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National Strength and Conditioning Association Position Statement on Strength and Conditioning of Female Athletes. Part II: Training Adaptations and Program Design

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Abstract

Dabbs, NC, Binkley, H, Bott, C, Fragala, MS, Herda, A, Moeskops, S, Moore, EWG, Smith-Ryan, A, and Triplett, NT. National Strength and Conditioning Association position statement on strength and conditioning of female athletes. Part II: Training adaptations and program design. *J Strength Cond Res* 40(8): 895–908, 2026 In preparing for competition, athletes and their coaches design and implement strength and conditioning regimens to maximize athletic performance. Males and females exhibit sex-specific physiological differences that may result in different needs, rates, or magnitudes of adaptation when implementing strength and conditioning programs. Yet, it should be clear that the basic principles of strength and conditioning remain relevant for all humans (e.g., progressive overload). Despite understanding the similar responses to strength and conditioning programs as male athletes, the provision, resourcing, consistency, and delivery of these programs is still restricted in many ways and fundamentally limits the actual potential of female athletes that is often incorrectly attributed to their biology. The purpose of Part II of this Position Statement is to update the original Position Statement that focused on resistance training of female athletes to be more comprehensive of strength and conditioning practice and to provide a deeper examination of physiology research relevant to the female athlete. Therefore, the Position Statement Part II is separated into four sections: (a) neuroendocrine responses and adaptations, (b) neuromuscular adaptions, (c) metabolic adaptations and, (d) program design.

Key Words: women, sports, adaptation, performance, resistance training, coaching, training

Introduction

As described in part I of the two-part position statement on female athletes, often sex and gender effects may be partially intertwined (122,194) and could influence the measurements in the literature that strength and conditioning professionals are using in practice. Therefore, this position statement on female athletes will use evidence from research that describes women by gender or female athletes by sex and collectively review as if all subjects are female as assigned by birth. Further, the population should be at least tier 2 or above as outlined in the operational terms to be considered evidence most appropriate to inform strength and conditioning for female athletes. A summary of evidence in Table 1 demonstrates the body of literature on training adaptations and program design that overwhelmingly supports that topics presented in more detail throughout the paper.

Participation by women and girls in sport has significantly increased since the original position statement in 1989. The increase in participation in sport at all levels both in the United States (171) and globally (176) has been influenced by several factors, including the civil rights law, Title IX (171).

Publications indicate a recent rise on topics related to or researching female athletes (127). However, research with female subjects within exercise science, sports science, and sports medicine remains limited with far greater amounts of research examining or isolating male subjects (24,136,165). Authors must highlight the fact that the quantity of high-quality research on female subjects is lacking and more scarce when further delimiting the population studied to female athletes (36,51) and even less information on highly trained female athletes. Therefore, the purpose of part II of the position statement is to focus on the foundations of biological sex differences for training adaptions and program design to *provide comprehensive recommendations related to practices in strength and conditioning when training female athletes.*

Neuroendocrine Response & Adaptations

The neuroendocrine system is largely responsible for regulating physiological adaptations including muscle cellular growth and development in response to strength training and conditioning in female athletes. Fluctuations of hormones across a normal menstrual cycle impact several physiological outcomes including inflammation, fatigue, sleep, and fuel utilization. It is important to understand the implications of these natural changes across a eumenorrheic cycle, as symptoms may impact training quality and performance. Hormonal contraceptive use among female athletes is common. With athletic performance as a primary consideration, female athletes may have an individual and varied effect of hormonal contraceptive on performance and training outcomes.

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Operational Terms

The following definitions are provided to establish context of the current evidence that was evaluated for this position statement.

- *Athlete:* participates in an official sports competition and engages in regular technical and tactical training for that competition (103).
- *Sex:* "a multidimensional construct based on a cluster of anatomical and physiological traits that include external genitalia, secondary sex characteristics, gonads, chromosomes, and hormones" (7). Classifications of sex are typically male, female, or intersex (also referred to as differences in sex development (DSD) and typically defined at birth).
- *Gender:* "a multidimensional construct that links gender identity (e.g., female, woman, girl), which is a core element of a person's individual identity; gender expression (e.g., feminine), which is how a person signals their gender to others through their behavior and appearance (such as hair style and clothing); and cultural expectations about social status, characteristics, and behavior that are associated with sex traits" (7).
- *Participant Classification Framework:* classification of individual participants in studies featuring exercise/training and/or sport performance outcomes. Tier 2 athletes regularly train about three times per week and train with a purpose to compete. Research conducted on female athletes tier 2 and above has been used whenever possible, thus guiding the scope of this position statement (102).

In response to strength training and conditioning, the neuroendocrine system is largely responsible for regulating physiological adaptations including muscle cellular growth and development (44,82). Integrated anabolic and catabolic mechanisms triggered by neuroendocrine signals impact the ability of skeletal muscle to adapt to training and generate force (82). Processes including hormone production, release, transportation, tissue uptake, and intracellular signaling affect the mechanisms and communication that govern cellular actions (82). It is the acute hormonal response to each workout or training session that drives muscle tissue growth and remodeling more so than chronic changes in resting hormonal concentrations in athletes (81). Sex-differences in the acute hormonal response to strength and conditioning sessions account for sex differences in muscle hypertrophy and strength adaptations in female athletes as compared with male athletes (135).

Among dozens of known hormones associated with human endocrine glands, research in athletic females has focused primarily on a few. Studies show that in contrast to male athletes who demonstrate elevations in anabolic hormones (testosterone, the superfamily of growth hormones [GHs], and insulin-like growth factor-1 [IGF-1]) in response to acute resistance exercise (81,82), female athletes experience stimulation of myofibrillar protein synthesis with low systemic testosterone concentrations (192). When an adequate stimulus is present, female athletes rely mostly on GHs for stimulating muscle protein synthesis, growth, and remodeling (81). The female hormone, estradiol, also appears to have an important effect on skeletal muscle structure and function in female athletes (17).

