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REVIEW

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# Sex differences in skeletal muscle fiber types: A meta-analysis

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## Abstract

Biopsies have been acquired from living men and women to determine proportions of Type I (slow-twitch) and II (fast-twitch) skeletal muscle fibers since the 1970s. Sex differences have been assumed but the literature has not been submitted to meta-analysis. Here, the aim was to generate effect sizes of sex differences in muscle fiber cross-sectional areas, distribution percentages, and area percentages. Data from 2875 men and 2452 women, who participated in 110 studies, were analyzed. Myofibrillar adenosine triphosphatase histochemistry was used in 71.8% of studies to classify fibers as Type I, II, IIA, and/or IIX; immunohistochemistry, immunofluorescence, or sodium dodecyl sulfate-polyacrylamide gel electrophoresis were used in 35.4% of studies to similarly classify myosin heavy chain (MHC) isoform content. Most studies involved biopsies from vastus lateralis (79.1%) in healthy individuals (92.7%) between 18 and 59 years old (80.9%). Men exhibited greater cross-sectional areas for all fiber types ($g = 0.40$–$1.68$); greater distribution percentages for Type II, MHC II, IIA, IIX fibers ($g = 0.26$–$0.34$); greater area percentages for Type II, IIA, MHC IIA, IIX fibers ($g = 0.39$–$0.93$); greater Type II/I and Type IIA/I fiber area ratios ($g = 0.63$, $0.94$). Women exhibited greater Type I and MHC I distribution percentages ($g = -0.13$, $-0.44$); greater Type I and MHC I area percentages ($g = -0.53$, $-0.69$); greater Type I/II fiber area ratios ($g = -1.24$). These data, which represent the largest repository of comparative muscle fiber type data from living men and women, can inform discussions about biological sex and its impact on pathologies and sports performance (e.g., explaining sex differences in muscle strength and muscle endurance).

KEYWORDS
anatomy, biopsy, men, muscles, physiology, quadriceps muscle, sex, women

## 1 | INTRODUCTION

Researchers have biopsied skeletal muscles from living men and women to determine muscle fiber types since the 1970s. In early studies, myofibrillar adenosine triphosphatase (mATPase) histochemistry was used to classify fibers as Type I ("slow twitch") or Type II ("fast twitch"), with additional subtypes established for Type II fibers (e.g., Type IIA, Type IIX [called Type IIB in some papers]). Later, immunohistochemistry and sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) were used to examine myosin heavy chain (MHC) isoform content, with strong correlations between proportional representations of MHC I, MHC IIA, and MHC IIX isoforms and proportional representations of Type I, Type IIA, and Type IIX fibers, respectively (Chalmers & Row, 2011; Damer et al., 2022; Fry et al., 1994; Scott et al., 2001; Staron, 1991). Because Type II fibers shorten at faster velocities and produce more force and power than Type I fibers, and because Type I fibers possess a greater capacity for oxidative energy production and are more endurant than Type II fibers (Bottinelli et al., 1996; 1999; Essén et al., 1975; Frontera et al., 2000; Garnett et al., 1979; Krivickas et al., 2001; 2006; Larsson et al., 1997; Stienen et al., 1996; Trappe et al., 2003; Widrick et al., 2002), a sex difference in muscle fiber type has implications for discussions about biological sex and its impacts on neuromuscular physiology, sport performance, and disease pathology. Differences in muscle fiber types might help to explain how men produce more force than women, as greater muscle mass in men than women does not appear to *fully* explain the sex difference in muscle strength (Nuzzo, 2023). A sex difference in muscle fiber types might also help to explain why women are more resistant to muscle fatigue than men are in certain exercise tasks (Hunter, 2016a; Nuzzo, 2023). Biological causes for sex differences in neuromuscular performance then have implications for discussions about transgender women (i.e., biological men) competing against biological women in the female category of sport (Hilton & Lundberg, 2021; Nokoff et al., 2023). A study of sex differences in muscle fiber types might also enhance understanding of potential sex differences in susceptibilities to the effects of aging (Doherty, 2001; Lexell, 1995), disease (Ciciliot et al., 2013; Talbot & Maves, 2016), and exercise participation (Straight et al., 2020).

In a recent narrative review, Nuzzo (2023) collated data from 34 studies that reported on skeletal muscle fiber types in men and women. Nuzzo (2023) concluded that men and women have similar proportional numbers (i.e., distribution percentages) of Type I and Type II fibers but that Type II fibers occupy a greater proportional area (i.e., area percentage) of muscle in men than women. Moreover, Type I muscle fibers occupy a greater area percentage of muscle in women, leading to higher Type II/I fiber area ratios in men than women (Nuzzo, 2023). Hunter (2016a) reached a similar conclusion after examining results from 13 studies. Nevertheless, the reviews by Nuzzo (2023) and Hunter (2016a) were narrative, and they were not concentrated on the topic of sex differences in muscle fiber types. Consequently, the literature searches were not exhaustive, and only mean values, without consideration of measurement variability and effect sizes, were presented (Hunter, 2016a; Nuzzo, 2023).

