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Physiological and Nutritional Aspects of Post-Exercise Recovery

Specific Recommendations for Female Athletes

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Abstract

Gender-based differences in the physiological response to exercise have been studied extensively for the last four decades, and yet the study of post-exercise, gender-specific recovery has only been developing in more recent years. This review of the literature aims to present the current state of knowledge in this field, focusing on some of the most pertinent aspects of physiological recovery in female athletes and how metabolic, thermoregulatory, or inflammation and repair processes may differ from those observed in male athletes.

Scientific investigations on the effect of gender on substrate utilization during exercise have yielded conflicting results. Factors contributing to the lack of agreement between studies include differences in subject dietary or training status, exercise intensity or duration, as well as the variations in ovarian hormone concentrations between different menstrual cycle phases in female subjects, as all are known to affect substrate metabolism during submaximal exercise. If greater fatty acid mobilization occurs in females during prolonged exercise compared with males, the inverse is observed during the recovery phase. This could explain why, despite mobilizing lipids to a greater extent than males during exercise, females lose less fat mass than their male counterparts over the course of a physical training programme.

Where nutritional strategies are concerned, no difference appears between males and females in their capacity to replenish glycogen stores; optimal timing for carbohydrate intake does not differ between genders, and athletes must consume carbohydrates as soon as possible after exercise in order to maximize glycogen store repletion. While lipid intake should be limited in the immediate post-exercise period in order to favour carbohydrate and protein intake, in the scope of the athlete's general diet, lipid intake should be maintained at an adequate level (30%). This is particularly important for females specializing in long-duration events. With protein balance, it has been shown that a negative nitrogen balance is more often observed in female athletes than in male athletes. It is therefore especially important to ensure that this remains the case during periods of caloric restriction, especially when working with female athletes showing a tendency to limit their caloric intake on a daily basis.

In the post-exercise period, females display lower thermolytic capacities than males. Therefore, the use of cooling recovery methods following exercise, such as cold water immersion or the use of a cooling vest, appear particularly beneficial for female athletes. In addition, a greater decrease in arterial blood pressure is observed after exercise in females than in males. Given that the return to homeostasis after a brief intense exercise appears linked to maintaining good venous return, it is conceivable that female athletes would find a greater advantage to active recovery modes than males.

This article reviews some of the major gender differences in the metabolic, inflammatory and thermoregulatory response to exercise and its subsequent recovery. Particular attention is given to the identification of which recovery strategies may be the most pertinent to the design of training programmes for athletic females, in order to optimize the physiological adaptations sought for improving performance and maintaining health.

1. Introduction

The large majority of exercise physiology research has been performed exclusively on male populations. Until the 1980s, it was widely presumed that the physiological responses to exercise did not truly differ between males and females. From this assumption, the design of training programmes and the recommendations for recovery strategies have been generalized to females, without any prior determination of whether such a direct transfer was viable. Since then, numerous studies focusing on gender[1,2] have uncovered some specificity in females' physiological response to exercise, and determined that gender is an important variable to control for in order to design robust research protocols. The females' response to various types of exercise and physical training is now better understood. It appears that the aerobic power and muscular strength of females are naturally lower than males, due to differences in body size and composition, hormonal status, socio-cultural influences and dietary habits.[3] Yet, despite these factors, well trained athletic females can deliver performances that are by far superior to those of poorly trained males. Within this context, a growing number of studies have turned their focus toward the effects of gender on recovery in sport, thereby contributing to a better comprehension of the similarities – and disparities – in the post-exercise recovery processes occurring in males and females. Nevertheless, the factors contributing to the lack of a global consensus can be attributed to differences observed in training and nutrition status, and to females' hormonal variations over the course of the menstrual cycle and the influence of the latter upon energy metabolism during exercise.[4]

This review aims to emphasize the subtle, yet potentially important characteristics observed in athletic females' post-exercise physiology, to identify the recovery strategies best suited to meet the demands of their sporting activity. This work will discuss which recovery practices should be prioritized in well trained athletic females, while also critiquing the effectiveness of the principal modalities of recovery. Recovery in this review is defined as the return to homeostasis of the various physiological systems presented,[5] following the metabolic, thermoregulatory, inflammatory challenges and muscle damage incurred by exercise training sessions. Optimal recovery therefore enables the athlete to perform the next training session feeling rested, not fatigued, healthy and injury-free.

This article reviews some of the major gender differences in the metabolic, inflammatory and thermoregulatory responses to exercise and its subsequent recovery, focusing on those that may be most pertinent to the design of training programmes for athletic females, specifically, in order to optimize the physiological adaptations sought for improving performance and maintaining health.

All studies presented in this review were chosen for their relevance and quality of design and findings. The databases and other sources searched were the US National Library of Medicine (PubMed), Adis, Elsevier and Human Kinetics. Using the search terms 'gender', 'sex differences', 'exercise' and 'recovery', papers were then selected for the quality of design and results and relevance to our themes. While the most recent and pertinent studies were selected, early, 'pioneer' studies from the 1970s and 1980s were also included when research on gender differences during exercise bloomed.

2. Recovery and Maintenance of Energy Stores: A Gender Difference?

Performance in long-duration activities that rely upon aerobic metabolism is related to the availability of endogenous energy substrates. In light of this, the fatigue induced by exercise can be linked to the athlete's inability to continue supplying adenosine triphosphate (ATP) to the working muscles, due to the exhaustion of endogenous energy stores.[6] This type of fatigue can also occur in athletes training multiple times per day, even in those not necessarily specialized in endurance activities, and can cause large quantities of energy to be expended.[7] The depletion of energy stores may set in progressively, when daily caloric intake does not compensate for the total energy expenditure linked to both basal metabolism and the practice of a sport. Recovery strategies must therefore take into account the specificities of females' metabolic response to exercise to ensure the maintenance of energy stores and to support the training workloads.

2.1 Metabolic Responses During Prolonged Exercise

Even though females were excluded from participating in the Olympic marathon until

1984, several studies demonstrated that they could actually perform better than males in ultra-endurance events.[8,9] For instance, Speechly et al.[8] showed that females, despite slower performances in a marathon than a given group of males, performed better than the latter when the race distance exceeded 90 km. Bam et al.[9] showed by way of linear regression analysis that females may potentially hold an advantage over males when the race distance of a running race reaches or exceeds 66 km. For Tarnopolsky,[1] this phenomenon would be linked to gender-based metabolic differences during prolonged exercise and, more specifically, to a females greater capacity for lipid oxidation, allowing them to maintain normoglycaemia and preserve muscle glucose during these very long events.

Tarnopolsky explains that the first studies to compare the metabolic responses of males and females during prolonged exercise date from the 1970s and 1980s.[10,11] All reported a gender effect, except that of Costill et al.[12] These results, however, were considered with caution, as these investigations had neither accounted for the occurrence of menstrual cycles, nor evaluated precisely, the training status of the subjects involved. Also, exercise intensity was determined relative to maximal oxygen consumption ($\dot{V}O_{2max}$) without adjusting for each individual's body mass. Since the 1990s, many studies have added to these preliminary results by factoring in these important methodological details in their protocols.[13,14]

2.1.1 Carbohydrate Utilization

Any discussion of gender differences in exercise metabolism must address the different hormonal environment that males and females are exposed to. Numerous studies have documented that estrogen is, at least in part, responsible for the decreased reliance upon hepatic glycogen stores, increased availability and oxidation of fatty acids, and decreased amino acid breakdown during exercise.[15-18]

In human studies, 17β-estradiol, the most abundant form of estrogen, has been found to decrease the hepatic glucose rate of appearance and disappearance and total oxidation, resulting in a relative sparing of hepatic glycogen stores during exercise.[17,18] The finding that exogenous estradiol administration reduces the magnitude of the adrenergic response (assessed by circulating epinephrine levels) to exercise in amenorrhoeic females[15] conveys that estrogen may influence exercise metabolism via its action on the sympathetic system. Ettinger et al.[19] have postulated that estrogen-induced lipolysis could be reducing epinephrine secretion via negative feedback by free fatty acids. In accordance with the greater reliance on carbohydrate oxidation during exercise, males display a larger catecholamine response to a given moderate-to-high intensity of exercise than females who are provided with a similar training status.[14,20]

Tarnopolski et al.[14] showed that after 3 days under a controlled diet in equally trained males and females running 15.5 km on a treadmill at a speed corresponding to 65% of $\dot{V}O_{2max}$, males displayed 25% greater rates of muscle glycogen utilization and 30% greater amounts of protein catabolism (determined by urea nitrogen excretion) than females. Roepstorff et al.[21] found that even though the rate of glucose appearance (glucose R_a; representing the rate of hepatic glucose production) was lower in females during a 90-minute cycling exercise at 58% of $\dot{V}O_{2max}$, glucose balance within the working muscle (consumption and release) did not differ between the genders.

