101	3.22%
Sports Medicine	101	3.22%
Frontiers in Physiology	100	3.19%

3.4. Keyword co-occurrence and cluster analysis

ME-related papers involved 52 research fields, as shown in **Table 5**. The top 5 research fields included Sports Sciences, Physiology, Nutrition Dietetics, Neurosciences, and Endocrinology Metabolism. Through cluster analysis and statistics of keywords in VOSviewer software, a total of 11544 keywords were obtained, and furthermore, keywords with a frequency of more than 5 times were screened and 1252 keywords reached the standard critical value. After merging and screening, the 10 keywords with the highest frequency were "running economy", "metabolism", "endurance", "skeletal muscle", "strength", "fatigue", "oxygen consumption", "carbohydrate", "energy consumption", and "leg stiffness."

Numerous ME-related papers focused on the characteristics of basic metabolism such as oxygen consumption and energy consumption and primarily explored the relationship between the rationality of technical action and ME (**Figure 4**). Consequently, 6 clusters were obtained through cluster analysis of keywords, as shown in **Table 6**. Different clusters were displayed in different colors. The node size indicated the occurrence frequency of keywords, and the connection between nodes indicated the correlation between various keywords. Through cluster analysis, the major hot research fields of ME are summarized in **Figure 5**.

Table 5. Hot research fields of movement economy

Rank	Field	Article number	Percentage	Rank	Field	Article number	Percentage
1	Sport science	2538	76.49%	6	Orthopaedic	71	2.41%
2	Physiology	1198	41.57%	7	Endocrinology metabolism	66	2.04%
3	Nutrition	409	13.71%	8	Rehabilitation	65	1.97%
4	Neuroscience	147	4.95%	9	Hospitality leisure sport tourism	65	1.74%
5	Psychology	73	3.95%	10	Engineering biomedical	56	1.51%

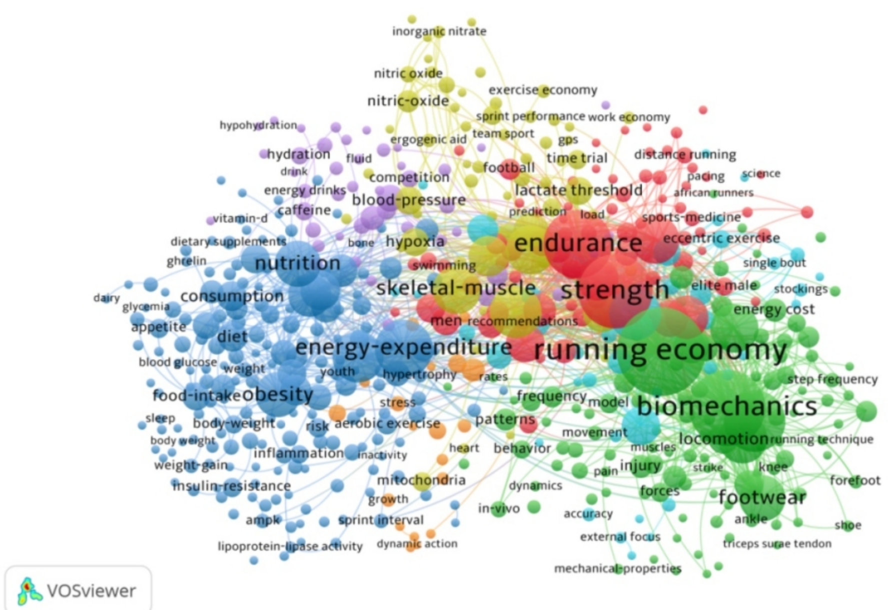

Figure 4. Co-occurrence network diagram of keywords related to movement economy

Table 6. High-frequency keywords of various clusters of movement economy

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Energy expenditure	Biomechanics	Strength	Intensity	Recovery
Body composition	Gait	Endurance	Aerobic performance	Induced muscle damage
Metabolism	Footwear	Resistance	Hypoxia	Perceived exertion
Nutrition	Running	Maximal oxygen-uptake	Efficiency	Adaptation
Carbohydrate	Fatigue	Oxygen-uptake	Lactate threshold	Eccentric exercise
Obesity	Stiffness	Power	Blood-pressure	Soreness

