REVIEW

Nutritional aspects of women strength athletes

J S Volek, C E Forsythe, W J Kraemer

Br J Sports Med 2006;40:742–748. doi: 10.1136/bjsm.2004.016709

Strength training elicits sports related and health benefits for both men and women. Although sexual dimorphism is observed in exercise metabolism, there is little information outlining the specific nutritional needs of women strength athletes. Many women athletes restrict energy intake, specifically fat consumption, in order to modify body composition, but this nutritional practice is often counter-productive. Compared to men, women appear to be less reliant on glycogen during exercise and less responsive to carbohydrate mediated glycogen synthesis during recovery. Female strength athletes may require more protein than their sedentary and endurance training counterparts to attain positive nitrogen balance and promote protein synthesis. Therefore, women strength athletes should put less emphasis on a very high carbohydrate intake and more emphasis on quality protein and fat consumption in the context of energy balance to enhance adaptations to training and improve general health. Attention to timing of nutrient ingestion, macronutrient quality, and dietary supplementation (for example, creatine) are briefly discussed as important components of a nutritionally adequate and effective strength training diet for women.

See end of article for authors' affiliations

Correspondence to:
Dr Jeff S Volek, Department of Kinesiology, 2095 Hillside Road, Unit 1110, University of Connecticut, Storrs, CT 06269-1110, USA; jeff.volek@uconn.edu

Accepted 10 July 2006
Published Online First 19 July 2006

Strength training for healthy women is endorsed by the American College of Sports Medicine[1] and has many beneficial effects on health[2 3] while also enhancing performance in other activities.[4] Women engaging in strength training range from young high school athletes,[5] to post-menopausal women,[2] to those competing in strength training sports (for example, weight lifting, power lifting, and body-building). Nutrition has a major influence on the magnitude of adaptation to training. Proper food intake and sound nutritional strategies will result in strength and muscular endurance improvements, and will facilitate athletic performance.[6] Nutritional needs are influenced by the metabolism of energy providing nutrients (that is, mobilisation, utilisation, and storage of energy substrates) at rest and during exercise. Nutritional recommendations for men and women strength athletes share many common elements and the reader is referred to other reports that discuss these in more detail.[7 8] The main purpose of this review is to point out subtle, but potentially important, gender differences in metabolism and to suggest related nutritional approaches for women engaged in strength training whose goals are muscular hypertrophy, power, and strength.

WOMEN AND STRENGTH TRAINING

The general benefits of strength training for both men and women include an increase in bone mass and lean mass,[9] improved body composition (due to decreased fat mass), cardiovascular fitness, strength, and an enhanced sense of well being.[3 10–12] Alterations in muscle strength and size following resistance training in women are similar to those in men,[13–16] given that the exercise stimulus is the same.[17] However, the relative increases in strength upon initiation of training may be greater in women partially because of lower baseline strength levels.[18] Basal hormonal differences (that is, decreased testosterone) ultimately limit the absolute amount of lean body mass that women can accrue with strength training.[19] The common fear that women will become too bulky or large with strength training is not physiologically possible and should not dissuade women from engaging in this mode of exercise.

GENDER DIFFERENCES IN EXERCISE METABOLISM

Several studies have compared submaximal exercise metabolism in women and men and indicate that although metabolism is qualitatively similar, there are subtle quantitative differences in the relative use of substrates, with women utilising proportionally more lipid and less carbohydrate than men,[20–23] a phenomena that has been attributed to dissimilarities in sex steroids between genders.[22 23] Women have been documented as possessing increased intramuscular muscle triglyceride (IMTG) stores compared to men,[24 25] partially due to the larger area occupied by type I (slow twitch) fibres.[26 27] Intramuscular triglyceride breakdown during submaximal exercise in women appears to be greater[24] or similar[25] compared to men. Few studies have examined gender differences during high intensity exercise or resistance training.

From available studies of resistance exercise conducted in men, metabolism during this type of exercise is reliant on anaerobic energy sources as indicated by investigations showing significant depletion of muscle phosphocreatine (PCr)[28] and glycogen immediately following weight lifting exercise,[29–31] especially in type II (fast

Abbreviations: DRI, dietary reference intakes; EPOC, excess post-exercise oxygen consumption; IMTG, intramuscular muscle triglycerides; MET, metabolic equivalent of task; PAL, physical activity level; PCr, phosphocreatine; REE, resting energy expenditure; RER, respiratory exchange ratio; TEA, thermic effect of activity; TEE, total daily energy expenditure twitch) muscle fibres.[32] Surprisingly, IMTG are also significantly depleted with resistance exercise in proportion to the pre-exercise level.[33] In comparison to men, women appear to use less glycogen during resistance exercise. For example, a repeated maximal knee extension protocol resulted in significant glycogen depletion in type I and II muscle fibres in trained and untrained men, but this was not found in women.[34] An attenuated reduction in glycogen in women after resistance exercise is consistent with similar observations after sprint exercise[35 36] and may result from lower glycolytic enzyme activity in women[37] or a suppressive effect of estradiol.[38] This gender difference in carbohydrate metabolism during resistance exercise may also be explained by the fact that women usually have a greater capacity for lipid breakdown and oxidation compared to men,[20] such that glycogen is spared more in women than in men.

In response to resistance training, women expend less total energy and have lower excess post-exercise oxygen consumption (EPOC) compared to men, which can be attributed to training status, body size, and hormonal differences.[39] However, EPOC is still elevated significantly in women after a strength training session, similar to the situation in men, which has important implications for improving energy balance and body composition.[40] Immediately following resistance exercise in women, the respiratory exchange ratio (RER) significantly declines indicating an increase in fat oxidation during recovery.[41] This significant decrease in RER post-exercise has been noted by several investigators when resistance exercise was compared against sitting[41–43] and against treadmill exercise with the same aerobic energy cost.[39] Elevations in fat oxidation post-exercise spare exogenous carbohydrate for glycogen replenishment[44] and underscore the importance of IMTG and dietary fat as an energy source.[45]

ENERGY BALANCE

Energy intake

Energy balance is an important nutritional consideration for strength athletes, particularly women.[6 46] Positive nitrogen status is necessary for optimal acquisition of lean body mass, and is related to energy balance. Negative energy balance is associated with increased catabolism of protein, which can compromise skeletal muscle hypertrophy.[19 47] Thus, adequate energy consumption should be the first priority for female athletes to sustain activity, promote muscular growth and optimal body composition, and maintain ideal health. There is a need to educate women on the importance of energy balance because a staggering two thirds of female collegiate athletes report wanting to lose weight and are attempting to decrease energy intake.[48] Female athletes are commonly reported as maintaining negative energy balance,[49] due to factors such as preoccupation with body image and societal pressures to achieve a low body fat percentage.[50 51] These self reported energy deficits, although not always accompanied by weight loss, are often associated with irregular menstrual cycles indicating that energy intake may not be appropriate.[52 53] Although female athletes typically use energy restriction as a means to improve body composition, female elite athletes with larger or more frequent daily energy deficits have higher body fat percentages,[54] perhaps due to an adaptive reduction in resting metabolic rate.