Androgens

In women, androgens are produced by the ovaries and adrenal glands (37). Despite the anabolic role of androgens (mostly testosterone) in men, little to no elevations in circulating testosterone are observed in response to acute resistance training in female athletes (82,188). However, with prolonged training, some acute elevations in testosterone have been observed in female athletes (129). Increases may be because of decreased degradation rate, as elite female athletes have shown lower urinary concentrations of steroid metabolites (33). Yet, among female athletes, large variability in serum testosterone concentrations exist, which can contribute to differences in muscle hypertrophy and strength development (53). In women, testosterone may have a role in muscular power, hypertrophy, and strength development during training and serve as an important indicator of the trainability of an individual (53,54).

In addition to circulating concentrations of testosterone, androgen receptors within skeletal muscle mediate adaptive responses in both male and female athletes (57,188). Differences in training-induced muscle hypertrophy appear related to both androgen receptor content and nuclear localization (57). Differences also appear in androgen receptor activity where resting androgen receptor phosphorylation differs between male and female athletes (125). Although men have higher baseline androgen receptor protein content than women, women appear to have greater androgen receptor phosphorylation at rest, unless phosphorylation is normalized to AR content (125). Differences imply that androgen receptor activity may be augmented independent of ligand levels in women (because of phosphorylation) with implications for muscle adaptations observed after resistance or endurance training (125).

Growth Hormones

Growth hormone (GH) is also an important hormone, which affects muscular adaptations to training in women, including

Table 1

Position statements on training adaptations and program design in female athletes.

Topic	Position statements
Program design	Using the research conducted on the analysis of the male version of the sport or comparing male and female athletes of dissimilar training backgrounds may mislead the practitioner (63,64,91,147). Programs should, therefore, be designed based primarily on a needs analysis of the athlete and the demands of the sport. Female athletes should be treated as individuals with respect to dosing tolerance, which highlights the importance of a rigorous monitoring system (64,89,109,145,159,184)
Program design and menstrual cycle	It is common (>65%) for female athletes to experience menstrual cycle–related symptoms across their menstrual cycle. Although research continues to expand in this area, it is important to consider the varying symptomology that can affect female athlete training readiness, sleep quality, and recovery status. Tracking menstrual cycle characteristics is important to optimize individual training and recovery (20,35,106,108,110)

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Table 2
Future research considerations.

Topic	Considerations
Program design	Cross-sectional longitudinal studies on female athletes are needed regarding resistance training, endurance training, and speed and agility training in specific sport athletes. It is critical in research and practice to compare training level and age to guide training prescription versus the typical comparison with a male counterpart Future research involving plyometric drills should provide videos, images, and technical models with movement amplitude or ground-contact times, to better understand the approach and to replicate in future research and training

muscle protein synthesis and repair. Although most research has measured the 22 kDa form, GH exists as a family of isoforms and fragments (26,65,141). Muscle protein synthesis is triggered from GH via hepatic production of IGF-1 and the Akt-mTOR signaling pathway. Although, resting concentrations of GH are higher in female athletes than in male athletes (80), with chronic training, resting concentrations of GH can be lower in female athletes compared with male athletes (175).

In response to resistance exercise training, circulating GH rises similarly in female and male athletes. After acute resistance exercise in female athletes, circulating GH concentrations increase two- to fourfold (52,66). The magnitude of the circulating GH increase is dependent upon the exercise stimulus and amount of total work performed. Exercise-induced increases in GH in female athletes are greater in training sessions consisting of high total work (10 RM load) and shorter rest intervals (1 minute) (80), using large muscle groups (82), multiset protocols (120), and when exercises correspond with rises in blood lactate and reductions in blood glucose (78,82). The magnitude of the exercise-induced rise in GH increases with training (175).

Estradiol

Although previously unrecognized for its role in adaptations to training, the female hormone estradiol (predominantly estrogen) is a major contributor to the sexual dimorphism in skeletal muscle mass and function (105). Estradiol has been shown to directly impact the structure and function of muscle, tendon, and ligaments and contribute to muscle mass and strength (17). In contrast to the anabolic actions of testosterone in men, estradiol appears to have a more protective effect on skeletal muscle (92). In its protective role against muscle damage, estradiol may decrease postexercise membrane disruption, act as an antioxidant, act as a membrane stabilizer, mediate inflammatory cell infiltration, and attenuate exercise-induced increases in heat shock proteins (39,133). Thus, in conditions of low estrogen (such as amenorrhea), vulnerability to injury may be possible (177). Yet the relationship between estrogen status and injury is complex and multifactorial involving postural stability, neurophysiological or visuospatial abilities, psychological state (anxiety), and tissue mechanical properties (29).

In addition, estradiol may influence contractile properties of skeletal muscle and muscle protein turnover (55). Estradiol influences the sensitivity of muscle to anabolic signaling (17,55) and stimulates muscle repair and regeneration through proliferation of satellite cells (39). Its effect supports muscle mass development by lowering protein turnover and enhancing sensitivity to resistance training (55,56). Estrogen appears to increase collagen synthesis but decrease stiffness through lysyl oxidase inhibition and decreased cross-linking (17). When estrogen levels are high, decreases in power and performance can result, and increasing the risk for ligament injuries among female athletes (17). In contrast, deficiencies in estradiol often seen with amenorrhea and aging, may also lead to increased apoptosis and reduced skeletal muscle mass and strength (21,73). Yet, taken together, in eumenorrheic women, the periodic rise of estrogen monthly before ovulation may offer long-term reparative benefits in muscle and tendon in response to training contributing to muscle, tendon, and bone strength over time (17).

After resistance exercise, acute increases in circulating estrogen have been reported, especially when female athletes are in a hypocaloric state (81,153). Increases in estrogen in response to resistance exercise may occur via increased activity of the aromatase enzyme (123), which may also contribute to increases in circulating testosterone (93). Because of the beneficial effects of estrogen on muscle, competitive female athletes may benefit from normal menstrual cycling to maximize their adaptations to training during the offseason or in the base phase of their training (17).

