Evidence on sex differences in sports performance

Michael J. Joyner[1,2], Sandra K. Hunter[3], Jonathon W. Senefeld[4]

[1]Department of Anesthesiology and Perioperative Medicine, Mayo Clinic, Rochester, Minnesota
[2]Department of Physiology and Biomedical Engineering, Mayo Clinic, Rochester, Minnesota
[3]School of Kinesiology, University of Michigan, Ann Arbor, Michigan
[4]Department of Health and Kinesiology, University of Illinois Urbana-Champaign, Urbana, Illinois

***Correspondence to:**
Michael J. Joyner, M.D., Department of Anesthesiology and Perioperative Medicine
Mayo Clinic | 200 First Street SW | Rochester, MN 55905 | 507-255-4288
joyner.michael@mayo.edu

ABSTRACT

Sex differences in sports performances continue to attract considerable scientific and public attention, driven in part by high profile cases of: 1) biological male (XY) athletes who seek to compete in the female category after gender transition, and 2) XY athletes with medical syndromes collectively known as disorders or differences of sex development (DSD). In this perspective we highlight scientific evidence that informs eligibility criteria and applicable regulations for sex categories in sport. There are profound sex differences in human performance in athletic events determined by strength, speed, power, endurance, and body size such that males outperform females. These sex differences in athletic performance exist before puberty and increase dramatically as puberty progresses. The profound sex differences in sports performance are primarily attributable to the direct and indirect effects of sex-steroid hormones and provide a compelling framework to consider for policy decisions to safeguard fairness and inclusion in sports.

Introduction

Sex differences in sports performances continue to attract considerable scientific and public attention, driven in part by high profile cases of: 1) biological male (XY) athletes who seek to compete in the female category after gender transition (i.e. transgender women athletes) (1–3), and 2) XY athletes with medical syndromes collectively known as disorders or differences of sex development (DSD). In this perspective we highlight scientific evidence that may inform eligibility criteria and applicable regulations for sex categories in sport and provide a compelling framework to consider for policy decisions to safeguard fairness and inclusion in sport. Three important caveats underpin this perspective. ***First,*** randomized controlled trials (RCTs) are often used to test the efficacy of therapeutic interventions in medicine, including sports medicine (4). However, RCTs are generally not required to establish informed policy in sports such as regulations on doping and use of anabolic androgenic steroids because of ethical and practical improbabilities. ***Second***, because the margin of victory is often very small in elite sport, sports policy makers routinely regulate competitive advantages of 1% or less (1, 5) (**Figure 1**). ***Third,*** many regulatory policies in sports are applied universally.

[Figure 1]

Historically, many forms of athletic competition have been categorized based on key determinants of athletic performance, including, sex, age, weight class, skill level, and disability grade. The criteria used to stratify athletic competition are intended to be objective and supported by relatively straightforward adjudication processes. Although these historical classification systems for sports are not without challenges, stratifying athletic competitions seeks to provide a “fair playing field” and a foundation for competitive pressure to select and optimize for talents and phenotypes associated with success within each sport, event, or position. An important distinction is to be made between “determinants” and “talents” — determinants represent categorical advantages conferred by physiological differences and talents represent skills or phenotypes that can be optimized for success with intensive training. Importantly, not all determinants are immutable (e.g. weight class) and not all talents are modifiable (e.g. height), and some stratifications are not the same for all sports. For example, although weight class is a stratification used in some sports (e.g. wrestling, weightlifting, rowing), weight class is not used as a stratification in other sports (e.g. track and field, swimming, soccer/football). As one exemplar sport to highlight these points, Olympic weightlifting uses two specific overhead barbell lifting techniques (‘snatch’ and ‘clean and jerk’, and the summation of these ‘total’) to assess maximal power of skeletal muscle and is stratified by both biological sex and body mass (weight class). As illustrated in **Figure 2**, world record performances for ‘total’ are greater among males compared to females and larger weight classes relative to smaller weight classes— supporting the notion of stratification by both sex and body mass. Notably, females in the largest weight class (87 kg or heavier) outperform males in the lowest weight class (55 kg) by about 12% and have markedly worse performance by about 20% than males in the comparable weight class (89 kg). In this framework, this perspective focuses on key *determinants* of sports performance that are conferred by an amalgamation of biological adaptations to male sex chromosomes (XY) and masculinizing puberty with male testosterone concentrations.

[Figure 2]

With this information as background, we make seven statements relevant to the topic of sex differences and sport performance. Each statement is then followed by key corroborating evidence that support the statement. This perspective focuses on sex differences rather than gender differences. Consequently, this perspective uses biological terms and sex chromosomes to describe males (XY) and females (XX), and generally refrains from using culturally specific terms to describe constructs of gender identity and gender expression.

Statement 1: Biological males as a group outperform biological females in athletic events dependent on strength, speed, power and endurance.

The evidence supporting this statement comes from sex differences in elite performance data and studies that establish the relationship between muscle power and athletic performance. Each year in the sport of track and field, for example, there are hundreds and generally thousands of males (including many under 18 years of age) who run faster, jump higher or throw farther than the female world record holder in every event. Among elite adult competitors, male-female performance gaps of about 10 to 40% are seen (**Figure 3**), with the largest performance gaps in events determined by maximal muscle power (6, 7). Because running, jumping, and throwing are foundational elements for many sports, this evidence is undoubtedly generalizable to sports and athletic events that require these elements as a part of the overall success in performance. In no sporting discipline that is determined by strength, speed, power or endurance are the performances of elite females equal to or better than performances by elite males, including ultradistance running, cycling, and swimming (8–10).

[Figure 3]

Statement 2: The male-female performance gap is evident before puberty.

The evidence supporting this statement comes from performance data of elite youth athletes before puberty and studies that establish sex differences in anatomical and physiological development of systems that are associated with physical performance before puberty. For example, among the best prepubescent athletes in the US, the male-female performance gap is about 3 to 5% in track and field running events (**Figure 4**) and about 5 to 10% in jumping events (11, 12). The magnitude of the male-female performance gap is smaller in swimming (about 1 to 5%) than in track and field (13). There are several bioplausible explanations for the male-female performance gaps seen before puberty in these sports. First, transient increases in sex hormones during early life (so called "minipuberty") are associated with increased growth velocity (14) and reduced adipose accumulation (15) among male infants compared with female infants, and greater muscle mass (16) and muscle strength (17) among boys compared to girls. Second, boys tend to run and jump more than girls during unstructured play and spend more time engaged in higher-intensity physical activity (18, 19). Such activities could produce an informal training effect in boys. The extent to which these sex differences in children reflect the impact of biology, socialization, or both is a matter of discussion (20), but differences in early childhood body composition indicate that at least some of the male-female performance gap among prepubertal children is due to intrinsic biological factors.

[Figure 4]

Statement 3: The male-female performance gap increases after the onset of puberty and is associated with changes in body structure, physiology and function.

The evidence supporting this statement comes from performance data of elite athletes across the lifespan. The sex-based performance gaps seen in children increase progressively during puberty and reach the adult level of ~10-40% in later teenage years, see **Figure 5**. Sex differences in body form and function that increase at puberty and contribute to the widening male-female performance gap include but are not limited to differences in: skeletal muscle mass, body fat, airway and lung size, oxygen carrying capacity in the blood, heart size, and endocrine patterns (1, 6, 7, 21, 22). Height represents an easy-to-understand metric of sex differences that emerge at puberty and increases to adulthood. In the United States, the medians (50th percentiles) for height among 10-year-old youths are marginally greater for boys (~139 cm) than girls (~138 cm). However, among 20-year-old adults, the medians for height are much greater among males than females (176.8 vs 163.3 cm, respectively), and the median for males is greater than the 97th percentile for females (175.5 cm) (23).

[Figure 5]

Statement 4: The principal driver of the increased male-female performance gap in adults is the surge in endogenous testosterone among biological males starting during puberty.

