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Relative Handgrip Strength as the Primary Determinant of Fatigue Resistance in Young Adults

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Abstract

International Journal of Exercise Science 19(7): 7003, 2026. Biological sex differences in strength, fat content, and cross-sectional area may influence fatigue resistance in young adults. This study examined the relationship between fatigue resistance and handgrip strength, body composition, viscoelastic properties, and hand–forearm anthropometry in university students. A cross-sectional study was conducted with 57 participants underwent assessments of handgrip strength, body composition (bioimpedance), forearm muscle mechanical properties, and anthropometry. Fatigue resistance during sustained maximal voluntary isometric contraction (MVIC) was evaluated as the time required for force to decline to 75% and 50% of MVIC. Pearman correlations and ANCOVA models were applied ($p < 0.05$). Men exhibited higher absolute and relative handgrip strength and greater fatigue resistance at both thresholds. Relative handgrip strength was the strongest and most consistent predictor of fatigue resistance ($r = 0.67$), outperforming body composition, viscoelastic properties, and anthropometric measures. At FR75%, sex and relative strength both predicted fatigue resistance; however, at FR50%, the sex effect disappeared once relative strength was controlled, indicating that observed sex differences were largely attributable to differences in strength rather than biological sex per se. Body composition showed limited predictive value: only fat mass modestly predicted FR50%, while percent body fat and fat-free mass were not associated with fatigue resistance. Forearm muscle tone and stiffness, despite being higher in men, did not explain variability in fatigue resistance. Anthropometric dimensions demonstrated minor associations but contributed little explanatory value beyond strength. Overall, the findings indicate that relative strength is the primary determinant of fatigue resistance, while sex, body composition, muscle mechanical properties, and anthropometry add minimal additional insight.

Keywords: Resistance fatigue, grip strength, body composition, sex differences, passive muscle properties.

Introduction

Neuromuscular fatigue is defined as a reversible decline in neuromuscular performance induced by exercise,[1,2] originating from both peripheral and central mechanisms. Peripheral fatigue involves perturbations within the muscle itself, such as metabolite accumulation, ultrastructural damage, or impaired excitation-contraction coupling.[3,4] In contrast, central fatigue is characterized

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by a reduction in the neural drive from the central nervous system to the muscle fibers.[5] The ability to resist this decline, known as fatigue resistance, critically impacts athletic performance[6] and is a recognized risk factor for overload injuries.[7] In healthy populations, fatigue can limit occupational efficiency and restrict participation in recreational activities.[8]

The reliable assessment of muscle fatigue is primarily based on measuring force-generating capacity.[9] Muscle endurance is commonly categorized as absolute or relative endurance.[10] Absolute endurance, measured by tests like the one-repetition maximum (1RM), reflects genuine inter-individual differences in maximal strength. Relative endurance, however, normalizes the task to an individual's maximal strength, thereby accounting for these baseline strength disparities. Muscle endurance based on maximum voluntary isometric contraction (MVIC) is often assessed by the time taken for force to decline during a sustained contraction. Nevertheless, the outcomes of such tests are highly variable, influenced by participant characteristics (e.g., sex, age), protocol details (e.g., intensity, duration), and the muscle's intrinsic viscoelastic properties and anthropometry.[10–12]

Sex differences in muscle endurance remain a subject of debate. Some studies report that women exhibit longer endurance times than men at low to moderate intensities,[13–15] an advantage that appears to diminish at higher intensities.[16–18] For instance, Hicks et al. (2001) noted the female endurance advantage decreases as contraction intensity increases. Conversely, other studies, such as that by González and Scheuermann (2011), report similar fatigability between sexes during repeated submaximal efforts. This study employs a high-intensity protocol (≈100% MVIC) to further investigate these potential sex-related differences. A systematic review found that minor to no sex differences in neuromuscular fatigue, but some evidence of greater fatigability in males during or immediately following resistance training were found when rest periods were shorter, and males were substantially stronger than women in relative terms, among others.[19]

The physiological basis for these discrepancies may stem from distinct hormonal and physiological profiles. Women often possess a larger proportion of type-I muscle fibers, greater relative capillarization, and reduced mechanical arterial compression, which confer enhanced fatigue resistance during submaximal efforts.[20,21] However, these inherent physiological differences are often moderated by other factors. Notably, an individual's training status and habitual activity level significantly influence the presence and magnitude of observed sex differences in fatigue.[22] For example, while women may demonstrate higher fatigue resistance at low intensities, this difference often disappears when males and women are matched for relative strength],[23] suggesting that baseline strength is a powerful confounding variable. Despite the growing body of evidence, few studies have simultaneously examined the relative contributions of strength, body composition, muscle mechanical properties, and anthropometric characteristics to fatigue resistance within a unified analytical framework. Moreover, it remains unclear to what extent sex differences in fatigue persist after statistically accounting for these interrelated factors.

Our previous research has confirmed that sex differences in handgrip strength are largely attributable to muscle mass. We also found that relative handgrip strength is negatively correlated with fat mass, and that higher fat content adversely affects forearm muscle stiffness and tone.[24] Given that myotonometry provides a highly reliable means of assessing these viscoelastic properties,[24,25] and considering their positive association with motor function, it is plausible that sex differences in body composition and muscle mechanical properties underpin variations in fatigue resistance.