Cortisol

The secretion rhythm of cortisol changes over the course of the week and according to competitive demands in professional female athletes (153). Cortisol rises in anticipation to exercise and sports competition to prepare female athletes for the upcoming psychological and metabolic demands (114,185). In female athletes, the training appears to promote a stress-related response in cortisol that can be observed before anticipated, nonspecific stressors (31). Resistance exercise protocols that cause increases in circulating GH (79) and blood lactate, and reductions in blood glucose (78), also result in increased circulating cortisol in female athletes. Yet, in comparison with male athletes, the cortisol response to acute exercise is attenuated in female athletes (45,52,185). This may be because of higher glucocorticoid sensitivity in female athletes (149) or the impact of female sex hormones on modulating activity of the sympathetic nervous system, adrenal glands, and HPA axis (185).

Training influences the magnitude of the cortisol response in female athletes. For example, elite female athletes have shown a lack in anticipatory rise in cortisol before exercise (31) but then exhibit higher cortisol secretion and different patterns of secretion (153). This is possibly because of training and adaptation (31,119), differences in appraisal of the stress of sport competition (185), or attenuation of the sympathoadrenal and HPA responsiveness by female sex hormones (185). Female sex hormones (estradiol and progesterone) may lower cortisol responsivity, thereby potentially altering the effects of cortisol over the menstrual cycle (96). It is also possible that changes in glucocorticoid receptor sensitivity are altered. Sensitivity to cortisol and catabolic, muscle sparing, or pathological influence is largely determined by circadian patterning and newly discovered variants of glucocorticoid isoforms (82). In addition, immune factors and proinflammatory cytokines modulate glucocorticoid sensitivity (45), accounting for differences observed in female athletes.

Hormonal Contraception

Hormonal contraceptive use is reported by about half of elite female athletes across 24 sports (100,119). The prevalence of hormonal contraceptive use in elite female athletes ranges from 50

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to 70%, depending on the country, sport, and athletic level (38,119,130). Studies from Denmark and Norway have shown higher use where hormonal contraceptives were used by 57% of elite female athletes in Denmark (Oxfeldt, 2020) and 68% of elite female cross-country skiers and biathletes in Norway (38). Combined oral contraceptives (OCs) are most commonly used (68.1%), with 30.0% using progestin-only contraceptives (implant = 13.1%, injection = 3.7%, and intrauterine system = 2.8%) (100). Combination OCs are the most commonly prescribed type of OC and are found in two different dosage varieties: monophasic and triphasic. Monophasic OC is the prevailing dosage type, characterized by consistent amounts of ethinyl estradiol and progestin throughout the month. Triphasic OCs are distinguished by a consistent dosage of ethinyl estradiol, whereas the synthetic progestin is delivered in low, moderate, and high amount over 3 weeks, attempting to mimic the gradual onset of progesterone seen in a eumenorrheic menstrual cycle. Elite athletes often choose to use hormonal contraceptives for perceived positive benefits including the ability to predict and/or manipulate the timing, frequency, and amount of menstrual bleeding (100). Most (77.4%) elite female athletes not using hormonal contraceptives report negative side effects during their menstrual cycle (primarily during days 1–2 of menstruation) (100). Thus, the perception and/or experience of attenuating negative side effects of the menstrual cycle may lead to the choice for female athletes to use hormonal contraceptive.

Hormonal contraceptive use may impact sports performance outcomes including measures of strength, hypertrophy, and recovery (muscle damage). Although some research has shown a positive influence of oral contraceptive use, other research has shown delayed recovery and higher levels of markers of muscle damage (see review) (178). Regarding performance across several team sports including soccer, handball, and volleyball, eumenorrheic high level female athletes and those using hormonal contraceptives performed similarly in strength and power (maximal voluntary isometric grip strength; 20-m sprint F; countermovement jump; and leg press) (25). Yet a meta-analysis across 42 studies with 590 subjects reported a trivial performance disadvantage in hormonal contraceptive uses compared with naturally menstruating female athletes (35). Taken together with athletic performance in mind, it may be most suitable for female athletes to follow an individualized choice when determining if hormonal contraceptives are appropriate.

Hormonal contraceptives may also influence muscle hypertrophy and strength by impacting androgenicity in female athletes (178). Hormonal contraceptive use reduces levels of androgens, especially testosterone, by inhibiting ovarian and adrenal androgen synthesis and by increasing levels of sex hormone–binding globulin (197). Moreover, hormonal contraceptive use impacts the excreted steroid hormone profile in female athletes where users excreted 40% less epitestosterone as compared to nonusers (156). This has implications for interpreting drug tests for female athletes, with hormonal contraceptive users demonstrating significantly greater testosterone/estrogen ratios (156,190). Use of hormonal contraception should be noted for all female drug tested athletes.

Neuromuscular Adaptations

Neural adaptations (both central and neural) are the foundation to speed, power, muscular development, endurance, and capacity to the adaptations established within the athlete. Despite the lack of female athlete–specific data in this area, an overview of the patterns that have been observed thus far are provided. The exercise stimulus/mode is the primary determinant of the recruited musculature. Aerobic training leads to adaptations within skeletal muscle that support increases in exercise capacity and performance in female athletes. Strength training combined with endurance training may further improve performance. Strength training of sufficient volume, intensity, and frequency leads to adaptations within skeletal muscle resulting in increased muscular strength and performance in female athletes.

Motor Unit Recruitment

Overall, there are few known neuromuscular differences between men and women relative to resistance training, as Roberts et al. extensively present (147). Neural adaptations often occur within weeks of commencing a regular exercise routine and before structural changes in untrained individuals. These primarily stem from central adaptations where the primary motor cortex is stimulated by movement demand. With repeated demand (training), the motor cortex and descending tracks become more efficient over time. The activation of alpha motor neurons initiates the contraction, but in novice athletes, afferent neurons are also very active as a protective mechanism, for example, through Golgi tendon organs (160). Over time and repetition, the afferent activity decreases and the alpha motor neurons predominate to elicit muscular adaptations to the activity demand. However, athletes and those experienced in athletic activity can continue to develop complex neural communication strategies among the neuromusculoskeletal systems (160). Percent motor unit activation, for example, is fairly low (60–70%) in untrained individuals, whereas it is much greater in trained individuals, upward of 90% (124,195). Even among endurance athletes across sex, reduced sympathetic nervous system activity is a result of high-level and consistent exercise, resulting in reduced systemic stress (lower-blood pressure, improved stroke volume, etc.) (14), with no sex-dependent differences present. Any subtle differences that do exist are often neuroendocrine driven and are presented in section six.