The evidence supporting this statement comes from studies that document the puberty-related increase in testosterone, the anabolic effects of testosterone on human biology, and the associations between endogenous testosterone and increased physical performance of males and females during adolescence. After minipuberty, endogenous testosterone levels begin to diverge in males and females at approximately 11 years of age, and they are bimodally distributed by 14 years of age, meaning there is no longer any meaningful overlap between males and females by 14 years (24). There is a robust correlation (r>0.98) between the surge in endogenous testosterone and the growth in the performance gaps for athletics and swimming (13). Testosterone, whether endogenous or exogenous, is a known and powerful steroid hormone that makes skeletal muscles bigger, stronger, and faster. Testosterone also increases bone size, bone strength, and bone density and promotes higher red blood cell counts. These effects have been demonstrated in animal models, populations, and via interventional studies. For muscle related properties, interventional studies show a dose-response relationship between exogenous testosterone and training-induced adaptations to both muscle size and strength (25, 26).

Statement 5: Changes in the female body during puberty and female physiology throughout an athletic career can contribute to the male-female performance gap by limiting training, performance, and muscle regeneration after injury or detraining among females.

The evidence supporting this statement comes from studies determining the effects of athletic performance on changes in the body unique to female puberty and physiology. Changes in the female body that males do not experience during female puberty include but are not limited to increased relative (or percentage) body fat (27); smaller adult height due to accelerated epiphyseal fusion (28); breast development that creates flexion torque during upright movement and standing countered by back muscles (29); and hormonal fluctuations across each menstrual cycle that can alter perceived performance because of discomfort, pain and fatigue, and altered temperature regulation and substrate metabolism (30). Of note, on average there are generally small, or non-significant fluctuations in physical performance among females across the menstrual cycle (31, 32), although these are acute fluctuations and are apart from the long-term changes outlined above and experienced by females during and after puberty. There are also anatomical and biomechanical sex differences in the lower extremity such as wider hips (larger angle between hips and knees, Q angle) in females that increase the risk (relative to males) of injury including patellofemoral pain, patellar subluxation, dislocation and instability, and anterior cruciate ligament injury in the knees (33, 34). Finally, many females take time off from training due to pregnancy and child birth and can suffer post-partum health issues that interfere with performance (35).

Statement 6: Endogenous testosterone suppression among XY athletes who have experienced masculinizing puberty, modestly reduces athletic performance, but a large male-female performance gap remains.

The evidence supporting this statement comes from case studies of real-world performances, systematic reviews, and cross-sectional studies of physical performance. A case report of an adult testosterone-suppressed XY swimmer (transgender woman) demonstrated although swimmer performance times slowed, both *relative* competitive success and *relative* ranking/placement markedly improved competing in the female category compared with success and ranking in the male category (36). Notably, the relative swimming performance decline after about two years of gender affirming hormone therapy (testosterone suppression and estrogen supplementation) was about 5%— a magnitude which is about 50% smaller than the typical male-female performance gap of 10% among top NCAA swimmers, suggesting a retained/legacy athletic advantage. Other studies of physical performance tests of US military personnel (37) and overweight/obese XY athletes (38) who completed at least one year of testosterone suppression show some evidence of better or similar physical performance relative to XX comparator group in the study (military personnel or normal weight athlete). In this context, although there are many nuances and caveats, generally the current evidence-base shows that testosterone suppression reduces physical performance but there are retained legacy advantages for at least one year after testosterone suppression, and several anatomical factors are largely unaffected by testosterone suppression (e.g. height and limb length).

There are bioplausible explanations for a retained athletic advantage among testosterone-suppressed XY athletes competing in the female category. First, testosterone suppression among adults cannot change anatomical and structural advantages conferred by male sex hormones and puberty— such as greater height and lung volume relative to females. Although sex hormone manipulation among youths may modestly change observed adult height relative to predicted adult height on the magnitude of about 2 to 4 cm (39–41), these modest changes are much smaller than sex-based differences in adult height (about 14 cm) and sex hormone manipulation does not change height among adults. Second, testosterone suppression is associated with modest reductions in both muscle mass and muscle strength, but a large sex-based difference in muscle mass and strength is retained (42, 43) (**Figure 6**). Third, testosterone suppression cannot replicate female-specific contributions to the male-female performance gap such as accelerated epiphyseal fusion or the physiological effects of the menstrual cycle. Fourth, there is growing evidence of a "muscle memory theory" in animal models (44–46) and cultured human cells (47). The "muscle memory theory" suggests that previously trained individuals acquire muscle mass and strength more quickly upon retraining, primarily thought to be due to relative permanence of myonuclear domain in skeletal muscle or training-induced changes in the epigenetic landscape of skeletal muscle (46). The "muscle memory theory" postulates that the beneficial effects of high testosterone on skeletal muscle and the response to training are retained even when androgens are absent (i.e., testosterone suppression). Consistent with this explanation, skeletal muscles of adult males retain robust adaptive response to resistance training after testosterone has been suppressed as part of therapeutic regimes to treat androgen sensitive tumors (48). The “muscle memory theory” is biologically plausible, has been recapitulated in preclinical models (animal models and human cell culture models), and has identified two potential synergistic physiological mechanisms (myonuclear permanence and epigenetics). However, the evidence supporting the muscle memory theory in humans is controversial and more research is warranted to experimentally test this hypothesis (46). In this framework, testosterone suppression among XY athletes likely does not reverse the male advantage in sports performance, but longer-term studies are needed.

[Figure 6]

Statement 7: When biological females (XX) use exogenous testosterone after puberty (e.g. “doping”) and train for sports, their performance is enhanced but the male-female performance gap does not close.

The evidence supporting this statement primarily comes from systematic doping among athletes. During the peak era of state-sponsored doping it was noted that female performances were more responsive to exogenous androgen administration than male performances (49, 50). In alignment with these observations among elite athletes, evidence from a recent randomized controlled trial enrolling physically active females supports a causal link between exogenous testosterone and improvements in both aerobic performance and lean mass (51). Performances of female (XX) athletes on testosterone supplementation nevertheless lagged behind those of male (XY) athletes. This lag remains even when the performances of the female athletes on testosterone supplementation are compared with male performances from decades before the era of widespread doping. Likewise, we are not aware of any current female athletes on testosterone supplementation competing successfully against elite male athletes. In combination with the known physical and physiological drivers of the male-female performance gap, these observations indicate that testosterone supplementation in female athletes is unlikely to erase the puberty-driven male advantage in sports performance.

Summary

There are profound sex differences in human performance in athletic events determined by strength, speed, power, endurance, and body size such that males outperform females. These sex differences in athletic performance exist before puberty and increase dramatically as puberty progresses. The sex differences are markedly greater in magnitude (10 to 40%) than the advantages that policy-making bodies seek to eliminate when they regulate equipment or drugs that could enhance performance. As one example, World Athletics amended regulations on shoe manufacturing after advanced footwear technology was linked to a 1 to 2% performance advantage relative to other racing footwear (52–54). Regulation of sports technology and potential performance enhancing drugs is typically based on an evidence-base that is general in nature and based on plausibility, mechanism of action, and real-world data as opposed to RCTs. In this context, exogenous androgens administered to female (XX biology) athletes improve performance but do not close the male-female performance gap and do not eliminate the male advantage. Testosterone suppression among male (XY biology) athletes who have undergone male puberty reduces performance but much of the male advantage is retained, including: 1) muscle strength, power, and size, 2) maximal aerobic capacity, and 3) other potentially performance enhancing attributes such as height and limb length. This evidence summary may provide a useful framework to understand claims about the nature and extent of the evidence that supports existing eligibility guidelines and to consider the merits of reforms that would govern the classification of transgender athletes and athletes with certain DSDs in competitive sports. Both the magnitude and duration of the influence of testosterone and puberty on sports performance should be recognized with appropriate consideration.

Acknowledgement

The graphical abstract was created in BioRender (https://biorender.com).

References

1. **Handelsman DJ**. Towards a Robust Definition of Sport Sex. .