Therefore, the aim of this study was to determine the relationship between handgrip strength, body composition, forearm muscle mechanical properties, and hand–forearm anthropometry with fatigue resistance during sustained maximal isometric handgrip in young adults. We further sought to evaluate whether sex differences in fatigue resistance remain after adjustment for these physiological and morphological variables. We hypothesized that relative handgrip strength, rather than sex per se, would emerge as the primary determinant of fatigue resistance.

Methods

Participants

A cross-sectional, quasi-experimental, correlational study with a non-probabilistic design conducted on a population of students from a kinesiology course was conducted with 57 university students (26 women and 31 men), aged between 18 and 25 years (mean age: 21.56 ± 1.9), recruited from the University of Viña del Mar. The participants were university students with no recruitment based on training level. Not all were involved in structured resistance training; therefore, the results should be interpreted within the context of a young sample that was predominantly non-resistance trained. Participant characteristics are summarized in Table 1. Average weight was 77.8 ± 12.3 kg for men and 69.5 ± 16.3 kg for women; height was 1.73 ± 0.01 m in men and 1.59 ± 0.06 m in women; and BMI was 26.01 ± 3.2 in men and 27.1 ± 0.1 in women. The sample size was calculated a priori using G*Power software (version 3.1, Universität Düsseldorf, Germany). A two-tailed significance level of $\alpha = 0.05$ and a statistical power ($1-\beta$) of 0.80 were assumed. For correlation analyses, the required number of participants was estimated to detect different magnitudes of association (Pearson's/Spearman's r), following Cohen's classification: small ($r = 0.10$), moderate ($r = 0.30$–0.40), and large ($r \geq 0.50$). The calculations indicated that approximately 85–47 participants are needed to detect moderate correlations ($r = 0.30$–0.40), and between 30 and 14 participants to detect large correlations ($r = 0.50$–0.70), with 80% power. Based on these values and the available resources, 57 students were recruited. Healthy young adults were fully informed about the study's objectives, and written informed consent was obtained from all participants. The study was approved by the Institutional Ethics Committee (Reference Number: CEC-UVM 32-25).

Participants completed a series of anthropometric and physical performance assessments in a single testing session. Initially, students who volunteered attended the science school laboratory, where anthropometric measurements were taken, including 11 hand–forearm dimensions, as described by Rostamzadeh et al. An experienced operator then used the MyotonPro device to assess the mechanical properties of the forearm muscles. After a detailed explanation of the procedure, grip strength was measured in both hands. Bioimpedance analysis was conducted afterward to determine body composition. Finally, the fatigue resistance protocol was carried out.

Protocol

Standardized techniques were used for all body measurements.[26] Each parameter was measured twice, and the mean of both values was recorded. Weight was measured using a SECA scale (model 700, precision 50 g, Germany), with participants standing in the center of the scale platform, wearing light clothing. Height was assessed using a SECA stadiometer, with participants standing upright, without shoes, shoulders relaxed, and facing away from the wall. Body mass index (BMI), expressed in kg/m², was calculated as weight (kg) divided by height squared (m²). A total of 11 hand–forearm anthropometric dimensions were measured according to the method described by Rostamzadeh et al.[27] A tape measure (Lufkin Executive Thinline 2 m, W606PM) was used, and each measurement was repeated twice for each hand. Care was taken to avoid excessive compression of the underlying tissues and to ensure accurate recordings during each measurement. Body composition was assessed using a direct segmental multi-frequency bioelectrical impedance analysis device (InBody 270, InBody Co. Ltd, South Korea). Measurements were conducted in temperature-controlled laboratories, following a standardized protocol. The device used an eight-electrode, multi-frequency segmental analysis and was regularly serviced and calibrated.

After collecting anthropometric measures and body composition data, muscle stiffness and oscillation frequency (indicative of tone, or the resting tension in the forearm flexor muscles, including the palmaris longus, flexor digitorum superficialis, and flexor carpi ulnaris) were assessed using the MyotonPRO device (Myoton AS, Tallinn, Estonia).[24] Briefly, the MyotonPRO probe was placed perpendicular to the skin surface over the muscle belly being measured. The examination began with the palmaris longus muscle, followed by the flexor carpi ulnaris, and concluded with the flexor digitorum superficialis (FDS). Measurements were performed on the dominant hand following previously reported protocols[24]

Handgrip strength was measured using a hydraulic dynamometer with an adjustable grip (Baseline® model, USA). Measurements were initially performed on the dominant hand. Participants were instructed to stand upright, with arms at their sides, and to squeeze with maximum force for 3 to 5 seconds, following standardized verbal cues from the researcher. The value obtained before resetting the dynamometer to 0 was recorded. This process was repeated three times for each hand, with a 2-minute rest between each trial. The highest value from the three trials of the dominant hand was used for analysis. The right hand was dominant in 96.5% of participants.

Handgrip muscle fatigue was assessed using a grip force transducer (Figure 1A). Prior to data collection, a unit conversion was performed to convert voltage readings from the channel into appropriate units for display, such as newtons (N). Each participant conducted a practice trial to familiarize themselves with the instruments and procedures. Then, participants were asked to squeeze maximally for 1 minute, ensuring the force decreased below 50% of its maximum. This test was repeated twice on the dominant hand, with a 2-minute rest for muscle recovery. Figure 1B displays an adjusted trace, indicating a 75% and 50% decrease in maximal voluntary contraction.

