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ORIGINAL ARTICLE

Epidemiology/Genetics

Sex differences in the secular change in waist circumference relative to BMI in five countries from 1997 to 2020

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Abstract

Objective: The objective of this study was to quantify changes over time in waist circumference (WC) relative to BMI by sex in the Americas (United States, Mexico, Chile, and Peru) and England.

Methods: Data from adults aged 25 to 64 years between 1997 and 2020 were analyzed, and US data were stratified by race and ethnicity groups. Sex-specific BMI and WC means and obesity and abdominal obesity prevalence were compared between the first and last surveys. Using data from all survey years, secular changes across the BMI and WC distributions were estimated, applying quantile regression models. BMI was added as a predictor of WC to estimate secular changes in WC relative to BMI. Interaction terms were included in all models to evaluate differences by sex.

Results: BMI and WC (except for Peru) showed larger secular increases at the upper-tails of the distributions in both sexes. Increases at the 50th and 75th WC percentiles relative to BMI were more pronounced in women than in men, with larger increases in US non-Hispanic White individuals and in England. In men, increases in WC independent of BMI were most evident in Mexico.

Conclusions: Disease risk associated with visceral fat is potentially underestimated by national surveillance efforts that quantify only secular changes in BMI.

INTRODUCTION

Obesity, defined as body mass index (BMI) ≥ 30 kg/m^2, has increased worldwide in the past few decades. More than 2.5 billion adults aged 18 years and older had overweight in 2022, and, of these, 890 million had obesity [1]. BMI, a marker of general adiposity, has been the anthropometric indicator most used to assess trends in body fatness at the population level [2] and is frequently used to assess cardiometabolic risk and associated disease [3–5].

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BMI alone is not sufficient as an indicator to assess health-related risks properly; its limitations as a measure of body fatness are widely recognized. BMI does not assess the distribution of body fat, and the adverse consequences of obesity may be strongly associated with the amount of visceral fat [6]. Waist circumference (WC), a marker of abdominal adiposity, is a simple, more sensitive measure that enables better assessment of visceral adiposity associated health risk [7]. WC is now recommended as a complementary measure alongside BMI in epidemiology studies and clinical practice [8].

WC and BMI are positively correlated at the individual level (Pearson correlation coefficient $r \sim 0.9$) [6]. As such, secular increases in mean

WC at the population level are speculated to have largely occurred due to the increases in BMI during the same period. An emerging global concern is a recent shift to increasing abdominal obesity (indicated by higher WC) independent of BMI [9].

Only a few studies have assessed secular changes in WC relative to BMI [6, 10–12] or body weight [13] and whether such changes differed by sex, countries, or race and ethnicity groups [9, 14]. Freedman and Ford, using US data, reported that the increase in mean WC between 1999 to 2000 and 2011 to 2012 was independent of BMI increases during that same time period in women, but not in men [6]. Albrecht et al. reported disproportionate increases in mean WC relative to BMI in the populations of the United States, Mexico, China, and England, particularly in women aged 20 to 29 years [14]. In the 1946, 1958, and 1970 British birth cohorts, Johnson et al. observed higher increases in WC independent of BMI in mid-adulthood in women, but not in men [15].

We expand on these research efforts by exploring recent secular changes in WC relative to BMI in other countries to assess whether the findings described previously are also observed in countries such as Chile and Peru, where recent increases in obesity have been more rapid. Using data from the Americas (United States, Mexico, Chile, and Peru) and England, our objective was to quantify secular changes in BMI, WC, and WC relative to BMI within each country and explore differences by sex.

Study Importance

What is already known?

- BMI alone is not sufficient as an anthropometric indicator to assess health-related risks.
- Waist circumference (WC) and BMI are highly positively correlated at the individual level.

What does this study add?

- Mixed patterns in the Americas (United States, Mexico, Chile, and Peru) and in England in adults aged 25 to 64 years were observed for secular changes in WC relative to BMI between 1997 and 2020.
- Increases in WC relative to BMI were observed, especially, but not exclusively, in women.

How might these results change the direction of research?

- Increases in disease risk at the population level, associated with visceral fat, are underestimated by national surveillance efforts that quantify only secular changes in BMI.
- More investigation is needed to identify the key modifiable factors underlying recent increases in WC relative to BMI.

