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Strength, power and aerobic capacity of transgender athletes: a cross-sectional study

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Accepted 13 March 2024

ABSTRACT

Objective The primary objective of this cross-sectional study was to compare standard laboratory performance metrics of transgender athletes to cisgender athletes.

Methods 19 cisgender men (CM) (mean±SD, age: 37±9 years), 12 transgender men (TM) (age: 34±7 years), 23 transgender women (TW) (age: 34±10 years) and 21 cisgender women (CW) (age: 30±9 years) underwent a series of standard laboratory performance tests, including body composition, lung function, cardiopulmonary exercise testing, strength and lower body power. Haemoglobin concentration in capillary blood and testosterone and oestradiol in serum were also measured.

Results In this cohort of athletes, TW had similar testosterone concentration (TW 0.7±0.5 nmol/L, CW 0.9±0.4 nmol/), higher oestrogen (TW 742.4±801.9 pmol/L, CW 336.0±266.3 pmol/L, p=0.045), higher absolute handgrip strength (TW 40.7±6.8 kg, CW 34.2±3.7 kg, p=0.01), lower forced expiratory volume in 1 s:forced vital capacity ratio (TW 0.83±0.07, CW 0.88±0.04, p=0.04), lower relative jump height (TW 0.7±0.2 cm/kg; CW 1.0±0.2 cm/kg, p<0.001) and lower relative $\dot{V}O_2$max (TW 45.1±13.3 mL/kg/min/, CW 54.1±6.0 mL/kg/min, p<0.001) compared with CW athletes. TM had similar testosterone concentration (TM 20.5±5.8 nmol/L, CM 24.8±12.3 nmol/L), lower absolute hand grip strength (TM 38.8±7.5 kg, CM 45.7±6.9 kg, p=0.03) and lower absolute $\dot{V}O_2$max (TM 3635±644 mL/min, CM 4467±641 mL/min p=0.002) than CM.

Conclusion While longitudinal transitioning studies of transgender athletes are urgently needed, these results should caution against precautionary bans and sport eligibility exclusions that are not based on sport-specific (or sport-relevant) research.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ There is currently a lack of laboratory data on strength, power and $\dot{V}O_2$max from transgender athlete populations.

WHAT THIS STUDY ADDS

⇒ This research compares laboratory measures of strength, power and $\dot{V}O_2$max of transgender male and female athletes to their cisgender counterparts.
⇒ Transgender women athletes demonstrated lower performance than cisgender women in the metrics of forced expiratory volume in 1 s:forced vital capacity ratio, jump height and relative $\dot{V}O_2$max.
⇒ Transgender women athletes demonstrated higher absolute handgrip strength than cisgender women, with no difference found relative to fat-free mass or hand size.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE, OR POLICY

⇒ This study provides sport governing bodies with laboratory-based performance-related data from transgender athletes.
⇒ Longitudinal studies are needed to confirm if these results are a direct result of gender affirmation hormone therapy.
⇒ Sports-specific studies are necessary to inform policy-making.

INTRODUCTION

Transgender athletes can experience conflict between the gender that they were assigned and their experienced gender.[1] The question of integrating transgender athletes into their affirmed gender categories is becoming more prominent, with sports' governing bodies using varied approaches, from bans on transgender women in the female category[2] requiring the reduction of testosterone in the female category for some time[3] to self-identification into the athletes chosen category.[4]

As part of gender affirmation hormone therapy (GAHT), some transgender women undergo testosterone suppression (target ≤1.8 nmol/L[5]) coupled with oestrogen supplementation (target 400–600 pmol/L[5]), while some transgender men undergo testosterone supplementation (National Health Service (NHS, UK) target 15–20 nmol/L,[6] Endocrine Society Target 11–34.7 nmol/L[7]). Testosterone is known to impact sporting performances, with differences in circulating testosterone concentration between cisgender men (CM) and women proposed to explain most of the laboratory-measured differences in sports performance.[8 9] GAHT of transgender men and women alters the body composition of transgender athletes via testosterone-mediated effects on fat-free mass[8] and oestrogens on subcutaneous fat distribution[9] and maintenance of muscle mass.[10] An often-held assumption against transgender women athletes competing in the female category of sport is that transgender women have benefited from a high testosterone concentration from assigned male-at-birth puberty until the administration of GAHT that cannot be mitigated[11] and that cisgender

To cite: Hamilton B, Brown A, Montagner-Moraes S, *et al*. *Br J Sports Med* Epub ahead of print: [*please include* Day Month Year]. doi:10.1136/bjsports-2023-108029

women competitors are unable to achieve similar benefits naturally.[12] To date, this assumption has yet to be tested and confirmed in transgender athlete cohorts. The low serum testosterone concentrations from an assigned female-at-birth puberty would hypothetically not give transgender men the competitive advantages of higher testosterone concentrations over CM, and this viewpoint is reflected in the current inclusion sports policies for transgender men.[2]

Lab-derived data on a cohort of transgender athletes, as requested in article 6.1b of the International Olympic Committee Framework On Fairness, Inclusion And Non-Discrimination based on Gender Identity and Sex Variations,[4] must be generated to better inform a decision-making process.[13] Therefore, the primary aim of this study was to compare cardiorespiratory fitness, strength and body composition of transgender women and men athletes to that of matched cisgender cohorts.

METHODS

Study design

This cross-sectional study involved a single visit to the laboratory at the School of Applied Sciences, University of Brighton, UK. Each participant arrived at ~9:00 hours. after an overnight fast and departed from testing at ~15:00 hours. The complete study design can be found in the study protocol, available as a preprint.[14]

Recruitment

Following ethical approval (ref: 9496), 75 (19 CM, 12 transgender men, 23 transgender women and 21 cisgender women) participants were recruited through social media advertising on Meta Platforms (Facebook and Instagram, Meta Platforms, California, USA) and X (Twitter, California, USA). Following the initial response, all participants were provided with the participant information sheet by email at least 7 days before being invited to travel to the laboratory, with further oral information about the study procedures and written informed consent provided on their visit to the laboratory.

Participants and eligibility criteria

Participants were required to participate in competitive sports or undergo physical training at least three times per week. Following written consent, participants were asked to record their last four training sessions and self-rate their training intensity for each session on a scale of 1–10 (10=maximum intensity). The mean of the four sessions was recorded to represent the athletes' training intensity. The transgender athletes must have completed ≥1 year of GAHT, voluntarily disclosed during consent and verified during blood test analysis. The full inclusion/exclusion criteria can be found in the study protocol, available as a preprint.[14] Two cisgender women and one transgender man could not provide blood samples and were consequently excluded from all analyses as their endocrine profiles could not be verified. Furthermore, two transgender women and one cisgender woman were excluded from all analyses due to testosterone concentrations exceeding recommended female testosterone concentrations (2.7 nmol/L[15]).

Laboratory assessments

Blood sampling and analysis

Prior to venous blood sampling, haemoglobin concentration ((Hb)) was sampled via the third drop of a Unistik 3 Comfort lancet (Owen Mumford, Woodstock, UK) finger prick capillary blood sample analysed immediately using a HemoCue 201+ (HemoCue AB, Ängelholm, Sweden). Capillary blood was used for (Hb) analysis for practical reasons such as ease of use. It is important to note that the HemoCue 201+used in the present study is expected to yield higher (Hb) values than venous blood.[16] After capillary sampling, one 10 mL whole venous blood sample was collected from an antecubital vein into a BD serum tube (Becton, Dickinson and Company, Wokingham, Berkshire, UK) for serum extraction. Once collected, the tubes were left at room temperature (18°C±5°C) for 1 hour and then stored in a fridge (3°C±2°C) for up to 4 hours before being centrifuged (PK 120 centrifuge, ALC, Winchester, Virginia, USA) using a T515 rotor at 1300G for 10 min at 4°C, before storage at −80°C until analysis. Before analysis, the samples were stored between −25°C and −15°C, thawed at room temp until liquid, vortexing to remix samples, centrifuged at 2876G for 8 min to remove any precipitant and then analysed for participant's testosterone and oestradiol concentrations on an immunoassay analyser (Roche Cobas 8000 e801, Roche Diagnostics, Burgess Hill, UK).