2.1.2 Lipid Utilization

Estrogen has been repeatedly found to promote free fatty acid availability and lipid oxidation during exercise, possibly via an increased sensitivity to the lypolytic action of catecholamines.[19,22]

Also, even though intramuscular triglyceride content is dependent upon dietary fat consumption[23] these intramuscular stores are generally much larger in females than in males,[24] and are utilized to a greater extent in females during prolonged exercise at a moderate intensity (90 minutes, 58% of $\dot{V}O_{2max}$).[21,25] During this exercise trial, Roepstorff et al.[21] demonstrated, by measuring the arterio-venous difference in nonesterifed fatty acids, that females consume 47% more nonesterifed fatty acids within the working

Table I. Summary of studies where whole-body substrate metabolism was reported in trained males and trained females with exercise duration >60 min: only data from studies using trained subjects are reported in the present table. Significant gender difference was calculated at p = 0.02 using a two-tailed independent t-test (adapted from Tarnopolsky,[27] with permission)

Study (y)	Exercise	No. of subjects		RER	
		females	males	females	males
Costill et al.[28] (1976)	60 min run at 70% $\dot{V}O_{2max}$	12	12	0.83	0.84
Blatchford et al.[29] (1985)	90 min walk at 35% $\dot{V}O_{2max}$	6	6	0.81	0.85
Tarnopolsky et al.[14] (1990)	15.5 km run at ~65% $\dot{V}O_{2max}$	6	6	0.88	0.94
Philips et al.[30] (1993)	90 min cycle at 35% $\dot{V}O_{2max}$	6	6	0.82	0.85
Tarnopolsky et al.[14] (1990)	60 min cycle at 75% $\dot{V}O_{2max}$	8	7	0.92	0.96
Tarnopolsky et al.[13] (1997)	90 min cycle at 65% $\dot{V}O_{2max}$	8	8	0.89	0.92
Roepstorff et al.[21] (2002)	90 min cycle at 58% $\dot{V}O_{2max}$	7	7	0.89	0.91
Melanson et al.[31] (2002)	400 kcal at 40 + 70% $\dot{V}O_{2max}$	8	8	0.87	0.91
Riddell et al.[32] (2003)	90 min cycle at 60% $\dot{V}O_{2max}$	7	7	0.93	0.93
Zehnder et al.[33] (2006)	180 min cycle at 50% $\dot{V}O_{2max}$	9	9	0.86	0.88

RER = respiratory exchange ratio; $\dot{V}O_{2max}$ = maximal oxygen consumption.

muscles than their male counterparts. This result is verified by Mittendorfer et al.[26] during a prolonged exercise protocol (90 minutes) of moderate intensity (50% $\dot{V}O_{2max}$). Aside from the greater utilization of plasma nonesterifed fatty acids, Mittendorfer et al.[26] observed greater lipolytic activity in female than in male subjects that were matched by training level and fat-mass percentage.

Taken together, these findings convey that females possess larger intramuscular triglyceride stores and rely more heavily upon this substrate during exercise, as is confirmed by Tarnopolsky[27] in a meta-analysis of the literature. The gender-based differences in whole-body substrate oxidation during exercise are reflected in the lower respiratory exchange ratio of females compared with males for a given exercise intensity and duration of exercise, as displayed in table I.

2.1.3 Protein Utilization

Tarnopolsky et al.[14] showed that a rise in urinary nitrogen concentration (i.e. an indicator of protein utilization) occurs in males within the 24 hours following endurance exercise compared with a control day, while no significant difference is observed in females. This reveals that proportionally greater amounts of amino acids are oxidized by males during exercise than females. These results were then confirmed in a study by Phillips et al.[30] who used nitrogen balance and L-[1-^{13}C]-leucine tracing to demonstrate that males oxidize more protein and leucine than females. These findings were completed by McKenzie et al.[34] who showed that females utilize leucine as an energy substrate to a lesser extent than males during a 90-minute pedalling exercise at 65% $\dot{V}O_{2max}$, both before and after a 31-day endurance training programme.

Interestingly, these authors also reported that even though before the training programme, leucine oxidation doubled during exercise compared with the resting state, no differences were observed in this variable at the end of the training period. Given that the enzyme, that limits the intramuscular oxidation of branched-chain amino acids, branched chain-2-oxodehydrogenase (BCOAD), does not differ between the genders,[34] the difference in branched chain amino acid utilization could be of hepatic origin, and likely be linked to the sparing of glycogen occurring in this same organ.[35]

2.1.4 Beyond Gender Differences: the Effect of Menstrual Cycle Phase Upon Exercise Metabolism

A recent review by Oosthuyse and Bosch,[36] gathers the current state of knowledge on the influence of ovarian hormones on carbohydrate, protein and fat metabolism throughout the menstrual cycle phase. Several studies have attempted to describe how the changing levels of estrogen and progesterone throughout the menstrual cycle could alter the metabolic response to exercise. Many report conflicting results due to important confounding factors that outweigh the effect of ovarian hormone variations, including nutritional status, fitness level, the intensity of exercise and the total energy demand of exercise. Studies that carefully controlled for these variables reported some significant alterations in carbohydrate, free fatty acids and protein metabolism in the early follicular phase (characterized by low circulating estrogen and progesterone concentrations) compared with the mid-luteal phase (high estrogen and progesterone concentrations).

Substrate oxidation during exercise is influenced by the modulation of sympatho-adrenergic receptors. Via its action upon β-adrenergic receptors,[22] estrogen reduces the rate of carbohydrate oxidation, while increasing free fatty acid availability and oxidation capacity during exercise.[15,37] Some studies have identified such variations in carbohydrate and fat oxidation between the follicular and the luteal phases, provided that the intensity of exercise was high enough (60% of $\dot{V}O_{2max}$ or more) and that the subjects were in an overnight-fasted state.[38,39] Estrogen was also found to augment the capacity for muscle glycogen storage, as has been observed in the luteal phase compared with the early follicular phase.[40]

Increased protein catabolism during exercise (60 minutes of running at 70% of $\dot{V}O_{2max}$) has been observed during the luteal phase compared with the early follicular phase,[41] as shown by greater excretion of urinary urea nitrogen. This is thought to be caused by higher circulating progesterone levels (or a lower estrogen to progesterone ratio), promoting protein catabolism,[42] while estrogen reduces protein oxidation.[37] It has also been reported, however, that this increase in amino acid catabolism was diminished when carbohydrate supplementation was provided during exercise,[43] demonstrating that the hormonal fluctuations over the menstrual cycle may only be secondary to other factors such as substrate availability.