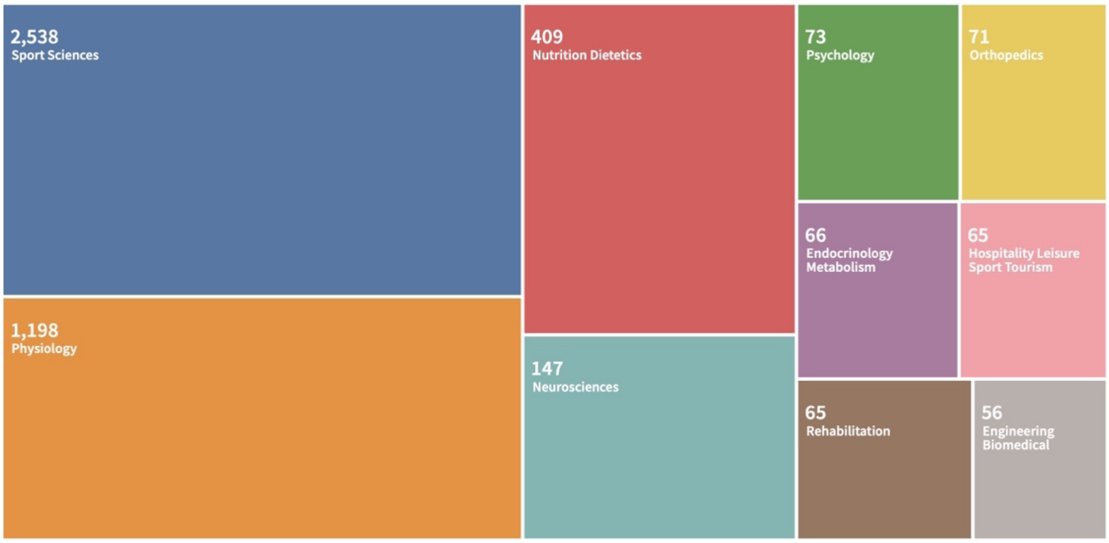

Figure 5. Major hot research fields of ME

3.4.1. Nutrition and metabolism in the process of energy consumption during exercise

In cluster 1, i.e. the red cluster plate, the top 6 co-occurrence keywords with the highest frequency were “energy consumption”, “body composition”, “metabolism”, “nutrition”, “carbohydrate”, and “obesity”, indicating that energy consumption and nutrition metabolism during exercise were the hot research topics in ME. On the one hand, the human body provides energy for metabolism by ingesting various nutrients in food such as carbohydrates, and on the other hand, it consumes energy through physical activities. Different dietary nutrition arranges, such as ketogenic diet or high-sugar and low-fat diet, cause different metabolic reactions and further affect the energy supply of physical activities, specifically manifested as changes in body mass (BM), basal metabolic rate (BMR), body fat rate (BF%), and other indicators. Higher BF% and higher BM produce more energy metabolism consumption during exercise, leading to lower ME. In previous studies on marathon races, Giovanni Tanda et al. pointed out that the lower BF% was usually related to better endurance running performance, but the race performance was mainly related to the amount of training in the case of BF% < 15% [5–6]. Meanwhile, Maciejczyk M et al. indicated that for athletes with similar BM and different body composition ratios, athletes with higher BF% had lower RE and consumed more energy [7]. BM is one of the important determinants of ME, and 94% of ME differences can be explained by BM [8]. The increase in BM is usually accompanied by an increase in BMR, which leads to more energy consumption. Under the same exercise intensity, the energy metabolism cost can be reduced and ME can be improved by adjusting the nutrition strategy to control the BM. In previous research on the relationship between body composition and ME, it was found that the subjects with lower body mass index (BMI) had lower energy costs in the exercise of the same intensity, suggesting a higher ME [9]. Notably, Merry A. Bestard et al. also revealed that a high-sugar and high-fat diet did not affect swimming economy at 50-70% VO_{2max}. Hence, ME may also be affected by exercise intensity and exercise items in addition to nutrition intake and body composition.