Therefore, the purpose of the current study was to use meta-analysis to generate effect sizes of sex differences in cross-sectional areas, distribution percentages, and area percentages of various skeletal muscle fiber types as determined by biopsy in living humans. Such information has potential to clarify differences in neuromuscular anatomy and physiology between men and women and thus inform ongoing discussions about biological sex and its impacts on neuromuscular physiology, sport performance, and disease pathology (Hilton & Lundberg, 2021; Hunter, 2014; 2016a; 2016b; Jones et al., 2021; Nokoff et al., 2023; Nuzzo, 2023; Roberts et al., 2020; Vinciguerra et al., 2023). Such information also meets calls for more sex-segregated data in biomedical research (Schilaty et al., 2018; Smith, Mckay, Ackerman, et al., 2022; Smith, Mckay, Kuikman, et al., 2022).

## 2 | METHODS

### 2.1 | Literature search

Thirty-four papers with relevant data were already known to the author based on a previous narrative review (Nuzzo, 2023). However, an updated and more exhaustive literature search was performed in March of 2023. The search involved a mixed approach that was similar to that described by Greenhalgh and Peacock (2005). It relied on the investigator's personal knowledge from previous research on the topic (Nuzzo, 2023), checking of personal digital files, relevant keyword searches in PubMed and Google Scholar, and "snowballing" strategies (i.e., reference and citation tracking). Keyword searches in PubMed and Google Scholar included various combinations of words such as, but not limitited to, "biopsy," "fast twitch," "female," "fiber type," "male," "men," "muscle fiber," "sex," "slow twitch," and "women." No date restrictions were placed on the search. Tables of muscle fiber type data presented in other papers were also a focus of the search strategy (Cagnie et al., 2015; Chalmers & Row, 2011; Damer et al., 2022; Gouzi et al., 2013; Hunter, 2016a; Naruse et al., 2023; Ng et al., 1998; Nuzzo, 2023; Staron et al., 2000; Straight et al., 2020).

### 2.2 | Eligibility

A study was eligible for inclusion into the meta-analysis if the following conditions were met: (a) data were published in a journal paper; (b) the paper was published in English; (c) muscle biopsies were performed on living humans; (d) muscle fiber percent distribution or percent area data were reported; and (e) mean values of muscle fiber percent distribution or percent area were reported for both men and women. Common reasons for exclusion included: data acquired at autopsy; data not segregated by sex or acquired in only men or only women; or no data on muscle fiber percent distribution or percent area reported. Also, the following papers were excluded due to duplication of data: (a) the paper by Bell and Jacobs (1989) was excluded because the authors presented the same data elsewhere (Bell & Jacobs, 1990) (included); (b) the paper by Froese and Houston (1987) was excluded because the authors presented the same data elsewhere (Froese & Houston, 1985) (included); (c) a paper by Jaworowski et al. (2002) was excluded because the authors presented the same data elsewhere (Holmbäck et al., 2003) (included). A paper by Evertsen et al. (1999) was also excluded, because, although the authors reported no sex difference in muscle fiber distribution percent of the vastus lateralis muscle in cross-country skiers, the authors did not present the sex-specific means. Papers that included means but no standard deviations (SD) or standard errors for the muscle fiber type outcomes of interest were still included in the research. The absence of SDs or standard errors prevented such data from contributing to the computed effect sizes. However, these data still contributed to the sex-specific weighted means for muscle fiber type outcomes. A