Despite these metabolic alterations during exercise across the different menstrual phases, controversy still exists, as other well controlled studies have found no differences between menstrual cycle phases.[44,45] Casazza et al.[44] have proposed that the hierarchy of factors affecting substrate oxidation during a given intensity of exercise in females was: energy flux > oral contraceptive use > recent carbohydrate nutrition, menstrual cycle effects. Little is known on how extensively these ovarian hormone fluctuations may actually impact the athletes' post-exercise needs for optimal recovery of energy stores; are these hormone-driven fluctuations important enough to recommend that the diet composition be altered to optimize the replenishment of glycogen stores, intramuscular triglyceride stores or protein turnover? Again, the influence of ovarian hormones on exercise metabolism appears secondary to factors such as nutritional status/energy availability, exercise intensity, and overall energy demand of exercise.[44]

2.2 Metabolic Responses After Prolonged Exercise

Henderson et al.[46] showed that if a greater fatty acid mobilization occurs in females during prolonged exercise compared with males, the inverse is observed during the recovery phase. This could explain why, even though females mobilize lipids to a greater extent than males during endurance exercise,[46] they lose less fat mass than their male counterparts during a physical training programme, as several studies have demonstrated.[47] Some experimental data have indeed revealed that some metabolic disturbances caused by an exercise session could still be observed several hours after its completion.[20,46,48,49] Henderson et al.[46] showed that the rate of lypolysis was still elevated 21 hours after a 90-minute pedalling exercise at 45% of $\dot{V}O_{2max}$, or 60 minutes at 65% of $\dot{V}O_{2max}$ in males, whereas significant differences in lipolysis are no longer observed in females by that point (figure 1).

To further elucidate the effect of gender on the evolution of post-exercise metabolism, Henderson et al.[50] compared the evolution of glycaemia in sedentary males and females over the 3 hours succeeding a 90-minute pedalling

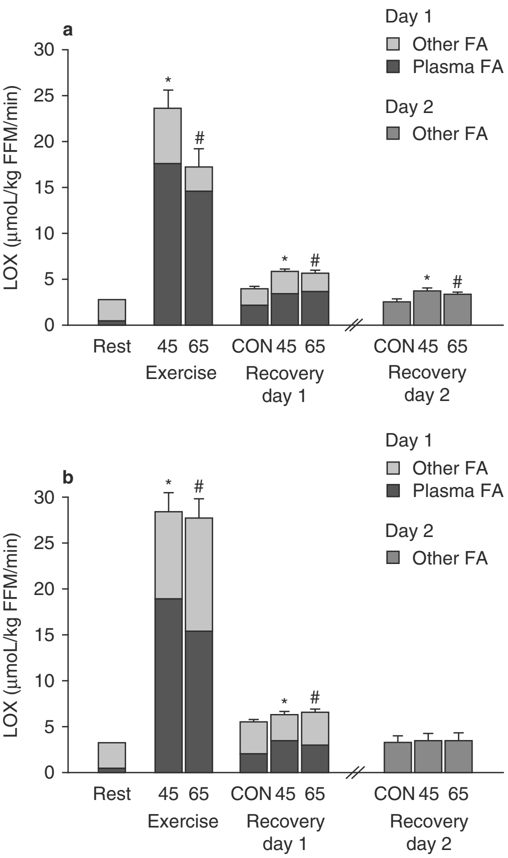

Fig. 1. Lipid oxidation (LOX). Fatty acid (FA) oxidation rate in (**a**) males and (**b**) females. FA oxidation by a combination of tracer-derived measurement and indirect calorimetry on day 1 and solely by indirect calorimetry on day 2. Values are mean ± standard error of the mean. Males: n = 10 for days 1 and 2; females: n = 8 for day 1 and n = 6 for day 2; control (CON) trial; 45, 45% peak oxygen consumption ($\dot{V}O_{2peak}$) trial; 65, 65% $\dot{V}O_{2peak}$ trial. Recovery, day 1; average from 30 min post-exercise. Recovery, day 2; the next day following exercise bouts (reproduced from Henderson et al.,[46] with permission). **FFM** = fat-free mass; * indicates total FA oxidation in 45% $\dot{V}O_{2peak}$ trial that was significantly different from corresponding timepoints in the CON trial, $p < 0.05$. FA oxidation was significantly elevated above CON during exercise at either intensity in both genders ($p < 0.05$). Plasma FA oxidation was elevated above CON during exercise and recovery for both exercise intensities, while the other (non-plasmatic) FA oxidation was significantly elevated above ($p < 0.05$), but not during post-exercise recovery; **#** indicates total FA oxidation in 65% $\dot{V}O_{2peak}$ trial that was significantly different from corresponding timepoints in the CON trial, $p < 0.05$; **//** indicates only one separating day1 and day 2.

bout at 45% of $\dot{V}O_{2max}$ and after pedalling for 60 minutes at 65% of $\dot{V}O_{2max}$ using labelled glucose. Because euglycaemia is influenced by the time of day, a control situation during which the sedentary subjects continued to go about their normal routine was included. Results revealed an increase in the rates of blood glucose appearance and disappearance as well as a greater metabolic clearance during the two exercise situations compared with the control setting in both genders. However, differences between males and females appeared when comparing the metabolic responses post-exercise with the control situation. Three hours after ceasing exercise, male subjects were found to have higher rates of blood glucose appearance and disappearance, higher metabolic clearance and a lower glycaemia, while no differences were found in females for any of these parameters between the post-exercise and control situations. These results suggest that compared with males, females have a greater ability to maintain glycaemia during the recovery period following prolonged exercise, which could explain why lipolysis occurs to a lesser degree in females during this phase. They also confirm their previous results,[46] which revealed a weaker reliance on post-exercise lipolysis and a more precise glucoregulation in females compared with males.

In all, given that females mobilize lipids to a greater extent during exercise, that their lipid stores are greater and that they show a better propensity to spare glycogen, females have a greater ability than males to maintain constant energy substrate stores during exercise, as well as during the recovery period.[50] These metabolic specificities imply the necessity for gender-specific nutritional recovery strategies.[1,35]

2.3 Strategies for Nutritional Recovery and Repletion of Energy Substrates After Prolonged Exercise

Most of the research performed in sports nutrition and energy metabolism during exercise has been performed on male subjects. Nevertheless, numerous recent studies have determined some of the specificities for restoring energy parameters in female subjects.

2.3.1 Carbohydrate Intake

Kuipers et al.[51] studied glycogen resynthesis following a bike ergometer exercise to exhaustion in endurance-trained athletes (i.e. seven males and nine females). During the 2.5 hours following the end of exercise, subjects consumed a 25% maltodextrin-fructose solution (carbohydrates: 471 ± 5 g and 407 ± 57 g for males and females, respectively). Glycogen repletion occurred in similar proportions in males and females.