2. **Lundberg TR**, **Tucker R**, **McGawley K**, **Williams AG**, **Millet GP**, **Sandbakk Ø**, **Howatson G**, **Brown GA**, **Carlson LA**, **Chantler S**, **Chen MA**, **Heffernan SM**, **Heron N**, **Kirk C**, **Murphy MH**, **Pollock N**, **Pringle J**, **Richardson A**, **Santos-Concejero J**, **Stebbings GK**, **Christiansen AV**, **Phillips SM**, **Devine C**, **Jones C**, **Pike J**, **Hilton EN**. The International Olympic Committee framework on fairness, inclusion and nondiscrimination on the basis of gender identity and sex variations does not protect fairness for female athletes. *Scand J Med Sci Sports* 34: e14581, 2024. doi: 10.1111/sms.14581.

3. **Nokoff NJ**, **Senefeld J**, **Krausz C**, **Hunter S**, **Joyner M**. Sex Differences in Athletic Performance: Perspectives on Transgender Athletes. *Exerc Sport Sci Rev* 51: 85–95, 2023. doi: 10.1249/JES.0000000000000317.

4. **Bullock GS**, **Ward P**, **Hughes T**, **Thigpen CA**, **Cook CE**, **Shanley E**. Using Randomized Controlled Trials in the Sports Medicine and Performance Environment: Is It Time to Reconsider and Think Outside the Methodological Box? *J Orthop Sports Phys Ther* 53: 331–334, 2023. doi: 10.2519/jospt.2023.11824.

5. **Handelsman DJ**, **Hirschberg AL**, **Bermon S**. Circulating Testosterone as the Hormonal Basis of Sex Differences in Athletic Performance. *Endocr Rev* 39: 803–829, 2018. doi: 10.1210/er.2018-00020.

6. **Hunter SK**, **S Angadi S**, **Bhargava A**, **Harper J**, **Hirschberg AL**, **D Levine B**, **L Moreau K**, **J Nokoff N**, **Stachenfeld NS**, **Bermon S**. The Biological Basis of Sex Differences in Athletic Performance: Consensus Statement for the American College of Sports Medicine. *Med Sci Sports Exerc* 55: 2328–2360, 2023. doi: 10.1249/MSS.0000000000003300.

7. **Senefeld JW**, **Hunter SK**. Hormonal Basis of Biological Sex Differences in Human Athletic Performance. *Endocrinology* 165: bqae036, 2024. doi: 10.1210/endocr/bqae036.

8. **Besson T**, **Macchi R**, **Rossi J**, **Morio CYM**, **Kunimasa Y**, **Nicol C**, **Vercruyssen F**, **Millet GY**. Sex Differences in Endurance Running. *Sports Med* 52: 1235–1257, 2022. doi: 10.1007/s40279-022-01651-w.

9. **Senefeld J**, **Smith C**, **Hunter SK**. Sex Differences in Participation, Performance, and Age of Ultramarathon Runners. *Int J Sports Physiol Perform* 11: 635–642, 2016. doi: 10.1123/ijspp.2015-0418.

10. **Tiller NB**, **Elliott-Sale KJ**, **Knechtle B**, **Wilson PB**, **Roberts JD**, **Millet GY**. Do Sex Differences in Physiology Confer a Female Advantage in Ultra-Endurance Sport? *Sports Med* 51: 895–915, 2021. doi: 10.1007/s40279-020-01417-2.

11. **Atkinson MA**, **James JJ**, **Quinn ME**, **Senefeld JW**, **Hunter SK**. Sex Differences in Track and Field Elite Youth. *Med Sci Sports Exerc* 56: 1390–1397, 2024. doi: 10.1249/MSS.0000000000003423.

12. **Brown GA**, **Shaw BS**, **Shaw I**. Sex-based differences in track running distances of 100, 200, 400, 800, and 1500m in the 8 and under and 9–10-year-old age groups. *European Journal of Sport Science* 24: 217–225, 2024. doi: 10.1002/ejsc.12075.

13. **Senefeld JW**, **Clayburn AJ**, **Baker SE**, **Carter RE**, **Johnson PW**, **Joyner MJ**. Sex differences in youth elite swimming. *PLoS One* 14: e0225724, 2019. doi: 10.1371/journal.pone.0225724.

14. **Kiviranta P**, **Kuiri-Hänninen T**, **Saari A**, **Lamidi M-L**, **Dunkel L**, **Sankilampi U**. Transient Postnatal Gonadal Activation and Growth Velocity in Infancy. *Pediatrics* 138: e20153561, 2016. doi: 10.1542/peds.2015-3561.

15. **Davis SM**, **Kaar JL**, **Ringham BM**, **Hockett CW**, **Glueck DH**, **Dabelea D**. Sex differences in infant body composition emerge in the first 5 months of life. *J Pediatr Endocrinol Metab* 32: 1235–1239, 2019. doi: 10.1515/jpem-2019-0243.

16. **Malina RM**, **Bouchard C**, **Beunen G**. Human Growth: Selected Aspects of Current Research on Well-Nourished Children. *Annu Rev Anthropol* 17: 187–219, 1988. doi: 10.1146/annurev.an.17.100188.001155.

17. **Sartorio A**, **Lafortuna CL**, **Pogliaghi S**, **Trecate L**. The impact of gender, body dimension and body composition on hand-grip strength in healthy children. *J Endocrinol Invest* 25: 431–435, 2002. doi: 10.1007/BF03344033.

18. **Belcher BR**, **Berrigan D**, **Dodd KW**, **Emken BA**, **Chou C-P**, **Spruijt-Metz D**. Physical activity in US youth: effect of race/ethnicity, age, gender, and weight status. *Med Sci Sports Exerc* 42: 2211–2221, 2010. doi: 10.1249/MSS.0b013e3181e1fba9.

19. **Saint-Maurice PF**, **Bai Y**, **Vazou S**, **Welk G**. Youth Physical Activity Patterns During School and Out-of-School Time. *Children (Basel)* 5: 118, 2018. doi: 10.3390/children5090118.

20. **Van Der Horst K**, **Paw MJCA**, **Twisk JWR**, **Van Mechelen W**. A brief review on correlates of physical activity and sedentariness in youth. *Med Sci Sports Exerc* 39: 1241–1250, 2007. doi: 10.1249/mss.0b013e318059bf35.

21. **Petek BJ**, **Chung EH**, **Kim JH**, **Lampert R**, **Levine BD**, **Phelan D**, **Danielian A**, **Dean PN**, **Dineen EH**, **Fernandez AB**, **Husaini M**, **Krishnan S**, **Shah AB**, **Stewart KM**, **Wasfy MM**. Impact of Sex on Cardiovascular Adaptations to Exercise: JACC Review Topic of the Week. *J Am Coll Cardiol* 82: 1030–1038, 2023. doi: 10.1016/j.jacc.2023.05.070.

22. **Ripoll JG**, **Guo W**, **Andersen KJ**, **Baker SE**, **Wiggins CC**, **Shepherd JRA**, **Carter RE**, **Welch BT**, **Joyner MJ**, **Dominelli PB**. Sex differences in paediatric airway anatomy. *Exp Physiol* 105: 721–731, 2020. doi: 10.1113/EP088370.

23. **CDC**, **National Center for Health Statistics**. Data Table of Stature-for-age [Online]. [date unknown]. https://www.cdc.gov/growthcharts/html_charts/statage.htm.

24. **Senefeld JW**, **Lambelet Coleman D**, **Johnson PW**, **Carter RE**, **Clayburn AJ**, **Joyner MJ**. Divergence in Timing and Magnitude of Testosterone Levels Between Male and Female Youths. *JAMA* 324: 99–101, 2020. doi: 10.1001/jama.2020.5655.

25. **Bhasin S**, **Woodhouse L**, **Casaburi R**, **Singh AB**, **Bhasin D**, **Berman N**, **Chen X**, **Yarasheski KE**, **Magliano L**, **Dzekov C**, **Dzekov J**, **Bross R**, **Phillips J**, **Sinha-Hikim I**, **Shen R**, **Storer TW**. Testosterone dose-response relationships in healthy young men. *Am J Physiol Endocrinol Metab* 281: E1172-1181, 2001. doi: 10.1152/ajpendo.2001.281.6.E1172.