Body composition and bone mass

Participants' body mass was measured (OMRON Healthcare, Kyoto, Japan) while participants were lightly dressed, representing clothed body mass. Body composition and bone mass were measured by DXA (Horizon W, Hologic, Massachusetts, USA). Each participant underwent a whole-body, a proximal-femur and a lumbar spine scan. The participant was asked to lie on the scan bed, and the first author (BH) performed all participant placement and scanning for the three scans. Due to inbuilt assumptions of body fat percentage for the head and scanning bed area imitations, whole-body less head data are reported for the whole-body scan. Body mass index (BMI), Fat Mass Index (FMI) and Fat-Free Mass Index (FFMI) were calculated by taking the appropriate mass value and dividing it by height (m^2).

Lung function

Lung function was measured using a Vitalograph Alpha spirometer (Vitalograph, Kansas, USA) with an antibacterial filter and a nose clip on the bridge of the participant's nose. Each participant was asked to perform the flow-volume-loop spirometry to test forced vital capacity (FVC), forced expiratory volume in 1 s (FEV_1) and peak expiratory flow. The test was repeated until a trend of declining performance occurred. The highest numeric value for each metric obtained during a test with the correct procedure was then recorded. The FEV1:FVC ratio was used to assess the presence of obstructed lung function.

Strength

Strength was measured using a handgrip dynamometer (TAKEI 5401, TAKEI Scientific Instruments, Japan). The participants' hand sizes were also measured around the metacarpophalangeal joints of both hands prior to testing. Each hand was tested three times in sequential order of left-right to allow each hand to rest; the mean scores were taken from the three attempts for each hand.

Lower body power

Lower body power was measured with the countermovement jump on a JUM001 Jump Mat (Probotics, Alabama, USA). During the test, if the participant went beyond 45° of countermovement or the hands came off the hips, the test would be declared void for that attempt. After recording three legitimate attempts, the mean scores were recorded.

Cardiopulmonary exercise testing

Cardiopulmonary exercise testing was performed using a 95T Engage Treadmill ergometer (Life Fitness, Illinois, USA) and a COSMED QUARK (COSMED, Rome, Italy). All $\dot{V}O_2$max tests were conducted and analysed by the first author (BH) to avoid interinvestigator variability.[17] The ramp protocol of Badawy and Muaidi treadmill $\dot{V}O_2$max testing[18] was used for each $\dot{V}O_2$max test, involving gradual increases in speed every 3 min at a 1% incline. One cisgender man and two cisgender women were excluded from the analysis as they did not meet the required respiratory exchange ratio of ≥1.1 to classify the test as maximal (cisgender men (CM), n=18, transgender men (TM), n=11; cisgender women (CW) n=16; transgender women (TW), n=21).

Statistical analysis

Data meeting the assumptions of normality and homogeneity of variance were analysed using a one-way analysis of variance along with Bonferroni post hoc corrections for pairwise comparisons. Data not meeting the parametric assumptions were compared using a Kruskal-Wallis ANOVA with Dwass-Steel-Critchlow-Fligner post hoc test for multiple comparisons, with an alpha level of 0.05 for both types of analysis. Statistical analysis and presentation are consistent with the checklist for statistical assessment of medical papers statement[19] found in online supplemental files 1–3 at Hamilton *et al*, The Strength, Power and Aerobic Capacity of Transgender Athletes: A Cross-Sectional Study (Internet). OSF; 2023. Available from: osf.io/a684b.

Equity, diversity and inclusion statement

The author group consists of early (n=3) and senior researchers (n=3) from different disciplines and universities (n=3). Two authors are members of a marginalised community; the lead early-career author is a transgender woman, and one of the junior authors is a woman from the global south. Our study population included male and female transgender athletes from within the UK participating in competitive sports in comparison with cisgender male and female athletes participating in competitive sports; thus, findings may not be generalisable to global athlete populations.

RESULTS

Participant characteristics

Our investigation encompassed a diverse cohort of athletes, with endurance sports representing 36% of the athlete cohort, team sports representing 26% and power sports representing 38%. No cisgender or transgender athletes were competing at the national or international level. No significant differences were found in age ($F_{(3–66)}$=1.9, p=0.14), training intensity score ($\chi^2_{(3)}$=1.2, p=0.76) or length of GAHT between transgender men and transgender women ($F_{(1–32)}$=0.5, p=0.48,table 1).

Significant differences were found in height ($F_{(3–66)}$=21.3, p<0.001), with CM being taller than transgender men ($t_{(66)}$=3.8, p=0.002, table 1). Transgender women were also taller than transgender men ($t_{(66)}$=3.3, p=0.01) and cisgender women ($t_{(66)}$=6.5, p<0.001, table 1).

Significant differences were found in clothed mass ($F_{(3–66)}$=10.6, p<0.001), with transgender women found to be heavier than cisgender women ($t_{(66)}$=5.6, p<0.001, table 1).

BMI was also significantly different between the groups in this Study ($F_{(3–66)}$=3.6, p=0.02). Transgender women athletes demonstrated higher BMI than cisgender women ($t_{(66)}$=2.9, p=0.03, table 1), with no further differences observed.

Blood measures

There was a significant gender effect on testosterone concentration ($F_{(3–66)}$=80.6, p<0.001). CM (20.5±5.8 nmol/L) exhibited significantly higher total testosterone concentration than transgender women (0.7±0.5 nmol/L, $t_{(66)}$= 11.1, p<0.001, figure 1A). Transgender men (24.8±12.3 nmol/L) had elevated total testosterone concentration compared with transgender women ($t_{(66)}$=11.3) and cisgender women (0.9±0.4 nmol/L, $t_{(66)}$=10.9, both p<0.001, figure 1A). There was also a significant gender effect on oestradiol concentration ($F_{(3–66)}$=7.6, p<0.001), with transgender women (742.4±801.9 pmol/L) showing higher oestradiol concentration than CM (104.3±24.8 pmol/L, $t_{(66)}$=4.4 p<0.001), cisgender women (336.0±266.3 pmol/L, $t_{(66)}$=2.7, p=0.045) and transgender men (150.2±59.4 pmol/L, $t_{(66)}$=3.4, p=0.01, figure 1B).

Transgender women's total testosterone concentration (0.7±0.5 nmol/L) falls within the recommendations for GAHT of ≤1.8 nmol/L,[5] and oestradiol concentrations (742.4±801.9 pmol/L) exceed the target of 400–600 pmol/L[5] for GAHT. Transgender men's testosterone concentration (24.8±12.3 nmol/L) exceeds the NHS target of 15–20 nmol/L[6] for GAHT, although not the Endocrine Society target of 11–34.7 nmol/L.[7]

Differences were reported in (Hb) concentration ($F_{(3–66)}$=3.3, p=0.03), although a post hoc Bonferroni analysis showed no differences between the various groups (CM 142.8±12.5 g/L; transgender men, 143.3±19.5 g/L; transgender women, 131.3±14.2 g/L; cisgender women, 133.3±12.7 g/L; figure 1C).