Different studies demonstrated an improved glycogen repletion when carbohydrates (or carbohydrates + proteins) are consumed immediately after exercise instead of a few hours later.[52,53] Tarnopolsky et al.[13] compared the rate of glycogen resynthesis in males and females following a 90-minute exercise bout at 65% of $\dot{V}O_{2max}$ and the ingestion of three solutions: one a placebo, one containing 1 g/kg of carbohydrate, and one containing 0.7 g/kg of carbohydrate/0.1 g/kg of protein/0.02 g/kg of lipids, immediately after and 1 hour following exercise. Glycogen resynthesis occurred faster for both genders with both test solutions than with the placebo, with no differences between males and females (figure 2). Finally, a study by Roy et al.[54] showed that, in ten young females, the post-exercise intake of 1.2 g/kg of carbohydrate, 0.1 g/kg of protein and 0.02 g/kg of lipids during a period of training (four training sessions per week) resulted in an increased time to exhaustion at 75% of $\dot{V}O_{2max}$ and tended to diminish protein oxidation over the week following the protocol. These data therefore show that, when carbohydrate intake is proportional to body mass, no significant differences appear between males and females in their capacity to replenish their glycogen stores. In light of these findings, when the time allotted between two training sessions is l<8 hours, both female and male athletes must consume carbohydrates as soon as possible after exercise in order to maximize the replenishment of glycogen stores. There is an undeniable interest in breaking up the total intake of carbohydrates into smaller portions in the early phase of recovery, especially when it is not possible or practical for the athlete to eat a full meal shortly after a training session.[53] Carbohydrate-rich meals are recommended during recovery. Adding 0.2–0.5 g of protein per day and per kg to carbohydrates in a 3 : 1 (carbohydrate : protein) ratio is recommended. This holds particular importance when the athlete's training sessions occur twice daily and/or are very prolonged.[52,55] Let us recall that no difference is observed in terms of glycogen repletion when carbohydrates are consumed in the form of solids and liquids.[56] Carbohydrates with a moderate-to-high glycaemic index supply energy quickly for glycogen resynthesis during recovery and must therefore be prioritized in energy-replenishing snacks following exercise.[57]

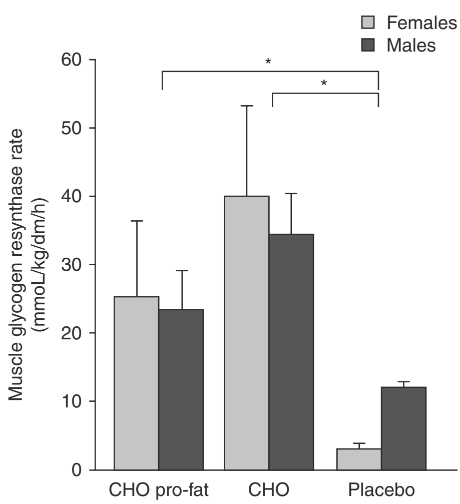

Fig. 2. Rate of glycogen resynthesis for each trial over the first 4 h post-exercise (reproduced from Tarnopolsky et al.,[13] with permission). **CHO** = carbohydrate; **dm** = dry matter; * indicates $p < 0.05$ compared with placebo.

In all, the daily intake of female athletes must reach 5 g/kg of carbohydrates of bodyweight per day.[58] If the training volume is high and training sessions occur at least once daily, this can increase to 6–8 g/kg of bodyweight per day. Given the tendency of female athletes to limit their daily caloric intake, it appears necessary to ensure that these needs be met daily in order to maintain adequate energy balance.[59]

2.3.2 Lipid Intake

Despite the importance of sufficient daily intake in essential fatty acids, many female athletes considerably limit their consumption of lipids (down to lipids only providing 10–15% of daily caloric intake), believing that they may compromise performance and increase body fat mass.[60]

However, in addition to compromising their health, these very low-fat diets reduce intramuscular triglyceride stores that are crucial for supplying free fatty acids to the muscles during recovery, especially for athletes in long-duration disciplines or those often training multiple times per day. Larson-Meyer et al.[60] showed that the lipid intake for female athletes specializing in long events must reach 30% of daily caloric intake to ensure a rapid resynthesis of intramuscular triglyceride stores. If post-exercise lipid intake is insufficient, the depletion of intramuscular triglyceride stores is still observed 2 days following exercise.[60,61] As some studies have demonstrated the very low lipid intake in this population,[62] it has also been hypothesized that a very low lipid intake (i.e. 10–15% of caloric intake) coupled with a high endurance training volume could be detrimental to performance by compromising intramuscular triglyceride stores.[63]

Also, even though this study by Larson-Meyer et al.[61] did not report any decrease in performance during a 2-hour running trial following a short-term low-lipid diet (3 days, 10% of caloric intake), this diet did yield a modification of the athletes' lipid profiles, as had already been proven in another study by Leddy et al.[64] They showed that a low-lipid diet increases triglyceride concentration and decreases the concentration of high-density lipoprotein cholesterol (HDL-C), leading to a lowered ratio of total cholesterol; HDL-C, an adverse consequence in terms of cardiovascular health. Even though no study to date has yet demonstrated this, this observation suggests, according to Larson-Meyer et al.,[61] that endurance athletes must make sure that they consume a sufficient amount of lipids daily, particularly if they or someone in their family have any problems linked with their lipid profiles. Future studies are needed to observe the effect of a chronic hypolipidic diet on prolonged exercise performance.

In conclusion, it appears that while carbohydrate and protein intake should be favoured immediately post-exercise, in the scope of the athlete's general diet, lipids intake should be maintained at a sufficient level. If fat consumption supplies less than 15% of daily caloric intake, there exists the risk of a deficiency in essential fatty acids and vitamin E.[59] Female athletes should therefore be advised to consume vegetable oils, nuts and 'fatty' fish, such as tuna and salmon, on a regular basis.[59]

2.3.3 Protein Intake

It is well known that chronic aerobic exercise diminishes amino acid utilization. However, the metabolic oxidation capacity of amino acid augments as a result of an improved activity of the limiting enzyme, glutamate dehydrogenase (BCOAD).[16] For this reason, male and female athletes must increase their daily protein intake.

Concerning proteins, it is recommended that female athletes maintain a daily energy intake superior to those recommended for the standard population, in order to ensure that the mechanisms of recovery, on a structural standpoint, are able to occur (1.2–1.4 g/kg of bodyweight per day, compared with 0.8 g/kg of bodyweight.[58] Phillipps et al.[30] demonstrated that a daily protein intake of 0.8 g/kg/day leads to a negative nitrogen balance in female athletes. Many studies performed on female athletes present evidence for the fact that this intake is often at the lower end of these recommendations, if not below them, particularly in amenorrhoeic athletes.[65,66] For female athletes specializing in strength sports, these recommendations reach 1.4–1.8 g/kg of bodyweight, given the extent of muscular damage caused by this type of activity. Foods containing proteins with a high biological availability (a high retention and utilization rate by the body) should be emphasized. Meats, fish, eggs and dairy products offer complete sources of protein (providing all essential amino acids), and it is particularly important for vegetarian or vegan athletes to pay attention to their protein sources to ensure that all essential amino acid requirements are met, usually by combining different sources such as nuts, whole grains and legumes.[67] Also, protein-rich animal foods are an important source of dietary iron, the latter helping to limit the risk of anaemia, a problem of particular concern for female athletes.[68] Volek et al.,[69] also consider that female athletes should be aware that animal protein sources provide vitamin B_{12} and D, thiamin, riboflavin, calcium, phosphorus, iron and zinc.[70]

2.4 Metabolic Responses during and following Brief Intense Exercise

During brief, high-intensity exercise, the work performed by skeletal muscle relies heavily upon the breakdown of phosphocreatine stores and the recruitment of glycolysis to ensure the resynthesis of energy. Under these conditions, the resulting decrease in intramuscular pH and the accumulation of inorganic phosphate play an important role in the development of muscular fatigue.[71] For this reason, it has been suggested that a rapid clearance of lactate and H^+ ions after intense exercise is essential for recovery in order to restore work capacity quickly, particularly in the context of sports activities involving repetitive short and intense exercise bouts.[72] Several studies performed on the effect of gender upon the metabolic response during and post-exercise contribute interesting clues regarding the methods of recovery that must be prioritized in athletic females after such brief, high-intensity exercise.