In response to resistance training, female athletes in general display differing adaptations to muscle cross-sectional area in their upper vs. lower body, in the upper body for female athletes (62). Judge et al. (72) reported neural drive for muscular activation is enhanced in female athletes after resistance training, resulting in improvements of 15% in maximal voluntary isometric contractions and 24% in rapid isometric contractions. Likewise, patterns of enhanced muscular activation amplitude are replicable after plyometric exercise training as Chimera et al. demonstrated by 6 weeks of plyometric training enhanced coactivation of synergistic muscles during a jump task in female athletes (18). Female athletes have been reported to have a greater proportion of low-threshold motor units, reflective of the percentage of type I fibers (168,170), which may also contribute to females' greater fatigue resistance (61). Yet any shift in fiber type distribution is dependent on sport or activity demands; for example, high-intensity resistance exercise enhances high-threshold motor unit and type II fiber activation, prolonged endurance activities improve low-threshold motor unit and type I fiber activation, and repeated sprint training stimulates all repeatedly. Motor unit firing rate decreases in female athletes with age, as Piasecki et al. reported a reduction from young to middle age to master athletes (44–83 years), while maintaining a high level of

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performance (140). Further, female athletes maintain a high resistance to fatigue throughout prolonged activities and contractions compared with male athletes, yet it is believed that this is because of a metabolic limitation induced by hypoxia, limited oxygen perfusion, and vascular constriction in male athletes but not in female athletes (150). Overall, any apparent sex-related differences in motor unit recruitment patterns documented before and after training adaptations are limited in conclusive and definitive responses because of the limited body of literature in female athletes, with a greater disproportion of female athlete evidence to support these patterns of adaptation. Lulic-Kuryllo and Inglis indicated that there are very few studies that included primarily female subjects and caution drawing conclusions because of the limited total sample available yet provide a thorough review of the existing data (94).

Muscular Adaptations-Aerobic

Endurance training leads to adaptations in both the cardiovascular and musculoskeletal system that support increases in exercise capacity and performance. Within skeletal muscle, aerobic adaptations to exercise training enable increased endurance capacity and performance via more efficient oxygen delivery and utilization (42). Mitochondrial oxidative capacity of type I skeletal muscle fibers, increased capillarization, and myoglobin concentrations (transporter of oxygen within skeletal muscle fibers) facilitate improvements in oxygen delivery and utilization for endurance performance (184). Despite similar mechanisms of adaptations to exercise, sex-based differences exist in some underlying mechanisms of aerobic adaptations (12,84), including muscle gene expression (84), mechanisms of oxygen delivery where male athletes exhibit higher respiratory exchange ratio (146), and substrate metabolism where female athletes have lower carbohydrate oxidation (95).

Vascular adaptations and muscle capillary density facilitate oxygen delivery to skeletal muscle for sustained endurance performance. New capillaries grow in the muscle to accommodate increased cardiac output and blood flow in response to endurance training. Although skeletal muscle capillary density is related to aerobic capacity in male athletes (146), in female athletes, other mechanisms appear more important for endurance performance (146). Female athletes have smaller cardiac volume, wall thickness (6), and fewer vascular adaptations (5) than male athletes. Female athletes also have lower vasoconstriction, vascular resistance (6), and arterio-venous oxygen difference (6).

Although oxygen delivery mechanisms appear blunted, female athletes appear to compensate via mitochondrial adaptations within skeletal muscle. With endurance training, increases in the number, size, density, and efficiency of the mitochondria occur to increase endurance capacity and performance. Female athletes have higher mitochondrial oxidative function, intrinsic mitochondrial respiration, and mitochondrial oxygen affinity (p50mito) than male athletes (12), which may compensate for the lower oxygen delivery during exercise (12). Yet, myoglobin content appears similar in male athletes and female athletes (115), indicating similar oxygen delivery capacity within the skeletal muscle.

Female athletes also have differences in substrate metabolism, as compared to male athletes (95), where female athletes rely less on carbohydrates and more on lipids for fuel during sustained exercise (29,95). Sex-based differences in substrate metabolism are because of differences in muscle substrate availability and fiber type distribution, with possible regulation by estradiol and adipokines (adiponectin and leptin) (95). Female athletes also have greater content and closer contact of intramyocellular lipids with mitochondria to accommodate greater lipid metabolism (29). With training, peroxisome proliferator-activated receptor γ coactivator 1α (PGC-1α), a transcription factor, that regulates lipid metabolism via the tricarboxylic acid cycle and the mitochondrial fatty acid oxidation pathway increases (15), contributing to mitochondrial and metabolic adaptations to endurance training. In female athletes, lipid metabolism during exercise is facilitated by greater abundance of the fatty acid transporter CD36 and inhibition of malonyl-CoA to facilitate lipid metabolism during exercise (43,113). Female athletes also have lower metabolic sensitivity to ADP (43,113), which may hinder energy metabolism for performance but serve as a protective mechanism against fatigue.

Sex-based differences in aerobic adaptations to exercise have implications for training program design to improve mitochondrial oxidative delivery and capacity. With the same training program, female athletes may show greater relative improvements in aerobic fitness and strength than male athletes, but male athletes start and finish with higher levels of performance (184). Thus, carefully designed training programs in terms of intensity, frequency, duration, and periodization facilitate adaptations that improve endurance performance (184). Resulting local adaptations in skeletal muscle, such as increased mitochondrial biogenesis and capillary density, aid in the body's ability to transport and use oxygen to generate energy and, therefore, delay the onset of muscle fatigue during prolonged aerobic performance (71). Moreover, endurance performance is improved in female endurance athletes who add heavy strength training to their normal endurance training (75), without impairing adaptations in the ability to develop force at low contraction velocities or muscle hypertrophy (186). However, concurrent training may attenuate strength training–associated changes in the ability to develop force at higher muscular contraction velocities (186). Yet, without adequate recovery, endurance athletes may experience intolerance to training because of skeletal muscle disruptions including fiber size variation, internal nuclei, and z-disc streaming.