DXA assessment

Fat mass

There was a significant gender effect on percentage fat mass ($F_{(3–66)}$=6.6, p<0.001), with CM having a lower percentage fat

Table 1 Participant characteristics

	Cisgender men (n=19)	Transgender men (n=12)	Cisgender women (n=21)	Transgender women (n=23)
Age (years)	37±9	34±7	30±9	34±10
Training intensity	7 (IQR 2)	7 (IQR 2)	7 (IQR 2)	7 (IQR 2)
Length of GAHT (years)	–	4±5	–	6±4
Height (m)	1.8±0.1*	1.7±0.1†‡	1.6±0.1	1.8±0.1*
Clothed mass (kg)	76.4±7.7*	73.1±12.1	60.6±6.6	83.9±19.9*
BMI (kg/m^2)	23.6±1.8	25.7±3.9	22.5±1.9	26.2±6.0*

Data represents mean±SD or median (IQR).
*Denotes significantly different from cisgender women.
†Denotes significantly different from cisgender Men.
‡Denotes significantly different from transgender women.
BMI, body mass index; GAHT, gender affirmation hormone therapy.

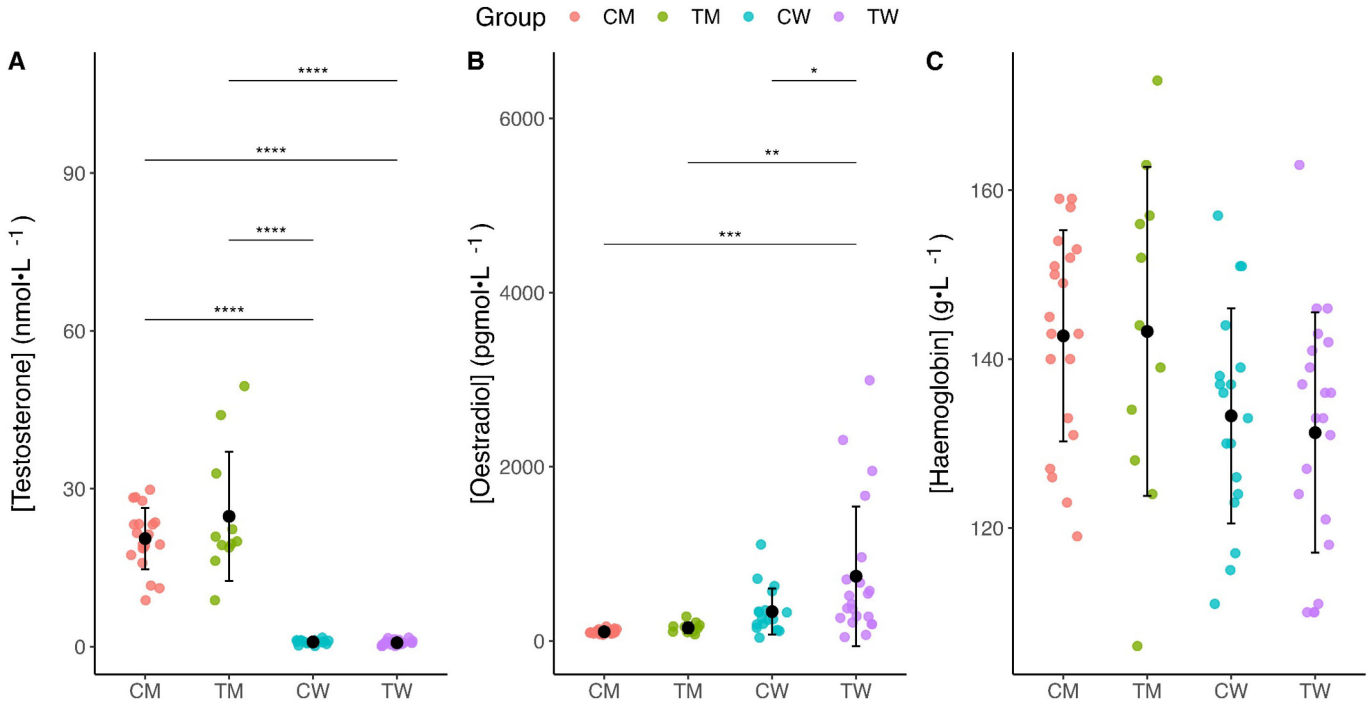

Figure 1 Blood measures. (A) testosterone; (B) oestradiol; (C) haemoglobin. *p<0.05, **p<0.01, ***p<0.001, ****p<0.0001. CM, cisgender men; CW, cisgender women; TM, transgender men; TW, transgender women.

mass than transgender women ($t_{(66)}$=−4.4, p<0.001, table 2), with no other differences observed. A significant gender effect was also found on absolute fat mass ($F_{(3–66)}$=6.6, p<0.001), with transgender women having more absolute fat mass than CM ($t_{(66)}$=3.8, p=0.002, table 2) and cisgender women ($t_{(66)}$=3.9, p=0.002, table 2). FMI measures revealed a gender effect ($F_{(3–66)}$=5.2, p=0.003), with transgender women found to have a higher FMI than CM ($t_{(66)}$=3.7, p=0.002, table 2) and cisgender women ($t_{(66)}$=2.8, p=0.04, table 2). Android to gynoid ratio analysis ($F_{(3–66)}$=10.7, p<0.001) revealed cisgender women had a lower ratio than transgender men ($t_{(66)}$=−2.9, p=0.03, table 2), and transgender women ($t_{(66)}$=−4.0, p=0.001, table 2).

Fat-free mass

There was a significant gender effect on absolute fat-free mass ($F_{(3–66)}$=24.6, p<0.001), with CM having significantly more absolute fat-free mass than transgender men ($t_{(66)}$=3.5, p=0.01, table 2). Cisgender women had less absolute fat-free mass than transgender men ($t_{(66)}$=−3.5, p=0.01, table 2) and transgender women ($t_{(66)}$=−6.6, p<0.001, table 2). No gender-based effects were found when comparing transgender women athletes to cisgender women athletes, or transgender men athletes to CM athletes in the measures of FFMI ($F_{(3–66)}$=3.7, p=0.02, table 2), percentage of fat-free mass ($F_{(3–66)}$=2.4, p=0.08, table 2) or appendicular FFMI ($F_{(3–66)}$=5.1, p=0.003, table 2).

Bone mineral density

No differences in whole-body bone mineral density (BMD) ($F_{(3–66)}$=4.6, p=0.01), femoral neck BMD ($F_{(3–66)}$=1.0, p=0.39, table 2), total proximal femur BMD ($F_{(3–66)}$=1.5, p=0.22, table 2) or total lumbar spine BMD ($F_{(3–66)}$=0.4, p=0.78, table 2) were found between transgender athletes and cisgender athletes (table 2).

Lung function

Lung function data for all groups can be found in table 2. FEV_1 had an effect of gender ($F_{(3–66)}$=14.7, p<0.001), with CM having greater FEV_1 than transgender men ($t_{(66)}$ = 4.5, p<0.001, figure 2A). Transgender women also had greater FEV_1 than cisgender women ($t_{(66)}$=4.2, p<0.001, figure 2A) and transgender men ($t_{(66)}$=2.9, p=0.03, figure 2A). There was a similar effect of gender on FVC ($F_{(3–66)}$=21.6, p<0.001, figure 2B), with CM having greater FVC than transgender men ($t_{(66)}$=5.2, p<0.001, figure 2B). Transgender women also had greater FVC than cisgender women ($t_{(66)}$=5.6, p<0.001, figure 2B) and transgender men ($t_{(66)}$=4.0, p=0.001, figure 2B). A significant effect of gender was also seen on the FEV_1:FVC ratio ($F_{(3–66)}$=3.3, p=0.03 figure 2C), with transgender women showing a reduced FEV_1:FVC ratio compared with cisgender women ($t_{(66)}$=−2.8, p=0.04, figure 2C) with no differences observed in transgender or CM. Peak expiratory flow ($F_{(3–66)}$=5.5, p=0.002) had a minor gender-based effect, with cisgender women having lower peak expiratory flow than transgender women ($t_{(66)}$−3.0, p=0.02, figure 2D).