3.4.2. Biomechanical factors affecting ME

In cluster 2, i.e. the green cluster plate, the co-occurrence keywords with the highest frequency were “biomechanics”, “gait analysis”, “footwear”, “running”, “fatigue”, and “stiffness”, mainly focusing on the biomechanical factors of

ME during running. ME is also known as RE, and 54% of RE changes can be explained by biomechanical factors [10]. Among the biomechanical factors that affect ME, the endogenous factors include gait (step length, frequency, stride length, etc.) and lower limb stiffness, etc., and the exogenous factors include the type of shoes, the time of touching the ground, and the running site, etc. Gait retraining is often used to treat common running-related injuries (RRI) and to improve performance. In general, the longer the stride, the shorter the time of touching the ground, leading to a higher energy metabolism cost [11]. Morgan. et al. found that 3 weeks of training to reduce step length can improve RE in 9 subjects [12]. However, due to the large individual differences (endurance, running experience, etc.), different gait and stride patterns may combine to produce similar ME. At present, no research has clearly pointed out the most economical running gait [13–14]. Generally, subjects have a higher ME when they exercise at their preferred stride. On this basis, moderate adjustment of stride can effectively improve ME [15]. When fatigue occurs, the gait of subjects is adjusted with the changes in space-time parameters, kinematics, and dynamics.

In addition, some exogenous factors can also affect ME, such as environmental factors (temperature, wind speed, etc.) and wearable devices. Different types of running shoes can obviously affect the running performance but do not exert a significant improving effect on the athletic ability of subjects. The reason may be that wearing running shoes externally affects a series of biomechanical factors such as plantar pressure, gait frequency, and muscle activity, but does not change the subjects' athletic ability. In two studies by Joe P. Warne and Fabrice Vercruyssen et al., it was found that the running performance of the subjects wearing minimalist style running shoes was higher than that of the subjects wearing traditional running shoes, but the ME of the subjects themselves was not improved [16–17]. It is indicated that the difference in ordinary running shoes has little impact on ME. When the athletes reach the fatigue state after a short-distance cross-country race, there is no significant difference in the ME of athletes wearing different kinds of running shoes [17]. Therefore, improving RE requires barefoot training or wearing barefoot running shoes for training. Compared with running with shoes, barefoot running can produce greater vertical stiffness, which increases the total amount of exercise and contributes to the improvement of RE. Warne et al. showed that after 4 weeks of barefoot simulation training, the athletes in the barefoot test group exhibited higher vertical stiffness and leg stiffness than those in the shoe-wearing test group. The greater the leg stiffness, the higher the storage and release efficiency of elastic potential energy, implying that the type of shoes is one of the external factors affecting ME [18].

3.5. Physiological manifestation and influencing factors of ME

In cluster 3, i.e. the blue cluster plate, the main keywords were "strength", "endurance", "resistance training", "maximum oxygen uptake", "oxygen uptake", and "power." ME represents the complex interaction of physiological and biomechanical factors [19]. The research hotspots in cluster 3 mainly focused on various physiological indicators, the impact of changes in physical qualities (such as strength and endurance) on ME, and common training methods to improve ME. Aerobic physiological indicators are often used to measure the performance of long-distance running. A high maximum oxygen uptake (VO_{2max}) is a prerequisite for good performance in middle and long-distance running. VO_{2max} is defined as the maximum rate of oxygen absorption and utilization during vigorous exercise [20]. VO_{2max} is primarily affected by congenital genetic factors, so it is difficult to improve ME by elevating VO_{2max} through training [21]. For long-distance runners with equivalent athletic ability, ME is often considered to be a better performance predictor than VO_{2max} [10, 22]. There are three methods commonly used to quantify ME: oxygen uptake per unit time (VO_2, ml/kg/min), oxygen consumption costs at a given submaximal velocity (EO_2, ml/kg/m), and aerobic energy cost (E_{aer}, J/kg/m) [5, 23–24]. Aerobic energy cost is generally considered more reliable. The energy equivalent generated by oxygen consumption during exercise depends on the metabolic substrate (relative content of sugar, fat, and protein) and exercise intensity. Aerobic exercise and anaerobic exercise alternate under different exercise intensities, resulting in incomplete oxidation of some substrates. Hence, it is considered more accurate to calculate aerobic energy consumption through the respiratory exchange rate (RER) [25].