Muscular Adaptations-Anaerobic

Sports training and conditioning elicits mechanical and physiological mechanisms leading to chronic adaptations in muscular strength, power, hypertrophy, and performance. Similar to male athletes, adaptations to short-term training in female athletes are primarily neuromuscular (54) and increased voluntary activation of the trained muscles (53). Neural adaptations to training involve both improved intra- and intermuscular coordination and disinhibition of inhibitory mechanisms. Increases in intramuscular coordination (recruitment and rate coding) contribute to muscular increases in force production, which can be transferred to sport-specific performance. Despite early research showing neural mechanisms primarily account for neuromuscular adaptations early on in training programs, further neural adaptations remain feasible with the right training program and stimulus (16).

Characteristics of the contractile structures of skeletal muscle influence adaptations to training, force generation, fatiguability, and energy metabolism in sport (1). Resistance training elicits large improvements in muscular strength and hypertrophy

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dependent on volume and frequency of training in female athletes (51). Skeletal muscles of elite female athletes are highly adaptive to specific training stimuli, yet adaptations vary widely among individual athletes (162,184). Over time, skeletal muscle adaptations to training contribute to strength gains (169). Although neural mechanisms account for initial strength increases in female athletes (53), in trained female athletes, muscular adaptations persist with continued training (16,85,112,170). For example, elite level female basketball players are able to achieve neural adaptations to plyometric training (16). In addition, longitudinal evaluation of competitive female weightlifters has shown strength increases over 10–15 years (85), although the largest rate of strength increases occurs within the first year of training (85,112).

Changes in muscular strength are associated with the magnitude of change in muscle size, and similar between women and men (111,169). In elite level female athletes in sports such as ice hockey and track, muscle strength and size are strongly correlated with performance (128,144). Muscle strength and size develop over time in high level female athletes (144,167). Muscular adaptations to strength and conditioning persist with resistance training of sufficient loads in high level female athletes. Skeletal muscles of elite female athletes are highly adaptive (e.g., increased power, reduced fascicle length) to specific training stimuli (184). In addition to strength, hypertrophy (cross-sectional fiber area of type I and II fibers) (99), and neural recruitment, adaptations also include changes in muscle architecture (increases in pennation angle) (22) and fiber composition (169). In addition to muscle morphological characteristics, skill and technique are important indicators of performance outcomes, especially in sports requiring explosive power in a single effort, such as field events and weightlifting (97).

Female athletes experience substantial gains in power and strength with appropriate and targeted training (50). A combination of traditional resistance training exercises and weightlifting variations at various loads, in addition to volleyball practice, seem to be effective at increasing maximal strength and vertical jump height in NCAA division I female volleyball athletes over the course of about 2.5 years of training (74). Similarly, 8 weeks of plyometric training increased performance and muscle hypertrophy (thigh cross-sectional area) of elite female athletes (basketball) (16). Moreover, adding velocity-based resistance training to the usual training regimen of competitive female cyclists improves muscle strength/power (117). Adding heavy strength training to endurance training increased muscle strength, performance, and size without affecting endurance running performance or running economy (187). Yet, adaptations are attributable to training programs of sufficient load and intensity (of generally greater than 60% of repetition maximum), as female university rugby athletes demonstrated no improvements in fitness across collegiate seasons (41). This was because of the training phase as there was an increase in fitness in the preseason and maintenance throughout the season to postseason. Given the variability in responses, careful monitoring of adaptations will enable coaches and athletes to evaluate the effectiveness of training programs and make adjustments according to the athlete's individual needs and phase of training they are in (184).

Despite muscular adaptations resulting in increased muscle strength and size in female athletes, sex-related differences in muscle mass and hypertrophy (99,128,138) account for the lower absolute muscle strength achievable in female athletes (101,111). The greater absolute strength achievable in male athletes is due primarily to larger muscle fiber size (111,142,156). Differences in muscle hypertrophic potential are because of both sex-related differences in endocrine and genetic factors affecting skeletal muscle (191). Female athletes have higher expression of genes that encode proteins in growth factor pathways known to be important in regulating muscle mass: growth factor receptor-bound 10 (GRB10), which encodes a protein that inhibits IGF-1 signaling, and activin A receptor IIB, which encodes a myostatin receptor (191). Qualitative features (muscle cross-sectional area and enzyme activity) (70) and lower glycolytic capacity lower lactate dehydrogenase and phosphofructokinase activity (70) may also contribute to strength and performance differences in female athletes. Many of these adaptations occur with progressive resistance training, similar to male athletes (142); however, the magnitude of these adaptations *may* be lower in female athletes (169).

As skeletal muscles of elite female athletes are highly adaptive to specific training stimuli, and adaptations vary widely among individual athletes (162,184), careful monitoring of adaptations enable coaches and athletes to evaluate the effectiveness of training programs and make adjustments according to the athlete's individual needs (50,184).

Metabolic Adaptations

Understanding the function of the metabolic system is critical to knowing the physiologic process of the other body systems, and to designing training programs for sport and physical activity. Although there are not large differences in how the metabolic system functions among male and female athletes, there are some differences that relate to the amount and type of muscle mass one is able to achieve. These differences can result in variation in the magnitude of training-related adaptations, but the lack of research comparing male and female athletes of similar training backgrounds limits the understanding of the metabolic system and how it adapts in female athletes. In addition, there is a lack of data with high-level athletes across a spectrum of competitive sports, who may have very different responses and adaptations to training because of their physiological characteristics.

Anaerobic

The primary anaerobic energy system pathways include ATP-PCr and glycolysis. The ATP-PCr pathway is dependent on availability of phosphocreatine, whereas both pathways are dependent on the presence of pathway-specific enzymes, all of which are stored in skeletal muscle, particularly type II muscle fibers, which male athletes have in greater proportion (69,168). Although both male and female athletes have the capacity to undergo muscle hypertrophy with various types of anaerobic training, the level of absolute hypertrophy attained by male athletes will exceed that of female athletes, resulting in greater storage potential for phosphocreatine, glycogen, and anaerobic pathway enzymes and greater overall glycolytic capacity (40,148).