26. **Huang G**, **Basaria S**, **Travison TG**, **Ho MH**, **Davda M**, **Mazer NA**, **Miciek R**, **Knapp PE**, **Zhang A**, **Collins L**, **Ursino M**, **Appleman E**, **Dzekov C**, **Stroh H**, **Ouellette M**, **Rundell T**, **Baby M**, **Bhatia NN**, **Khorram O**, **Friedman T**, **Storer TW**, **Bhasin S**. Testosterone dose-response relationships in hysterectomized women with or without oophorectomy: effects on sexual function, body composition, muscle performance and physical function in a randomized trial. *Menopause* 21: 612–623, 2014. doi: 10.1097/GME.0000000000000093.

27. **Veldhuis JD**, **Roemmich JN**, **Richmond EJ**, **Rogol AD**, **Lovejoy JC**, **Sheffield-Moore M**, **Mauras N**, **Bowers CY**. Endocrine control of body composition in infancy, childhood, and puberty. *Endocr Rev* 26: 114–146, 2005. doi: 10.1210/er.2003-0038.

28. **Weise M**, **De-Levi S**, **Barnes KM**, **Gafni RI**, **Abad V**, **Baron J**. Effects of estrogen on growth plate senescence and epiphyseal fusion. *Proc Natl Acad Sci U S A* 98: 6871–6876, 2001. doi: 10.1073/pnas.121180498.

29. **McGhee DE**, **Steele JR**. Breast Biomechanics: What Do We Really Know? *Physiology (Bethesda)* 35: 144–156, 2020. doi: 10.1152/physiol.00024.2019.

30. **Carmichael MA**, **Thomson RL**, **Moran LJ**, **Wycherley TP**. The Impact of Menstrual Cycle Phase on Athletes' Performance: A Narrative Review. *Int J Environ Res Public Health* 18: 1667, 2021. doi: 10.3390/ijerph18041667.

31. **McNulty KL**, **Elliott-Sale KJ**, **Dolan E**, **Swinton PA**, **Ansdell P**, **Goodall S**, **Thomas K**, **Hicks KM**. The Effects of Menstrual Cycle Phase on Exercise Performance in Eumenorrheic Women: A Systematic Review and Meta-Analysis. *Sports Med* 50: 1813–1827, 2020. doi: 10.1007/s40279-020-01319-3.

32. **D'Souza AC**, **Wageh M**, **Williams JS**, **Colenso-Semple LM**, **McCarthy DG**, **McKay AKA**, **Elliott-Sale KJ**, **Burke LM**, **Parise G**, **MacDonald MJ**, **Tarnopolsky MA**, **Phillips SM**. Menstrual cycle hormones and oral contraceptives: a multimethod systems physiology-based review of their impact on key aspects of female physiology. *J Appl Physiol (1985)* 135: 1284–1299, 2023. doi: 10.1152/japplphysiol.00346.2023.

33. **De Ste Croix M**, **ElNagar YO**, **Iga J**, **Ayala F**, **James D**. The impact of joint angle and movement velocity on sex differences in the functional hamstring/quadriceps ratio. *Knee* 24: 745–750, 2017. doi: 10.1016/j.knee.2017.03.012.

34. **Skouras AZ**, **Kanellopoulos AK**, **Stasi S**, **Triantafyllou A**, **Koulouvaris P**, **Papagiannis G**, **Papathanasiou G**. Clinical Significance of the Static and Dynamic Q-angle. *Cureus* 14: e24911, 2022. doi: 10.7759/cureus.24911.

35. **Davenport MH**, **Ray L**, **Nesdoly A**, **Thornton J**, **Khurana R**, **McHugh T-LF**. We're not Superhuman, We're Human: A Qualitative Description of Elite Athletes' Experiences of Return to Sport After Childbirth. *Sports Med* 53: 269–279, 2023. doi: 10.1007/s40279-022-01730-y.

36. **Senefeld JW**, **Hunter SK**, **Coleman D**, **Joyner MJ**. Case Studies in Physiology: Male to female transgender swimmer in college athletics. *J Appl Physiol (1985)* 134: 1032–1037, 2023. doi: 10.1152/japplphysiol.00751.2022.

37. **Chiccarelli E**, **Aden J**, **Ahrendt D**, **Smalley J**. Fit Transitioning: When Can Transgender Airmen Fitness Test in Their Affirmed Gender? *Mil Med* 188: e1588–e1595, 2023. doi: 10.1093/milmed/usac320.

38. **Hamilton B**, **Brown A**, **Montagner-Moraes S**, **Comeras-Chueca C**, **Bush PG**, **Guppy FM**, **Pitsiladis YP**. Strength, power and aerobic capacity of transgender athletes: a cross-sectional study. *Br J Sports Med* 58: 586–597, 2024. doi: 10.1136/bjsports-2023-108029.

39. **Boogers LS**, **Wiepjes CM**, **Klink DT**, **Hellinga I**, **van Trotsenburg ASP**, **den Heijer M**, **Hannema SE**. Transgender Girls Grow Tall: Adult Height Is Unaffected by GnRH Analogue and Estradiol Treatment. *J Clin Endocrinol Metab* 107: e3805–e3815, 2022. doi: 10.1210/clinem/dgac349.

40. **Roberts SA**, **Carswell JM**. Growth, growth potential, and influences on adult height in the transgender and gender-diverse population. *Andrology* 9: 1679–1688, 2021. doi: 10.1111/andr.13034.

41. **Willemsen LA**, **Boogers LS**, **Wiepjes CM**, **Klink DT**, **van Trotsenburg ASP**, **den Heijer M**, **Hannema SE**. Just as Tall on Testosterone; a Neutral to Positive Effect on Adult Height of GnRHa and Testosterone in Trans Boys. *J Clin Endocrinol Metab* 108: 414–421, 2023. doi: 10.1210/clinem/dgac571.

42. **Harper J**, **O'Donnell E**, **Sorouri Khorashad B**, **McDermott H**, **Witcomb GL**. How does hormone transition in transgender women change body composition, muscle strength and haemoglobin? Systematic review with a focus on the implications for sport participation. *Br J Sports Med* 55: 865–872, 2021. doi: 10.1136/bjsports-2020-103106.

43. **Hilton EN**, **Lundberg TR**. Transgender Women in the Female Category of Sport: Perspectives on Testosterone Suppression and Performance Advantage. *Sports Med* 51: 199–214, 2021. doi: 10.1007/s40279-020-01389-3.

44. **Egner IM**, **Bruusgaard JC**, **Eftestøl E**, **Gundersen K**. A cellular memory mechanism aids overload hypertrophy in muscle long after an episodic exposure to anabolic steroids. *J Physiol* 591: 6221–6230, 2013. doi: 10.1113/jphysiol.2013.264457.

45. **Nielsen JL**, **Rasmussen JJ**, **Frandsen MN**, **Fredberg J**, **Brandt-Jacobsen NH**, **Aagaard P**, **Kistorp C**. Higher Myonuclei Density in Muscle Fibers Persists Among Former Users of Anabolic Androgenic Steroids. *J Clin Endocrinol Metab* 109: e266–e273, 2023. doi: 10.1210/clinem/dgad432.

46. **Snijders T**, **Aussieker T**, **Holwerda A**, **Parise G**, **van Loon LJC**, **Verdijk LB**. The concept of skeletal muscle memory: Evidence from animal and human studies. *Acta Physiol (Oxf)* 229: e13465, 2020. doi: 10.1111/apha.13465.

47. **Pataky MW**, **Dasari S**, **Michie KL**, **Sevits KJ**, **Kumar AA**, **Klaus KA**, **Heppelmann CJ**, **Robinson MM**, **Carter RE**, **Lanza IR**, **Nair KS**. Impact of biological sex and sex hormones on molecular signatures of skeletal muscle at rest and in response to distinct exercise training modes. *Cell Metab* 35: 1996-2010.e6, 2023. doi: 10.1016/j.cmet.2023.10.010.