METHODS

Data were obtained from five nationally representative health examination surveys (HES). All countries' HES collect cross-sectional data from the civilian noninstitutionalized population using face-to-face interviews and direct measurements of height, weight, and WC (see Table S1 for detailed description of the HES design and methods). Further information, compiled by the Encuestas de Salud de las Americas y el Reino Unido (Health Surveys of the Americas and the United Kingdom, ESARU) network of HES researchers, is available in Mindell et al. [16].

Chile

Chilean data were obtained from the Encuesta Nacional de Salud (National Health Survey, ENS) 2003, 2010, and 2017 [17]. ENS provides information on prioritized health conditions and their treatment. Individuals aged 65 years and over were oversampled, with one eligible person sampled per household. Study protocols and ethical consent forms were approved by the ethics committee of the Pontificia Universidad Católica de Chile (Pontifical Catholic University of Chile, PUC) and the Ministry of Health. Individuals selected for inclusion provided informed and signed consent before participation.

Mexico

For Mexico, we used the Encuesta Nacional de Salud y Nutrición (National Health and Nutrition Survey, ENSANUT) 2006, 2012, and 2018. Conducted every 6 years by Mexico's Instituto Nacional de Nutrición (National Institute of Nutrition, INSP), ENSANUT characterizes the health and nutritional status of the Mexican population [18]. Data collection was approved by the INSP internal review board, and all participants gave informed consent.

Peru

For Peru, we included the Encuesta Demográfica y de Salud Familiar (Demographic and Family Health Survey, ENDES) 2018, 2019, and 2020. ENDES characterizes communicable and noncommunicable diseases (NCD) in the Peruvian population (surveys before 2018 assessed only the health status of women of reproductive age and of children aged under 5 years).

United States

US data were obtained from the National Health and Nutrition Examination Survey (NHANES), conducted by the National Center for Health Statistics. NHANES uses a complex, multistage sample design. Participants complete in-home interviews followed by medical examinations in mobile examination centers. The National Center for Health Statistics ethics review board approved the survey, and participants gave informed consent. We used data from the ten 2-year cycles conducted continuously from 1999-2000 to 2017-2018. For this study, we combined consecutive 2-year cycles into pooled 4-year time periods to increase sample sizes.

England

Data were obtained from the Health Survey for England (HSE), which annually draws a new sample of people living in private households using multistage stratified probability sampling [19]. All adults in selected households are eligible for interview. Relevant committees granted research ethics approval. Participants gave verbal consent for interview. We used yearly data from 1997 to 2019.

Analytical sample

Data from available survey years between 1997 and 2020 were extracted for comparability. Our analytical sample comprised adults aged 25 to 64 years with complete data on and height and WC; pregnant or breastfeeding women were excluded. This age range was selected for comparability across studies with respect to the World Health Organization (WHO) STEPwise Approach to NCD Risk Factor Surveillance [20].

Anthropometric variables

Trained personnel used standardized protocols to collect anthropometric data. Height was measured without shoes using either a fixed or portable stadiometer, and weight was measured without shoes in light clothing on a beam balance or digital scale. Except for the United States, WC was measured at the midpoint between the lower edge of the rib cage and the top of the iliac crest. In the United States, measurement was taken at the top of the iliac crest. BMI was calculated as weight in kilograms divided by height in meters squared.

We excluded participants with outlying values (height < 130 or >200 cm; BMI < 10 or >58 kg/m^2; and WC < 50 or >200 cm). BMI was grouped into four categories: underweight (<18.5 kg/m^2); normal weight (18.5–24.9 kg/m^2); overweight (25.0–29.9 kg/m^2); and obesity (≥30.0 kg/m^2) [21]. Separate estimates are provided for ≥25.0 kg/m^2, class I obesity (30.0–34.9 kg/m^2), and class II/III obesity (≥35.0 kg/m^2). Abdominal obesity was defined as WC ≥ 88 cm (for women) or ≥102 cm (for men), based on WHO and the National Heart, Lung, and Blood Institute/North American Association for the Study of Obesity committee recommendations [22].

Statistical analysis

Descriptive analyses

Estimates for the first and last survey periods were stratified by sex and country. US data were stratified by the following race and ethnicity groups (collected via self-report): non-Hispanic (NH) White; NH Black; and Mexican-American. Direct age-standardized estimates were calculated using the 2000 US Census population (5-year age bands) [23].