Statistical analysis

The normality of the distribution was assessed using the Shapiro-Wilk test, and homogeneity of variances was evaluated with Bartlett's test. For variables that did not meet the assumptions of normality or homogeneity, a log transformation was applied, followed by back-transformation for presentation of results. Continuous variables are presented as mean ± standard deviation (SD). Sex differences in anthropometric variables, body composition, handgrip strength, relative strength, and fatigue resistance were analyzed using unpaired Student's t-tests. Effect sizes for between-sex differences were calculated using Cohen's d and interpreted as small (0.20), medium (0.50), large (0.80), and very large (>1.20). Changes in maximal voluntary isometric contraction (MVIC) over time were analyzed using a two-way repeated-measures analysis of variance (ANOVA), with sex as the between-subject factor and time as the within-subject factor. When a significant main effect or interaction was detected, Tukey's post hoc test was applied. Associations between fatigue resistance (FR75% and FR50%) and relative handgrip strength, body composition, muscle mechanical properties, and anthropometric variables were assessed using Pearson's correlation coefficient (r). Correlation strength was interpreted as follows: 0.00–0.10 (very weak), 0.10–0.39 (weak), 0.40–0.69 (moderate), 0.70–0.89 (strong), and 0.90–1.00 (very strong). Correlation analyses

were conducted separately for men and women. To compare correlation coefficients between sexes, Fisher's z transformation was applied using the following equation:
where z1 and z2 are Fisher-transformed correlation coefficients for men and women, and *n*1and *n*2 are their respective sample sizes.

Analyses of covariance (ANCOVA) were performed to evaluate the effects of sex on fatigue resistance while adjusting for relative handgrip strength, body composition variables (percent body fat, fat mass, and fat-free mass), muscle mechanical properties (tone and stiffness), and hand–forearm anthropometric measurements. In all ANCOVA models, fatigue resistance (FR75% or FR50%) was treated as the dependent variable, sex as a fixed factor, and the corresponding physiological or anthropometric variable as a covariate. The assumption of homogeneity of regression slopes was verified prior to each model. Adjusted means (estimated marginal means,

$$Z = \frac{z1 - z2}{\sqrt{\frac{1}{n1 - 3} + \frac{1}{n2 - 3}}}$$

EMM) were reported when appropriate. Statistical significance was set at $p < 0.05$ for all analyses, and all tests were two-tailed. All statistical procedures were performed using GraphPad Prism version 8.01 for Windows (GraphPad Software, San Diego, CA, USA).

Results

Participant characteristics and sex differences

Table 1 presents a descriptive summary of the sample. Age and BMI were similarly distributed between sexes. As expected, weight, height, and all body composition parameters were significantly higher in men compared to women (t-test, $p < 0.05$). Handgrip strength was significantly higher in men than in women (men: 47.03 ± 10.94, women: 27.96 ± 7.26, $p < 0.0001$), with a very large effect size (Cohen's d = 2.05), indicating a strong sex effect on maximal grip strength. When expressed relative to body mass, relative grip strength was also higher in men (men: 0.61 ± 0.12, women: 0.41 ± 0.10, $p < 0.0001$). Fatigue resistance at 75% MVIC was higher in men (7.78 ± 3.83) than in women (3.97 ± 7.17, $p < 0.0001$), with a moderate-to-large effect size (Cohen's d ≈ 0.66). Similarly, fatigue resistance at 50% MVIC was higher in men (26.83 ± 15.49) than in women (14.83 ± 8.22, $p < 0.001$), with a large effect size (Cohen's d ≈ 0.97).

Table 1. Demographics. body composition. grip strength and time to fatigue.

Parameters Young adult (18-25)	Men (n=31)	Women (n=26)	p
Age (years)	21.48± 1.7	21.21± 1.7	0.56
Weight (kg)	77.84± 12.63	69.53± 16.31	0.03
Height (m)	1.73± 0.075	1.59± 0.06	<0.0001
Body mass index (BMI) (kg/m^2)	26.01± 3.28	27.09± 5.86	0.38
Body fat mass (kg)	17.11± 6.24	26.43± 11.27	0.0003
Percent body fat (%)	21.51± 5.66	36.72± 7.35	<0.0001
Fat free mass (FFM) (kg)	61.16± 9.08	43.13± 6.67	<0.0001
Handgrip strength. (kg)	47.03± 10.94	27.96± 7.26	<0.0001
Relative grip strength ($kg/kg/m^2$)	0.61± 0.122	0.41± 0.101	<0.0001
FR75%	7.78± 3.83	3.97± 1.7	<0.0001
FR50%	26.83± 15.49	14.83± 8.22	0.0008

Note: Results are presented as mean ± SD; FR75%: Time until force declines to 75% of maximal voluntary contraction, FR50%: Time until force declines to 50% of maximal voluntary contraction: Significant differences were assessed by an unpaired t-test.