The magnitude of adaptation regarding anaerobic energy system use is dependent on the mode of training employed. There are several training methods that target the glycolytic energy system pathway, including interval training of varying intensities and durations. High-intensity interval training is a time-efficient training modality used to improve metabolic conditioning and cardiovascular fitness in short periods of time using repeated intense bursts of exercise (49). Intermediate distance activities that target alactic glycolysis, such as middle-distance running (400–1,500 m) and swimming (100–800 m), provide both

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prolonged activity and short, fast bursts, lasting 1–5 minutes (58). Overall, it is still unclear whether male and female athletes adapt similarly to interval-based training, although it is generally believed that female athletes undergo attenuated adaptations (1). This could be because of lower levels of metabolic stress, which would result in a reduced adaptation to the training stimulus (1). Further, female athletes present more efficient oxygen cost of running than male athletes at various running intensities (59) while maintaining their running economy at each respective velocity. This pattern is also observed longitudinally as the athlete ages (2).

Aerobic

Aerobic endurance events are oxygen-dependent and optimally stimulate the aerobic oxidative energy systems (i.e., Kreb's cycle, electron transport chain, and lipid oxidation) to continuously supply energy, whereas the other systems supply additional ATP with faster turnover (i.e., PCr and glycolysis) (48). The oxidative pathways are dependent upon the cardiorespiratory system's ability to supply oxygen and remove metabolic wastes, so examining sex differences in cardiovascular function is relevant. Several research reviews have presented differences in male and female athletes under various conditions (1,13,83,192). It is well-established that female endurance athletes are more fatigue-resistant during prolonged events despite having overall lower aerobic capacity ($\dot{V}O_{2max}$) relative to body size and slower performance times than male athletes (8,32). This is thought to be partially because of muscle fiber type distribution (168), with a greater proportion of type I oxidative fibers and additional differences the result of the smaller average heart size in female athletes (196), thereby reducing absolute cardiac output and oxygen saturation capacity. Consequently, compared with male athletes, female athletes oxidize a greater amount of fat and a lesser amount of carbohydrate and protein (23,174). This is supported by the findings of Cardinale (12) who determined that female athletes have nearly 1/3 greater mitochondrial respiration than male athletes. These differences may present an advantage to female athletes in ultra-endurance events especially (180).

Aerobic Training Adaptations and the Cardiovascular System

Aerobic training adaptations differ in magnitude between male and female athletes regarding the cardiovascular system in particular (139), which can impact oxygen delivery to the muscle tissue and subsequent oxidative energy production. The cardiovascular training adaptations in female athletes compared with male athletes as a result of endurance training include more modest increases in blood volume and similar or lesser increases in heart dimensions such as left ventricular chamber size and wall thickness (6,30). Female athletes have similar adaptations compared with male athletes regarding left ventricle function, including a greater ejection fraction (155). Trained male athletes have limited right ventricle performance at high work rates and female athletes do not, suggesting less stress on the pulmonary arteries for female athletes and more efficient running demands (32). All of this impacts overall aerobic performance with female athletes compensating for smaller hearts and less oxygen carrying capacity by different mechanisms.

One mechanism related to recovery that has shown sex differences is heart rate variability (e.g., R-R interval, between heartbeat time variation [HRV]) (77). In general, higher HRV is associated with higher resilience to stress and higher levels of fitness in male and female athletes. Heart rate variability characteristics have been found to differ by sex (77), including the low-frequency power sex difference (females $<$ males) and lesser of a difference when age is factored in such as the standard deviation for the average interval between R spikes. Both characteristics are related to women's heart activity is vagal, parasympathetic dominant compared with higher sympathetic dominance of men's heart activity. More research is needed on female athletes' recovery with HRV.

Program Design

Absolute differences in performance between male and female athletes has largely been addressed (64). However, it is important to note for practitioners that prior examination of sex differences in athletic performance used evidence in nonathlete cohorts potentially conflating training or activity differences for sex differences. The focus of the following sections (resistance training; speed, agility, and plyometric training; endurance training) is to examine if evidence of adequate quality, quantity, and agreement exists to justify prescription guidelines for female athletes different to that has been developed using evidence from studies with disproportionate representation of male athletes (24,136). The following sections will focus on female athletes approximately 18–35 years of age while recognizing a future need to develop guidelines for women as their ovarian hormonal profiles change for transitions in life stages (i.e., puberty, pregnancy, peri- and postmenopause) during their athletic careers.

Resistance Training

Resistance training prescription is reliant on mostly short-term studies that indicate greater similarities than differences in relative adaptation to resistance training (64,147). The broad variables of volume and frequency were reported to be critical in the mostly untrained female subjects for improvements in strength (51). However, the dearth of studies in trained female subjects makes definitive statements regarding adaptations to resistance training a difficult endeavor (63,64,89,91,147). The interpretation and use of research of the evidence of sex differences related to muscle function must be considered in context to the relevance of the population and their needs. Therefore, the most prevalent sex difference cited in the literature may have limited implications for subsequent training prescription for many female athletes where the primary outcome is strength and power.

In research ranging from fiber type (158) to dexterity (87), sex differences that may have been considered moderate or even large in subelite athletic populations become marginal when examined in elite populations. It is this complexity in the interpretation of purported sex differences within resistance training or physiological adaptation to exercise research that has large implications when making generalized recommendations for resistance training prescription for female athletes. The differences in systematic provision of strength and conditioning training within sport environments (109) may unknowingly confound research seeking to examine sex differences even when the same training age or tier is reported of the subjects. Based on the existing growing body of literature exploring sex-specific approaches to training, commonly considered factors of training age, training history, individual genetics, sport needs, and female athlete goals need to be the primary drivers when developing resistance training

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prescription guidelines. In addition, unique to female athletes, consideration for menstrual cycle symptoms have been shown to impact training readiness, sleep quality, and recovery and should be included when considering approaches to training design.

Female athletes are relatively equally adaptive to resistance training prescription to that of male athletes (64,89). Although variations in maximum loads lifted are evident in muscle hypertrophy and maximal strength, it remains unclear whether male athletes exhibit greater relative skeletal muscle hypertrophy than female athletes during long-term high resistance training (64). For example, it is known that upper-body strength is much lower in female athletes, even when controlled for body size, unlike what is observed in the lower body. Therefore, if upper-body strength is critical for the sport, additional emphasis on development (e.g., needs analysis) may result in greater volume or focus on upper-body strength development. Consequently, expectations for improvements in strength and power by female athletes should not differ from that of the male athlete and should instead be developed based on need (64). As outlined previously, skeletal muscle of elite female athletes is highly adaptive to specific training stimuli, yet adaptations vary widely among individual athletes (162,184).