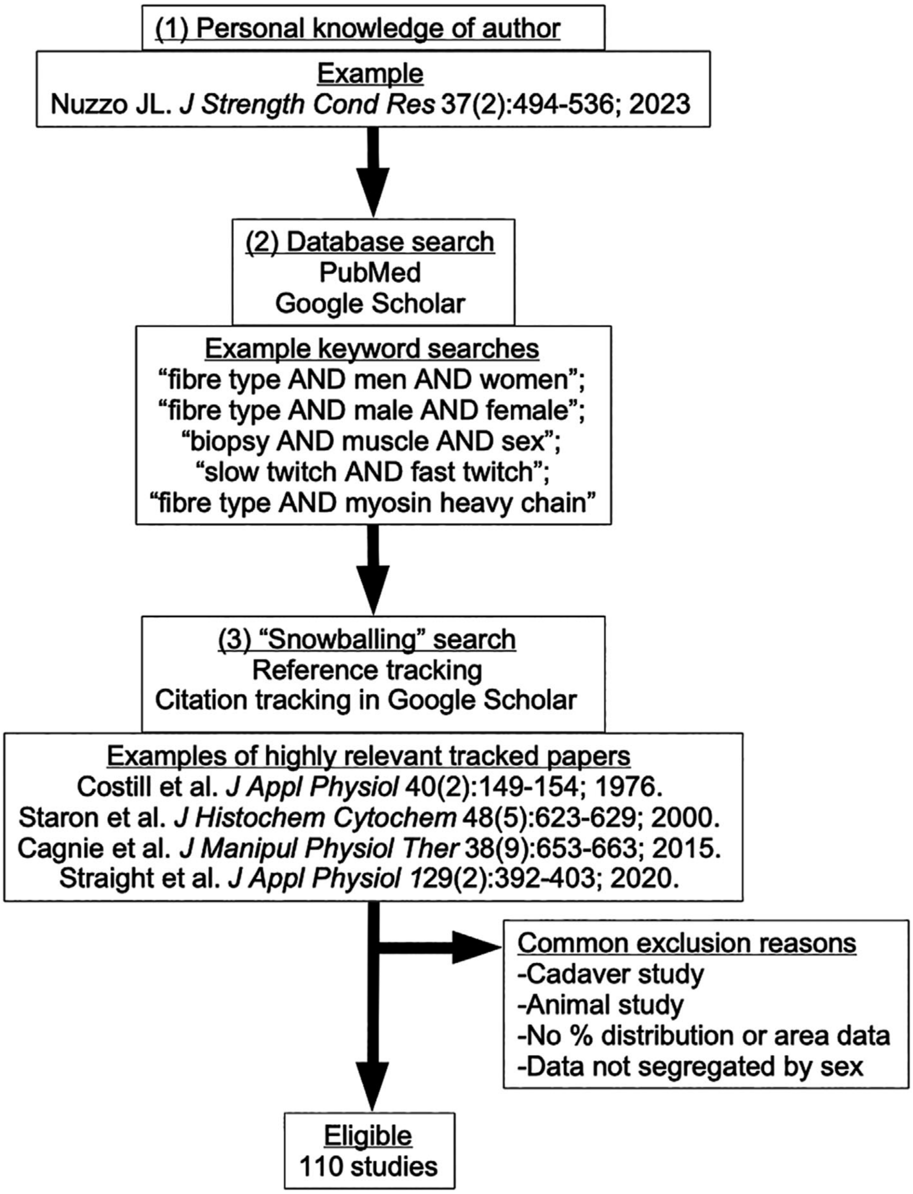


**FIGURE 1** Flow diagram of search strategy and exclusion process.

flow diagram of the search strategy and exclusion process is presented in Figure 1.

## 2.3 | Data extraction

Data that were extracted from eligible papers included author name, study year, country, sample size, age, health status (i.e., healthy or patient group), muscle biopsied, method used to analyze the biopsies, and means and SDs for fiber cross-sectional area, fiber distribution percent, fiber area percent, and fiber area ratios. For papers that presented muscle fiber type data before and after interventions, only measurements from baseline were extracted. When authors reported fiber size as diameter rather than cross-sectional area, the data were converted to area using an online calculator (https://www.omnicalculator.com/math/area-of-a-circle) (area $= \pi \times r^2$). When authors reported variance as standard error, the data were converted to SD by multiplying the standard error by the square root of the sample size. When authors presented data in figures, data were extracted using a graph digitzer (WebPlotDigitizer, https://apps.automeris.io/wpd/).

Classification of muscle fiber types has evolved over time (Chalmers & Row, 2011; Damer et al., 2022; Fry et al., 1994; Scott et al., 2001; Staron, 1991). Thus, because researchers have reported muscle fiber type data using different taxonomies, a decision was made by the author to extract data of the fiber type classifications reported most commonly across the entirety of the relevant literature. The extracted and analyzed muscle fiber type classifications were: Type I, Type II, Type IIA, Type IIX, MHC I, MHC II, MHC IIA, and MHC IIX. Of note, results from mATPase histochemistry and MHC isoform methods correlate (e.g., Type I vs MHC I) (Fry et al., 1994; Staron, 1991). Thus, in the current paper, Type I and MHC I fibers can be considered Type I slow twitch fibers, Type IIX and MHC IIX fibers can be considered Type II fast twitch fibers, and Type IIA and MHC IIA can be considered Type II intermediate fast twitch fibers. The Type and MHC data that corresponded to each other (i.e., Type I and MHC I) were not combined in the current analysis, because, although their correlations are strong (Fry et al., 1994, Staron, 1991), they not perfect, and it was clear that enough data were available from both types of outcomes that they could be analyzed separately.

### 2.4 | Statistical analysis

Version 29 of the Statistical Software Package for the Social Sciences (SPSS, Armonk, US) was used to analyze the data and create plots for the meta-analysis. Random effects meta-analyses were used to generate effect sizes (Hedges *g*) with 95% confidence intervals (CI) and prediction intervals (Inthout et al., 2016) for sex differences in muscle fiber types. Separate meta-analyses were performed for cross-sectional areas, distribution percentages, area percentages for Type I, Type II, Type IIA, Type IIX, MHC I, MHC II, MHC IIA, and MHC IIX muscle fibers. Meta-analyses were also performed for Type I/II, Type II/I, and Type IIA/I fiber area ratios. Forest plots were used to graphically display the results from the meta-analyses. Each Forest plot displayed the effect sizes of individuals studies and the overall effect size and 95% CI. Effect sizes equal to 0.2, 0.5, and 0.8 are often considered small, moderate, and large, respectively; however, such benchmarks are arbitrary and should not be interpreted rigidly (Lakens, 2013). Confidence intervals not crossing zero indicate overall effects that are statistically significant (i.e., $p \le 0.05$) (Cumming, 2009). Also, in the Forest plots, when applicable, data were separated by age group (< 18, 18–59, and > 59years). The age group-specific effect sizes were presented along with the overall effect size across all individuals. The overall effect size was the main statistic of interest, with age group-specific effect sizes presented as preliminary results. Funnel plots were generated to explore potential publication and other bias. Tests of heterogeneity were also conducted. Sex-specific weighted means for fiber cross sectional areas, distribution percentages, area percentages, and fiber area ratios were also computed. All of the data and results associated with the research are available either in the text, Appendix S1, or at the Open Science Framework (https://osf.io/m97z3/).