48. **Nilsen TS**, **Johansen SH**, **Thorsen L**, **Fairman CM**, **Wisløff T**, **Raastad T**. Does Androgen Deprivation for Prostate Cancer Affect Normal Adaptation to Resistance Exercise? *Int J Environ Res Public Health* 19: 3820, 2022. doi: 10.3390/ijerph19073820.

49. **Collantes DB**, **Senefeld JW**, **Larson KF**, **Coleman DL**, **Joyner MJ**, **Kipp S**. Sex differences in elite track and field performances and inferences about steroid doping. .

50. **Franke WW**, **Berendonk B**. Hormonal doping and androgenization of athletes: a secret program of the German Democratic Republic government. *Clin Chem* 43: 1262–1279, 1997.

51. **Hirschberg AL**, **Elings Knutsson J**, **Helge T**, **Godhe M**, **Ekblom M**, **Bermon S**, **Ekblom B**. Effects of moderately increased testosterone concentration on physical performance in young women: a double blind, randomised, placebo controlled study. *Br J Sports Med* 54: 599–604, 2020. doi: 10.1136/bjsports-2018-100525.

52. **Hoogkamer W**, **Kipp S**, **Kram R**. The Biomechanics of Competitive Male Runners in Three Marathon Racing Shoes: A Randomized Crossover Study. *Sports Med* 49: 133–143, 2019. doi: 10.1007/s40279-018-1024-z.

53. **Langley JO**, **Langley B**. The effect of advanced footwear technology on elite male marathon race speed. *Eur J Appl Physiol* 124: 1143–1149, 2024. doi: 10.1007/s00421-023-05341-x.

54. **Senefeld JW**, **Haischer MH**, **Jones AM**, **Wiggins CC**, **Beilfuss R**, **Joyner MJ**, **Hunter SK**. Technological advances in elite marathon performance. *J Appl Physiol (1985)* 130: 2002–2008, 2021. doi: 10.1152/japplphysiol.00002.2021.

55. **Alvares LAM**, **Santos MR**, **Souza FR**, **Santos LM**, **Mendonça BB de**, **Costa EMF**, **Alves MJNN**, **Domenice S**. Cardiopulmonary capacity and muscle strength in transgender women on long-term gender-affirming hormone therapy: a cross-sectional study. *Br J Sports Med* 56: 1292–1298, 2022. doi: 10.1136/bjsports-2021-105400.

Figures

Figure 1. Margin of victory at 2020 Olympic Games. The margin of victory (X axis) as a percentage difference from 1st place (gold medal) up to 8th place for females (red triangles in the top four rows) and males (blue circles in the bottom four rows) contested at the 2020 Tokyo Summer Olympic Games among selected events, including track running (800 m and 10,000 m) and freestyle swimming (100 m and 1500 m) events. The top three medal winners (gold, silver, and bronze) were within 1.1% or less for these events. Data abstracted from Olympic Games website (https://olympics/com).

Figure 2. Sex differences in world record performance for the sport of Weightlifting. Scatter and line plots display world record performances for males (blue circles) and females (red triangles) competing in the sport of Weightlifting across contemporary weight classes. Data extracted from publicly available data source associated with international sport organization (International Weightlifting Federation) accessed on 9 October 2024. Dagger symbol (†) denotes the largest weight class for males (greater than 109 kg) and females (greater than 87 kg).

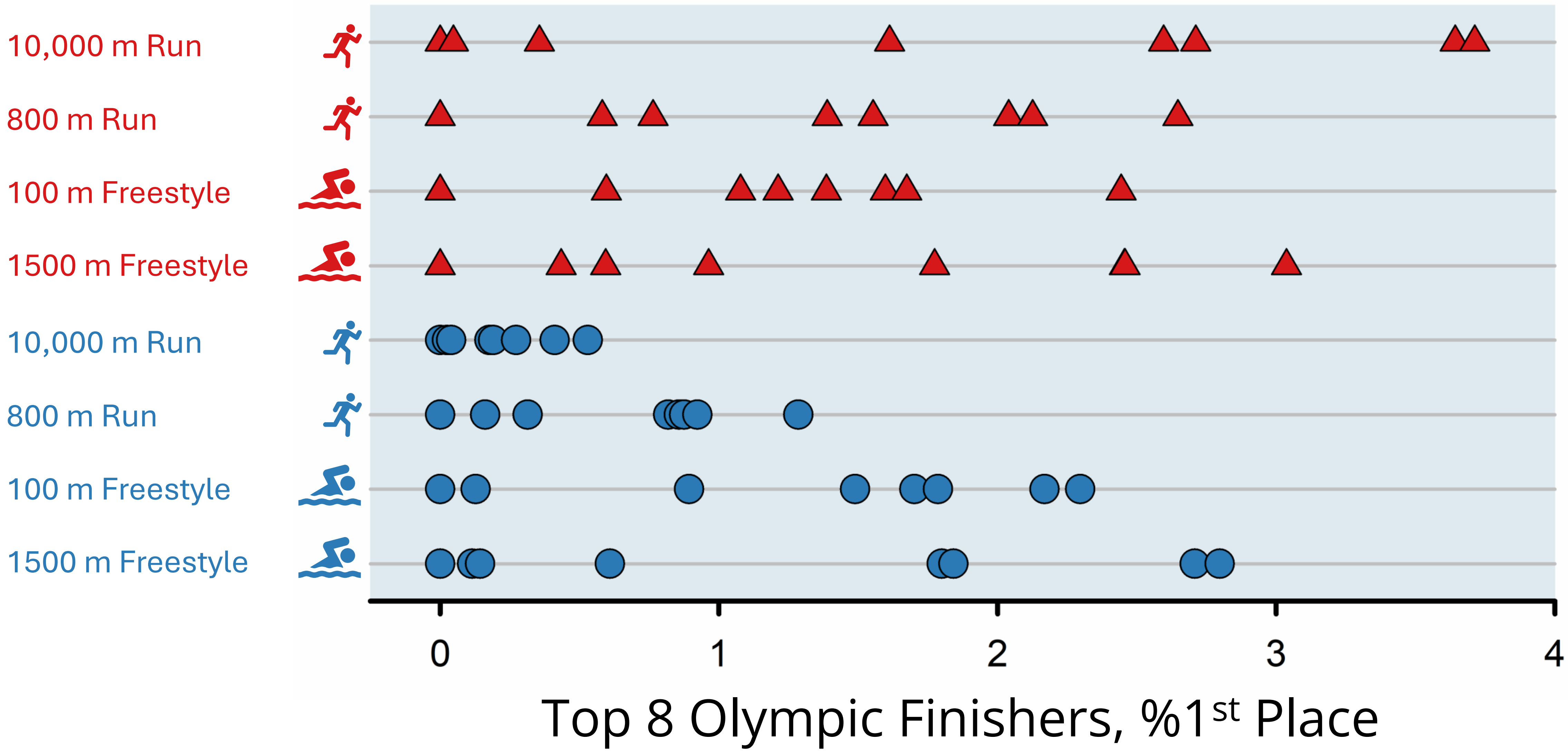
Figure 3. Male performance advantage in track and field events. Vertical bar charts display the average sex-based difference among the top 100 outdoor track and field performances of all-time. The blue vertical bars indicate the male performance advantage and represent the male level of performance relative to the female level of performance. The red vertical bars indicate the female level of performance (relative to itself) which is calculated to be 100%. This figure was generated using previously published data (6).