Resistance Training Prescription Relative to the Menstrual Cycle

To date, the evidence exploring the effect of menstrual cycle phase and exercise performance, specifically, most relevant to resistance training prescription outcomes indicates that there is only a trivial impact of phase of cycle on exercise performance in eumenorrheic women (108), and that different phases of the menstrual cycle in naturally cycling female women observes trivially or minimally altered measures of strength and hypertrophy between phases (9). Most relevant to the current position statement is evaluating if sufficient quality evidence exists for "phase-based training" for the female athletes that have confirmed eumenorrheic menstrual cycles (118). Further, the number of female athletes that "phase-based training" may apply to, if evidence were supportive, would still exclude application to the numerous female athletes using hormonal contraceptives (e.g., oral contraceptive pill, implant, injection, intrauterine [IUD], patches, vaginal rings, etc.), have menstrual irregularities (34), or are peri- or postmenopausal.

The most comprehensive and recent evaluation of the evidence on the menstrual cycle and performance is present in a series of meta-analyses (20,35,108) and the synthesis of evidence in athletes (tier 2 and higher) (163) and could not conclude any systematic relationship between menstrual cycle phase and measures of performance (110). As such, there is not sufficient evidence to support modifying resistance training prescription based upon menstrual cycle phase for most active female athletes. Based on the current available body of research demonstrating minimal effects of menstrual cycle periodization, these small effects may be meaningful in elite female athletes trying to maximize small margins, and thus, an individualized approach is recommended (118). Most importantly, tracking menses and athlete menstrual cycle consistency and symptomology is an important step in supporting female athlete training design and implementation. Although prescription based on menstrual cycle phase or "cycle-based training" has limited evidence for implementation for most active women (118), it is important to consider that most female athletes experience varying symptomology across the menstrual cycle that can affect program variables such as training readiness, sleep quality, and recovery status. Responses to these symptoms should be monitored and considered for adjustments to training. The majority of female athletes will perform optimally across all phases of the menstrual cycle; however, added considerations around recovery and symptom relief should be explored (106,107).

Speed, Agility, and Plyometric Training

Research examining long-term structured training programs that focus on speed, agility, and plyometric methodologies are equally scarce when seeking evidence of the adaptation of female athletes to such programs. The current understanding of sex-specific effects does not provide enough evidence to make a female-specific recommendation for speed, agility, or plyometrics prescription for female athletes. There are an insufficient number of studies conducted in female sports (24.0% of overall studies, respectively), insufficient reporting of effect size values, and training prescription and studies missing an active/passive control group and randomization (143). Each sport presents a unique speed and/or agility profile, and thus, a demand and positional analysis is an important first step in the design of an intervention aimed at improving speed or agility. For example, in elite rugby sevens, female players frequently achieve velocities above 90% of their maximum sprint velocity (46) and cover greater high-intensity running distances (with a lower number of directional changes) than handball players. This gives practitioners clues on how important sprinting speed is in rugby 7's as compared with handball. Even positions must be considered within the sport itself. A deep dive into understanding sport demands can be found in the literature (181).

The research has also suggested that female athletes present with greater change-of-direction (COD) deficits, but this may not be because of their sex but instead might reflect inadequate COD-specific training experience, and strength deficiencies (46). What requires scrutiny is the limited time, if any, devoted to executing eccentric strength training, COD-specific and decelerative drills, and the possible overemphasis of short straight sprints and concentric-based resistance training. In general, there is not enough evidence to suggest that female athletes require a different intervention to target speed or agility. Instead, practitioners must focus on what underpins qualities of efficient COD and sprint speed and design interventions. It is the principle of individualization that will dictate the tailoring of dose, not the sex of the athlete. Furthermore, training regimens centered on strength power and linear speed development may not be sufficient to ensure faster COD velocities and lower COD deficits if athletes are not regularly exposed to COD training strategies. To increase the ability to tolerate high entry velocities in COD maneuvers, targeted drills are required (46).

Plyometric training can assist in the development of qualities that underpin COD, agility, and even linear speed through known increased motor unit recruitment and rate of force development and, therefore, can be effective in improving jump performance, sprint test performance, and COD test performance in female athletes (154). Plyometrics also play a role in risk reduction of noncontact ACL injuries in female athletes. A key element is that the sessions are supervised with technique feedback, so sound knee alignment is emphasized (173).

For a drill to be considered "plyometric," it must involve true reflex-induced forces with preceding ground contact, when ground contact is "bracketed by preceding and subsequent aerial

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phases," (10) which is necessary to intensify the process. Unloaded ballistic jumps such as the countermovement jump are not considered to be plyometric, nor are box jumps, a popular form of exercise. Plyometrics, being a method, like resistance training, is incredibly varied, with many drill types to choose from: leaps, bounds and hops, drop jump vertical jump, and levels of intensity (light tier, medium tier, intense/ping tier) (164). The intensity of a plyometric drill is dictated by but not limited to peak vertical ground reaction forces, impulse, eccentric rate of force development, peak joint torque, athlete skill level, and athlete training age (10,189). The choice of plyometric drill or intensity level will depend on the motor skill level of the athlete and the adaptations (10). Simply tallying the number of foot contacts per session is an insufficient strategy for plyometric prescription as it ignores all factors related to intensity (10).

Despite the benefits of plyometric training demonstrated for female athletes about reducing injury risk, particularly to the ACL, the adoption of this training method is not universal across women's sports. For example, plyometrics at the women's first team versus men's first team in elite soccer was not found to be significantly less but would be practically significant (40% versus only 20% reporting prescription for their athletes) (109). Yet, in women's rugby, practitioners report that 95% of coaches implement plyometric training. Therefore, variations in the implementation of plyometric training may reflect the varied training status, training environments, or resourcing, whereas the premise, prescription, and benefit of plyometrics in female athletes is not seemingly sex-specific and should be delivered according to existing, yet limited, training principles and guidelines (121,172,173). Several high-quality reviews related to plyometric training have been published, with a particular focus on the effects on athletic performance (e.g., agility, muscular strength, sprint, and jump performance) in athletes. Training duration appears to influence the effectiveness of plyometric training, as longer training durations (>10 weeks) provide larger improvements in athletic performance (172).