## 3 | RESULTS

### 3.1 | Study characteristics

A total of 110 studies, which ranged in publication year from 1976 to 2022, were included in the analysis (see Appendix S1). Four studies (Costill et al., 1976; Nygaard et al., 1983; Rolf et al., 1997; Sjøgaard, 1982) did not contribute effects for any of the outcomes because the authors reported only means and no SDs or standard errors. Thus, 106 studies contributed to one or more of the effect sizes in the meta-analysis. Some studies included multiple groups of men and women and thus contributed multiple effects to the analysis. All 110 studies contributed to one or more of the weighted means. The 110 studies included data from 2875 men and 2452 women, who comprised 157 study groups. The means ± SD of the sample sizes for men and women were 26.1 ± 32.9 (minimum = 4; maximum = 215) and 22.3 ± 27.5 (minimum = 4; maximum = 203), respectively.

Table 1 presents the number of studies by country, age group, health status, and muscle biopsied. Most studies were conducted in Sweden (*n* = 27, 24.5%) and the United States (*n* = 27, 24.5%). The vast majority of studies included participants who were healthy (*n* = 102, 92.7%) and 18–59 years old (*n* = 89, 80.9%). Athletes were participants in 11.8% of studies. The vastus lateralis was the muscle most frequently biopsied (*n* = 87, 79.1%). mATPase was the method used most frequently to determine muscle fiber type (*n* = 79, 71.8%).

### 3.2 | Muscle fiber type variables

All Forrest plots from the meta-analysis are provided in the supplementary figures (Figures S1-S26). Table 2 provides a summary of the findings from the meta-analyses for each muscle fiber type outcome (i.e., number of effects, Hedges *g*, 95% CIs, and 95% predictions intervals). Table 2 also displays the weighted means each of the muscle fiber type outcomes. Muscle-specific weighted means for Type I distribution percentages are presented in Table 3. For vastus lateralis, weighted means for other muscle fiber type outcomes are also presented in Table 3.

Men exhibited larger cross-sectional areas for Type I, Type II, Type IIA, Type IIX, MHC I, MHC I, MHC II, MHC IIA, and MHC IIX muscle fibers (Figures S1–S8). Men exhibited greater distribution percentages for Type II, MHC II, MHC IIA, and MHC IIX muscle fibers (Figures S10, S14–S16). Women exhibited greater distribution percentages for Type I and MHC I muscle fibers (Figures S9, S13) and there were no sex differences in distribution percentages for Type IIA and Type IIX muscle fibers (Figures S11, S12). Men exhibited greater area percentages for Type II, Type IIA, MHC IIA, and MHC IIX muscle fibers (Figures S18, S19, S22, S23). Women exhibited greater area percentages for Type I and MHC I muscle fibers (Figures S17, S21) and there was no sex difference in area percentage for Type IIX muscle fibers (Figure S20). Men exhibited greater Type II/I and Type IIA/I fiber area ratios (Figures S25, S26). Women exhibited greater Type I/II fiber area ratios (Figure S24).

The figures in Appendix S1 also display effect sizes by age group. The results from this preliminary analysis appear to show that age and sex interact to impact the size of the sex difference for some muscle fiber type outcomes, most notably Type I distribution percent (girls < boys; women > men in middle age; women = men in older age) and Type IIA and Type IIX distribution percent (girls > boys; women < men in middle age; women = men in older age). When data from youth and older adults are excluded, a statistically significant sex difference is present for Type IIA distribution percentage (men > women, Figure S11).