ME is closely related to aerobic endurance, which can be improved through endurance and strength training. Danielle et al. found that after 10 weeks of strength and endurance training, the 2km running performance of athletes was improved [24]. Endurance training and strength training produce different forms of adaptation. Endurance training mainly improves VO_{2max} by increasing cardiac output, mitochondrial density, enzyme concentration and activity, and capillary density, while strength training mainly activates the nerve muscle, stimulates the muscle fiber to be more hypertrophy, makes the muscle fiber more coordinated, and thereby increases the maximum strength [26]. Simultaneous strength and endurance training has no negative impact on endurance, but diversified adaptation reduces strength improvement, known as the "interference effect". Kenji Doma et al. pointed out that strength and endurance training at the same time could enhance endurance adaptation to a greater extent and improve ME [27]. However, strength training tends to cause exercise fatigue. Insufficient fatigue recovery exerts adverse effects on the performance of subsequent endurance training. Therefore, it should be prudent to combine resistance training with endurance training. Moreover, simultaneous strength training and plyometrics training has a positive effect on neuromuscular metabolic adaptation and running performance. Plyometrics training is also one of the important training methods to improve ME [28–31]. Plyometrics training can increase tendon stiffness, make muscle elastic potential better stored and released, enhance muscle power, and increase ME. A meta-analysis by Balsalobre Fernández C et al. revealed that 2–3 times of strength training [including 2–4 times of 40%–70% one repetition maximum (1RM) resistance training and plyometrics training] per week for 8–12 weeks can improve the RE of long-distance runners [32]. Short-term resistance training and plyometrics training can improve RE and running performance by enhancing neuromuscular metabolic adaptation [33].

3.6. Effects of special environment on ME-related physiological indexes

In cluster 4, i.e. the yellow cluster plate, the high-frequency keywords were "intensity", "aerobic performance", "hypoxia", "efficiency", "lactate threshold", and "blood pressure", indicating that the hotspots of this plate mainly focused on the impact of changes in human skeletal muscle, aerobic capacity, and blood composition on ME under different environmental sports conditions, such as high pressure and hypoxia. Reasonably changing the training and living environment while performing routine training (such as strength and endurance training) can effectively improve the sports performance of subjects. Compared with normoxia training, altitude/hypoxia training is considered to improve the performance of athletes in sea-level sports [34–35]. People at a high altitude are found to have higher muscle movement efficiency (ratio of mechanical power to metabolic energy consumption) than people at sea level [36]. Training in the high altitude/hypoxia environment contributes to improving the endurance performance and submaximal exercise efficiency of athletes at sea level. The common hypoxia training methods are living high training low (LHTL) and living high training high (LHTH). After several weeks of hypoxia training, the aerobic performance indexes such as VO_{2max} and hemoglobin content can be improved [37–38]. Park et al. found that 4 weeks of LHTL significantly enhanced the ME and metabolism (HR, VO_2, VCO_2, and blood lactate concentration) of subjects, and also improved the performance of 3000-meter and 5000-meter time trials [39]. The influence mechanism of hypoxia training on ME may be that the altitude/hypoxia environment increases carbohydrate consumption [40]. Katayama et al. suggested that the body's utilization of carbohydrates was increased when exercising in a moderate hypoxia environment compared with exercising in a normoxia environment with the same relative intensity [18, 41]. The body changes from lipid oxidation to carbohydrate oxidation, reducing O_2 and energy consumption, improving the mechanical efficiency of exercise, and eventually enhancing ME [42]. Also, metabolic adaptation to altitude/hypoxia environment may enhance muscle hemodynamic function, and mean arterial blood pressure is one of the important physiological predictors of male marathon performance [39, 43]. On the contrary, some scholars believe that LHTL cannot improve athletic performance. Clark et al. found that there was no significant change in ME, lactate metabolism index, and pH value of athletes [fraction of inspiration O_2 (FIO_2), 16.27%] after 20 consecutive nights of normobaric hypoxia exposure. The reasons for the different results may be related to the altitude and the length of exposure. Therefore, Levine et al. held that an altitude of not more than 3000 meters, a residence time of at least 18 days, and an exposure time of at least 12 hours per day could positively affect ME during LHTL. Alexandra M. Coates et al. pointed out that most basic physiological indicators, such as lactate threshold and VO_{2max}, could better reflect running performance. However, such physiological indicators only predict the running performance within a distance of 50 kilometers. With the increase in the running distance, the correlation between the changes in traditional physiological indicators and the performance of running is significantly reduced [44].