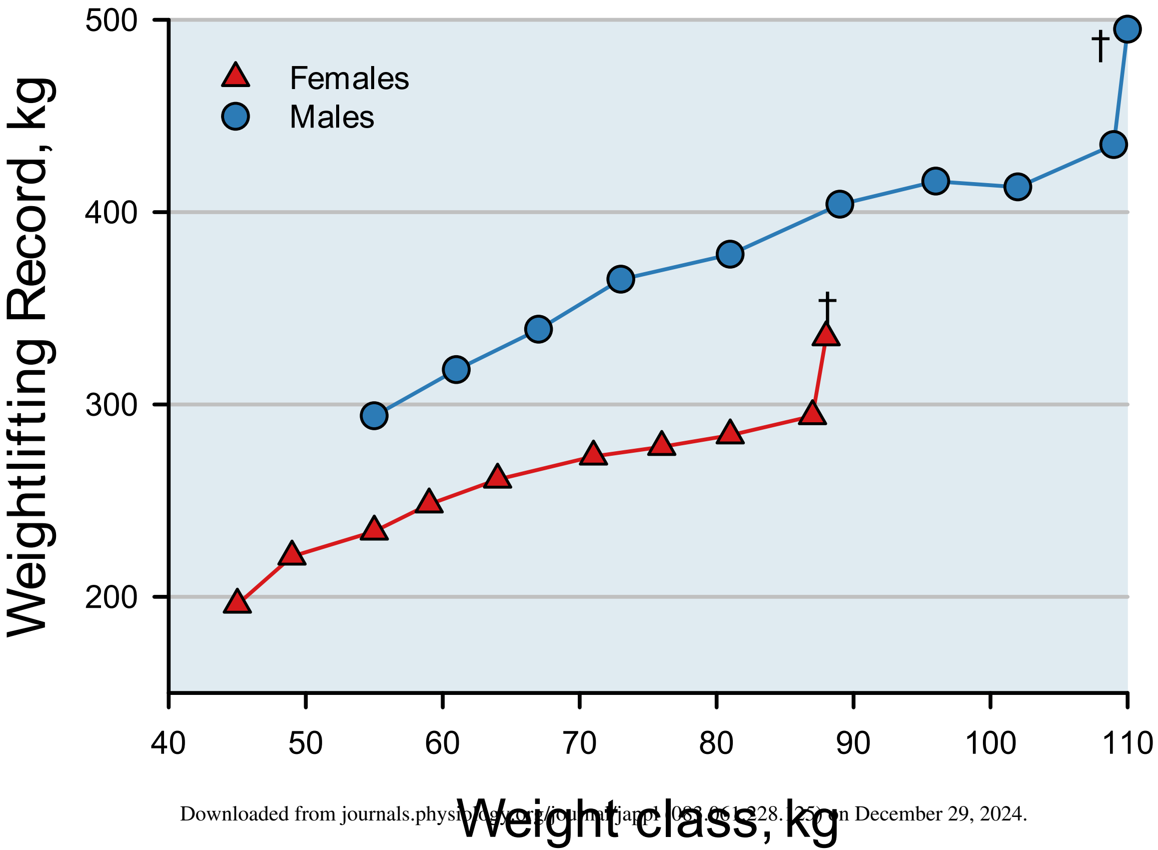
Figure 4. Sex differences in elite athletic performance across age among youths. Scatter and line plots display the male-female performance gap evident before ages of puberty and the increase in the male-female performance gap across youth years for track and field and freestyle swimming events among top competitors in the US. Symbols represent group means,

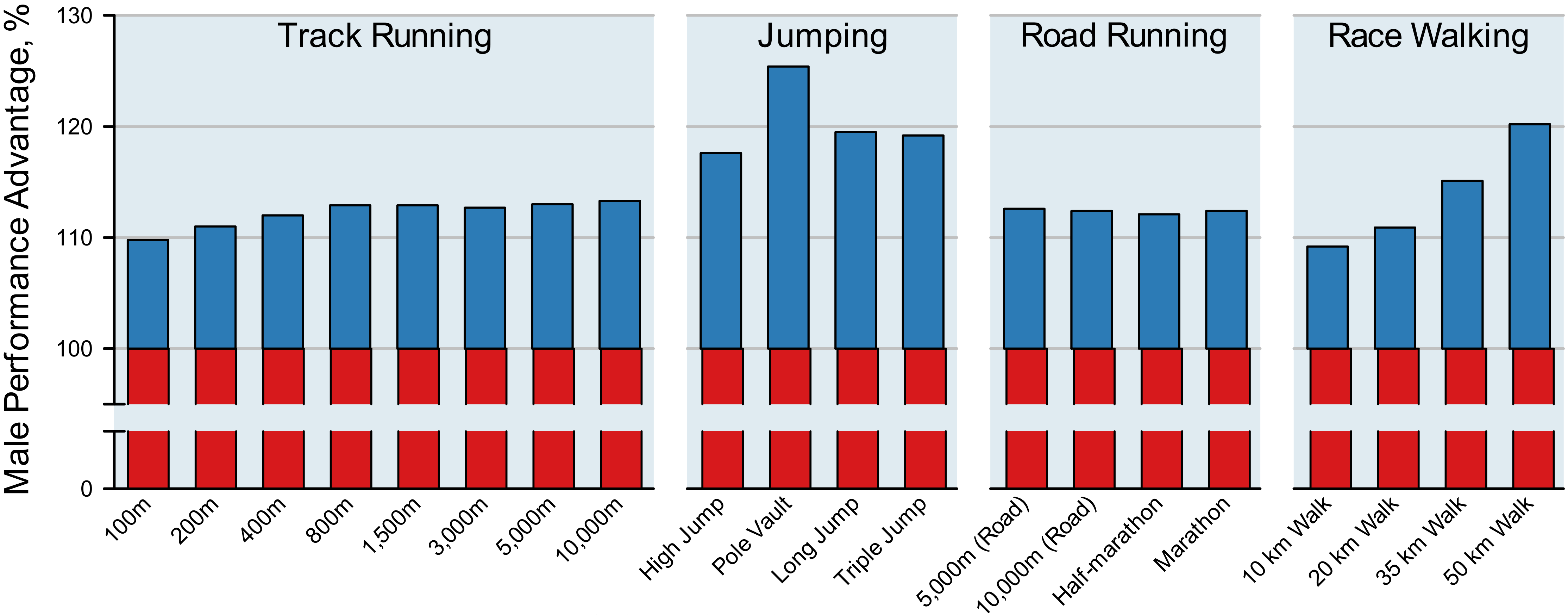
and the error bars represent standard error which are often not discernible due to large, homogenous samples. This figure was generated using previously published data (11, 13).

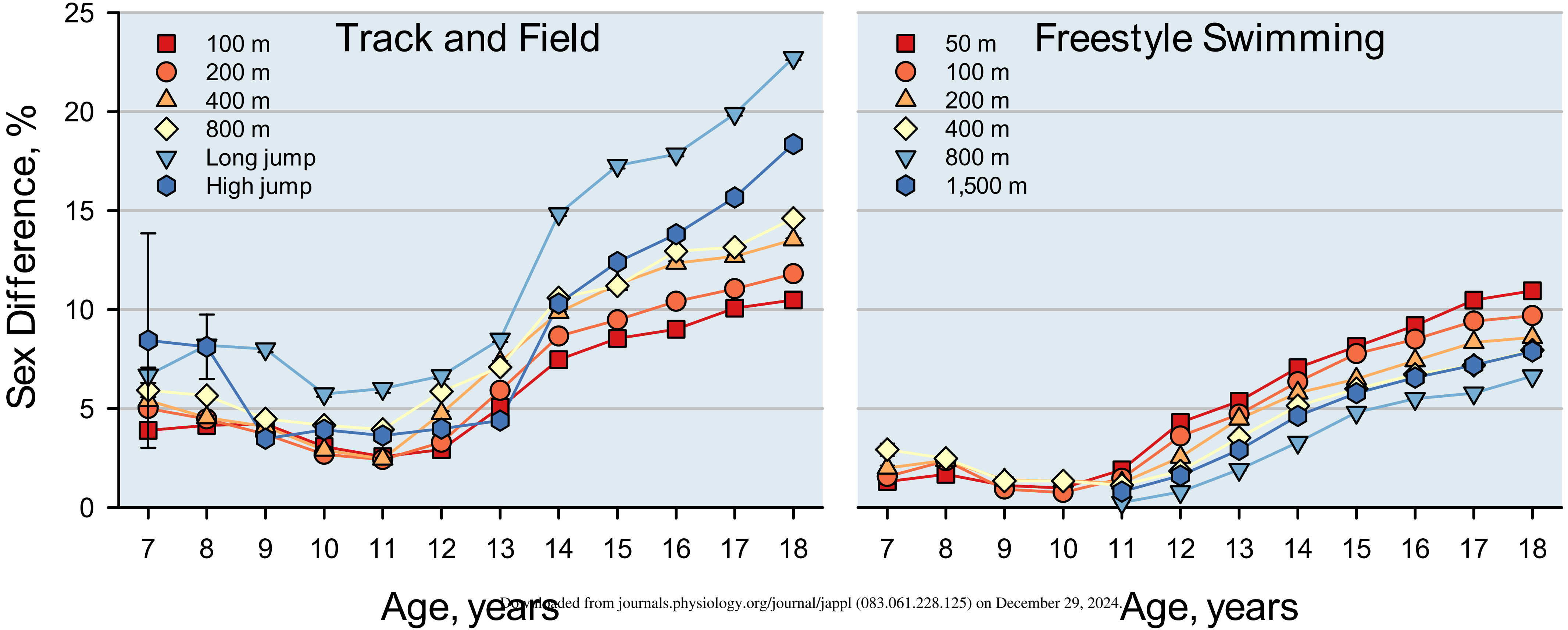
Figure 5. Sex differences in elite freestyle swimming performance across the lifespan. Blue scatter and line plot displays the increase in sex differences of the top 10 US freestyle swimming performances averaged across all contested event distances in long course meters, including 50, 100, 200, 400, 800, and 1,500 m events. This figure was generated using previously published data (7, 9, 13).