Females with low energy intake often complain of fatigue, irritation, and poor athletic performance.[55] Amenorrheic females in negative energy balance, as indicated by low thyroxine (T4) and triiodothyronine (T3) levels, have slower PCr recovery rates measured by ^{31}phosphorus magnetic resonance spectroscopy compared to eumenorrheic athletic counterparts without thyroid hormone disturbances.[56] Negative energy balance associated with thyroid alterations may alter a female athlete's ability to perform repeated bouts of exercise. Low energy intake, disordered eating, and/or cognitive dietary restraint among female athletes are also associated with low bone mineral density and increased risk of skeletal stress fractures.[56 57] Reproductive function is also disturbed when energy availability is inadequate, which may lead to infertility when sustained over longer periods of time.[53 56 58] Further, when energy intake is low, the athlete is at greater risk of not obtaining adequate nutrients (carbohydrate, protein, fat, vitamins, and minerals).

Energy expenditure

Resistance exercise increases EPOC and resting energy expenditure (REE) in women to the same degree as endurance exercise of the same caloric output.[39 41 59–61] Increases in energy expenditure appear to occur primarily during and immediately after the exercise bout,[60] unless multiple sets are performed to failure, in which case REE will be elevated for extended periods (24–36 h) post-exercise.[40 62] Therefore, resistance exercise can significantly elevate 24 h energy expenditure and should be compensated for with increased energy intake to prevent negative energy balance. The best time for women to increase food consumption seems to be during and after exercise to take advantage of the enhanced sensitivity of skeletal muscle to take up glucose and amino acids. Attention to energy needs during and following exercise should be of high priority to ensure optimal athletic performance.

How much energy is needed?

Several approaches can be taken to determine energy requirements to maintain energy balance. The World Health Organization recommends estimating energy needs based on assessments of total daily energy expenditure (TEE).[63] The most common method to estimate TEE in healthy non-athletic individuals is to multiply REE by physical activity level (PAL) (that is, $TEE = REE \cdot PAL$).[64 65] For athletes, inclusion of the energy cost of their specific exercise activity, known as the thermic effect of activity (TEA), based on exercise time, intensity and duration, should be added to the TEE equation, to accurately account for all energy expended throughout the day[46]: the TEE equation for athletes is therefore: $TEE = REE \cdot PAL + TEA$.

Determination of REE

REE should be carefully calculated as it is an important determinant of TEE. REE is most accurately measured in the laboratory using indirect calorimetry, but can also be estimated using predictive equations that incorporate anthropometric variables. The most commonly used predictive equation is that developed by Harris and Benedict [655+9.5 wt (kg)+1.9 ht (cm)−4.7 age (years)] even though many studies have questioned its accuracy.[66–68] Recently, it has been demonstrated that the Owen equation [795+7.18 wt (kg)] for estimation of REE is more accurate for use with normal weight non-athletic young women ($BMI \leqslant 25$ kg/m^2), while the Bernstein equation [7.48 wt (kg)−0.42 ht (cm)−3.0 age (years)−844] is more accurate for overweight young women (BMI 25–30 kg/m^2).[68]

Determination of PAL

Physical activity level can be determined with the use of accelerometers, heart rate monitors, activity diaries, and/or self reported activity estimates.[63 65 69] Combining the use of more than one of these methods over a period of several days will provide a more accurate determination of average PAL than one method alone. Alternatively, PAL can be determined by estimating average activity level. The new dietary reference intakes (DRI) report states that PAL values range from 1.0–1.4 for sedentary individuals to 1.9–2.5 for those who are very active.[69] Depending on the activity level of their occupation and habitual daily activity, women strength athletes may be considered moderately active (PAL 1.6) to extremely active (PAL 2.5).

Determination of TEA

The energy cost of weight lifting exercise is determined based on the Compendium of Physical Activities[70] and is expressed in metabolic equivalents of task (METs). Weight lifting has an energy cost of 6.0–8.0 METs. The thermic effect of weight lifting can be calculated by multiplying body weight in kilograms by the duration of the activity in hours, and then multiplying by the MET value (TEA = wt (kg)·duration (h)·MET).

TEE equation

Using the above calculations to estimate energy requirements for a healthy 68 kg young woman (BMI $\leqslant$25 kg/m^2) with a moderately active lifestyle (1.6 PAL), who engages in 1.5 h of strength training per day, TEE is approximately 2665 kcal/day: TEE = [795+7.18·68 kg]·1.6+[68 kg·1.5 h·6.0 MET] = 2665 kcal/day.

The American Dietetic Association, the Dietitians of Canada, and the American College of Sports Medicine recommend that strength athletes should consume 44–50 kcal/kg bodyweight/day to maintain body weight and activity due to their increased body size and high level of fat free mass in comparison to endurance athletes.[46] For a 68 kg woman, this would equate to a TEE of 3000–3400 kcal/day, which would be appropriate if the woman maintained a healthy body weight and did not significantly increase body fatness. Since this recommendation for energy intake was based on male bodybuilders[71] and it is recognised that females have a lower REE and EPOC than males, appropriate total energy intake for female strength athletes may be slightly lower. Our recommendation for women who engage predominately in resistance exercise training is to consume 39–44 kcal/kg bodyweight/day. According to several investigators, women are at risk of energy imbalance disorders (weight loss and menstrual disturbances) when energy intakes are less than 1800–2000 kcal/day (less than 30 kcal/kg bodyweight/day).[46 50 58 72]

Influence of the menstrual cycle on TEE

The phase of the menstrual cycle may also be taken into consideration when estimating energy requirements. In adult pre-menopausal women, REE is shown to be slightly increased in the luteal phase compared to the follicular phase.[73] Women may be encouraged to consume slightly more energy during the follicular phase of their menstrual cycle to ensure optimal athletic performance.