Handgrip strength

Handgrip strength data can be found in table 2. Absolute right handgrip strength was significantly different between the groups ($F_{(3–66)}$=10.5, p<0.001), with CM having greater absolute right handgrip strength than transgender men ($t_{(66)}$=2.9, p=0.03, figure 3B). Transgender women also had greater absolute right handgrip strength than cisgender women ($t_{(66)}$=3.2, p=0.01, figure 3B). Absolute left handgrip was significantly different between the groups ($F_{(3–66)}$=8.6, p<0.001). However, no differences were found between transgender and cisgender athletes (figure 3A). There was no effect on the right ($F_{(3–66)}$=0.8, p=0.53, figure 3F) or left-hand grip strength ($F_{(3–66)}$=1.0, p=0.39, figure 3E) relative to fat-free mass, nor was there any gender

Table 2 Body composition, BMD data, handgrip strength, lower anaerobic power and cardiopulmonary exercise testing

	Cisgender men	Transgender men	Cisgender women	Transgender women
Fat mass				
Fat mass (%)	21.5±5.9	27.9±7.4	26.6±6.0	31.5±9.1*
Absolute fat mass (kg)	15.4±5.5	19.3±8.1	15.0±4.6	25.8±13.2†*
Fat Mass Index (kg/m^2)	4.8±1.6	6.8±2.8	5.5±1.6	8.2±4.5†*
Android to gynoid ratio	1.05±0.17	0.95±0.14†	0.78±0.08*	0.97±0.17†
Fat-free mass				
Fat-free mass (%)	73±10	66±6	65±15	67±6
Absolute fat-free mass (kg)	55.2±4.7	47.8±5.6*	40.3±3.8*	52.4±7.6†
Fat-free mass index (kg/m^2)	17.1±2.0	16.9±1.9	15.0±1.2*	16.4±2.7
Appendicular fat-free mass index (kg/m^2)	8.6±1.1	8.2±1.2	7.2±0.6*	8.0±1.3
BMD (g/cm^2)				
Whole body less head	1.22±0.10	1.15±0.10	1.10±0.08*	1.17±0.13
Femoral neck	0.95±0.14	0.93±0.14	0.87±0.11	0.92±0.13
Total proximal femur	1.07±0.11	1.05±0.13	0.99±0.10	1.03±0.14
Total lumbar spine	1.08±0.12	1.11±0.14	1.08±0.12	1.06±0.14
Lung function				
FEV_1 (L)	4.5±0.6	3.6±0.5‡*	3.5±0.4‡*	4.2±0.6
FVC (L)	5.4±0.7	4.1±0.6‡*	3.9±0.5‡*	5.1±0.6
FEV_1:FVC ratio	0.84±0.05	0.87±0.04	0.88±0.04‡	0.83±0.07
PEF (L/min^1)	518±92†	427±98	412±79	506±113†
Handgrip strength				
Absolute right handgrip (kg)	45.7±6.9	38.8±7.5‡*	34.3±3.8‡*	40.7±6.8
Relative right handgrip to hand size (kg/cm)	0.1±0.0	0.1±0.0	0.1±0.0	0.1±0.0
Relative right handgrip to fat-free mass (kg/kg^{FFM})	0.8±0.1	0.8±0.1	0.8±0.2	0.9±0.1
Lower body anaerobic power				
Absolute countermovement jump (cm)	46.4±6.7	43.5±7.9	40.7±5.8	36.4±7.9*
Relative countermovement jump to fat-free mass (cm/kg^{FFM})	0.8±0.1†	0.9±0.2‡	1.0±0.2‡	0.7±0.2
Absolute peak power (W)	6810±681†	6560±712†	5655±588	6486±865†
Relative peak power to fat-free mass (W/kg^{FFM})	124±16	138±13	141±14*	126±22
Absolute average power (W)	1078±364†	1036±397†	580±311	899±460
Relative average power to fat-free mass (W/kg^{FFM})	20±7	21±7	14±7	17±9
Cardiopulmonary exercise testing				
Absolute VO_2max (mL/min)	4467±641	3635±644*	3226±450*	3682±551*
Relative VO_2max to mass (mL/kg/min)	59.1±8.4‡	50.1±11.5	54.1±6.0‡	45.1±7.6
Relative VO_2max to FFM (mL/kg^{FFM}/min)	81.1±14.4	76.2±12.0	80.0±8.8	71.7±15.2
Anaerobic threshold (%VO_2max)	88.1±8.7	85.2±6.1	87.3±6.3	85.1±6.2

Data represent mean±SD.
Data from transgender and cisgender athletes.
*Denotes significantly different from cisgender men.
†Denotes significantly different from cisgender women.
‡Denotes significantly different from transgender women.
BMD, bone mineral density; VO_2max, maximal O_2 uptake.;

effect on the right ($F_{(3-66)}$=1.6, p=0.20, figure 3D) or left-hand grip-strength ($F_{(3-66)}$=2.1, p=0.11) relative to hand size.

Lower body anaerobic power

Lower body anaerobic power data are shown in table 2. Gender had a significant effect on absolute countermovement jump height ($F_{(3-66)}$=7.2, p<0.001), with CM having greater absolute jump height than transgender women ($t_{(66)}$=4.5, p<0.001, figure 4A). A significant effect of gender was found in countermovement jump height relative to fat-free mass ($F_{(3-66)}$=10.1, p<0.001, figure 4B), with transgender women found to have lower countermovement jump height relative to fat-free mass than both cisgender women ($t_{(66)}$=−5.3, p<0.001) and transgender men ($t_{(66)}$=−3.2, p=0.01, figure 4B).

There was a significant difference in absolute peak power ($F_{(3-66)}$=8.7, p<0.001), with cisgender women having reduced peak power compared with transgender men ($t_{(66)}$=−3.3, p=0.01) and transgender women ($t_{(66)}$=−3.6, p=0.004, figure 4C). Peak power relative to fat-free mass had a more negligible gender effect ($F_{(3-66)}$=4.2, p=0.01), with no difference in peak power relative to fat-free mass found between transgender and cisgender athletes (figure 4D).

There was a significant gender effect of absolute average power ($F_{(3-66)}$=5.9, p=0.001), with cisgender women having reduced absolute average power compared with transgender men ($t_{(66)}$=−3.1, p=0.02, figure 4E). There was no effect of gender on average power relative to fat-free mass ($F_{(3-66)}$=2.6, p=0.06, figure 4F).

Cardiopulmonary exercise testing

Cardiopulmonary exercise testing data are shown in table 2. A significant effect of gender was found on absolute $\dot{V}O_2$max