**TABLE 1** Characteristics of study ($n = 110$) methods and samples.

| Category | *n* | % study total |
|---|---|---|
| Country | | |
| Australia | 3 | 2.7 |
| Canada | 15 | 13.6 |
| Croatia | 1 | 0.9 |
| Denmark | 9 | 8.2 |
| Finland | 4 | 3.6 |
| France | 2 | 1.8 |
| Greece | 2 | 1.8 |
| Japan | 2 | 1.8 |
| South Korea | 1 | 0.9 |
| Netherlands | 2 | 1.8 |
| Norway | 1 | 0.9 |
| Russia | 2 | 1.8 |
| Spain | 3 | 2.7 |
| Sweden | 27 | 24.5 |
| Switzerland | 4 | 3.6 |
| United Kingdom | 4 | 3.6 |
| United States of America | 27 | 24.5 |
| Venezuela | 1 | 0.9 |
| Muscle | | |
| Biceps brachii | 6 | 5.5 |
| Gastrocnemius medialis | 2 | 1.8 |
| Gastrocnemius lateralis | 5 | 4.5 |
| Longissimus/ES | 7 | 6.4 |
| Multifidus | 5 | 4.5 |
| Rectus femoris | 2 | 1.8 |
| Semitendinosus | 1 | 0.9 |
| Soleus | 1 | 0.9 |
| Tibialis anterior | 2 | 1.8 |
| Triceps brachii | 2 | 1.8 |
| Vastus lateralis | 87 | 79.1 |
| Method for fiber typing | | |
| mATPase | 79 | 71.8 |
| MHC immunohistochemistry | 16 | 14.5 |
| MHC SDS-PAGE | 21 | 19.1 |
| MHC immunofluorescence | 2 | 1.8 |
| Age group | | |
| Youth (<18 years) | 7 | 6.4 |
| Adult (18–59 years) | 89 | 80.9 |
| Older adult (≥60 years) | 24 | 21.8 |
| Health status | | |
| Mixed group | 1 | 0.9 |
| Healthy | 102 | 92,7 |
| Non-athlete | 89 | 80.9 |
| Athlete | 13 | 11.8 |
| Bodybuilders | 2 | 1.8 |
| Dancers | 2 | 1.8 |
| Jumpers | 1 | 0.9 |
| Mixed group | 1 | 0.9 |
| Orienteers | 1 | 0.9 |
| Powerlifters | 3 | 2.7 |
| Runners—long distance | 1 | 0.9 |
| Runners—middle distance | 2 | 1.8 |
| Runners—sprinters | 2 | 1.8 |
| Speed skaters | 1 | 0.9 |
| Throwers—javelin | 1 | 0.9 |
| Throwers—shot, discus | 1 | 0.9 |
| Patients | 20 | 18.2 |
| Anorexia nervosa | 1 | 0.9 |
| Chronic heart failure | 1 | 0.9 |
| COPD | 2 | 1.8 |
| Diabetes | 3 | 2.7 |
| Low back pain | 8 | 7.3 |
| Multiple sclerosis | 2 | 1.8 |
| Obesity | 3 | 2.7 |
| Peripheral artery disease | 1 | 0.9 |

Abbreviations: COPD, chronic obstructive pulmonary disease; mATPase, myofibrillar adenosine triphosphatase; MHC, myosin heavy chain; SDS-PAGE, sodium dodecyl sulfate-polyacrylamide gel electrophoresis.

## 4 | DISCUSSION

The purpose of the current study was to use meta-analysis to generate effect sizes of sex differences in cross-sectional areas, distribution percentages, and area percentages of various skeletal muscle fiber types in living men and women. Data from 2875 men and 2452 in 110 studies were analyzed. The results reveal that men exhibit greater cross-sectional areas for all muscle fiber types and greater area percentages for Type II muscle fibers. Women exhibit greater distribution and area percentages for Type I fibers. Consequently, women exhibit greater Type I/II fiber area ratios than men, whereas men exhibit greater Type II/I fiber ratios than women.

Similar to conclusions reached in narrative reviews that considered fewer studies (Hunter, 2016a; Nuzzo, 2023), the current meta-analysis confirmed that Type II muscle fibers comprise a larger area of male than female skeletal muscle, whereas Type I muscle fibers comprise a larger area of female than male skeletal muscle. Consequently, Type II/I fiber area ratios are greater in men than women. However, unlike previous reviews that concluded there may be no difference in fiber distribution percentages between men and women (Hunter, 2016a, Nuzzo, 2023), the current meta-analysis revealed that distribution percentages of Type I muscle fibers are greater in women than men, whereas distribution percentages of Type II muscle fibers tend to be greater in men than women, though the effects are small-to-moderate in size.