Maximal voluntary contraction

Handgrip strength is significantly higher in men than in women (Pérez et al.). Therefore, to eliminate differences in maximal strength, muscle relative endurance was assessed. Figure 1C shows the percentage change in 100% MVIC over 1 minute. A two-way repeated-measures ANOVA revealed that men have greater muscle endurance than women at both FR%75 and FR%50 during 1 minute of MVIC ($F_{(1,55)}$ =12.75, $p < 0.0001$). When force dropped to 75% of MVIC, the time was 7.78 seconds for men and 3.97 seconds for women. Additionally, when force dropped to 50% of MVIC, the time was 14.8 seconds for women and 26.8 seconds for men.

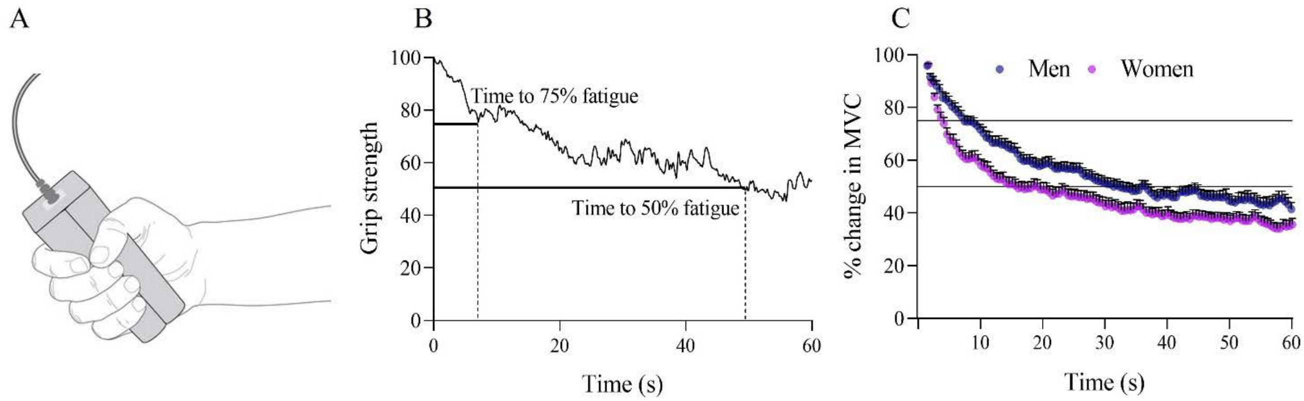

Figure 1. Experimental setup and average force-time curve showing changes in maximal voluntary isometric contraction (MVIC) over 1 minute by sex. **A**. Grip force transducer used for fatigue measurement. **B**. Determination of fatigue resistance at 75% and 50% of maximal grip strength. **C**. Males exhibited higher fatigue resistance at both FR75% and FR50% compared to women. The horizontal lines in the figure indicate the times at which MVIC drops to 75% and 50%.

Relationship between relative strength and fatigue resistance

Figure 2 illustrates the association between relative handgrip strength and fatigue resistance at the points where MVIC decreases to 75% and 50%. At 75% MVIC, women showed a moderate positive correlation between relative handgrip strength and fatigue resistance (r = 0.60), whereas men exhibited a weaker but still significant correlation (r = 0.42) (Figure 2A). Before conducting ANCOVA, the assumption of homogeneity of slopes was confirmed, as the interaction between relative handgrip strength and sex was not significant (p = 0.66). This indicates that the relationship between the covariate and fatigue resistance was comparable between men and women. The ANCOVA revealed a significant main effect of sex (F = 5.15, p = 0.028), with men showing higher adjusted fatigue resistance than women (7.31 vs. 5.71) (Figure 2B). The covariate, relative handgrip strength, also had a significant effect (F = 13.12, p = 0.00068), indicating that individuals with greater relative strength tended to exhibit greater fatigue resistance. At 50% MVIC, the pattern of associations was similar. Women demonstrated a moderate and significant correlation between relative strength and fatigue resistance (r = 0.52), whereas men again showed a weak positive correlation (r = 0.23) (Figure 2C). In this model, sex did not have a significant effect on fatigue resistance after controlling for relative handgrip strength (F = 0.58, p = 0.393). In contrast, relative handgrip strength remained a significant predictor (F = 7.04, p = 0.011), indicating that individuals with higher relative strength consistently exhibited greater fatigue resistance regardless of sex. These results highlight relative handgrip strength as the key factor explaining variability in muscular fatigue resistance at 50% MVIC (Figure 2D).