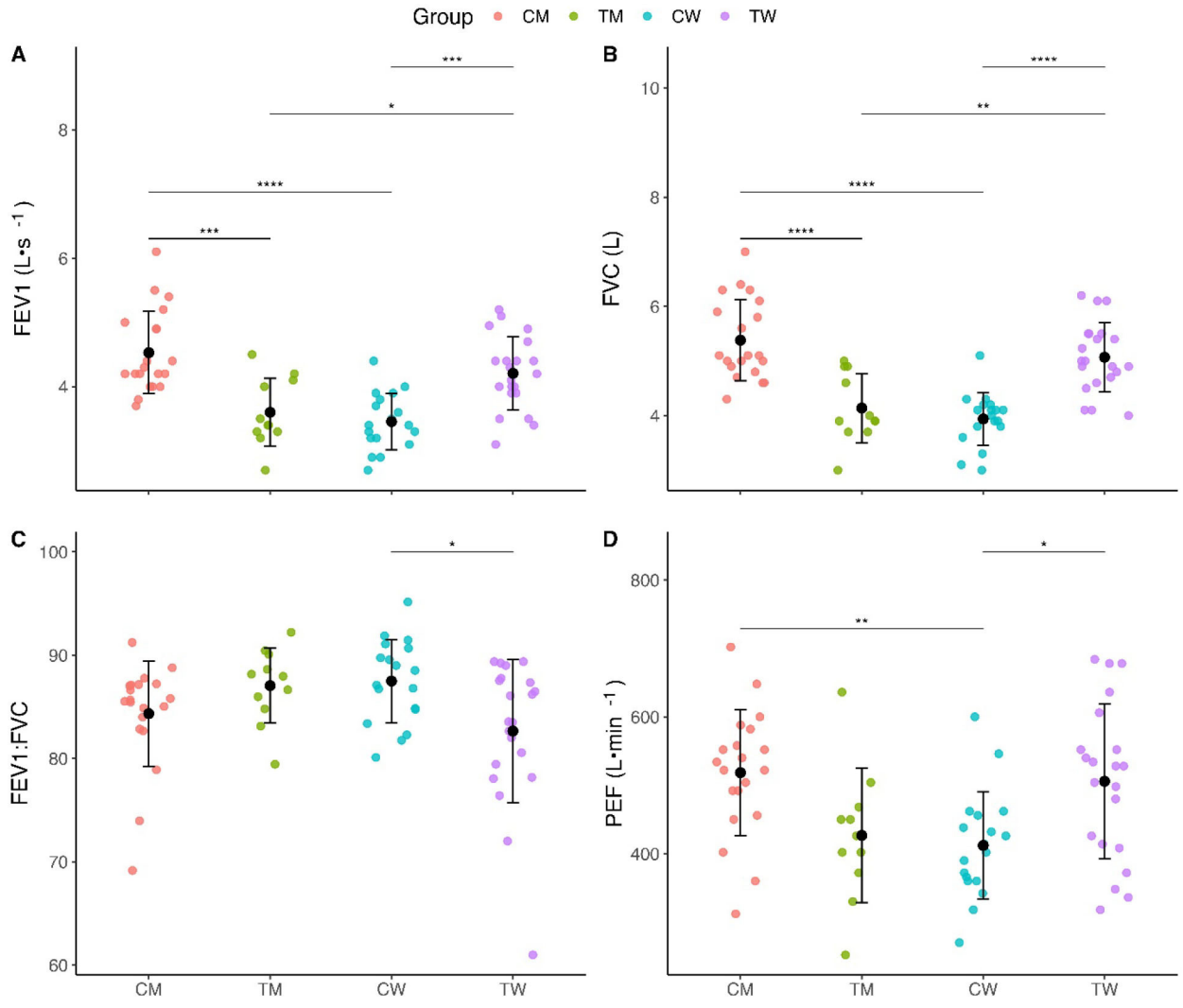

Figure 2 Lung function measures. (A) Forced rxpiratory volume in 1 s (FEV_1); (B) forced vital capacity (FVC) (C) modified Tiffeneau-Pinelli Index (FEV_1:FVC); (D) peak expiratory flow (PEF). *p<0.05, **p<0.01, ***p<0.001, ****p<0.0001. CM, cisgender men; CW, cisgender women; TM, transgender men; TW, transgender women.

($F_{(3-62)}$=14.1, p<0.001) with CM having greater absolute $\dot{V}O_2$max than transgender men ($t_{(66)}$=3.8, p=0.002, figure 5A) and transgender women ($t_{(66)}$=4.3, p<0.001, figure 5A). Relative $\dot{V}O_2$max to body mass also showed a significant gender effect ($F_{(3-62)}$=9.8, p<0.001) with transgender women having lower relative $\dot{V}O_2$max than CM ($t_{(66)}$=−5.3, p<0.001, figure 5B) and cisgender women ($t_{(66)}$=−3.3, p=0.01, figure 5B). No significant gender effect was found on the measure of $\dot{V}O_2$max relative to fat-free mass ($F_{(3-62)}$=2.0, p=0.12).

Gender affected the absolute anaerobic threshold ($F_{(3-62)}$=14.1, p<0.001), with cisgender (3924±628 mL/min) men having a higher absolute anaerobic threshold than transgender men (3089±546 mL/min, $t_{(66)}$=4.2, p<0.001, figure 5C), and transgender women (3122±438 mL/min, $t_{(66)}$=4.8, p<0.001, figure 5C). No significant gender effect was found on the measure of anaerobic threshold as a percentage of $\dot{V}O_2$max ($F_{(3-62)}$=0.8, p=0.51, figure 5D). A gender effect was also seen on the anaerobic threshold relative to body mass ($F_{(3-62)}$=10.7, p<0.001), with transgender women (38.3±6.6 mL/kg/min) showing a lower relative anaerobic threshold than both cisgender women (47.2±6.1 mL/kg/min, $t_{(66)}$=−3.3, p=0.01, figure 5E) and CM (52.2±9.5 mL/kg/min, $t_{(66)}$=−5.4, p<0.001, figure 5E). CM also showed a higher relative anaerobic threshold than transgender men (42.1±9.9 mL/kg/min, $t_{(66)}$=3.3, p=0.01, figure 5E). Anaerobic threshold relative to fat-free mass also had a small gender effect ($F_{(3-62)}$=3.2, p=0.03), with transgender women (60.8±12.2 mL/kg^{FFM}/min) having a lower anaerobic threshold relative to fat-free mass than CM (71.2±13.3 mL/kg^{FFM}/min, $t_{(66)}$=−2.8, p=0.045, figure 5F).

DISCUSSION

The results presented in this study provide valuable insights into laboratory-based performance-related metrics of gender-diverse athletes participating in competitive sports. Given the primary aim of GAHT,[20] it is noteworthy that although this study is cross-sectional in design, transgender women's oestradiol was higher than that of cisgender women (figure 1B). The presence of outliers affecting transgender women's oestrogen concentration (figure 1B) is evident. This underscores that transgender women in this cohort of athletes exhibit a distinct endocrine profile from CM and share a similar endocrine profile with cisgender women, whom many transgender women aim to integrate into a sporting category. One of the most noticeable disparities between gender groups was in height and mass (table 1), with CM and transgender women