**TABLE 2** Sex differences in muscle fiber type characteristics as determined by random-effects model meta-analyses.

| Fiber type characteristic | No. effects | Effect size: Hedges *g* | 95% CI LB, UB | 95% PI LB, UB | Men *n* | Men Mean | Men SD | Women *n* | Women Mean | Women SD |
|---|---|---|---|---|---|---|---|---|---|---|
| CSA (μm$^2$) | | | | | | | | | | |
| Type I | 63 | 0.75* | 0.58, 0.92 | −0.26, 1.76 | 1403 | 4440.0 | 951.5 | 1279 | 3775.2 | 883.3 |
| Type II | 23 | 1.68* | 1.26, 2.09 | −0.12, 3.47 | 396 | 4671.4 | 2067.4 | 377 | 3127.3 | 1447.2 |
| Type IIA | 48 | 1.42* | 1.18, 1.66 | 0.00, 2.84 | 1117 | 4923.0 | 1166.8 | 1025 | 3507.4 | 793.9 |
| Type IIX | 38 | 1.40* | 1.05, 1.76 | −0.62, 3.43 | 996 | 4310.1 | 1024.9 | 905 | 2844.1 | 739.0 |
| MHC I | 21 | 0.40* | 0.21, 0.59 | −0.07, 0.87 | 305 | 4862.6 | 841.1 | 280 | 4259.5 | 793.4 |
| MHC II | 11 | 1.08* | 0.73, 1.44 | 0.02, 2.15 | 178 | 5234.4 | 1387.9 | 149 | 3669.2 | 1177.4 |
| MHC IIA | 12 | 0.81* | [0.45, 1.18 | −0.31, 1.94 | 153 | 4643.0 | 700.5 | 152 | 3769.2 | 937.9 |
| MHC IIX | 10 | 1.37* | 1.11, 1.64 | 1.06, 1.67 | 141 | 3730.6 | 492.3 | 138 | 2191.4 | 572.6 |
| Distribution % | | | | | | | | | | |
| Type I | 97 | −0.13* | −0.24, −0.03 | −0.79, 0.53 | 2149 | 50.6 | 9.3 | 1774 | 53.2 | 9.4 |
| Type II | 21 | 0.34* | 0.03, 0.64 | −0.78, 1.46 | 520 | 47.5 | 13.2 | 419 | 45.5 | 13.4 |
| Type IIA | 76 | 0.10 | 0.00, 0.19 | −0.25, 0.44 | 1732 | 33.6 | 7.1 | 1420 | 32.4 | 6.4 |
| Type IIX | 71 | 0.07 | −0.05, 0.18 | −0.54, 0.67 | 1718 | 15.2 | 5.1 | 1404 | 14.3 | 6.0 |
| MHC I | 51 | −0.44* | −0.59, −0.30 | −1.09, 0.20 | 905 | 41.0 | 8.9 | 872 | 46.8 | 8.6 |
| MHC II | 10 | 0.26 * | 0.05, 0.47 | 0.01, 0.51 | 230 | 53.2 | 9.2 | 150 | 50.9 | 9.6 |
| MHC IIA | 44 | 0.33* | 0.11, 0.55 | −0.84, 1.49 | 777 | 43.5 | 8.3 | 764 | 39.5 | 9.5 |
| MHC IIX | 32 | 0.33* | 0.16, 0.49 | −0.21, 0.86 | 655 | 18.4 | 7.3 | 651 | 14.8 | 7.4 |
| Area % | | | | | | | | | | |
| Type I | 31 | −0.53* | −0.76, −0.30 | −1.55, 0.49 | 597 | 49.3 | 12.4 | 514 | 54.8 | 14.2 |
| Type II | 8 | 0.93* | 0.60, 1.26 | 0.52, 1.34 | 129 | 59.2 | 13.0 | 132 | 52.9 | 12.3 |
| Type IIA | 25 | 0.40* | 0.20, 0.59 | −0.21, 1.01 | 450 | 33.4 | 8.5 | 368 | 29.6 | 9.3 |
| Type IIX | 25 | 0.19 | −0.04, 0.41 | −0.63, 1.00 | 450 | 15.0 | 5.2 | 368 | 13.4 | 6.2 |
| MHC I | 13 | −0.69* | −0.92, −0.47 | −0.95, −0.44 | 202 | 37.5 | 4.9 | 157 | 47.2 | 7.4 |
| MHC IIA | 12 | 0.39* | 0.10, 0.68 | −0.32, 1.10 | 186 | 50.3 | 4.9 | 142 | 45.2 | 6.7 |
| MHC IIX | 10 | 0.50* | 0.26, 0.75 | 0.21, 0.78 | 150 | 14.9 | 4.0 | 131 | 9.8 | 4.2 |
| Area ratio | | | | | | | | | | |
| Type I/II | 7 | −1.24* | −1.85, −0.62 | −3.16, 0.69 | 134 | 1.05 | 0.12 | 117 | 1.36 | 0.28 |
| Type II/I | 9 | 0.94* | 0.53, 1.35 | 0.00, 1.88 | 88 | 1.27 | 0.33 | 79 | 1.00 | 0.30 |
| Type IIA/I | 10 | 0.63* | 0.29, 0.96 | −0.04, 1.29 | 110 | 1.17 | 0.21 | 89 | 1.02 | 0.14 |

Abbreviations: CI, confidence interval; CSA, cross-sectional area; LB, lower bound; M, men; MHC, myosin heavy chain; PI, prediction interval; UB, upper bound; W, women.
*Statistically significant effects ($p \le 0.05$).

The cause of these sex differences in muscle fiber types is unknown. Esbjörnsson et al. (2021) have suggested that sex differences in physical activity patterns, interacting with sex differences in hormones (Haizlip et al., 2015), could contribute to sex differences in muscle fiber type. For example, men participate in physical activity and sport at higher rates than women do (Deaner et al., 2012; Gerovasili et al., 2015; Nuzzo, 2023; Van Tuyckom et al., 2010). Men are also more likely than women to prefer exercise at high intensities (Nuzzo, 2023). Thus, sex differences in physical activity preferences and participation might cause men to more regularly use fast-twitch muscle fibers in their daily lives.