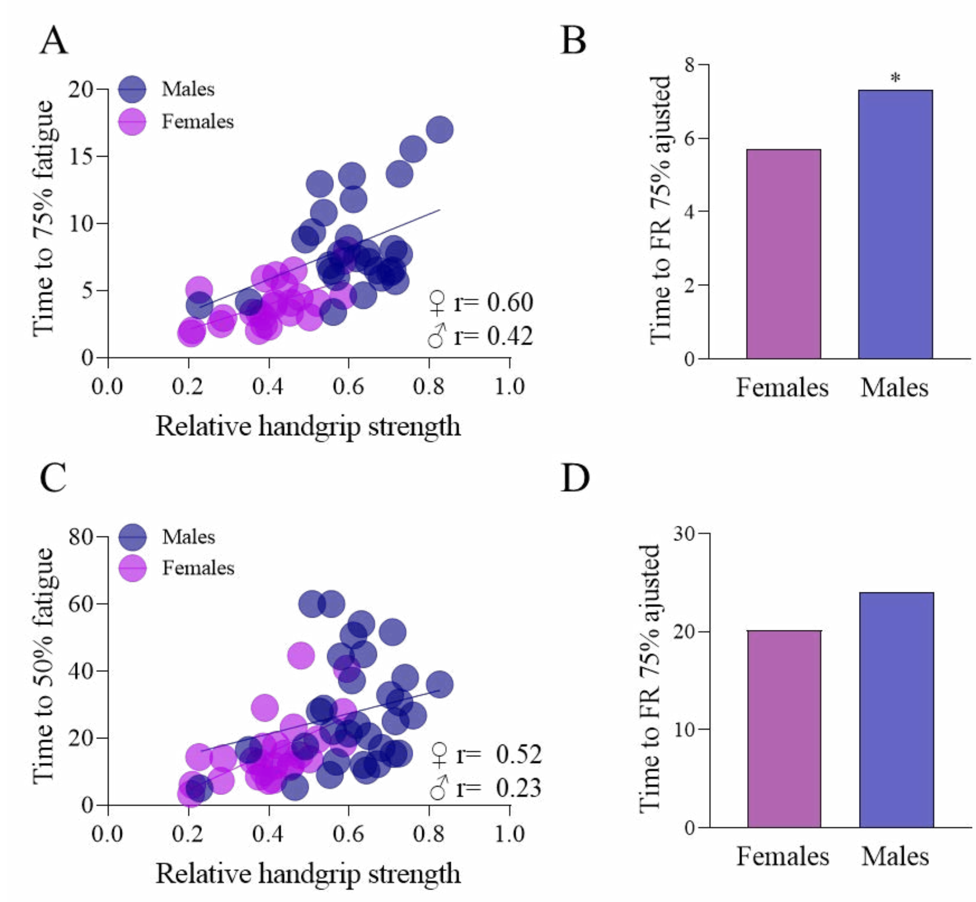

Figure 2. A. Fatigue resistance at 75% MVIC (FR75%) shows a significant moderate positive correlation with relative handgrip strength in women (r = 0.60) and a weaker, yet significant, positive correlation in males (r = 0.42). **B**. ANCOVA results revealed significant effects of both sex and the covariate (relative handgrip strength) on fatigue resistance, with adjusted means indicating higher fatigue resistance in men (7.31) compared to women (5.71). **C**. Fatigue resistance at 50% MVIC (FR50%) is moderately and positively correlated with relative handgrip strength in women (r = 0.52), while males show a weak positive correlation (r = 0.23). **D**. The ANCOVA indicated that relative handgrip strength significantly predicted fatigue resistance (F = 7.04, p = 0.011), whereas the effect of sex was not significant after adjustment (F = 0.58, p = 0.393), suggesting that differences in fatigue resistance are primarily explained by relative strength rather than sex. $p < 0.05$.

Fatigue resistance and body composition

Figure 3 presents the correlations between fatigue resistance (FR75% and FR50%) and different body composition variables. For FR75%, percent body fat showed a weak negative correlation in both women (r = –0.23) and males (r = –0.15), indicating that higher fat percentage was slightly associated with lower fatigue resistance (Figure 3A). Similarly, body fat mass was weakly and negatively correlated with FR75% in women (r = –0.29) and males (r = –0.16) (Figure 3B). In contrast, fat-free mass was not correlated with FR75% in either sex (women: r = –0.02; males: r = 0.09) (Figure 3C). When fatigue resistance declined to 50% MVIC (FR50%), the pattern remained consistent. Percent body fat showed a weak negative correlation with FR50% in women (r = –0.20) and males (r = –0.30) (Figure 3D). Body fat mass also demonstrated weak negative correlations with FR50% in both women (r = –0.30) and males (r = –0.31) (Figure 3E). Finally, fat-free mass showed no meaningful relationship with FR50% in males (r = –0.02) and only a weak positive correlation in women (r = 0.23) (Figure 3F).