CARBOHYDRATE

High carbohydrate diets are generally recommended for athletes, including women, because of their role in maintaining adequate glycogen levels.[46] The advent of the biopsy needle in the mid-1960s allowed histological and biochemical studies of human muscle before, during, and after exercise. Subsequent work detailing the importance of muscle glycogen as a fuel for active muscle during prolonged exercise, and the role of glycogen depletion with fatigue, ushered in the age of high carbohydrate diets as the optimal diet for athletes. This glycogen centric viewpoint led to the development of carbohydrate loading strategies to super-saturate muscle glycogen levels, delay glycogen depletion, and prolong the onset of fatigue, thereby improving performance.[74] Carbohydrate loading regimens have been modified[75] but remain popular today for many endurance activities. We argue however, that high carbohydrate diets may not be optimal for the performance of women strength athletes.

One reason that high carbohydrate diets are not optimal for women strength athletes relates to the finding that women use significantly less glycogen during resistance exercise than men[34] and synthesise less glycogen in response to a given amount of dietary carbohydrate.[76] In order for women to glycogen load to the same extent as men, it is suggested that they increase carbohydrate intake to provide >8 g/kg bodyweight/day carbohydrate.[77 78] For example, for a 68 kg woman requiring 2665 kcal/day with a carbohydrate recommendation of 9 g/kg bodyweight/day, this translates to 612 g of carbohydrate (2448 kcal) or 92% of her daily caloric allotment. Clearly this would mean that protein and fat intake would be suboptimal. Further, when women were matched for lean body mass with men and compared, consuming a high carbohydrate diet resulted in absolute and relative increases in muscle glycogen that were much lower than for men, and only significant for women if total energy intake was substantially greater than habitual intake.[77] Overtime, the increased energy required to obtain adequate glycogen synthesis in women would lead to an energy imbalance. Further, if women choose to not increase energy intake, but just increase carbohydrate, other important macronutrients (that is, fat and protein) would need to be displaced. This displacement could lead to deficiencies in essential protein and fat, and compromise a myriad of physiological processes from nitrogen balance to maintenance of adequate levels of sex steroid hormones.[79]

Carbohydrate containing foods are still necessary in the diet to meet energy needs. However, they do not need to be consumed in the same quantity as suggested for endurance athletes.[80] Generally, carbohydrates with low glycaemic indices should be chosen to reduce the risk factors for cardiovascular disease, stroke, and diabetes as observed in women who consume higher glycaemic carbohydrates.[81 82] Low glycaemic carbohydrates are rich in dietary fibre and contain important micronutrients, such as iron and B vitamins. These micronutrients are commonly found to be suboptimal in diets of women athletes[50 72] based on evaluations of self-reported food intake and some biochemical indices of mineral and vitamin status.[52 83–85] Fruits, vegetables, brown rice, enriched whole grain breads, whole grain prepared cereals, rolled oats, beans, legumes, and sweet potatoes are good examples of low glycaemic carbohydrate foods that strength training women should consume.

PROTEIN

Protein recommendations for strength and power athletes have been determined to be 1.4–1.8 g/kg, which is higher than the Recommended Dietary Allowance (RDA) of protein for healthy adults bodyweight.[86] These recommendations are largely derived from studies conducted in men but are probably appropriate for women.[6] Consumption of protein at these levels is within the acceptable macronutrient range for protein (10–35% of total energy intake) as concluded in the most recent Institute of Medicine DRI report.[69]

Although studies are inconsistent with regards to gender differences in protein metabolism,[23] there is some indication that leucine oxidation is greater in men,[87] and women may oxidise less protein during exercise because they derive more of their exercise energy needs from fat.[88 89] Protein oxidation in men during exercise, therefore, seems to contribute more to whole body substrate oxidation.[90]

An area of particular interest in protein nutrition is the concept of timing[91] and the differences that may exist between genders. In contrast to men, women have an attenuated increase in muscle protein fractional synthetic rate when amino acids are provided after exercise,[23] suggesting that women may need to consume more protein after resistance exercise in order to elicit the same anabolic environment. Studies predominately in men indicate that infusion of amino acids or exogenous administration of amino acids after exercise with or without carbohydrate stimulates protein synthesis, and the largest increases are seen when protein is provided before exercise.[19] Also in men, protein supplementation between meals (15 g essential amino acids+30 g carbohydrate) led to a significantly greater protein balance over a 16 h testing period compared to consumption of three nutritionally mixed meals alone.[92] Since the increase in protein synthesis after protein ingestion is transient, consuming frequent doses of high quality protein between meals may provide the ideal anabolic stimulus. Collectively, these studies indicate that in order to create an optimal anabolic environment to help maintain and build lean body mass for strength training women, small amounts of high quality, rapidly digested protein with carbohydrate are important before exercise, after exercise, and between meals.

High protein diets have long been criticised on the basis of deleterious effects on bone due to their greater acid load that requires neutralisation by calcium salts.[93] Women are at increased risk of osteoporosis as they age, so any potential adverse effects on bone health should be avoided. However, the justification to limit protein based on this criticism may not be warranted. Using dual stable calcium isotopes to quantify calcium kinetics in women, Kerstetter *et al*[93] found that a high protein diet did not have any negative effects on net bone balance. Further, a protein supplement (42 g protein, 24 g carbohydrate, 2 g fat) given to young women and men throughout a 6 month strength and conditioning program, increased insulin growth factor-1 and serum bone alkaline phosphatase (indicating increased bone formation) compared to a carbohydrate supplement of equal caloric value.[94] Dietary unprocessed sources of protein contain both calcium and phosphorus and can contribute to increased dietary calcium and phosphorus intake. High protein intake does not appear to have adverse consequences for bone health in females, but rather, may be beneficial.[95] Another criticism of high protein diets is that habitual consumption in excess of recommended intakes promotes chronic renal disease through increased glomerular pressure and hyperfiltration.[96] On the contrary, the effects of high protein diets consumed by healthy humans were recently reviewed and it was concluded that there is insufficient proof to limit protein intake for the purpose of preserving renal health in healthy adults.[97] The Institute of Medicine has also concluded that there is no clear evidence indicating that high protein diets have other deleterious effects including increased risk of cancer or cardiovascular disease.[69] The final most common criticism against high protein diets in relation to strength athletes is that increasing protein intake beyond the recommended level is unlikely to result in additional increases in lean tissue because there is a limit to the rate at which protein tissue can be accrued.[46] The argument against this statement is that even if there is a limit to gains in lean mass with high protein ingestion, increasing evidence shows that dietary substitution of carbohydrate with protein results in a variety of favourable health effects including enhanced weight loss, reduction in truncal adipose tissue, optimal maintenance of blood glucose, and improved lipid profile.[98]