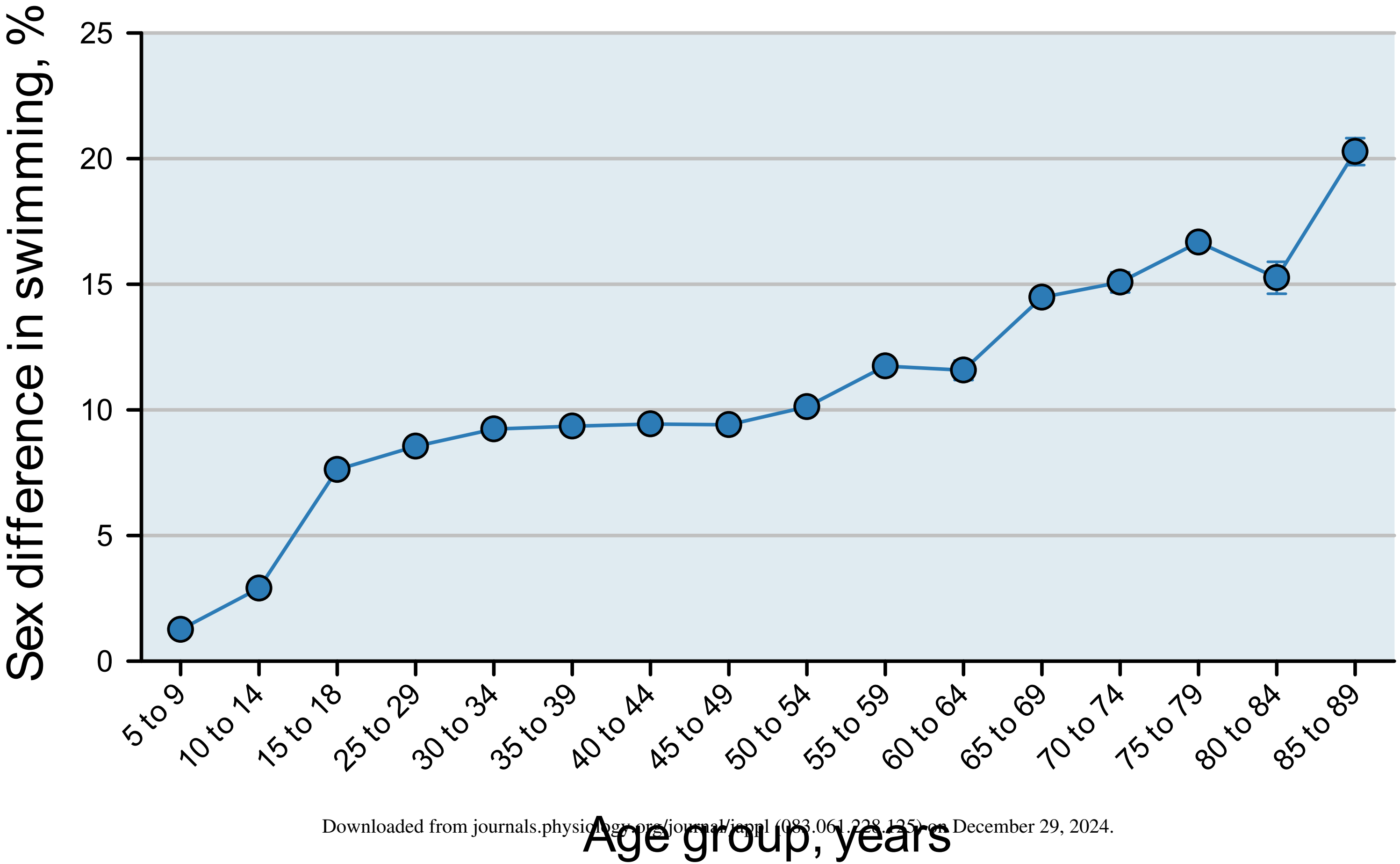
Figure 6. Physiological adaptations associated with testosterone suppression. Bar charts display lower handgrip strength (A and D), maximal aerobic capacity (B and E), and skeletal muscle mass (C and F) among XY transgender women (orange bars) compared to XY males not undergoing hormone therapy (blue bars). Comparator groups of XX females (red bars) had the lowest values for these physiological measurements. Panels A through C were generated using previously published data (55) representing 15 XY non-athletes after about 14 years of hormone therapy (including estrogen therapy and testosterone suppression) compared to 13 XY males and 14 XX females. Panels D through F were generated using previously published data (38) representing 23 XY transgender women athletes who were overweight or obese (on average) after an average of four years of hormone therapy (testosterone suppression with or without estrogen therapy), 37 XY male athletes, and 21 XX female athletes.