The pre-exercise phosphagen (ATP, adenosine diphosphate, phosphocreatine) concentrations do not differ between genders.[73] Nonetheless, Ruby and Robergs[74] reported a greater glycolytic activity in males than females during exercise. In this regard, Jacobs et al.[75] had already shown that males reach higher concentrations of intramuscular lactate than females following anaerobic exercise tests. These results were then confirmed by the *in vivo* study of Russ et al.,[76] which showed that males rely more heavily upon glycolysis than females, even though their reliance upon the flux of phosphocreatine and aerobic pathways for force production did not show parallel gender effects. This difference could be explained by a greater cross-sectional area of type II muscle fibres[77] and/or a greater glycolytic enzyme activity.[77] Recently, Wüst et al.[78] reinforced this hypothesis by demonstrating that the lower resistance of males to fatigue would be more strongly linked to gender differences in muscle fibre type distribution than to differences in motivation, muscular size, oxidative capacity or local blood flow.

In this context, Esbjörnsson-Liljedahl et al.[73] showed that over 3 all-out 30-second sprints separated by 20 minutes of passive recovery, females were able to maintain a steadier level of performance than males. Despite similar fitness levels (physically active, noncompetitive) females showed a lower accumulation of metabolic products than males, particularly within the type II fibres.[73] During the recovery phase, females have a greater capacity for recycling their ATP supply than males, granting them a better aptitude to take on the next intense, brief exercise bout.

2.5 Chronic Fatigue and Management of Daily Energy Balance

In female athletes, the maintenance of energy balance, is a topic in need of particular attention, because of the frequently observed concerns with physical appearance and the social pressures pushing them to maintain a low percentage of fat mass.[58,69,70,79] A positive energy balance is indeed necessary to ensure optimal metabolic recovery and to promote the muscular regeneration processes in order to withstand the training loads.[7] However, the literature reports the daily caloric intake as often insufficient in high-level female athletes, particularly those involved in sports in which a thin silhouette confers an advantage.[59,80] Figure 3[80] shows that the energy balance of high-level gymnasts remains almost always negative throughout the day. Maintaining the equilibrium between daily energy intake and expenditure by way of well adapted nutritional recovery methods concerns all athletes in any sport who must train daily or multiple times per day.

A negative energy balance is associated with a chronic state of fatigue, decreased alertness, sleep disturbances and a rise in protein catabolism, which may compromise the mechanisms for muscle re-synthesis.[7] It therefore appears necessary to inform female athletes of the importance of maintaining an adequate daily energy intake, especially since two-thirds of them express the desire to lose weight and to limit their daily caloric intake.[81] However, these dietary behaviours are not always associated with weight loss (due to a decrease in resting metabolism[80]), but rather to disturbances in the menstrual cycle.[82]

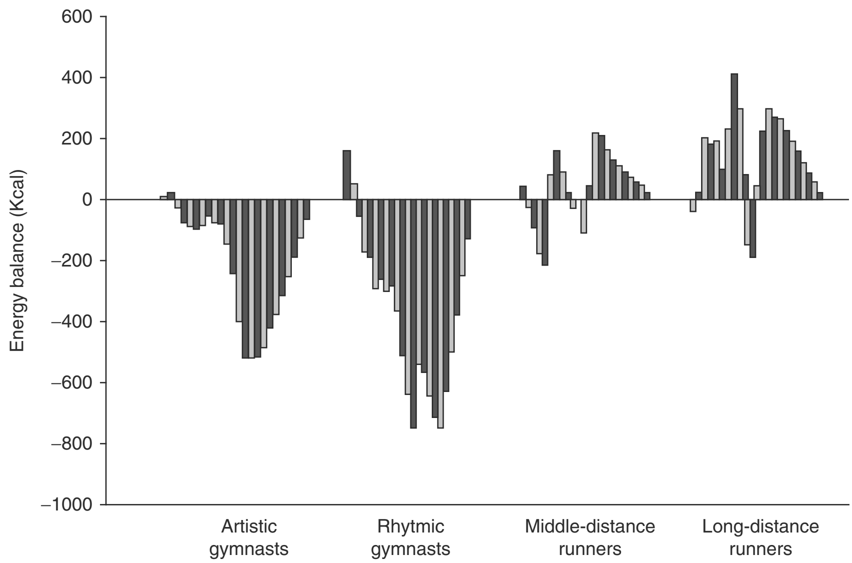

Fig. 3. Comparison of within-day energy balance in four groups of elite athletes. Each group has 24 bars, beginning with wake-up and ending 24 h later. The bars represent 4 h for each h in the day. Energy surpluses and deficits are represented, respectively, by variations above and below the zero (0) energy-balance line (reproduced from Deutz et al.,[80] with permission).

The majority of female athletes require a minimum of 2300–2500 kcal/day (9263–10 460 kJ) in order to maintain their body mass (45–50 kcal/kg/day).[58,59] Those involved in endurance sports, such as marathon running or triathlon, have energy needs susceptible to reach as much as 4000 kcal/day (16 736 kJ).[59] The literature reveals that a relatively high carbohydrate intake is usually recommended for athletes during the recovery period, independently of gender, due to the role of carbohydrates in maintaining glycogen stores.[83] However, increasing the daily caloric intake of female athletes solely via increased carbohydrate consumption does not appear as an optimal solution.[35] A female athlete consuming about 2000 kcal/day is not able to significantly increase her glycogen stores solely by increasing the percentage of carbohydrates that compose her diet. In fact, she would have to boost her caloric intake by 30% over the course of 4 days in order to reach a carbohydrate intake superior to 8 g/kg.[25] From a practical standpoint, this is neither habitual nor acceptable among athletes watching their weight permanently. Moreover, such a large shift of caloric sources toward carbohydrates is likely to lead to deficiencies in some essential proteins and lipids, and compromises nitrogen balance necessary for maintaining normal sexual steroid hormone levels.[84] In this context, several authors[60,69] recommend a lipid intake of 30% of daily energy needs for female athletes.

3. Recovery and Musculoskeletal Regeneration Processes

3.1 Recovery From Exercise-Induced Muscle Damage

Certain exercises that induce important local mechanical constraints can be accompanied, in the hours and days following their execution, by muscle aches. This delayed-onset muscle soreness is symptomatic of a number of physiological disturbances at the level of the muscle cell and interstitial fluid: inflammatory processes, oedema, muscle fibre lysis, etc. The recovery methods following any exercise able to generate this type of response in female athletes must take into account the extent of the muscle damage caused and the inflammatory response observed.

3.1.1 Severity of Muscle Damage and Post-Exercise Inflammatory Response

The Case of Long-Duration Exercise

Several studies revealed a smaller elevation in plasma creatine kinase (CK; an enzyme indicating the severity of muscular damage) in females than in males, following aerobic exercise.[85,86] Shumate et al.[85] examined the evolution of plasma CK after graded exercise on a bike ergometer. The mean increase in CK levels was 664 U/L in males and 153 U/L in females. Similarly, Janssen et al.[87] showed that male marathon runners displayed a higher plasma CK elevation than females. Apple et al.,[86] also demonstrated that the rise in plasma CK levels in female runners was 5.5 times inferior to their male counterparts after a marathon. By contrast, Nieman et al.[88] did not observe any gender differences in the post-exercise inflammatory response following a marathon. These results should, however, be considered with caution, as this type of field study limits the ability to quantify the actual workload that such an event imposes upon each participant; some of these discrepancies could be because of the lower workload performed by females.