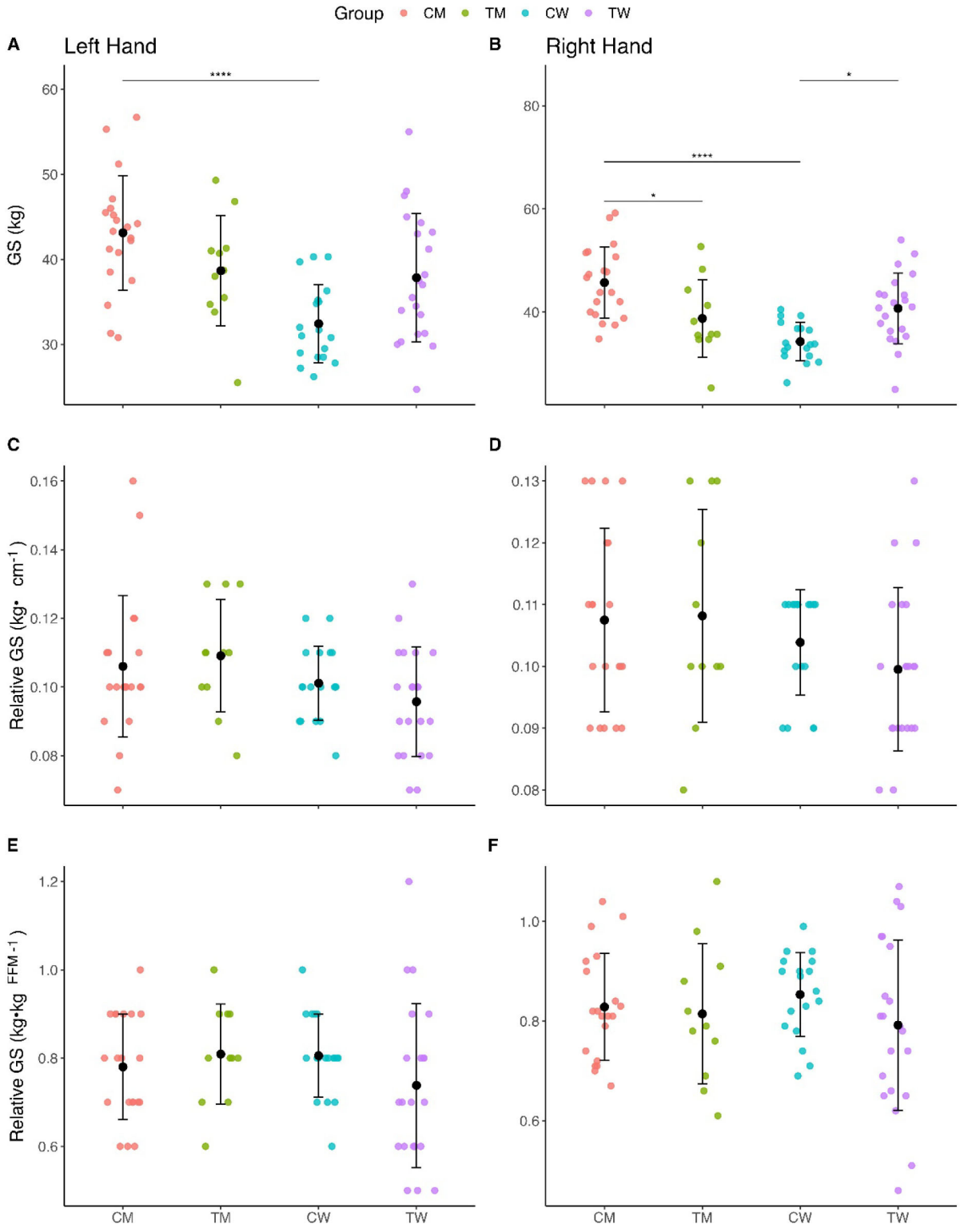

Figure 3 Absolute and relative handgrip strength (GS) measures. (A) Absolute strength (right hand); B) Absolute strength (left hand) (C) relative strength to hand size (right hand); (D) relative strength to hand size (left hand); (E) relative strength to fat-free mass (FFM) (right hand); (F) relative strength to fat-free mass (left hand). *p<0.05, ***p<0.001, ****p<0.0001. CM, cisgender men; CW, cisgender women; TM, transgender men; TW, transgender women.

being taller and heavier than their cisgender and transgender counterparts (table 1). Body composition measures (fat mass % and fat-free mass %, table 2) between transgender women and cisgender women found no difference. However, transgender women are, on average as a cohort taller and heavier.

In this cohort, the average difference in haemoglobin (Hb) between cisgender women and CM athletes was 7% (figure 1C), lower than previously described (12%[8]). Notably, the (Hb) profiles of all the athlete groups were not significantly different, concurring with earlier research[21] and contradicting research in

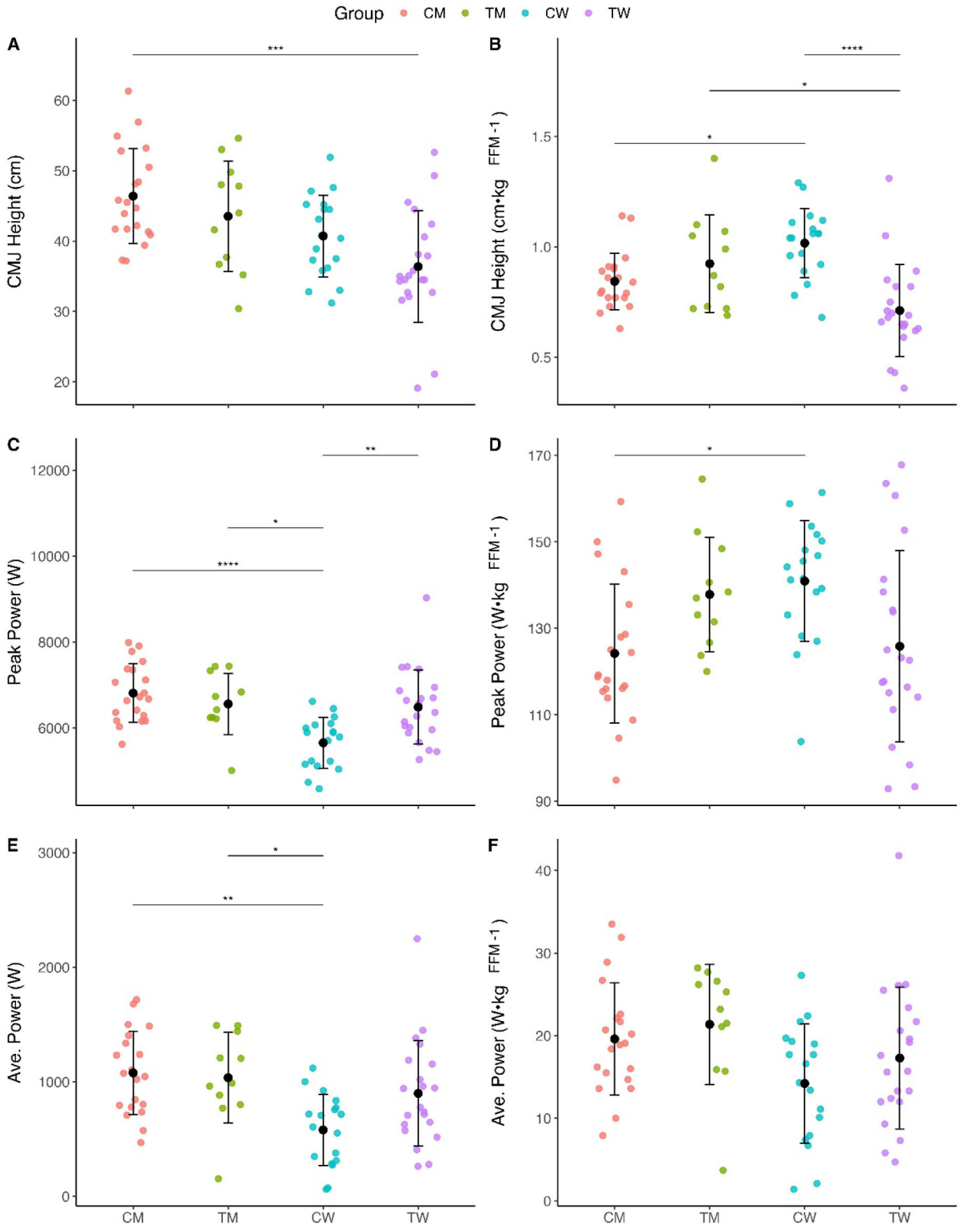

Figure 4 Absolute and relative anaerobic power measures. (A) Absolute CMJ height; B) Relative CMJ height to fat-free mass (FFM); (C) absolute peak power; (D) relative peak power to FFM; (E) absolute average power; (F) relative average power to FFM. *p<0.05, **p<0.01, ***p<0.001, ****p<0.0001. CM, cisgender men; CMJ, Counter Movement Jump; CW, cisgender women; TM, transgender men; TW, transgender women.

sedentary populations.[22] (Hb) is crucial in O_2 transport[23] and vital for endurance sports performance,[24] with O_2 delivery to the tissues a limiting factor in $\dot{V}O_2$max attainment.[25] The lack of differences in (Hb) is consistent with the lack of observed difference in absolute $\dot{V}O_2$max between transgender women, transgender men and cisgender women in this cohort. However, as cardiac output, the most crucial variable influencing $\dot{V}O_2$max[25] was not assessed in the present study, a more comprehensive mechanistic explanation for the similar maximal aerobic capacity between groups cannot be provided.