The results might help to explain sex differences in exercise and sports performance. For example, as muscle *fiber* cross-sectional areas are greater in men than women, this helps to explain how cross-sectional area of *whole muscle* in women is 60%–70% of that of men (Nuzzo, 2023). Moreover, the percentage of whole muscle area occupied by Type II muscle fibers is greater in men than women. Thus, as Type II fibers produce more force and power than Type I fibers (Bottinelli et al., 1996; Bottinelli et al., 1999; Frontera et al., 2000; Krivickas et al., 2001; Krivickas et al., 2006; Larsson et al., 1997; Stienen et al., 1996; Trappe et al., 2003; Widrick et al., 2002), larger muscle sizes and greater Type II fiber distribution and area

**TABLE 3** Weighted means of type I muscle fiber distribution percentages in various muscles, with weighted means for other muscle fiber types provided for vastus lateralis.

| | | Weighted means | | | | | |
|---|---|---|---|---|---|---|---|
| | | Men | | | Women | | |
| Muscle | Fiber type | *n* | Mean | SD | *n* | Mean | SD |
| Bicep brachii | Type I | 57 | 47.7 | 8.3 | 45 | 58.1 | 18.5 |
| Gastrocnemius lateralis | Type I | 77 | 54.8 | 8.8 | 108 | 54.8 | 5.9 |
| Gastrocnemius medialis | Type I | 22 | 61.8 | 7.8 | 28 | 47.8 | 14.1 |
| Longissimus/ES | Type I | 150 | 62.7 | 6.2 | 129 | 67.6 | 7.1 |
| Multifidus | Type I | 123 | 59.5 | 8.5 | 97 | 58.6 | 7.8 |
| Tibialis anterior | Type I | 30 | 75.1 | 2.7 | 30 | 75.8 | 1.1 |
| Triceps brachii | Type I | 17 | 47.2 | 3.9 | 13 | 44.1 | 7.8 |
| Vastus lateralis | Type I | 1654 | 48.0 | 7.3 | 1303 | 50.6 | 6.9 |
| Vastus lateralis | Type IIA | 1732 | 33.6 | 7.1 | 1420 | 32.4 | 6.4 |
| Vastus lateralis | Type IIX | 1718 | 15.2 | 5.2 | 1404 | 14.3 | 6.0 |
| Vastus lateralis | MHC I | 905 | 41.0 | 8.9 | 872 | 46.8 | 8.6 |
| Vastus lateralis | MHC IIA | 777 | 43.5 | 8.3 | 764 | 39.5 | 9.5 |
| Vastus lateralis | MHC IIX | 655 | 18.4 | 7.3 | 651 | 14.8 | 7.4 |

Abbreviations: ES, erector spinae; MHC, myosin heavy chain.

percentages among men than women help to explain how muscle strength in women is ~60% of muscle strength of men (Nuzzo, 2023). Conversely, as Type I fibers possess a greater capacity for oxidative energy production than Type II fibers (Essén et al., 1975; Garnett et al., 1979), and women exhibit greater distribution and area percentages of Type I fibers than men, this might help to explain how women are less fatigable than men during some resistance exercise tasks (Hunter, 2014; 2016a; Nuzzo, 2023).

The extent to which sex differences in muscle fibers type might differently impact responses to resistance exercise between men and women also warrants consideration, though evidence of a differential impact is generally lacking. For example, a bout of eccentric resistance exercise damages Type II muscles fibers more than Type I fibers (Fridén et al., 1983; Jones et al., 1986; Lieber et al., 1991; Macaluso et al., 2012; Magal et al., 2010). Thus, as men have greater distribution and area percentages of Type II fibers, one might expect men to experience more muscle damage from eccentric resistance exercise than women. This, however, does not appear to be the case. Two reviews on the topic have concluded that men and women experience similar magnitudes of muscle soreness and strength loss after a bout of eccentric resistance exercise (Morawetz et al., 2020; Nuzzo, 2023). Whether sex differences in muscle fiber type might impact muscle fiber adaptations to *weeks* of resistance exercise also warrants consideration. Regarding hypertrophy of specific muscle fibers, Straight et al. (2020) reviewed results from 35 studies and found that men and women over the age of 55 experience similar increases in sizes of MHC I and MHC II muscle fibers after weeks of resistance exercise. Regarding muscle fiber type "transitions," the most consistent finding is that Type IIX and hybrid muscle fibers transition to Type IIA fibers after weeks of resistance exercise, but evidence of a sex difference in such transitions is lacking (Bamman et al., 2003; Fry et al., 1994; Guadalupe-Grau et al., 2009; Häkkinen et al., 2002; Kosek et al., 2006; McGuigan et al., 2001; Sharman et al., 2001; Staron et al., 1994; Williamson et al., 2001). Thus, how differences in muscle fiber types between men and women might differently impact adaptations to a given exercise intervention remains to be understood.