The Case of Strength Exercise

Muscle function: Studies comparing the evolution of strength following a strength exercise bout in males and females report conflicting results, some showing no gender-based difference, and others a better recovery in females.[2]

Borsa and Sauers[89] examined the effect of gender on recovery following a traumatizing strength exercise consisting of 50 eccentric and concentric maximal contractions of the elbow flexors. After the exercise bout, both genders revealed important muscle aches, a reduced amplitude of joint movement and a significant decrease in strength. After adjusting for the pre-exercise value, the degree of strength loss was similar for both genders (–15.3% vs –18.2% for males and females, respectively). In the same manner, Rinard et al.[90] did not report any gender differences in strength loss and recovery kinetics after 70 maximal eccentric contractions. Hakkinen[91] had earlier observed that after a strenuous leg extensor exercise (20 maximal contractions), even though the percentage of strength lost over the repetitions did not differ between genders, the recovery of maximal force 1-hour post-exercise was greater in females. Later, Linnamo et al.[92] demonstrated the same trend toward a greater central fatigue in males after an explosive strength loading exercise. Moreover, Sayers and Clarkson[93] did not observe any gender differences in relative strength loss after 50 maximal voluntary eccentric contractions, but they did find a greater incidence of extreme strength losses (>70%) in females compared with males. These authors also added that the females showing the largest losses actually recovered faster than the males who had shown the same degree of strength loss post-exercise. This finding suggests that females are able to recover to a functional level more rapidly than males. This hypothesis has also been strengthened by Sewright et al.,[94] who revealed a greater strength loss in females than in males immediately following 50 maximal eccentric contractions. This significant difference, however, disappeared 6-hours post-exercise (figure 4).

Taken together, the heterogeneity of these results does not allow us to state that females differ significantly from males in terms of the strength aspects of recovery.[2] However, these findings show that females are subjected to muscle damage from the practice of strength exercises, and therefore this must be taken into account in the planning of recovery methods following this type of exercise.

Muscle damage and inflammatory response: The protective effect of estrogen upon skeletal muscle inflammation and repair has been well documented in animal models.[95,96] Studies have reported that 17β-estradiol exerted a protective effect upon the extent of total muscle damage,[95,97] in part by reducing leucocyte infiltration into damaged muscle cells thus preventing additional or excess release of oxidizing agents. The few studies performed on human subjects report differing results. MacIntyre et al.[98] examined muscle aches, strength loss and the intramuscular accumulation of neutrophils (playing a role in the immune system) in premenopausal females and males after

300 maximal voluntary knee extensions. After this exercise, the evolution of muscle pain strength loss differed between genders, females generally showing a greater degree of damage after 20–24 hours compared with males. They showed a greater neutrophil accumulation than males at +2 hours (but not at +4 hours), despite males having accomplished a larger workload. These results suggest that females have a stronger neutrophil response than males in the early post-exercise period. Stupka et al.[99] have compared the evolution in granulocyte (i.e. phagocyte) count in the plasma, of CK and histological markers of muscle damage 24, 48 and 144 hours after an eccentric exercise at 120% of the one-repetition maximum. The results of this study reveal that if disruptions of the Z lines were visible at the level of the sarcomeres within the vastus lateralis muscle involved in that exercise, no significant gender difference was observed in the extent of post-exercise damage. But this study also revealed a higher plasma granulocyte count in males 48 hours after the exercise, suggesting that the inflammatory response was attenuated in females compared with males by that point in time. While these findings could appear to conflict with those of MacIntyre et al.,[98] the absence of any difference 4 hours post-exercise in the latter's study could imply a different evolution of post-exercise inflammatory cell infiltration in females and males. It is important to note, however, that in the Stupka et al. study the females[99] were all oral contraceptive users and tested during the equivalent of the late follicular phase, whereas MacIntyre et al.'s protocol[98] did not appear to account for the menstrual cycle phase. Estrogen levels in females taking oral contraceptives are known to be lower than non-oral contraceptive users, and this could have accentuated the discrepancy between the studies' findings. Furthermore, Tiidus et al.[100] demonstrated that in rats, the protective effect of estrogen on neutrophil infiltration did not occur with synthetic estrogen supplementation. In light of these results, Clarkson and Hubal[2] stated that females demonstrate an earlier post-exercise inflammatory response, but that this response remains weaker than in males over the long term.

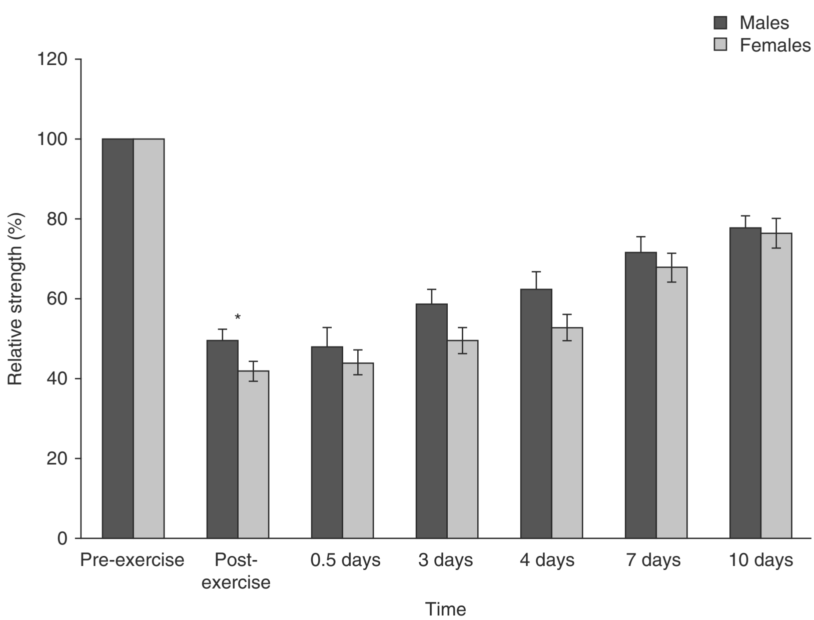

Fig. 4. Relative strength loss and recovery over time (at baseline, immediately after exercise, and 0.5, 3, 4, 7, 10 days after exercise) expressed as mean ± standard error of the mean. Females exhibit significantly greater strength loss immediately after exercise, but there is no significant effect of gender at any other timepoint (reproduced from Sewright et al.,[94] with permission). * indicates $p < 0.05$.

For Peake et al.,[101] a potential explanatory hypothesis would involve the infiltration of leucocytes into muscle cells post-exercise, which could differ in males and females because of the differences they show in membrane permeability following a muscle-damaging exercise.

In this perspective, recovery strategies making use of cold exposure to reduce the post-exercise inflammatory response appear particularly beneficial to the athletic woman. It has been proven that vasoconstriction and the reduction of metabolic activity had the effect of decreasing tissue swelling, inflammation, the immediate sensation of pain and the degree of severity of an injury.[102] Experimental evidence shows that the local application of cold, started promptly after a muscle injury and maintained for a prolonged time period, limits the process of cell destruction by leucocytes and improves nutrient perfusion through the tissues.[103] In the acute treatment of musculoskeletal trauma, cold application is an adequate method by which to improve cellular survival against local hypoxia generated by the inflammatory process and the formation of oedema.[104]

Future studies will need to determine whether recovery by cold-water immersion or whole-body cryostimulation would be susceptible to yield greater benefits to female athletes, given the specificity of their inflammatory response, compared with that of males.

3.2 Recovery From Exercise-Induced Bone Damage

3.2.1 Bone Turnover and Stress Fracture

The majority of physical activities exert strong pressures upon the skeletal system, thereby increasing bone cell turnover. The mechanisms for osteogenesis and bone recovery being largely dependent upon calcium intake and overall caloric intake[58,105] as well as hormonal status.[106,107]

Howat et al.[66] report that the diets of female athletes are frequently poor in calcium, especially when dairy product consumption is low or nonexistent. This contributes to the compromising of their bone health and increasing their risk for stress fractures.[59,105] It therefore seems essential during recovery, to promote calcium consumption to aid the bone remodelling processes.[105] In spite of this, female athletes often fail to maintain a sufficient calcium intake, especially when dairy products are not included in their diet. Several studies have thus shown that daily calcium intake can vary between 500 and 1623 mg/day in female athletes, with most of them not even reaching 1000 mg/day.[108] By contrast, the recommended daily intake of calcium is 1300 mg/day for females aged between 9 and 18 years and 1000 mg/day for females aged between 19 and 50 years. The results of a recent study by Josse et al.[109] illustrate the beneficial impact of milk consumption on bone turnover in young females over the course of a 12-week strength training programme. Five times per week, subjects consumed either twice 500 mL of fat-free milk (1200 mg/day of calcium and 360 IU/day of vitamin D), or an isoenergetic carbohydrate drink immediately and 1 hour after each strength training session (figure 5a and b). The milk group showed a larger rise in serum 25-hydroxyvitamin D (vitamin D acting to promote calcium absorption and bone turnover) levels than the control group, while parathyroid hormone (responsible for bone resorption by enhancing the release of calcium into the bloodstream) levels decreased in the milk group only. The greater lean mass gains observed in the milk group also suggest larger gains in bone mass and, finally, fat mass decreased in the milk group only. These results emphasize the important role of calcium as part of nutritional strategies for optimal bone health and recovery.