No differences in BMD were observed between transgender and cisgender women athletes in this study (table 2), despite

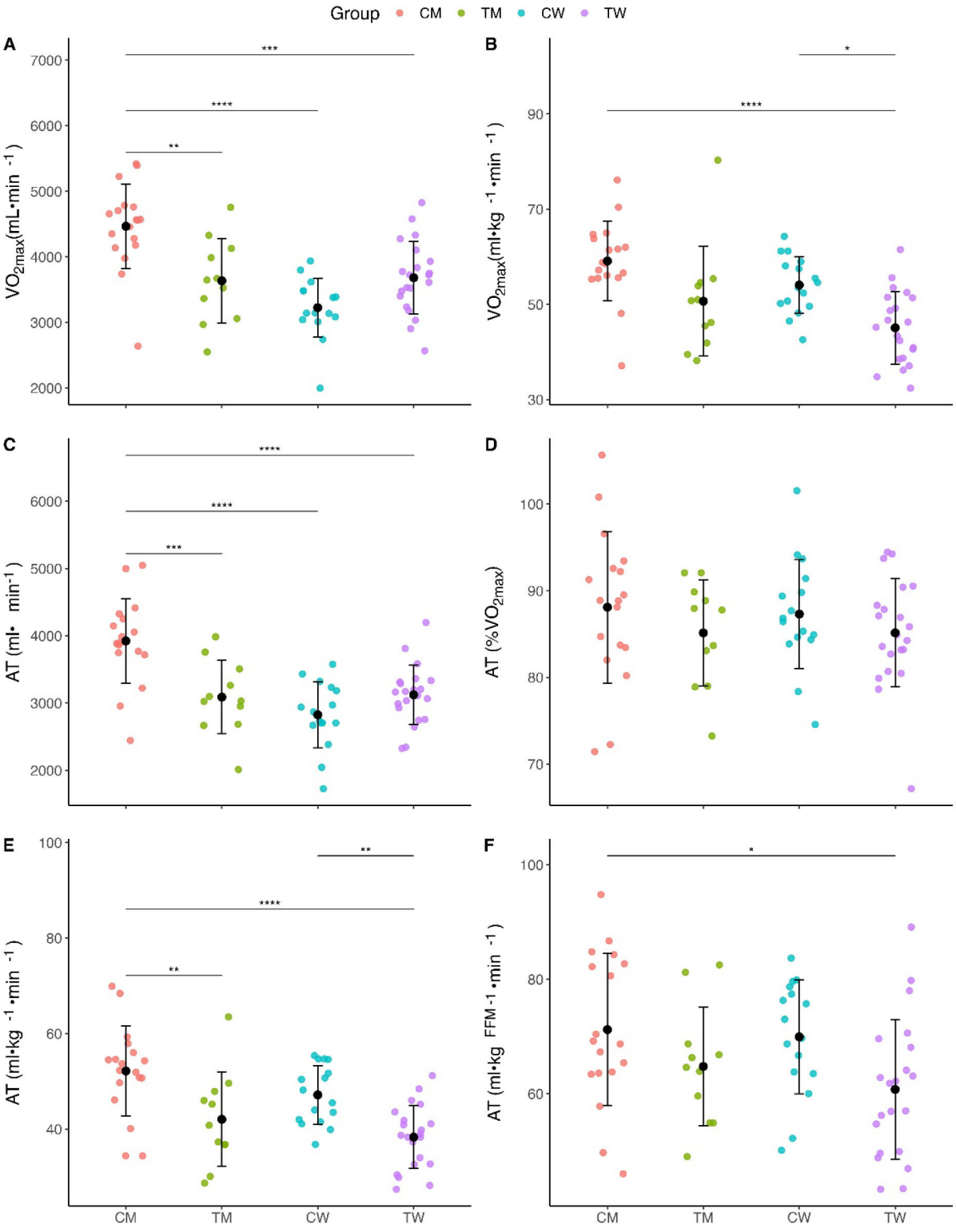

Figure 5 Absolute and relative cardiopulmonary exercise testing measures. (A) Absolute VO_2max; (B) relative VO_2max to body weight; (C) absolute anaerobic threshold (AT); (D) anaerobic threshold (%VO_2max); (E) relative anaerobic threshold relative to body mass; (F) AT relative to at-free mass (FFM). *p<0.05, **p<0.01, ***p<0.001, ****p<0.0001. CM, cisgender men; CW, cisgender women; TM, transgender men; TW, transgender women.

prior research hypothesising that transgender women athletes have a significant BMD advantage over cisgender women.[11] The sample size for each gender was n<30 participants and may be insufficient to characterise BMD differences reliably. Exercise has been shown to have a protective effect on BMD in CM[26] and CW,[27] and our results suggest a protective effect of exercise in transgender women, given that there is evidence of low BMD in transgender women with low weekly sports activity.[28] Nevertheless, the results suggest the complexity of bone health in athlete populations and the need for a more comprehensive assessment to understand the long-term impact of GAHT on transgender athletes' BMD.

The differences observed in body composition in this population (table 2) indirectly show the potential role of androgens in body composition, owing to the role of oestradiol in fat accumulation[29] and transgender women's oestradiol concentrations (figure 1B) and fat mass (table 2) being greater than all other groups. Body composition differences may have implications for sports that prioritise exercise economy,[30] defined as the average $\dot{V}O_2$ relative to body mass between submaximal intensities,[31] as athletes with a higher fat mass percentage will present with a lower exercise economy owing to the increased O_2 cost of exercise.[32] The android-to-gynoid ratio analysis (table 2) suggests that hormone therapy (figure 1A,B) influences differences in fat distribution patterns. However, fat distribution patterns of the present transgender female athlete cohort (table 2) do not reach ratios previously reported in cisgender female populations (0.8).[33] Understanding these variations is essential for evaluating performance in sports where body composition is a determining factor, for example, weightlifting or boxing.

Cisgender women had lower absolute fat-free mass than transgender men and transgender women (table 2). When analysing absolute fat and fat-free mass data (table 2), these results can be affected by sample size and/or athlete diversity limitations. A purposefully designed future study with height-matched and sport-matched cisgender and transgender female athletes is crucial to understanding differences in these parameters, as they are influenced by height disparities (table 1) and variations in sampled sports.

FVC, FEV_1 and FEV_1:FVC ratio are higher in athletes than in the normal sedentary control individuals,[34] and there is no difference in all three metrics between aerobic athletes and anaerobic athletes.[35] Therefore, the lung function differences observed in figure 2A,B may be attributed to factors such as skeletal size benefiting lung capacity and function,[36] with transgender women's FVC results (figure 2B) suggesting gender-affirming hormone care did not impact changing lung volumes owing to the GAHTs lack of effect on skeletal stature.[11] Transgender women showed a significantly reduced FEV_1:FVC ratio compared with cisgender women (figure 2C). The FEV_1:FVC ratio has been used as a screening index for identifying obstructive lung conditions globally,[37] as a lower FEV_1 owing to obstruction of air escaping from the lungs will reduce the FEV_1:FVC ratio. Transgender women's results (figure 2C) suggest obstructed airflow in the lungs[38] when compared with cisgender women. However, this observation of transgender women is unlikely to be pathological (<0.70),[39] as seen in chronic obstructive pulmonary disease.

Nevertheless, this reduced airflow could potentially lead to exercise-induced dyspnoea, resulting in performance limitations[40] in comparison to cisgender women. When comparing both the CM and transgender women athletes' groups with identical heights (1.8 m, table 1), while both groups exhibit similar FVC, transgender women demonstrate a lower FEV_1, leading to a reduced FEV_1:FVC ratio compared with CM, although not significant. If there were a significant difference between CM and transgender women, our preliminary hypothesis would have attributed this divergence to testosterone suppression in transgender women. However, comparing transgender women to cisgender women who do not share similar height and or exhibit a comparable FVC, the observed differences become more complex to interpret. The possibility arises that factors beyond hormonal influences, such as varying levels of aerobic training, may contribute to the significant difference found in the FEV_1:FVC ratio between transgender women and cisgender women. Further longitudinal investigation is required to elucidate if the causation underlying these pulmonary function disparities is indeed testosterone suppression.