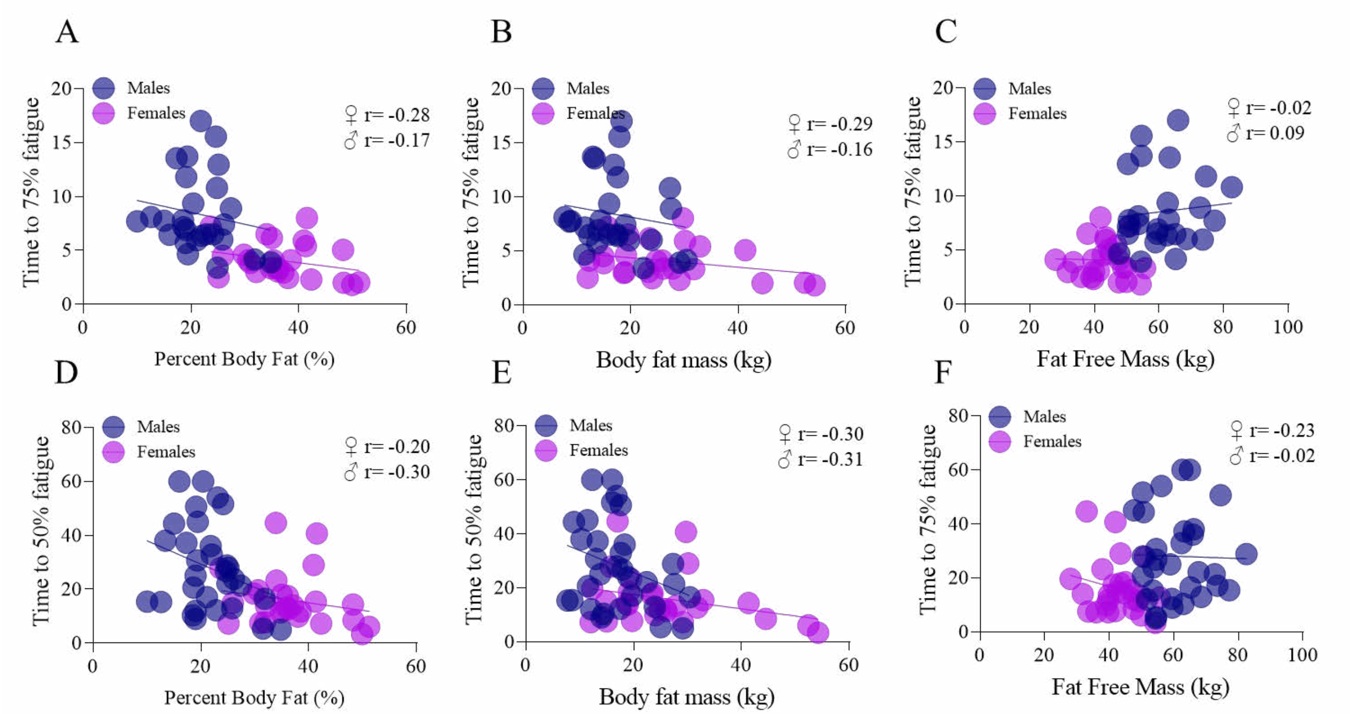

Figure 3. Association between fatigue resistance (FR75%, FR50%) and body composition. A. There is a weak negative correlation between FR75% and percent body fat in women (r = -0.23), and males (r = -0.15). **B**. There is a weak negative correlation between FR75% and body fat mass in women (r = -0.29), and males (r = -0.16). **C.** There is no correlation between FR75% and fat free mass in males (r = 0.09) and in women (r = -0.02). **D**. There is a weak negative correlation between FR50% and percent body fat in women (r = -0.20), and males (r = -0.30). **E**. There is a weak negative correlation between FR50% and body fat mass in women (r = -0.30), and males (r = -0.31). F. There is a weak negative correlation between FR50% and fat free mass in women (r = 0.23), while it has not correlation (r = -0.02) with fat free mass in males.

Table 2 summarizes the ANCOVA models evaluating whether body composition variables predict fatigue resistance at 75% (FR75%) and 50% (FR50%) MVIC, while controlling for sex. For percent body fat, the homogeneity of slopes assumption was met for both FR75% and FR50%. The covariate did not significantly predict fatigue resistance at either level (FR75%: p = 0.197; FR50%: p = 0.067). However, sex had a significant effect on FR75% (p = 0.001), with men showing higher adjusted fatigue resistance (7.80 vs. 4.70). No sex differences were found for FR50% (p = 0.437). For body fat mass, the covariate was not a significant predictor of FR75% (p = 0.219), but it significantly predicted FR50% (p = 0.045). Sex had significant effects on both FR75% (p = 0.001) and FR50% (p = 0.036), with men consistently showing higher adjusted fatigue resistance. The sex differences were larger at FR50% (difference of 8.4 units) compared with FR75% (difference of 3.8 units). For fat-free mass, the covariate did not significantly predict fatigue resistance at either threshold (FR75%: p = 0.657; FR50%: p = 0.537). In contrast, sex remained significant in several models, although its effect was generally smaller than that of relative strength.

Fatigue resistance and muscle properties

Table 3 presents the ANCOVA results evaluating the influence of sex and forearm muscle mechanical properties (tone and stiffness) on fatigue resistance at FR75%. For the Palmaris longus, neither muscle tone nor stiffness significantly predicted fatigue resistance (p = 0.13 and p = 0.08, respectively). However, a significant sex effect was observed for muscle stiffness (p = 0.03), with men exhibiting higher adjusted stiffness values than women (8.01 vs. 5.05). For the Flexor carpi ulnaris, muscle tone did not significantly contribute to fatigue resistance (p = 0.31), and the sex effect approached but did not reach significance (p = 0.06), although adjusted means indicated higher tone in men. In contrast, stiffness displayed a significant sex effect (p = 0.03), again showing higher adjusted stiffness values in men (7.99 vs. 4.97). For the Flexor digitorum superficialis, sex had a strong and significant effect on muscle tone (p = 0.0001), with men exhibiting markedly higher values (8.01 vs. 5.12). Muscle stiffness also showed a significant sex effect (p = 0.02), with men presenting greater stiffness (8.16 vs. 4.95). Similar to the previous muscles, the covariate did not significantly predict fatigue resistance. Across all anthropometric models, sex remained a significant predictor of fatigue resistance (table 3).

Table 2. ANCOVA results examining the effects of sex and body composition variables on fatigue resistance at 75% (FR75%) and 50% (FR50%) MVIC.