Despite these documented benefits of protein, supplementation, and high protein diets, many women choose to be vegetarians.[72] Vegetarianism limits total protein intake and places women at higher risk of iron deficiency anaemia.[46] Women require iron at higher concentrations than men and iron deficiency anaemia is one of the most prevalent nutrient deficiencies observed in women athletes.[99] Animal proteins provide the most bio-available sources of iron (heme) and thus can help protect women from fatigue, lethargy, and malaise. Women strength athletes should be aware of the importance of animal proteins, as they provide all the essential amino acids and are excellent sources of vitamin B-12 and D, thiamine, riboflavin, calcium, phosphorus, iron, and zinc.[83]

Practically, a variety of high quality animal protein sources, such as lean pork and beef, poultry, fish, eggs, and low fat dairy products, should be consumed daily by strength training women. Given the importance of protein before and after exercise, and between meals for maintenance and promotion of lean muscle growth, it may be prudent to use a protein supplement such as whey or casein.

FAT

Sports nutrition researchers have recently become interested in the physiological and performance effects of high fat diets. This emerging research has focused primarily on endurance exercise, but may be applicable to strength athletes due to the enzymatic and metabolic adaptations achieved with such diets. These enzymatic adaptations are to some extent muscle fibre-type specific and depend on the increase in dietary fat intake. The time course of metabolic adaptations also remains unclear, but at least several weeks are necessary for complete transition to optimal fat utilisation. Animal and human studies have consistently demonstrated that low carbohydrate, high fat diets consumed for more than 7 days decrease muscle glycogen content and carbohydrate oxidation, which is compensated for with markedly increased rates of fat oxidation,[100–103] even in well trained endurance athletes who already demonstrate increased fat oxidation.[101] The source of enhanced fat oxidation appears to be circulating free fatty acids, ketones, and triglyceride derived very low density lipoproteins,[102 104 105] the latter probably resulting from enhanced skeletal muscle lipoprotein lipase activity.[106] As discussed, women seem to rely less on glycogen for resistance exercise than men.[21] Thus, high fat diets may be advantageous for women strength athletes to complement energy production derived from IMTG and circulating lipids while concurrently sparing muscle glycogen.[41]

Despite the importance of adequate dietary fat intake, many women athletes still limit fat consumption and follow extremely low fat diets (<10–15% energy as fat) with the belief that fat may impair exercise performance and increase adiposity.[107] However, in addition to compromising health, low fat diets reduce IMTG stores, and a certain quantity of dietary lipid may be crucial for supplying free fatty acids to exercising muscle. Investigators have demonstrated that women endurance athletes in energy balance need to obtain at least 30% of their energy from dietary fat to ensure rapid replenishment of IMTG following exercise.[107] If fat intake is sub-optimal, there is continued IMTG depletion following exercise for up to 2 days, which may limit performance in subsequent exercise sessions.[108] The same application may hold true for strength athletes.

In addition to serving as an important energy source, adequate fat intake has several other critical functions. Given that many women are at risk of being hypocaloric,[109] fat provides the most energy per gram of all the macronutrients and can help achieve positive energy balance. Dietary fat maintains sex hormone concentrations[79 110] and may prevent menstrual disturbances. If fat intake drops below 15% of energy consumption, there is a high probability that essential fatty acid intake will be low unless the athlete is conscious of food selection. Fat intake greater than 15% of energy from unprocessed sources may help to prevent the female athlete triad as its consumption will help attain energy balance, improve bone health, and avoid depressed sex hormone concentrations.

Dietary unprocessed sources of fat provide mixtures of different fatty acids. For example, fat in lean pork provides equal proportions of monounsaturated and saturated fatty acids, with high quantities of the essential n-6 linoleic acid. The predominant saturated fatty acid in beef fat is stearic acid which is shown to have neutral effects on cardiovascular disease risk.[111] To obtain the correct fatty acid balance, dietary fatty acids should come from sources found naturally in lean protein foods, nuts, seeds, nut butters, fatty fish (for example, salmon and trout), fish oil supplements, flaxseed oil, safflower oil, canola oil, sunflower oil, corn oil, avocados, and egg yolks. These foods can be easily incorporated into the diet by using them as quick snacks (for example, nuts), adding them to other dishes (for example, avocado with pasta, flaxseed oil on salads), and eating them as the major component of meals (for example, salmon for dinner, eggs for breakfast). Ideally, women should avoid all fats found in processed foods due to their highly saturated nature and tendency to be partially or fully hydrogenated. If the foods suggested here are eaten, carbohydrate intake can be reduced, fat metabolism will be enhanced, and IMTG stores will be increased to help support physical activity. Careful choice of fat quality is also necessary to provide fat soluble antioxidants, which may protect against lipid peroxidation that commonly increases after intense resistance exercise.[112]

CREATINE

A large body of scientific literature over the last decade has documented the physiological and performance effects of creatine supplementation. Short term creatine supplementation improves anaerobic performance, and long term creatine supplementation consistently augments strength and lean body mass gains with resistance training.[113] Although the majority of studies have been in men, a significant amount of research indicates women are also responsive to creatine supplementation. Short term creatine supplementation enhanced high intensity exercise performance in women,[114 115] but in contrast to the situation in men, failed to reduce measures of leucine oxidation and plasma leucine rate of appearance.[116] The significance of this latter finding is unknown because other studies have not shown an acute effect of creatine on protein metabolism, suggesting other mechanisms are responsible for the long term effects of creatine on lean body mass.[113] Studies that have examined strength and body composition responses during a resistance training program indicate women respond favourably to creatine supplementation.[117 118]

SUMMARY

The nutritional needs of women engaged in strength training are important and are generally similar to those recommended for men.[7 8] Women in particular should ensure adequate energy is consumed to optimise adaptations to training and improve general health. There are gender differences in exercise metabolism that may justify specific nutritional recommendations for women. These include less emphasis on carbohydrate intake and more attention to protein intake after exercise. In addition, generous consumption of healthy fats from a variety of sources is encouraged to support a positive energy balance, increased use of lipid sources, hormonal balance, and optimal health. Like men, women respond to the favourable effects of creatine supplementation during resistance training.