Inadequate caloric intake also undermines bone health by suppressing hypothalamic-pituitary gonadal axis activity, resulting in low estrogen production and ensuing menstrual cycle disturbances.[110,111] Estrogen plays a multi-factorial role in maintaining bone health in premenopausal females, by both slowing bone resorption[107] and stimulating its formation.[106] The elevated occurrence of osteopaenia and increased rate of bone fractures is well documented in premenopausal athletic females with hypothalamic amenorrhoea and in anorexic females.[112,113] Athletes who restrict caloric intake despite important training loads, compromise the hormonal

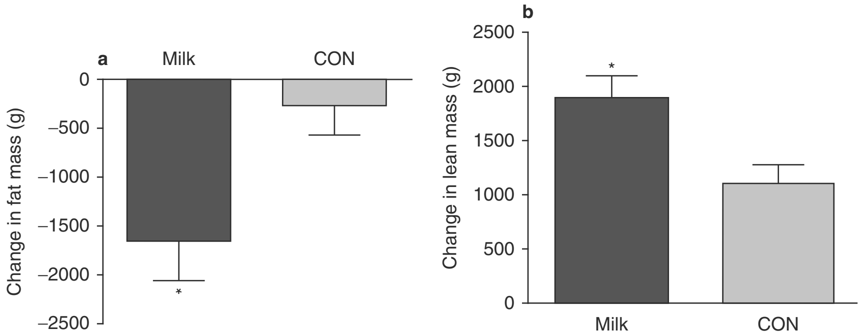

Fig. 5. Evolution of fat mass and lean mass before and after 12 weeks of strength training in groups having consumed (**a**) milk following training sessions (n = 10) or (**b**) an isoenergetic carbohydrate drink (control [CON], n = 10). Values are mean ± SE (reproduced from Josse et al.,[109] with permission). * indicates significantly different from CON in the pre- to post-training difference (p < 0.05).

processes involved in bone remodelling, placing themselves at a risk for bone loss comparable to postmenopausal females. In this regard, maintaining adequate energy availability holds particular importance through puberty and until late adolescence, when females reach their peak bone mass.[114]

Vitamin D status is another important factor in preserving bone health. Athletes living in Nordic countries and training mostly indoors often show a poor vitamin D status; a level ≥80 nM is necessary to maintain good bone health.[115] Studies show that the daily supply in vitamin D averages 5 μg per day (200 IU/day) in females aged between 19 and 50 years. It is therefore advisable to compensate for this deficit with a well adapted diet, or by way of luminotherapy. Finally, adequate protein intake should be included in the nutritional recovery strategies aiming to preserve bone health, in order to limit, over the short term, the risks of stress fractures, and over the long term, the onset of osteoporosis.

4. Recovery and Return to Homeostasis: Is there a Gender Difference?

4.1 Recovery and Metabolic Disturbances

4.1.1 Active Recovery

An analysis of the literature on the benefits of active recovery reveals the latter as especially advantageous when performed between two exercise sessions that are closely scheduled in time (<1 hour) and which rely heavily upon anaerobic processes.[116] It is therefore particularly useful when two maximal performances must be executed within a time frame that is too short to allow a return to homeostasis by way of passive recovery.

Many studies have shown that an active recovery yields a more rapid return to resting blood lactate concentrations, compared with a passive recovery.[117] Similarly, Yoshida et al.[118] discerned that active recovery limits the accumulation of inorganic phosphate after an intense, 2-minute exercise bout compared with a passive mode of recovery. Other results showed that maintaining a sub-maximal intensity of exercise enables a quicker return of intramuscular pH to its resting value after a high-intensity effort.[118,119] It appears appropriate to recommend that females maintain a moderate intensity of exercise between two high-intensity exercise bouts that are separated by a relatively short time span for recovery (i.e. <1 hour).

Carter et al.[120] showed a greater decrease in arterial blood pressure after exercise in females than that in males, such that it may decrease below its pre-exercise value during passive recovery. Given that the return to homeostasis after an effort relying heavily upon glycolytic processes appears to be linked to maintaining good venous return,[121] it is conceivable that female athletes would find a greater advantage to active recovery modes than their male counterparts at the circulatory level.[120] Furthermore, a recent study by Jakeman et al.[122] has proven the effectiveness of wearing compression socks during the recovery period in females. These authors demonstrated that muscle aches were significantly diminished by their use, and that the loss in knee extensor strength was reduced. In addition, jumping performance (squatting jump with counter movement) was significantly superior following this mode of recovery. Such findings strongly support the concept that improving venous return during recovery in athletic females is an essential parameter contributing to muscle performance.

4.1.2 Recovery by Immersion

To our knowledge, only one study has examined the effect of gender on recovery by immersion after aerobic exercise.[123] The results of this study show that a 30-minute immersion in alternating hot (36°C) and cold (12°C) baths generates a greater drop in blood lactate concentrations than a passive recovery mode. However, we will mention that even though this method appears to accelerate post-exercise lactate clearance significantly, these differences remain small. New studies are necessary to determine whether this type of recovery can yield positive effects upon the level of performance of female athletes, when used between repeated anaerobic exercise sessions. Nonetheless, it appears that basic indications can be provided to female athletes regarding this recovery mode, and this not only for traumatizing exercises.

4.2 Recovery and Thermoregulation

Reaching a high core temperature as a result of an imbalance between the mechanisms of thermogenesis and thermolysis during prolonged exercise has been well identified in the literature as a physiological factor that limits performance.[124] The rise in core temperature during exercise is a normal consequence to any form of exercise over long durations and is controlled by the interaction of vascular, muscular and metabolic responses.[125] In response to these, the organism adapts by augmenting both peripheral blood flow and sweat loss. We will show that post-cooling methods during recovery can offer specific benefits to the female athlete.

4.2.1 Evaporation and Hydration Strategies for Recovery

Sweat Loss during Exercise

In their review of the literature on the effects of gender upon thermoregulation during exercise, Kacibua-Uscilko and Grucza[126] report that females differ from males in their exogenous heat storage and thermolytic capacities, as well as their endogenous heat production during exercise. These differences are mainly attributed to a lower body mass to surface area ratio, greater subcutaneous fat stores and a lower exercise capacity in females. A higher fat-mass percentage augments thermal stress by increasing the metabolic cost of performing a given exercise task.[127,128] In addition, the larger subcutaneous fat layer in females increases the distance between the active, heat-producing tissues (i.e. skeletal muscle) and the skin, reducing the rate of nonevaporative heat loss, and decreasing the body surface area to bodyweight ratio.[129]

Nevertheless, when these differences are accounted for in research studies, differences between the genders are still observed. When subjected to an identical thermal rating, females were found to sweat less than males while maintaining the same body temperature as a result of greater efficiency of the sweat evaporation process. Grucza[130] also showed that females sweat less than males, without demonstrating a greater concomitant rise in rectal and body temperature. This author has provided evidence for the fact that this difference can be explained by a greater amount of evaporated sweat (58.7% vs 52.0% of total sweat lost, respectively) and a lower amount of dripping sweat in females, compared with males (21.2% vs 34.1% of total sweat loss in females and males, respectively).