The effectiveness of speed, agility, and plyometric training depends on the training design, the length of the intervention period, and the skill of the coach supervising the sessions. Many studies have shown, for example, that long-term plyometric interventions (i.e., 3–5 sessions a week for 5–12 months) represent an effective training method for enhancing bone mass in prepubertal/early pubertal children, young women, and premenopausal women (98). Short-term plyometric interventions (i.e., 2–3 sessions a week for 6–15 weeks) can change the stiffness of various elastic components of the muscle-tendon complex that can positively impact speed and power (98). However, a short-term change in tissue morphology does not mean a lasting prophylactic effect on a knee ligament, like an ACL.

Regarding training design, it is common in research to describe certain variables, such as the type of exercises used, the training duration, recovery status, frequency, volume, and intensity of the training. However, there is a lack of transparency about other potentially important concurrent factors that may explain some of the variations in the results, such as how the drill was performed. Almost no research studies include videos or images of a technical model of each plyometric drill. This is extremely problematic and leads to assumptions or biased assertions. In fact, key performance variables in the exercise or drill technique, such as the movement amplitude or ground-contact times, are not typically described in any of the reviewed studies' protocols (3,151,152,172,29).

Endurance Training

Before designing and implementing an endurance training program, a thorough needs analysis of the specific energy system demands for the sport (and position if applicable) is required (4). Specifically, practitioners should evaluate the nature of the activity (e.g., continuous, intermittent), intensity, duration, distances covered, work: rest ratios, and the musculoskeletal and neuromuscular strain involved in the sport (86,116). The habitual needs analysis process must also consider the athlete's sport-related goal, level of competition, and training age (4). Another consideration is iron status. Research indicates that iron deficiency is more prevalent in female athletes who participate in endurance events (27,157). Female athletes are more likely to be iron deficient than male athletes (76,132), thus having an awareness of the symptoms associated with a compromised iron status is important (e.g., lethargy, reduced performance, fatigue, low mood) (161). Therefore, where required, multidisciplinary collaboration is needed with qualified physicians and a dietitian to treat iron deficiency and maximize the athlete's endurance performance potential (11,19,137).

Furthermore, as body composition (i.e., total body mass expressed in terms of fat mass, lean mass, and bone mineral density) can affect movement economy and thus performance, understanding the individual athlete's optimal energy intake for function is necessary. This might be particularly important for female endurance athletes whereby balancing energy intake, and total energy intake can be a challenge because of the high volumes of training (60). An assessment of the female athlete's current level of conditioning and training status is needed to assist with goal setting, establish the starting point for the training program, and for on-going monitoring purposes. The contemporary gold standard approach for assignment of exercise intensity involves percentages of maximal rate of oxygen uptake ($\dot{V}O_{2max}$) as identified with cardiorespiratory incremental maximal exercise testing (67). Although $\dot{V}O_{2max}$ provides an overall picture of an individual's ability to deliver oxygen to the working muscles during endurance work, it is important to examine the oxygen uptake ($\dot{V}O_2$) kinetics and determine each metabolic threshold for the purpose of endurance exercise prescription. The $\dot{V}O_2$ kinetics response to an incremental test and thus increases in work rate relates to distinct and highly individual metabolic boundaries: the lactate threshold (LT) and the critical power (CP), which is closely associated with maximal lactate steady state (MLSS). The position of these thresholds, which are only accurate through testing, provide boundaries for intensity domains in endurance exercise prescription. The boundary for low and moderate intensity work is performed under the LT (90). This work can be performed continuously for several hours with no, or only a modest degree of metabolites being accumulated (67). The heavy intensity domain is between LT and CP/MLSS and is associated with the accumulation of metabolites and greater fatigue. Above the CP/MLSS, the rate of ATP resynthesis continues to rise over time and is termed the severe intensity domain (67). Time to exhaustion decreases as intensity increases and the end of exercise coincides with high level of metabolite accumulation and fatigue. Because of individual differences in genetics, fitness levels, and training experience, LT and CP/MLSS will occur at different percentages of $\dot{V}O_2$ max among subjects regardless of (90). Thus, domains are better than a fixed percentage approach (%HR, $\%\dot{V}O_{2max}$) to individualize endurance exercise prescription. It has been shown through metabolic testing (67) that compared with male athletes, the $\%\dot{V}O_{2max}$ and %HR max at which LT and CP/MLSS occur

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were greater in female athletes. In other words, there was a higher percentage of $\dot{V}O_2$ and heart rate at which LT and MLSS occurred in female athletes as compared to male athletes (67). Previously mentioned sex differences in muscle fiber composition, oxidative capacity, metabolism, and cardiac function may play a role (67). However, this simply means that individual training thresholds must be established for all athletes under the care of a physical performance practitioner and that, possibly, those thresholds could occur at higher heart rates for female endurance athletes. This information has implications for heart rate–based endurance training prescriptions.

Conclusions

Although much is understood about physiological function in male athletes and female athletes, in general there is much less available information regarding sex differences in athletic populations, and some differences previously attributed to biological sex may, in fact, be simply because of the level of physical training. Therefore, greater scrutiny in interpretation of existing research and methodological approaches to future research on female athletes is warranted. With increased participation in organized sports and sports training, there are now more individuals who fit the criteria of training necessary to study the physiological variables in question (24,179,185) and examining female athletes from a biopsychosocial perspective (102,126,134). Research for women's sports highlighting game and positional demands is limited (68). Research designed to either tease out sources of differences (i.e., psychosocial, sex, or their intersection) and/or written with language that acknowledges how intertwined these aspects are in alignment with the standards put forth by the National Academies of Sciences, Engineering, & Medicine (122), along with other supporting evidence (7,47,166) is needed. More specific future research recommendations are presented in Table 2.

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