We present the following outcomes: 1) height, weight, and BMI means; 2) BMI status; 3) mean WC; and 4) abdominal obesity. Secular changes were computed as the difference in means/prevalence between the first and last survey periods. Wald tests were performed to test the null hypothesis of no secular change (sex-specific tests) and to test for equality of change between men and women.

Secular changes in BMI and WC distributions

Quantifying secular changes in the means of BMI and WC through linear regression can obscure shifts in both the location and shape of the distributions [12]. Previous work [9, 12] has considered BMI and WC as separate outcomes. For comparison, using all available survey years, quantile regression was applied to estimate secular change (each year relative to the first) at the 5th, 25th, 50th (median), 75th, and 95th percentiles. Survey year was treated as a categorical variable (first year as referent), and the models included continuous age and age^2 (to allow for nonlinear relationships of BMI and WC with age) [6]. Sex-by-year interaction terms estimated differences in the magnitude of secular changes by sex.

Secular change in WC relative to BMI

Replicating previous analyses [9, 12], we first used linear regression with BMI included as a predictor to quantify secular change in mean WC. The models included age, age^2, BMI, BMI^2 (to allow for nonlinear relationships of WC with BMI), and interaction terms with survey year to estimate differences in secular changes by sex and by BMI. To facilitate interpretation, using model coefficients, we quantified sex-specific secular changes in mean WC relative to BMI at overweight and obesity cut-points (25, 30, and 35 kg/m^2). Second, analyses were repeated using quantile regression to estimate change over time at the aforementioned WC percentiles at the three BMI cut-points.

For all regression analyses, postestimation Wald tests were used as tests of significance for men and women and then for sex differences. All analyses accounted for each survey's complex design. NHANES analytical guidelines for combining consecutive 2-year cycles into 4-year periods were implemented [24]. Statistical significance was set at $p < 0.05$ for two-tailed tests, with no adjustment for multiple comparisons. Data set preparation and analysis were performed in SPSS version

24.0 (IBM Corp., Armonk, New York) and Stata version 18.0 (StataCorp LLC, College Station, Texas).

RESULTS

Descriptive analyses

Table S2A (height, weight, and BMI) and S2B (WC) present age-standardized estimates for the outcomes in the first and last study periods.

Secular change in mean BMI and WC

Except for Peru (both sexes), BMI and WC means increased in each country and US race and ethnicity group in both sexes. With regards to sex differences, mean BMI increased more in women than in men in England (1997 vs. 2019: 1.6 kg/m^2 women, 0.9 kg/m^2 men; $p = 0.003$ for sex difference); the same pattern was observed for mean WC in Chile (2003 vs. 2017: 6.0 cm women, 4.1 cm men; $p = 0.037$), England (1997 vs. 2019: 6.0 cm women, 2.0 cm men; $p < 0.001$), and in US NH White individuals (1999–2002 vs. 2015–2018: 6.6 cm women, 4.0 cm men; $p = 0.018$).

Secular change in overweight (including obesity), obesity, and abdominal obesity

Except for Peru and US NH Black women, prevalence of overweight (including obesity), obesity, and abdominal obesity increased in each country and US race and ethnicity group in both sexes.

Overweight (including obesity) prevalence increased more in women than in men in England (1997 vs. 2019: 8.7 percentage points [pp] women, 4.4 pp men; $p = 0.045$ for sex difference) but increased more in men than in women in US NH Black individuals (1999–2002 vs. 2015–2018: 11.6 pp men, 3.1 pp women; $p = 0.006$). Obesity in the United States increased more in men than in women in the NH White (1999–2002 vs. 2015–2018: 14.9 pp men, 8.0 pp women; $p = 0.035$) and NH Black (15.9 pp men, 8.4 pp women; $p = 0.026$) groups. Abdominal obesity increased more in women than in men in Chile (2003 vs. 2017: 17.6 pp women, 10.4 pp men; $p = 0.052$) and in England (1997 vs. 2019: 18.4 pp women, 7.7 pp men; $p < 0.001$) but increased more in men than in women in US NH Black individuals (1999–2002 vs. 2015–2018: 14.6 pp men, 7.2 pp women; $p = 0.027$).

Secular change in BMI and WC distributions

Based on separate quantile regression models, predicted values at the first and last survey periods and the estimated secular changes (final year vs. first year) at the 5th, 25th, 50th, 75th, and 95th percentiles are shown in Table 1 (BMI) and Table 2 (WC). For brevity, only results for participants aged 25 years are shown (because the models contained only the main effect of age, the estimates of change are independent of age).