Body composition variable	Time to Fatigue resistance	Homogeneity of slopes (p)	Covariate effect (p)	Sex effect (adjusted p)	EMM Female	EMM Male	Difference (M-F)
Percent body fat (%)	FR75%	0.780	0.197	0.001*	4.70	7.80	3.1
	FR50%	0.304	0.067	0.437	20.1	24.4	4.3
Body fat mass (kg)	FR75%	0.655	0.219	0.001*	4.30	8.10	3.8
	FR50%	0.229	0.045*	0.036*	17.9	26.3	8.4
Fat free mass (kg)	FR75%	0.677	0.657	0.001*	4.30	8.40	4.1
	FR50%	0.541	0.537	0.001*	14.6	28.0	13.4

FR = fatigue resistance test; EMM = Estimated marginal means; p < 0.05.

Table 3. ANCOVA analysis of sex effects on fatigue resistance adjusted for muscle mechanical properties.

Muscle	Property	Homogeneity of slopes (p)	Covariate effect (p)	Sex effect (adjusted p)	EMM Female	EMM Male	Difference (M-F)
Palmaris longus	Tone	0.16	0.13	0.09	5.28	7.83	2.55
	Stiffness	0.17	0.08	0.03*	5.05	8.011	2.96
Flexor carpi ulnaris	Tone	0.45	0.31	0.06	4.99	7.96	2.97
	Stiffness	0.45	0.19	0.03*	4.97	7.99	3.02
Flexor superficial	Tone	0.31	0.12	0.0001*	5.12	8.01	2.89
	Stiffness	0.56	0.19	0.02*	4.95	8.16	3.21

Asterisks indicate statistically significant effects of sex after adjusting for the covariate (*p < .05). EMM = Estimated marginal means.

Fatigue resistance and anthropometric

Table 4 summarizes the ANCOVA models evaluating the influence of sex and various anthropometric components on fatigue resistance. The homogeneity of slopes assumption was met for all variables, indicating that the relationship between each anthropometric measure and fatigue resistance was comparable between men and women. Across all models, sex consistently showed a significant effect on fatigue resistance, with men exhibiting higher adjusted means than women for every anthropometric component evaluated. The magnitude of the sex difference varied depending on the variable, ranging from 3.3 to 5.5 units. Some anthropometric features demonstrated significant covariate effects. Specifically, hand breadth across the thumb (p = 0.019) and maximum internal grip diameter (p = 0.079, trend) showed associations with fatigue resistance, suggesting that hand dimensions may modestly contribute to fatigue performance. Overall, these results indicate that while certain hand dimensions exhibit minor associations with fatigue resistance, sex remains the strongest and most consistent predictor across all anthropometric models, with men showing substantially higher adjusted fatigue resistance than women.

Table 4. ANCOVA analysis of sex effects on fatigue resistance adjusted for anthropometric components.

Anthropometric components.	Homogeneity of slopes (p)	Covariate effect (p)	Sex effect (adjusted p)	EMM Female	EMM Male	Difference (M-F)
Hand length	0.58	0.119	0.0003*	3.9	8.8	4.9
Palm length	0.39	0.070	0.0001*	3.9	8.9	5.1
Hand breadth across thumb	0.84	0.019*	0.001*	3.6	9.1	5.5
Hand circumference	0.272	0.951	0.020*	4.5	8.4	3.9
Fist length	0.722	0.390	0.0001*	4.2	8.6	4.4
Fist circumference	0.521	0.544	0.0001*	4.8	8.1	3.3
Maximum internal grip diameter	0.588	0.079	0.031*	4.7	8.3	3.6
Hand depth	0.977	0.715	0.001*	4.6	8.3	3.7
Wrist circumference	0.652	0.454	0.002*	4.1	8.8	4.7
Forearm length	0.912	0.700	0.01*	4.6	8.3	3.7
Forearm circumference	0.089	0.885	0.001*	4.3	8.5	4.2

Discussion

The primary aim of this study was to examine the contribution of strength, body composition, forearm muscle mechanical properties, and anthropometry to fatigue resistance during sustained maximal handgrip in young adults. The principal finding is that relative handgrip strength emerged as the most consistent and robust determinant of fatigue resistance. Although men demonstrated greater absolute fatigue resistance than women, the effect of sex was markedly reduced and completely abolished at the FR50% level after adjustment for relative strength. These findings indicate that underlying neuromuscular capacity, rather than biological sex per se, predominately explains inter-individual differences in fatigue resistance.

Our results showed that women experienced a greater relative decrease in force during sustained maximal handgrip than men. Specifically, men maintained approximately 41% of their maximal grip force after 60 seconds, whereas women declined to about 35% over the same period. These findings partially contrast with previous studies reporting greater fatigue resistance in women during sustained isometric contractions, particularly at submaximal intensities.[16,29,30] West et al. (1995), for example, demonstrated that women exhibited significantly longer endurance times than men at 30%, 50%, and 75% of MVIC. However, the apparent female advantage in fatigue resistance diminishes as contraction intensity increases, and may even reverse during maximal efforts.[14,29] This provides a plausible explanation for why women in our study demonstrated a steeper decline in force under maximal conditions.