3.7. Exercise injury and recovery related to energy consumption

In cluster 5, i.e. the purple cluster plate, the main keywords were "recovery", "exercise-induced muscle damage", "perceived exertion", "adaptation", "centrifugal exercise", and "muscle pain." Exercise-induced muscle damage is prone to occur after unsuitable exercise or intensive centrifugal exercise, and muscle fiber damage has adverse effects on ME. Therefore, the Borg Rating of Perceived Exertion (RPE) scale is usually used to monitor the perceived exertion during exercise, which enables the athletes to adjust the exercise intensity through the perceived response and thereby effectively reduces the occurrence of muscle injuries [45–46]. Long-term high-intensity exercise also induces fatigue in the central nervous system and peripheral nerves and muscles, accompanied by increased RPE. The accumulation of exercise fatigue triggers exercise injuries. When fatigue occurs, the energy consumed by the body increases and muscle soreness appears, resulting in the decrease of ME. Hence, reducing exercise fatigue and injury can effectively improve ME [44].

The accumulation of fatigue effect also limits the development of optimal endurance in training [47]. Kenji Doma et al. believed that delayed-onset muscle soreness (DOMS) caused by resistance training was one of the factors affecting endurance performance when resistance and endurance training were performed simultaneously [47]. DOMS, one of the common muscle damages, often occurs after high-intensity centrifugal exercise of skeletal muscle, accompanied by the symptoms of inflammation, edema, and muscle function damage [48–49]. Exercise in the period after the occurrence of DOMS leads to changes in the muscle activation mode and the increased recruitment of type II fiber. As a result, more movement units must be activated to generate the same strength, resulting in significantly increased energy consumption per unit of time. William et al. further pointed out that human muscle damage caused changes in biomechanics such as stride length, increased proportion of anaerobic energy consumption, and decreased ME [50]. Low-intensity exercise in the early stage, such as low-intensity resistance exercise two weeks before training, can induce small-scale muscle damage. After repeated muscle damage exercise, the symptoms and signs of muscle damage caused by subsequent high-intensity exercise are weakened, which can reduce the incidence of muscle damage [27, 51–52].

4. Conclusion

Through the visual and bibliometric analyses of 3149 ME-related papers in the Web of Science Core Collection database, it is found that the research popularity on ME has been increasing year by year, and the upward tendency has leveled off in the past two years. The researches mainly come from universities in economically developed regions such as Europe and the United States, and the research links among countries are relatively close, showing a cluster distribution centered on the United States. At present, there are few studies related to ME in China.

ME-related researches present interdisciplinary characteristics involving multiple disciplines such as physiology, nutrition, and neuroscience, mainly focusing on five hotspots, including nutrition and metabolism related to exercise energy consumption, biomechanical factors affecting ME, physiological performance, the impact of special environment on ME, and exercise injury and recovery related to ME.

The current researches on ME primarily aim at periodic sports events, such as running and swimming. More non-periodic sports should be taken into consideration in future research, which is of great significance to the improvement of the rationality of sports technology. The analysis results provide a novel perspective for ME-related research in the future and also confer a reference for finding potential collaborators and research cooperation institutions.

Disclosure statement

The author declares no conflict of interest.

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