Authors' affiliations
J S Volek, C E Forsythe, W J Kraemer, Human Performance Laboratory, Department of Kinesiology, University of Connecticut, 2095 Hillside Road, U-1110, Storrs, CT 06269-1110, USA

Competing interests: none declared

What is already known on this topic

- Only two peer review papers specifically address the macronutrient requirements of strength athletes and neither specifically addressed the nutritional needs of women
- Gender differences in substrate use and replenishment have been reported, but nutrient recommendations for women are lacking

What this study adds

- Women should consume less carbohydrates and more protein after exercise than men
- Healthy fats from a variety of sources should be consumed
- Women respond to the favourable effects of creatine supplementation during resistance training

REFERENCES

1 American College of Sports Medicine Position Stand. The recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in healthy adults. *Med Sci Sports Exerc* 1998;**30**:975–91.
2 **Asikainen TM**, Kukkonen-Harjula K, Miilunpalo S. Exercise for health for early postmenopausal women: a systematic review of randomised controlled trials. *Sports Med* 2004;**34**:753–78.
3 **Pollock ML**, Evans WJ. Resistance training for health and disease: introduction. *Med Sci Sports Exerc* 1999;**31**:10–11.
4 **Kraemer WJ**, Mazzetti SA, Nindl BC, *et al*. Effect of resistance training on women's strength/power and occupational performances. *Med Sci Sports Exerc* 2001;**33**:1011–25.
5 **Faigenbaum AD**. Strength training for children and adolescents. *Clin Sports Med* 2000;**19**:593–619.
6 **Manore MM**. Exercise and the Institute of Medicine recommendations for nutrition. *Curr Sports Med Rep* 2005;**4**:193–8.
7 **Volek JS**. Strength nutrition. *Curr Sports Med Rep* 2003;**2**:189–93.
8 **Volek JS**. Influence of nutrition on responses to resistance training. *Med Sci Sports Exerc* 2004;**36**:689–96.
9 **Humphries B**, Newton RU, Bronks R, *et al*. Effect of exercise intensity on bone density, strength, and calcium turnover in older women. *Med Sci Sports Exerc* 2000;**32**:1043–50.
10 **Kraemer WJ**, Volek JS, Clark KL, *et al*. Physiological adaptations to a weight-loss dietary regimen and exercise programs in women. *J Appl Physiol* 1997;**83**:270–9.
11 **Kraemer WJ**, Nindl BC, Ratamess NA, *et al*. Changes in muscle hypertrophy in women with periodized resistance training. *Med Sci Sports Exerc* 2004;**36**:697–708.
12 **Nindl BC**, Harman EA, Marx JO, *et al*. Regional body composition changes in women after 6 months of periodized physical training. *J Appl Physiol* 2000;**88**:2251–9.
13 **Abe T**, DeHoyos DV, Pollock ML, *et al*. Time course for strength and muscle thickness changes following upper and lower body resistance training in men and women. *Eur J Appl Physiol* 2000;**81**:174–80.
14 **Ivey FM**, Roth SM, Ferrell RE, *et al*. Effects of age, gender, and myostatin genotype on the hypertrophic response to heavy resistance strength training. *J Gerontol A Biol Sci Med Sci* 2000;**55**:M641–8.
15 **Staron RS**, Leonardi MJ, Karapondo DL, *et al*. Strength and skeletal muscle adaptations in heavy-resistance-trained women after detraining and retraining. *J Appl Physiol* 1991;**70**:631–40.
16 **Staron RS**, Karapondo DL, Kraemer WJ, *et al*. Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. *J Appl Physiol* 1994;**76**:1247–55.
17 **Deschenes MR**, Kraemer WJ. Performance and physiologic adaptations to resistance training. *Am J Phys Med Rehabil* 2002;**81**:S3–16.
18 **Miller AE**, MacDougall JD, Tarnopolsky MA, *et al*. Gender differences in strength and muscle fiber characteristics. *Eur J Appl Physiol Occup Physiol* 1993;**66**:254–62.
19 **Tipton KD**, Wolfe RR. Protein and amino acids for athletes. *J Sports Sci* 2004;**22**:65–79.
20 **Riddell MC**, Partington SL, Stupka N, *et al*. Substrate utilization during exercise performed with and without glucose ingestion in female and male endurance trained athletes. *Int J Sport Nutr Exerc Metab* 2003;**13**:407–21.