BMI (except for men in Peru) and WC (except for both sexes in Peru) showed larger increases at the upper-tails of the distributions in both sexes. Significant differences by sex at the upper-tails were evident only in England. Increases between 1997 and 2019 at the 50th and 75th BMI percentiles were larger in women than in men (e.g., 50th percentile: 1.4 kg/m^2 women, 0.6 kg/m^2 men; $p = 0.001$ for sex difference). Over the same time period, median WC increased by 6.4 and 2.1 cm in women and men, respectively ($p < 0.001$ for sex difference).

Secular change in WC relative to BMI

Based on model coefficients with BMI included as a predictor of WC, the sex-specific secular changes (final year vs. first year) in mean WC (linear regressions) and at the 5th, 25th, 50th, 75th, and 95th percentiles (quantile regressions) at BMI = 25, 30, and 35 kg/m^2 are shown in Figures 1 through 5 (for full estimates, see Table S3A–G).

Linear regression: change in mean WC relative to BMI

Mixed patterns were observed for secular changes in mean WC relative to BMI. Mean WC decreased between 2018 and 2020 at each BMI level in both sexes in Peru.

In men, mean WC increased at each BMI level in Mexico, at BMI = 25 kg/m^2 in Chile, and at BMI = 30 kg/m^2 in England. In women, mean WC increased at each BMI level in Chile, Mexico, and England and in each US race and ethnicity group. Increases in mean WC were higher at higher BMI levels. For example, at BMI = 25 kg/m^2, increases in mean WC ranged from 0.7 cm in Mexico (2006 vs. 2018; 95% confidence interval [CI]: 0.0–1.4) to 2.8 cm in England (1997 vs. 2019; 95% CI: 2.3–3.3). At BMI = 35 kg/m^2, increases in mean WC ranged from 0.9 cm in Mexico (2006 vs. 2018; 95% CI: 0.4–1.5) to 3.8 cm in England (1997 vs. 2019; 95% CI: 3.0–4.5).

Sex differences in secular changes in mean WC relative to BMI were observed in US NH White individuals, US Mexican-American individuals, and in England, with larger increases in women than in men at each BMI cut-point.

Quantile regressions: change in WC distributions relative to BMI

Mixed patterns were observed for secular changes across the distributions of WC relative to BMI. Here, we discuss only the results at the 50th and 75th WC percentiles at BMI = 25 kg/m^2 and 30 kg/m^2 and present p values which summarize whether the change over time varied significantly by sex (for full results, see Table S3A–G).

TABLE 1 Predicted values of BMI (first and last) and difference (final minus first survey period) across centiles of BMI by sex and country.