Even though these experimental data suggest that the extent of water loss associated to exercise is proportionally lesser in females, they should, nonetheless, compensate for these losses with well adapted rehydration strategies.

Post-Exercise Rehydration Strategies

Recommendations for post-exercise rehydration are similar in males and females and aim to compensate for the water and electrolyte losses occurring during exercise. However, few studies have compared the hydration strategies adopted by both genders. On this topic, Broad et al.[131] have quantified the sweat losses and fluid intake of female soccer players. These authors reported that females drank, on average, 0.4 L/h during training and competition periods, which is lower than that reported for males. This difference may be mainly linked to morphological differences between genders, but also to lower metabolic heat production rates in females. However, electrolyte losses comparing the sweat of female soccer players less than 21 years of age and seniors on a British team over the course of one practice and one game appeared identical to those measured in their male counterparts.[132]

In light of these results, it appears that the same recommendations for rehydration during recovery given to males may be well adapted to females. Burke[79] did not bring forth any post-exercise hydration strategy specific to females. We therefore retain, that in the post-exercise period, it is necessary to replace, as rapidly as possible, the fluids lost during exercise. In subjects having lost 3% of body mass due to dehydration, Shirreffs et al.[132] showed that ingesting, small fractions of a 23 mmol/L sodium solution (150–200% of the water volume deficit) was the most effective method to compensate for the fluid losses caused by exercise. To speed the rehydration process in the context of multiple practices or competitions performed in one day, it appears advantageous to consume cool water (i.e. 12–15°C), slightly flavoured and containing 2% of carbohydrates and 1.15 g/L of sodium.[133] When the amount of time separating the performances is greater, the fluid recovery of female athletes can occur via a combination of water and solid food intake. In this context, urine clarity may serve as the most practical method for athletes to evaluate their hydration status.

4.2.2 Thermoregulation and Post-Cooling

Thermoregulatory Response Post-Exercise

Kenny and Jay[134] showed that, compared with males, females reveal a diminished ability to lower their temperature at the level of the oesophagus as well as that of the muscles previously activated by a given effort (figure 6). This difference appears linked to a higher threshold for females for post-exercise cutaneous vasodilation,[135] and to a greater drop in post-exercise arterial pressure, compared with males.[135]

In addition, the hormonal variations of the menstrual cycle modify the thermoregulatory response to exercise in females, such that the core temperature during rest and exercise may differ according to the phases of the menstrual cycle. In this way, Kacibua-Uscilko and Grucza[126] explain that the internal temperature fluctuates by more than 0.6°C, depending on the menstrual cycle phase, both at rest[136] as well as during

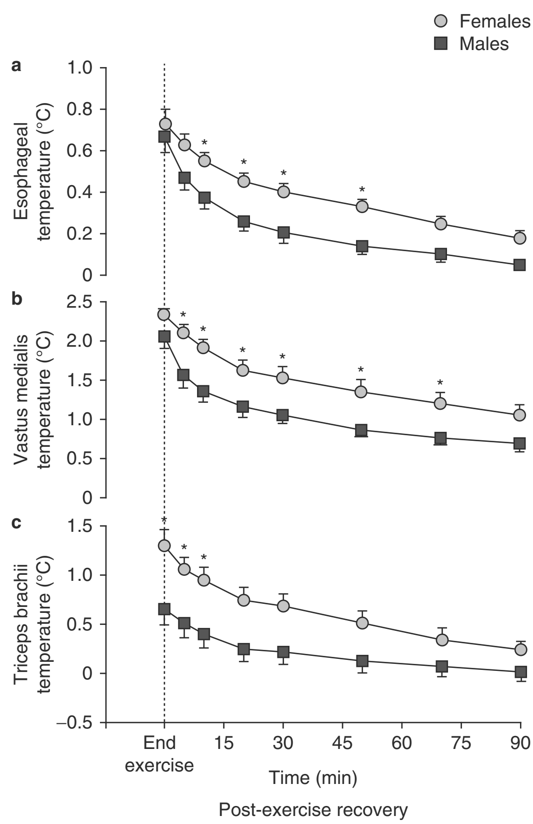

Fig. 6. (**a**) Changes from pre-exercise rest in esophageal temperature. (**b**) Vastus medialis muscle temperature measured 10 mm from the deep femoral artery and femur. (**c**) Triceps brachii muscle temperature measured 10 mm from the superior ulnar collateral artery and humerus. Data separated according to males and females. Values are mean ± standard error of the mean (reproduced from from Kenny and Jay,[134] with permission). * indicates significant difference between genders at an alpha level of $p < 0.05$.

exercise,[137] and even under warm conditions for exercise.[136] The rise in progesterone levels during the luteal phase (i.e. the post-ovulation phase) triggers a rise in body and skin temperature that delays the activation of perspiration mechanisms in both ambient and warm environmental conditions. However, if Marsh and Jenkins[138] report that no tangible proof exists to claim that the female athlete is confronted with a greater risk of heat stroke during exercise than that of the male athlete, then the findings gathered in this review still suggest that strategies of post-cooling are likely to be at least as beneficial for females as they may be for males.

Strategies for Post-Cooling

Given the lower thermolytic capacities of females in the post-exercise period, the cooling-off methods performed after an exercise session (post-exercise cooling), in particular those involving cold water immersion or wearing a cooling jacket, appear as a particularly interesting recovery method for females. Indeed, cold water immersion and the use of a cooling jacket both seem to reduce body temperature and heart rate efficiently.[139] Moreover, cold water immersion may cause an adjustment of blood flow distribution that could benefit the quality of performance delivered during the next exercise session.[139] The benefits of post-exercise cooling are most apparent following exercise performed in the heat.[140,141] A high internal thermal load can lead to an immediate drop in the level of performance and can slow the recovery to an optimal state of functioning.[142] In this way, the degree of thermal stress induced by exercise, or the inability to tolerate an imposed workload may result in a prolonged drop in performance. Previous studies highlighted the reduction in voluntary muscle activation following an exercise protocol to exhaustion due to whole-body hyperthermia, implying a selective reduction, by the CNS, of muscle activity following exercise.[143] According to these results, a decrease in maximal force could be the consequence of decreased CNS command upon the active muscles, acting as a protection mechanism aiming to limit metabolic heat production, and to thereby limit further rise in body temperature.[143] This also indicates that maintaining a high internal thermal load can impair performance during a subsequent exercise bout. While contradiction exists in the literature, post-exercise cooling is certainly beneficial as far as reducing the internal thermal load after exercise.[141] Even though future studies will need to confirm this hypothesis, it is conceivable that the reduction of thermal stress tied to exercise via post-cooling methods will demonstrate benefits of greater magnitude in females, given their lesser capacity to lower their internal temperature after exercise.

5. Conclusions

Performing elevated training workloads is susceptible to yielding deleterious effects if the organism is unable to recuperate completely between training sessions. In this context, the recovery phase must be considered as an inherent component of the training process and must, therefore, be granted the same degree of attention in its programming and management as the exercise sessions themselves. Given the effects of gender upon the physiological responses to exercise and during the post-exercise recovery period, it appears essential to customize recovery methods according to gender, so as to optimize the processes of physiological recovery and supercompensation while minimizing the risks of injury in the female athlete. Both athletes and those surrounding them must now acknowledge the necessity of investing time and financial means into the optimization of recovery. Further research must be performed in order to comprehend clearly the potential benefits that new methods of recovery may bring to the female athlete.

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