21 **Carter SL**, Rennie C, Tarnopolsky MA. Substrate utilization during endurance exercise in men and women after endurance training. *Am J Physiol Endocrinol Metab* 2001;**280**:E898–907.
22 **Braun B**, Horton T. Endocrine regulation of exercise substrate utilization in women compared to men. *Exerc Sport Sci Rev* 2001;**29**:149–54.
23 **Tipton KD**. Gender differences in protein metabolism. *Curr Opin Clin Nutr Metab Care* 2001;**4**:493–8.
24 **Steffensen CH**, Roepstorff C, Madsen M, *et al.* Myocellular triacylglycerol breakdown in females but not in males during exercise. *Am J Physiol Endocrinol Metab* 2002;**282**:E634–42.
25 **White LJ**, Ferguson MA, McCoy SC, *et al.* Intramyocellular lipid changes in men and women during aerobic exercise: a (1)H-magnetic resonance spectroscopy study. *J Clin Endocrinol Metab* 2003;**88**:5638–43.
26 **Staron RS**, Hagerman FC, Hikida RS, *et al.* Fiber type composition of the vastus lateralis muscle of young men and women. *J Histochem Cytochem* 2000;**48**:623–9.
27 **Hwang JH**, Pan JW, Heydari S, *et al.* Regional differences in intramyocellular lipids in humans observed by in vivo 1H-MR spectroscopic imaging. *J Appl Physiol* 2001;**90**:1267–74.
28 **Tesch PA**, Colliander EB, Kaiser P. Muscle metabolism during intense, heavy-resistance exercise. *Eur J Appl Physiol Occup Physiol* 1986;**55**:362–6.
29 **Pascoe DD**, Costill DL, Fink WJ, *et al.* Glycogen resynthesis in skeletal muscle following resistive exercise. *Med Sci Sports Exerc* 1993;**25**:349–54.
30 **Robergs RA**, Pearson DR, Costill DL, *et al.* Muscle glycogenolysis during differing intensities of weight-resistance exercise. *J Appl Physiol* 1991;**70**:1700–6.
31 **Roy BD**, Tarnopolsky MA. Influence of differing macronutrient intakes on muscle glycogen resynthesis after resistance exercise. *J Appl Physiol* 1998;**84**:890–6.
32 **Tesch PA**. Skeletal muscle glycogen loss evoked by resistance exercise. *J Strength Cond Res* 1998;**12**:67–73.
33 **Essen-Gustavsson B**, Tesch PA. Glycogen and triglyceride utilization in relation to muscle metabolic characteristics in men performing heavy-resistance exercise. *Eur J Appl Physiol Occup Physiol* 1990;**61**:5–10.
34 **Bell DG**, Jacobs I. Muscle fiber-specific glycogen utilization in strength-trained males and females. *Med Sci Sports Exerc* 1989;**21**:649–54.
35 **Esbjornsson-Liljedahl M**, Sundberg CJ, Norman B, *et al.* Metabolic response in type I and type II muscle fibers during a 30-s cycle sprint in men and women. *J Appl Physiol* 1999;**87**:1326–32.
36 **Esbjornsson-Liljedahl M**, Bodin K, Jansson E. Smaller muscle ATP reduction in women than in men by repeated bouts of sprint exercise. *J Appl Physiol* 2002;**93**:1075–83.
37 **Green HJ**, Fraser IG, Ranney DA. Male and female differences in enzyme activities of energy metabolism in vastus lateralis muscle. *J Neurol Sci* 1984;**65**:323–31.
38 **Hatta H**, Atomi Y, Shinohara S, *et al.* The effects of ovarian hormones on glucose and fatty acid oxidation during exercise in female ovariectomized rats. *Horm Metab Res* 1988;**20**:609–11.
39 **Braun WA**, Hawthorne WE, Markofski MM. Acute EPOC response in women to circuit training and treadmill exercise of matched oxygen consumption. *Eur J Appl Physiol* 2005;**94**(5–6):500–4.
40 **Schuenke MD**, Mikat RP, McBride JM. Effect of an acute period of resistance exercise on excess post-exercise oxygen consumption: implications for body mass management. *Eur J Appl Physiol* 2002;**86**:411–17.
41 **Binzen CA**, Swan PD, Manore MM. Postexercise oxygen consumption and substrate use after resistance exercise in women. *Med Sci Sports Exerc* 2001;**33**:932–8.
42 **Chad KE**, Quigley BM. Exercise intensity: effect on postexercise O2 uptake in trained and untrained women. *J Appl Physiol* 1991;**70**:1713–19.
43 **Phelain JF**, Reinke E, Harris MA, *et al.* Postexercise energy expenditure and substrate oxidation in young women resulting from exercise bouts of different intensity. *J Am Coll Nutr* 1997;**16**:140–6.
44 **Brooks GA**, Mercier J. Balance of carbohydrate and lipid utilization during exercise: the ''crossover'' concept. *J Appl Physiol* 1994;**76**:2253–61.
45 **van Loon LJ**. Use of intramuscular triacylglycerol as a substrate source during exercise in humans. *J Appl Physiol* 2004;**97**:1170–87.
46 Position of the American Dietetic Association, Dietitians of Canada, and the American College of Sports Medicine: nutrition and athletic performance. *J Am Diet Assoc* 2000;**100**:1543–56.
47 **Butterfield GE**. Whole-body protein utilization in humans. *Med Sci Sports Exerc* 1987;**19**:S157–65.
48 **Hinton PS**, Sanford TC, Davidson MM, *et al.* Nutrient intakes and dietary behaviors of male and female collegiate athletes. *Int J Sport Nutr Exerc Metab* 2004;**14**:389–405.
49 **Jonnalagadda SS**, Ziegler PJ, Nelson JA. Food preferences, dieting behaviors, and body image perceptions of elite figure skaters. *Int J Sport Nutr Exerc Metab* 2004;**14**:594–606.
50 **Manore MM**. Nutritional needs of the female athlete. *Clin Sports Med* 1999;**18**:549–63.
51 **Burke LM**, Cox GR, Culmmings NK, *et al.* Guidelines for daily carbohydrate intake: do athletes achieve them? *Sports Med* 2001;**31**:267–99.
52 **Beals KA**. Eating behaviors, nutritional status, and menstrual function in elite female adolescent volleyball players. *J Am Diet Assoc* 2002;**102**:1293–6.
53 **Loucks AB**. Energy availability, not body fatness, regulates reproductive function in women. *Exerc Sport Sci Rev* 2003;**31**:144–8.
54 **Deutz RC**, Benardot D, Martin DE, *et al.* Relationship between energy deficits and body composition in elite female gymnasts and runners. *Med Sci Sports Exerc* 2000;**32**:659–68.
55 **Dueck CA**, Manore MM, Matt KS. Role of energy balance in athletic menstrual dysfunction. *Int J Sport Nutr* 1996;**6**:165–90.