Strength results in figure 3 disagree with previous literature in a non-athlete transgender cohort using the same methodology that showed transgender women and CM had significantly different absolute and relative hand grip strength.[41] Our results showed no differences in absolute strength between transgender women and CM and no difference in relative handgrip between any of the groups in this study (figure 3). These results highlight the differences between athlete and sedentary populations. However, the results relative to hand size also concur with the notion that greater handgrip strength is caused by greater hand size,[42] as there were no differences in results between the four groups when normalised for hand size (figure 3C,D). Therefore, investigations with more accurate measures of strength are warranted in transgender athletes.

Transgender women presented lower absolute jump height than CM and lower relative jump height, normalised for fat-free mass, than transgender men and cisgender women (figure 4). These results in this study cohort suggest that transgender women lack lower body anaerobic power compared with the other groups. Transgender women's higher absolute peak power than cisgender women (figure 4C), coupled with higher fat mass potentially driven by higher oestradiol concentrations (figure 1B), suggest that transgender women had more inertia to overcome during the explosive phase of the countermovement jump, which may lead to decreased performance. However, when normalised for fat-free mass (figure 4D), transgender women's peak power was lower than that of cisgender women, showing that this cohort also lacks peak power relatively, indicating that the higher fat mass may not be the primary contributing factor. Further investigations are warranted to find the causation of this poor lower anaerobic power performance in transgender women.

The lack of differences in anaerobic threshold (%$\dot{V}O_2$max, figure 5D) suggests that the athletes in this study had a similar fitness status, which is an essential underlying finding given that CM showed greater absolute $\dot{V}O_2$max than all groups (figure 5A), with no differences between transgender women and cisgender women found, and transgender women exhibited lower relative $\dot{V}O_2$max compared with both CM and women (figure 5B). In this cohort, the finding of no statistical difference in absolute $\dot{V}O_2$max between transgender women and cisgender women contrasts the idea that transgender women's bigger lung size (table 2) is an inherent respiratory function advantage over cisgender women.[11] Both the absolute and relative $\dot{V}O_2$max differences between groups contradict one previous study in non-athlete transgender populations that found transgender women had higher absolute $\dot{V}O_2$peak and no difference in relative $\dot{V}O_2$peak compared with cisgender women.[41] This contradictory finding further highlights population differences between non-athlete and athlete cohorts while also contradicting literature hypothesising that there would be a baseline gap in aerobic capacity between transgender women and cisgender women.[11] The results in this athlete cohort warrant further research to elucidate the mechanisms behind this deviation, as they may be metabolic, as transgender women also exhibited a lower relative anaerobic threshold (figure 5E). The findings in table 2 reveal notable disparities in fat mass, fat-free mass, laboratory sports performance measures and hand-grip strength measures between cisgender male and transgender female athletes. These differences underscore the inadequacy of using cisgender male athletes as proxies for transgender women athletes. Therefore, based on these limited findings, we recommend that transgender

women athletes be evaluated as their own demographic group, in accordance with the principles outlined in Article 6.1b of the International Olympic Committee Framework on Fairness, Inclusion and Non-Discrimination based on Gender Identity and Sex Variations.[4]

Study limitations

The limitations of this study primarily relate to its cross-sectional design, making it challenging to establish causation or examine if the performance of athletes changes as a result of undergoing GAHT. Longitudinal studies are needed to examine how GAHT, and other factors impact athletes' physiology and performance over time. Additionally, the composition of the study cohort may not fully represent the diversity of athletes in elite sports from worldwide populations. Athletes from various sporting disciplines and performance levels were included, and the athlete training intensity was self-reported. Therefore, the results may suffer from selection and recall bias.[43] The results may not apply to all levels or ages of athletes, specifically as this research did not include any adolescent athletes competing at the national or international level. The athletes participating in the present study represented a variety of different sports, and this would have undoubtedly impacted the results of the study as different sports stress different training and sports modalities. Exercise type, intensity and duration all have an impact on physiological responses and overall laboratory performance metrics.[44] The subgroups of sports that emerged were also too dissimilar to allow meaningful subgroup analysis. The complexity and difficulty of this area of activity means that while this study provides a starting point for understanding the complex physiology in GAHT and athletic performance, this study does not provide evidence that is sufficient to influence policy for either inclusion or exclusion. However, this is the first study to assess laboratory-based measures of performance in transgender athletes, and this opens up interesting avenues for replication and extension into the longitudinal effects of GAHT on athletic performance.

Future research should include more extensive and diverse samples to enhance the generalisability of findings or smaller, more specific cohorts to hone in on a particular sports discipline. However, such studies may be complex due to the low numbers of transgender athletes. The recruitment method of this study also provided a limitation as social media advertising was used rather than recruitment from a clinical provider. Social media recruitment leaves this study open to sample bias as social media advertising, although great for recruiting hard-to-reach participants for observational studies,[44 45] does not represent a clinical population in 86% of comparisons.[44] As the participants were not recruited from a clinic, this also means that the gender-affirming treatment of the transgender athletes was not controlled. For example, different testosterone suppression methods have different efficacies,[46] and future studies should consider differences in the prescribed GAHT to participants. Lastly, the participants were not screened by a clinician before participation, and any medical conditions were self-reported in the physical activity readiness questionnaire (PAR-Q). This method of medical reporting leaves the data open to self-reporting bias, which can mislead descriptive statistics and causal inferences[47] as participants' cognitive processes, such as social desirability, can alter participants' responses.[48] Therefore, it is recommended to use a clinic to screen and recruit participants to avoid such bias in a longitudinal study of transgender athlete sports performance.

CONCLUSIONS

This research compares transgender male and transgender female athletes to their cisgender counterparts. Compared with cisgender women, transgender women have decreased lung function, increasing their work in breathing. Regardless of fat-free mass distribution, transgender women performed worse on the countermovement jump than cisgender women and CM. Although transgender women have comparable absolute $\dot{V}O_2$max values to cisgender women, when normalised for body weight, transgender women's cardiovascular fitness is lower than CM and women. Therefore, this research shows the potential complexity of transgender athlete physiology and its effects on the laboratory measures of physical performance. A long-term longitudinal study is needed to confirm whether these findings are directly related to gender-affirming hormone therapy owing to the study's shortcomings, particularly its cross-sectional design and limited sample size, which make confirming the causal effect of gender-affirmative care on sports performance problematic.

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Acknowledgements We thank Associate Professor Ada Cheung of the Department of Medicine (Austin Health) at the University of Melbourne, Australia for her valuable review of this work prior to publication.

Contributors BH, FMG and YPP designed the study. Material preparation, reporting and critical revision of the work were performed by BH, PGB, FMG and YPP. Data collection was performed by CC-C, AB, SM-M and BH. BH wrote the first draft of the manuscript, and all authors critically revised subsequent versions until all authors could approve the final manuscript. YPP is the guarantor.

Funding The study has been funded by a research grant awarded by the International Olympic Committee, Lausanne, Switzerland.

Competing interests YPP is a member of the IOC Medical and Scientific Commission, which recently published articles and framework documents on the topic. BH and FMG have recently published articles on the topic on behalf of the International Federation of Sports Medicine (FIMS). All authors declare no further conflict of interest or competing interests.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and ethical approval for this study has been granted by the School of Applied Sciences Research Ethics Committee of the University of Brighton, Brighton, UK (Ref: 9496). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request.

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