Sex differences in muscle fiber types can also be considered in relation to aging. Aging atrophies Type II muscle fibers more than Type I fibers, causing fast-to-slow twitch muscle fiber transition in older adults (Doherty, 2001; Lexell, 1995). Men exhibit greater proportions of Type II fibers than women, thus one might expect men would experience a greater proportional decrease in muscle strength with aging. However, mixed results have been reported regarding whether there is a sex difference in relative strength loss with aging (Charlier et al., 2015; Hughes et al., 2001; Oksuzyan et al., 2010). Preliminary analysis of an interaction between sex and age on muscle fiber type in the current research appears to show that the magnitude of the sex difference in Type I distribution percentage is impacted by age. Type I distribution percentage appears to be less in girls than in boys, then becomes greater in women than men in middle age, and then no sex difference exists between women and men older than 59 years of age. Distribution percentages for Type IIA and Type IIX demonstrate the opposite pattern. Type IIA and Type IIX distribution percentages appear to be greater in girls than in boys, then become greater in men than in women in middle age, and then no sex difference exists between women and men older than 59 years of age.

The extents to which sex differences in muscle fiber types might also associate with disease prevalence and severity can also be considered. Men have greater distribution and area percentages of Type II skeletal muscle fibers, and conditions such as Duchenne muscular dystrophy, which is more prevalent among males than females (Centers for Disease Control and Prevention, 2009; Romitti et al., 2015), impact Type II muscle fibers more than Type I fibers (Ciciliot et al., 2013; Talbot & Maves, 2016). Conversely, other conditions impact Type I skeletal muscle fiber more than Type II fibers, causing slow-to-fast muscle fiber transitions. Examples include spinal cord injury, diabetes, heart disease, and chronic obstructive pulmonary disease (Ausín et al., 2017; Ciciliot et al., 2013; Mador & Bozkanat, 2001; Mårin et al., 1994; Talbot & Maves, 2016; Torres et al., 2011). In the current research, too little data were available from patient groups to explore potential interactive effects of disease type with sex on muscle fiber types. Nevertheless, the current research illustrates that in future studies on the impact of disease on muscle fiber types participant sex should be controlled for and/or male and female data should be presented and analyzed separately (Schilaty et al., 2018; Smith, Mckay, Ackerman, et al., 2022; Smith, Mckay, Kuikman, et al., 2022).

Results from the current study confirm differences in fiber type distribution percentages across muscle groups, though this was not the primary aim of this research. The muscle-specific weighted means in Table 3 illustrate that Type I distribution percentages are higher in tibialis anterior (~75%), longissimus (~65), and multifidus (~59%) and lower in vastus lateralis and biceps and triceps brachii (~45–50%). Nevertheless, differences in Type I distribution percentages across muscle groups appear to be generally similar between men and women. As the majority of muscle biopsies in the current analysis were of vastus lateralis, a potential aim for future research could be to generate more precise sex-specific estimates of fiber type characteristics of skeletal muscles other than vastus lateralis during development, aging, and disease progression. However, practical issues of acquiring muscle biopsies from willing participants are acknowledged.

Finally, the current meta-analysis is not without limitations. First, the current research did not abide by procedures for literature searches that are often used in systematic reviews nor did the current research include assessments of study quality. Consequently, results from the analysis should be considered with some caution. Nevertheless, the search was thorough. It led to the discovery of 110 studies with sex-segregated muscle fiber type data. This is significantly more than the number of studies summarized in previous narrative reviews (Hunter, 2016a; Nuzzo, 2023), and narrative reviews would be more prone to investigator bias than the current meta-analysis. Second, in the current research, data from participants of all ages, health statuses, and exercise backgrounds were combined into one large analysis. If sex interacts with age, health status, and exercise background to impact muscle fiber types then the current approach might not be ideal. The preliminary analysis of the data partitioned by age suggests that inclusion of muscle fiber data from youth (<18 years) and older adults (>59 years) decreases or *under*estimates the size of sex differences for some outcomes (e.g., Type I distribution percent, see Figure S9). Thus, in studying sex differences in muscle fiber types, combining data across age groups is a conservative approach that favors the null hypothesis (i.e., no sex difference in muscle fibers in middle-aged adults). These preliminary results can be tested more formally in future meta-analyses after more muscle fiber type data are presented in youth and older adult samples.

## 5 | CONCLUSION

Results from the current meta-analysis reveal that sex differences in muscle fiber types exist. Men exhibit greater cross-sectional areas for all muscle fiber types, greater distribution percentages for Type II, MHC II, MHC IIA, and MHC IIX fibers, and greater area percentages for Type II, Type IIA, MHC II, MHC IIA, and MHC IIX fibers. Women exhibit greater distribution and area percentages for Type I and MHC I fiber types. Sex differences in muscle fiber types might help to explain greater muscle strength and power among men than women and greater muscle endurance among women than men for some resistance exercise tasks. These data, which are believed to be the largest repository of comparative muscle fiber type data in living men and women, can inform ongoing discussions about biological sex and its impact on neuromuscular physiology, disease pathology, and sports performance.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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