56 **Harber VJ**, Petersen SR, Chilibeck PD. Thyroid hormone concentrations and muscle metabolism in amenorrheic and eumenorrheic athletes. *Can J Appl Physiol* 1998;**23**:293–306.
57 **McLean JA**, Barr SI, Prior JC. Dietary restraint, exercise, and bone density in young women: are they related? *Med Sci Sports Exerc* 2001;**33**:1292–6.
58 **Loucks AB**, Verdun M, Heath EM. Low energy availability, not stress of exercise, alters LH pulsatility in exercising women. *J Appl Physiol* 1998;**84**:37–46.
59 **Crommett AD**, Kinzey SJ. Excess postexercise oxygen consumption following acute aerobic and resistance exercise in women who are lean or obese. *J Strength Cond Res* 2004;**18**:410–15.
60 **Melanson EL**, Sharp TA, Seagle HM, *et al.* Twenty-four-hour metabolic responses to resistance exercise in women. *J Strength Cond Res* 2005;**19**:61–6.
61 **Osterberg KL**, Melby CL. Effect of acute resistance exercise on postexercise oxygen consumption and resting metabolic rate in young women. *Int J Sport Nutr Exerc Metab* 2000;**10**:71–81.
62 **Melby C**, Scholl C, Edwards G, *et al.* Effect of acute resistance exercise on postexercise energy expenditure and resting metabolic rate. *J Appl Physiol* 1993;**75**:1847–53.
63 **Lof M**, Hannestad U, Forsum E. Comparison of commonly used procedures, including the doubly-labelled water technique, in the estimation of total energy expenditure of women with special reference to the significance of body fatness. *Br J Nutr* 2003;**90**:961–8.
64 **Kien CL**, Ugrasbul F. Prediction of daily energy expenditure during a feeding trial using measurements of resting energy expenditure, fat-free mass, or Harris-Benedict equations. *Am J Clin Nutr* 2004;**80**:876–80.
65 **Lof M**, Forsum E. Validation of energy intake by dietary recall against different methods to assess energy expenditure. *J Hum Nutr Diet* 2004;**17**:471–80.
66 **Frankenfield DC**, Rowe WA, Smith JS, *et al.* Validation of several established equations for resting metabolic rate in obese and nonobese people. *J Am Diet Assoc* 2003;**103**:1152–9.
67 **Garrel DR**, Jobin N, de Jonge LH. Should we still use the Harris and Benedict equations? *Nutr Clin Pract* 1996;**11**:99–103.
68 **Siervo M**, Boschi V, Falconi C. Which REE prediction equation should we use in normal-weight, overweight and obese women? *Clin Nutr* 2003;**22**:193–204.
69 **Trumbo P**, Schlicker S, Yates AA, *et al.* Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein and amino acids. *J Am Diet Assoc* 2002;**102**:1621–30.
70 **Ainsworth BE**, Haskell WL, Leon AS, *et al.* Compendium of physical activities: classification of energy costs of human physical activities. *Med Sci Sports Exerc* 1993;**25**:71–80.
71 **Manore MM**, Thompson J, Russo M. Diet and exercise strategies of a world-class bodybuilder. *Int J Sport Nutr* 1993;**3**:76–86.
72 **Manore MM**. Dietary recommendations and athletic menstrual dysfunction. *Sports Med* 2002;**32**:887–901.
73 **Meijer GA**, Westerterp KR, Saris WH, *et al.* Sleeping metabolic rate in relation to body composition and the menstrual cycle. *Am J Clin Nutr* 1992;**55**:637–40.
74 **Bergstrom J**, Hermansen L, Hultman E, *et al.* Diet, muscle glycogen and physical performance. *Acta Physiol Scand* 1967;**71**:140–50.
75 **Sherman WM**, Costill DL, Fink WJ, *et al.* Effect of exercise-diet manipulation on muscle glycogen and its subsequent utilization during performance. *Int J Sports Med* 1981;**2**:114–18.
76 **Tarnopolsky MA**, Atkinson SA, Phillips SM, *et al.* Carbohydrate loading and metabolism during exercise in men and women. *J Appl Physiol* 1995;**78**:1360–8.
77 **Tarnopolsky MA**, Zawada C, Richmond LB, *et al.* Gender differences in carbohydrate loading are related to energy intake. *J Appl Physiol* 2001;**91**:225–30.
78 **Tarnopolsky MA**, Ruby BC. Sex differences in carbohydrate metabolism. *Curr Opin Clin Nutr Metab Care* 2001;**4**:521–6.
79 **Volek JS**, Sharman MJ. Diet and hormonal responses: potential impact on body composition. In: Kraemer WJ, Rogol AD, eds. *The endocrine system in sports and exercise.* Oxford: Blackwell Publishing, 2005:426–43.
80 **Burke LM**, Kiens B, Ivy JL. Carbohydrates and fat for training and recovery. *J Sports Sci* 2004;**22**:15–30.
81 **Brynes AE**, Adamson J, Dornhorst A, *et al.* The beneficial effect of a diet with low glycaemic index on 24 h glucose profiles in healthy young people as assessed by continuous glucose monitoring. *Br J Nutr* 2005;**93**:179–82.
82 **Oh K**, Hu FB, Cho E, *et al.* Carbohydrate intake, glycemic index, glycemic load, and dietary fiber in relation to risk of stroke in women. *Am J Epidemiol* 2005;**161**:161–9.
83 **Manore MM**. Effect of physical activity on thiamine, riboflavin, and vitamin B-6 requirements. *Am J Clin Nutr* 2000;**72**:598S–606S.
84 **Mullins VA**, Houtkooper LB, Howell WH, *et al.* Nutritional status of U.S. elite female heptathletes during training. *Int J Sport Nutr Exerc Metab* 2001;**11**:299–314.
85 **Rokitzki L**, Sagredos AN, Reuss F, *et al.* Assessment of vitamin B6 status of strength and speedpower athletes. *J Am Coll Nutr* 1994;**13**:87–94.
86 **Lemon PW**. Is increased dietary protein necessary or beneficial for individuals with a physically active lifestyle? *Nutr Rev* 1996;**54**:S169–75.
87 **Lamont LS**, McCullough AJ, Kalhan SC. Gender differences in leucine, but not lysine, kinetics. *J Appl Physiol* 2001;**91**:357–62.
88 **Roepstorff C**, Steffensen CH, Madsen M, *et al.* Gender differences in substrate utilization during submaximal exercise in endurance-trained subjects. *Am J Physiol Endocrinol Metab* 2002;**282**:E435–47.
89 **Lamont LS**, McCullough AJ, Kalhan SC. Gender differences in the regulation of amino acid metabolism. *J Appl Physiol* 2003;**95**:1259–65.