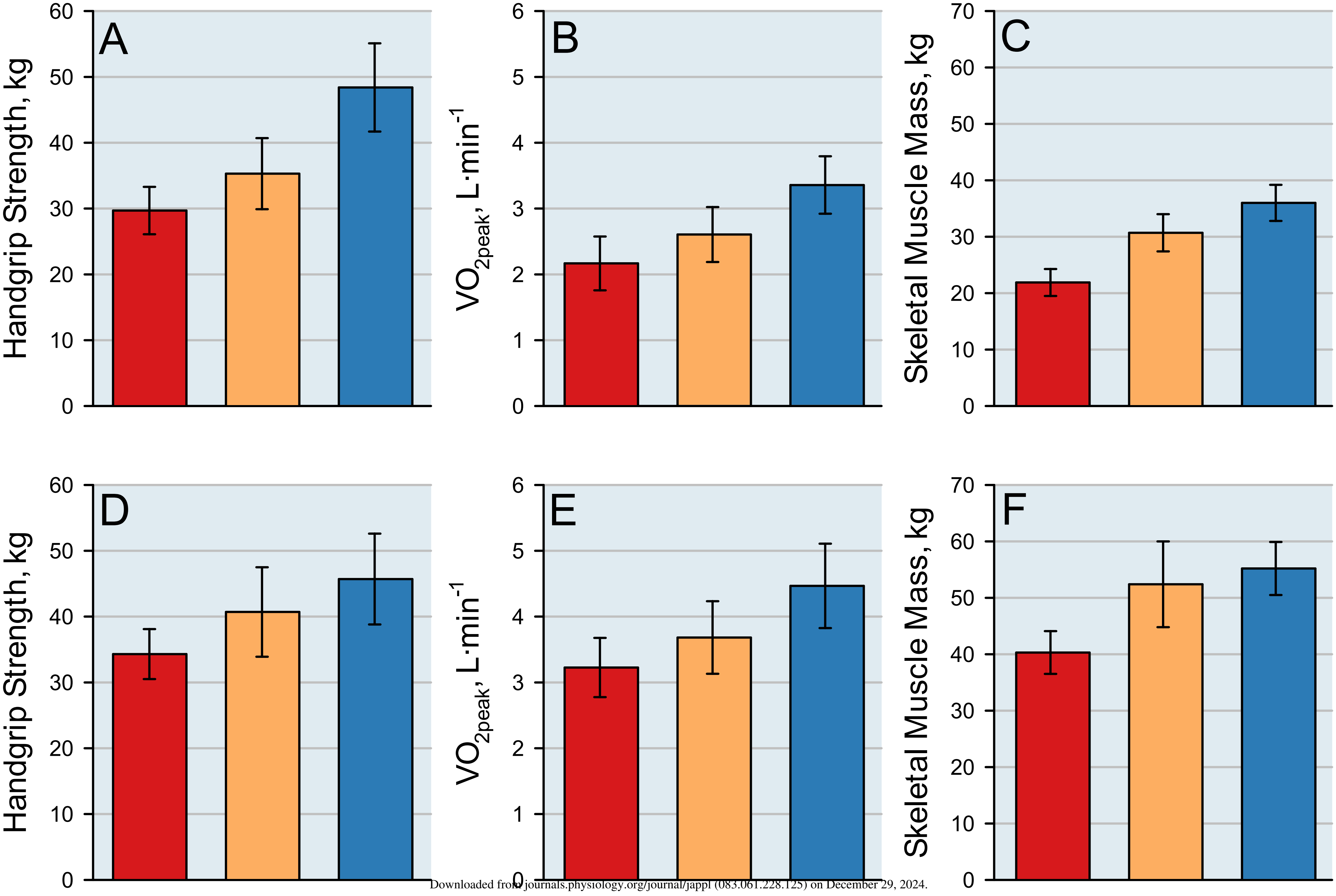

10,000 m Run
800 m Run
100 m Freestyle
1500 m Freestyle
10,000 m Run
800 m Run
100 m Freestyle
1500 m Freestyle
0
1
2
3
4
Top 8 Olympic Finishers, %1st Place


500
400
300
200
Weightlifting Record, kg
Females
Males
†
†
40
50
60
70
80
90
100
110
Weight class, kg


Male Performance Advantage, %
130
120
110
100
0
Track Running
Jumping
Road Running
Race Walking
100m
200m
400m
800m
1,500m
3,000m
5,000m
10,000m
High Jump
Pole Vault
Long Jump
Triple Jump
5,000m (Road)
10,000m (Road)
Half-marathon
Marathon
10 km Walk
20 km Walk
35 km Walk
50 km Walk

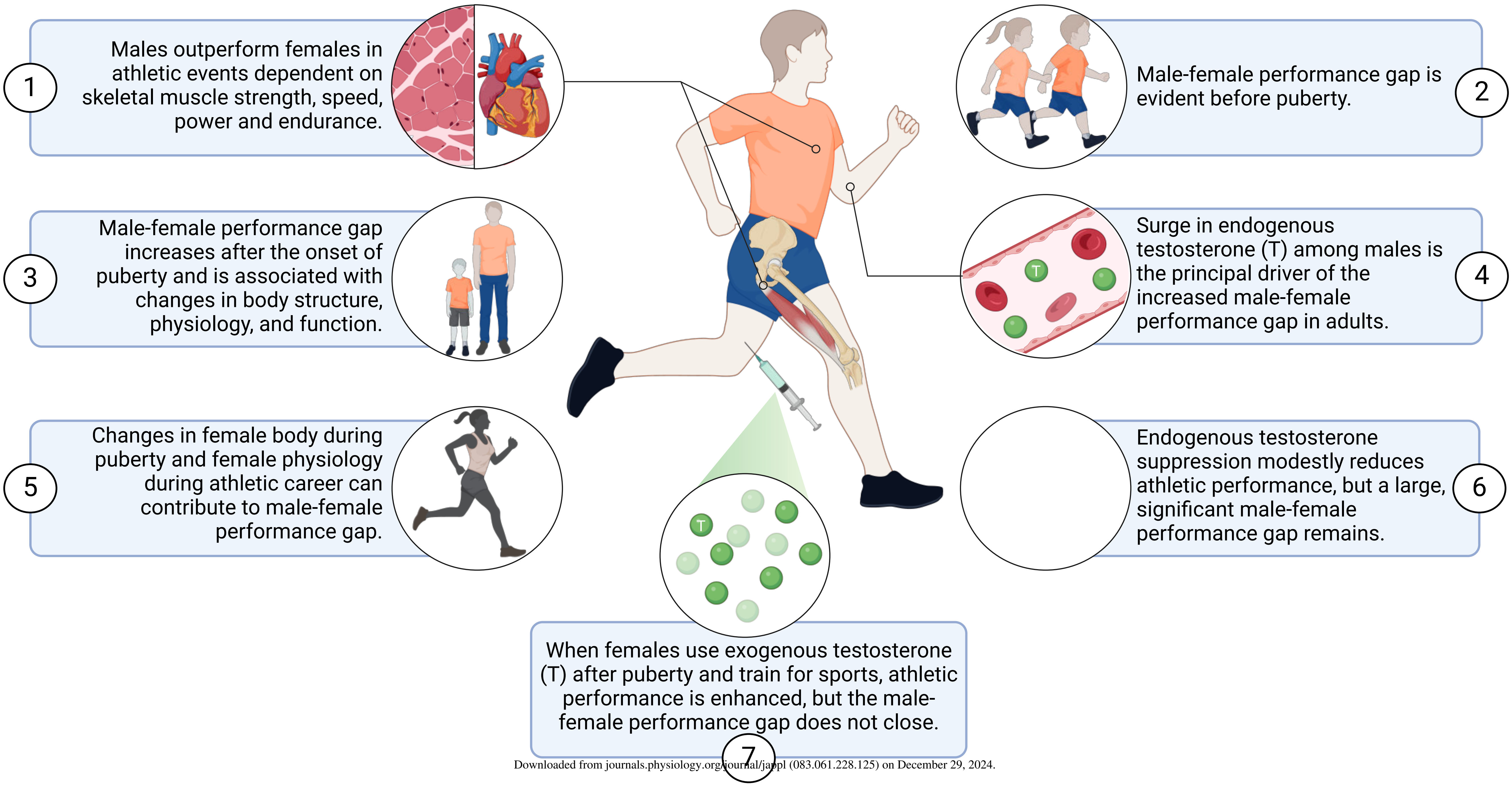

Track and Field
100 m
200 m
400 m
800 m
Long jump
High jump
Freestyle Swimming
50 m
100 m
200 m
400 m
800 m
1,500 m
Sex Difference, %
25
20
15
10
5
0
7
8
9
10
11
12
13
14
15
16
17
18
Age, years
Age, years


Sex difference in swimming, %
25
20
15
10
5
0
5 to 9
10 to 14
15 to 18
25 to 29
30 to 34
35 to 39
40 to 44
45 to 49
50 to 54
55 to 59
60 to 64
65 to 69
70 to 74
75 to 79
80 to 84
85 to 89
Age group, years


A
B
C
D
E
F
Handgrip Strength, kg
VO_{2peak}, L·min^{-1}
Skeletal Muscle Mass, kg
0
10
20
30
40
50
60
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70

Evidence on sex differences in sports performance

Impacts of sex chromosomes and hormones on limits of skeletal muscle performance



① Males outperform females in athletic events dependent on skeletal muscle strength, speed, power and endurance.

② Male-female performance gap is evident before puberty.

③ Male-female performance gap increases after the onset of puberty and is associated with changes in body structure, physiology, and function.

④ Surge in endogenous testosterone (T) among males is the principal driver of the increased male-female performance gap in adults.

⑤ Changes in female body during puberty and female physiology during athletic career can contribute to male-female performance gap.

⑥ Endogenous testosterone suppression modestly reduces athletic performance, but a large, significant male-female performance gap remains.

⑦ When females use exogenous testosterone (T) after puberty and train for sports, athletic performance is enhanced, but the male-female performance gap does not close.