Physiologically, sex differences in fatigue resistance are often attributed to differences in muscle fiber composition, vascular function, and peripheral fatigue mechanisms. Women are reported to possess a greater proportion of type I muscle fibers, higher capillary density, and reduced mechanical compression of intramuscular blood vessels, which collectively favor oxidative metabolism and enhance fatigue resistance during submaximal efforts.[16,29] However, these inherent physiological advantages appear to be moderated by relative strength and task intensity. Indeed, when males and women are matched for relative strength, sex differences in fatigue resistance often disappear.[23] This aligns with our ANCOVA findings showing that once relative strength was included as a covariate, the effect of sex was no longer significant at FR50%.

Consistent with this interpretation, relative handgrip strength emerged as the strongest predictor of fatigue resistance at both FR75% and FR50%. Greater relative strength was associated with longer endurance times. This agrees with previous work showing that handgrip strength is not only a general marker of health,[31] but also a key determinant of local muscular endurance.[32]

Moreover, stronger individuals have been reported to be more fatigable at high intensities regardless of sex, likely due to greater intramuscular pressure, vascular occlusion, and metabolite accumulation.[22,29] Therefore, strength appears to act both as a facilitator and a constraint on fatigue resistance depending on contraction intensity.

Training status likely plays a central modulatory role in these relationships. Participants in the present study displayed relatively low training status, as reflected by modest relative strength and elevated BMI values. This may have attenuated typical physiological sex differences observed in trained populations. Previous literature indicates that habitual activity level and neuromuscular conditioning can substantially influence both the magnitude and direction of observed sex differences in fatigue.[22,23] Thus, the sex differences observed in untrained or recreationally active individuals may reflect disparities in training background rather than intrinsic biological determinants.

Although body composition has been proposed as a determinant of fatigue resistance through mechanisms related to perfusion, metabolic efficiency, and muscle fiber distribution, our findings indicate that its predictive value is limited. Correlations between fatigue resistance and body composition variables were weak ($r < 0.30$). In the ANCOVA models, only fat mass modestly predicted FR50%, while percent body fat and fat-free mass did not significantly explain the variability in FR75%. Moreover, sex remained a stronger predictor than any individual body composition measure. These findings suggest that, in the context of maximal handgrip fatigue, body composition exerts only a minor influence compared to relative strength.

Regarding forearm muscle mechanical properties, research on their role in fatigue resistance is scarce. Chalchat et al. (2020) reported that fatigue induces reductions in stiffness and increases in viscosity; however, these changes represent consequences of fatigue rather than predictors. In contrast, our study assessed baseline mechanical properties and found that although men exhibited higher muscle tone and stiffness, these characteristics were not associated with variability in FR75% or FR50%. This supports the notion that passive biomechanical properties of muscle tissue do not primarily determine force sustainability.[33,34] Instead, fatigue during sustained contractions appears to be governed predominantly by neuromuscular activation strategies, metabolic efficiency, and motor unit recruitment behavior.[35]

Anthropometric characteristics showed only limited associations with fatigue resistance. While strong relationships between anthropometry and maximal grip strength have been consistently reported.[36–38] their ability to predict grip endurance remains controversial. In our study, certain variables, such as hand breadth across the thumb and maximal internal grip diameter, emerged as significant covariates; however, their contribution was clearly smaller than that of relative strength and sex. This indicates that hand–forearm morphology plays only a secondary role in explaining fatigue resistance.

Taken together, these findings indicate that apparent sex differences in fatigue resistance during sustained maximal handgrip are largely mediated by differences in relative strength and neuromuscular capacity rather than by sex-specific physiological characteristics alone. Once relative strength is taken into account, the independent influence of sex, body composition, muscle mechanical properties, and anthropometry becomes minimal.

The present study has several strengths but also important limitations. An important consideration is that both sexes in the present study displayed relatively low training status, as evidenced by elevated BMI values and modest relative strength. This may have attenuated physiological differences typically observed in trained populations. Consequently, inter-individual variability in strength and neuromuscular efficiency likely outweighed sex-specific factors. Furthermore, although a practice trial was conducted to familiarize participants with the equipment, a formal familiarization session on a separate day was not performed. This could have influenced the measurements of maximal voluntary isometric contraction (MVIC) and the fatigue test. Overall, the results indicate that sex differences in fatigue resistance largely reflect underlying differences in relative strength. Once strength is taken into account, the independent influence of sex, body composition, muscle mechanical properties, and anthropometry becomes minimal.

This study demonstrates that fatigue resistance during sustained maximal handgrip effort is influenced by multiple physiological and morphological factors; however, our findings consistently identify strength, particularly relative handgrip strength as the primary determinant of fatigue resistance. Men exhibited greater fatigue resistance than women during maximal efforts, but when relative strength was statistically controlled, sex differences were markedly reduced or disappeared entirely, especially at the 50% fatigue threshold (FR50%). This indicates that sex influences fatigue resistance primarily because it influences maximal and relative strength, rather than representing an independent physiological effect. Body composition, forearm muscle mechanical properties, and anthropometric characteristics contributed little additional explanatory power. These findings indicate that apparent sex differences in fatigue resistance are largely strength-mediated rather than driven by sex-specific physiological factors. Future studies employing larger, sex-balanced, and training-stratified samples are needed to further clarify the neuromuscular mechanisms through which strength governs fatigue resistance.

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