90 **Phillips SM**, Atkinson SA, Tarnopolsky MA, *et al.* Gender differences in leucine kinetics and nitrogen balance in endurance athletes. *J Appl Physiol* 1993;**75**:2134–41.
91 **Tipton KD**, Rasmussen BB, Miller SL, *et al.* Timing of amino acid-carbohydrate ingestion alters anabolic response of muscle to resistance exercise. *Am J Physiol Endocrinol Metab* 2001;**281**:E197–206.
92 **Paddon-Jones D**, Sheffield-Moore M, Aarsland A, *et al.* Exogenous amino acids stimulate human muscle anabolism without interfering with the response to mixed meal ingestion. *Am J Physiol Endocrinol Metab* 2005;**288**:E761–7.
93 **Kerstetter JE**, O'Brien KO, Caseria DM, *et al.* The impact of dietary protein on calcium absorption and kinetic measures of bone turnover in women. *J Clin Endocrinol Metab* 2005;**90**:26–31.
94 **Ballard TL**, Clapper JA, Specker BL, *et al.* Effect of protein supplementation during a 6-mo strength and conditioning program on insulin-like growth factor I and markers of bone turnover in young adults. *Am J Clin Nutr* 2005;**81**:1442–8.
95 **Devine A**, Dick IM, Islam AF, *et al.* Protein consumption is an important predictor of lower limb bone mass in elderly women. *Am J Clin Nutr* 2005;**81**:1423–8.
96 **Metges CC**, Barth CA. Metabolic consequences of a high dietary-protein intake in adulthood: assessment of the available evidence. *J Nutr* 2000;**130**:886–9.
97 **Martin WF**, Armstrong LE, Rodriguez NR. Dietary protein intake and renal function. *Nutr Metab (Lond)* 2005;**2**:25.
98 **Layman DK**. Protein quantity and quality at levels above the RDA improves adult weight loss. *J Am Coll Nutr* 2004;**23**:631S–636S.
99 **Beard J**, Tobin B. Iron status and exercise. *Am J Clin Nutr* 2000;**72**:594S–597S.
100 **Goedecke JH**, Elmer-English R, Dennis SC, *et al.* Effects of medium-chain triaclyglycerol ingested with carbohydrate on metabolism and exercise performance. *Int J Sport Nutr* 1999;**9**:35–47.
101 **Lambert EV**, Speechly DP, Dennis SC, *et al.* Enhanced endurance in trained cyclists during moderate intensity exercise following 2 weeks adaptation to a high fat diet. *Eur J Appl Physiol Occup Physiol* 1994;**69**:287–93.
102 **Phinney SD**, Bistrian BR, Evans WJ, *et al.* The human metabolic response to chronic ketosis without caloric restriction: preservation of submaximal exercise capability with reduced carbohydrate oxidation. *Metabolism* 1983;**32**:769–76.
103 **Rowlands DS**, Hopkins WG. Effects of high-fat and high-carbohydrate diets on metabolism and performance in cycling. *Metabolism* 2002;**51**:678–90.
104 **Helge JW**, Watt PW, Richter EA, *et al.* Fat utilization during exercise: adaptation to a fat-rich diet increases utilization of plasma fatty acids and very low density lipoprotein-triacylglycerol in humans. *J Physiol* 2001;**537**:1009–20.
105 **Schrauwen P**, Wagenmakers AJ, Marken Lichtenbelt WD, *et al.* Increase in fat oxidation on a high-fat diet is accompanied by an increase in triglyceride-derived fatty acid oxidation. *Diabetes* 2000;**49**:640–6.
106 **Kiens B**, Essen-Gustavsson B, Gad P, *et al.* Lipoprotein lipase activity and intramuscular triglyceride stores after long-term high-fat and high-carbohydrate diets in physically trained men. *Clin Physiol* 1987;**7**:1–9.
107 **Larson-Meyer DE**, Newcomer BR, Hunter GR. Influence of endurance running and recovery diet on intramyocellular lipid content in women: a 1H NMR study. *Am J Physiol Endocrinol Metab* 2002;**282**:E95–106.
108 **Decombaz J**, Fleith M, Hoppeler H, *et al.* Effect of diet on the replenishment of intramyocellular lipids after exercise. *Eur J Nutr* 2000;**39**:244–7.
109 **Burke LM**. Nutritional practices of male and female endurance cyclists. *Sports Med* 2001;**31**:521–32.
110 **Dorgan JF**, Reichman ME, Judd JT, *et al.* Relation of energy, fat, and fiber intakes to plasma concentrations of estrogens and androgens in premenopausal women. *Am J Clin Nutr* 1996;**64**:25–31.
111 **Yu S**, Derr J, Etherton TD, *et al.* Plasma cholesterol-predictive equations demonstrate that stearic acid is neutral and monounsaturated fatty acids are hypocholesterolemic. *Am J Clin Nutr* 1995;**61**:1129–39.
112 **Ramel A**, Wagner KH, Elmadfa I. Plasma antioxidants and lipid oxidation after submaximal resistance exercise in men. *Eur J Nutr* 2004;**43**:2–6.
113 **Volek JS**, Rawson ES. Scientific basis and practical aspects of creatine supplementation for athletes. *Nutrition* 2004;**20**:609–14.
114 **Eckerson JM**, Stout JR, Moore GA, *et al.* Effect of two and five days of creatine loading on anaerobic working capacity in women. *J Strength Cond Res* 2004;**18**:168–73.
115 **Tarnopolsky MA**, MacLennan DP. Creatine monohydrate supplementation enhances high-intensity exercise performance in males and females. *Int J Sport Nutr Exerc Metab* 2000;**10**:452–63.
116 **Parise G**, Mihic S, MacLennan D, *et al.* Effects of acute creatine monohydrate supplementation on leucine kinetics and mixed-muscle protein synthesis. *J Appl Physiol* 2001;**91**:1041–7.
117 **Brenner M**, Walberg-Rankin J, Sebolt D. The effect of creatine supplementation during resistance training in women. *J Strength Cond Res* 2000;**14**:207–13.
118 **Vandenberghe K**, Goris M, Van Hecke P, *et al.* Long-term creatine intake is beneficial to muscle performance during resistance training. *J Appl Physiol* 1997;**83**:2055–63.