BMI (kg/m^2)	Men			Women			Sex difference
	First, last	Change, β (95% CI)	*p* value	First, last	Change, β (95% CI)	*p* value	*p* value
Chile ($t_{2017} - t_{2003}$)							
5th	19.9 to 21.1	1.1 (0.3 to 1.9)	0.006	19.6 to 20.9	1.3 (0.5 to 2.1)	0.001	0.170
25th	22.8 to 23.8	1.0 (0.3 to 1.6)	0.004	22.6 to 24.1	1.5 (0.9 to 2.1)	<0.001	0.255
50th	25.3 to 26.6	1.3 (0.7 to 1.9)	<0.001	25.7 to 27.5	1.8 (1.0 to 2.6)	<0.001	0.300
75th	27.4 to 29.3	1.9 (1.1 to 2.6)	<0.001	29.5 to 31.3	1.8 (0.7 to 2.9)	0.001	0.965
95th	32.0 to 35.0	3.0 (1.1 to 4.8)	0.002	36.2 to 39.1	2.9 (1.3 to 4.5)	0.001	0.952
Mexico ($t_{2018} - t_{2006}$)							
5th	19.5 to 20.1	0.6 (0.2 to 1.1)	0.003	19.8 to 20.0	0.3 (−0.1 to 0.7)	0.194	0.241
25th	22.6 to 23.2	0.6 (0.3 to 0.9)	<0.001	23.3 to 24.0	0.7 (0.4 to 1.0)	<0.001	0.483
50th	25.6 to 26.6	1.0 (0.7 to 1.3)	<0.001	27.0 to 27.6	0.6 (0.3 to 0.9)	<0.001	0.048
75th	28.9 to 29.9	1.0 (0.7 to 1.4)	<0.001	30.8 to 31.7	1.0 (0.5 to 1.4)	<0.001	0.766
95th	34.7 to 36.1	1.4 (0.7 to 2.1)	<0.001	37.8 to 39.5	1.7 (0.8 to 2.5)	<0.001	0.656
Peru ($t_{2020} - t_{2018}$)							
5th	20.0 to 20.4	0.4 (0.1 to 0.7)	0.010	20.3 to 20.1	−0.2 (−0.5 to 0.2)	0.299	0.012
25th	22.7 to 23.0	0.3 (0.1 to 0.6)	0.016	23.4 to 23.5	0.1 (−0.2 to 0.3)	0.599	0.180
50th	25.3 to 25.5	0.2 (−0.1 to 0.4)	0.181	26.1 to 26.3	0.2 (0.0 to 0.5)	0.075	0.773
75th	28.2 to 28.2	0.0 (−0.3 to 0.3)	0.969	29.1 to 29.5	0.4 (0.0 to 0.7)	0.026	0.112
95th	33.2 to 33.3	0.1 (−0.7 to 0.8)	0.877	34.9 to 35.6	0.7 (0.1 to 1.3)	0.032	0.220
US NH White ($t_{2015–2018} - t_{1999–2002}$)							
5th	19.7 to 20.4	0.7 (0.0 to 1.4)	0.055	18.1 to 18.9	0.8 (0.2 to 1.4)	0.013	0.820
25th	22.9 to 23.6	0.7 (0.1 to 1.3)	0.024	21.0 to 21.8	0.9 (0.3 to 1.5)	0.002	0.661
50th	25.4 to 26.9	1.5 (1.0 to 2.1)	<0.001	24.3 to 25.9	1.7 (0.9 to 2.5)	<0.001	0.822
75th	29.0 to 31.4	2.4 (1.5 to 3.2)	<0.001	30.3 to 32.4	2.1 (0.8 to 3.3)	0.001	0.700
95th	35.7 to 40.8	5.0 (3.1 to 7.0)	<0.000	39.4 to 43.0	3.6 (2.2 to 5.0)	<0.001	0.254
US NH Black ($t_{2015–2018} - t_{1999–2002}$)							
5th	18.5 to 19.5	1.0 (0.0 to 2.0)	0.056	19.4 to 19.6	0.2 (−0.8 to 1.1)	0.749	0.243
25th	21.9 to 23.5	1.6 (0.9 to 2.3)	<0.001	23.8 to 24.6	0.8 (−0.1 to 1.7)	0.091	0.171
50th	25.9 to 27.5	1.6 (0.7 to 2.5)	0.001	28.7 to 30.5	1.9 (0.8 to 3.0)	0.001	0.652
75th	29.8 to 33.5	3.7 (2.6 to 4.8)	<0.001	34.9 to 37.1	2.2 (0.8 to 3.6)	0.002	0.092
95th	38.6 to 41.4	2.8 (0.5 to 5.1)	0.017	46.3 to 48.5	2.2 (0.8 to 3.7)	0.003	0.697
US Mexican-American ($t_{2015–2018} - t_{1999–2002}$)							
5th	19.9 to 21.1	1.2 (0.0 to 2.4)	0.057	19.5 to 20.0	0.5 (−0.7 to 1.8)	0.411	0.444
25th	23.8 to 25.4	1.5 (0.7 to 2.4)	<0.001	23.1 to 25.0	1.9 (1.3 to 2.5)	<0.001	0.498
50th	26.4 to 28.9	2.5 (1.7 to 3.3)	<0.001	26.5 to 28.9	2.4 (1.4 to 3.4)	<0.001	0.877
75th	29.8 to 33.4	3.6 (2.7 to 4.6)	<0.001	32.0 to 35.5	3.5 (2.1 to 4.8)	<0.001	0.832
95th	37.6 to 42.5	4.9 (1.3 to 8.4)	0.007	42.4 to 45.3	2.9 (0.3 to 5.5)	0.028	0.384
England ($t_{2019} - t_{1997}$)							
5th	19.8 to 20.0	0.1 (−0.3 to 0.5)	0.600	18.6 to 18.8	0.2 (−0.1 to 0.5)	0.217	0.720
25th	22.6 to 23.0	0.4 (0.1 to 0.6)	0.007	21.1 to 21.6	0.5 (0.3 to 0.8)	<0.001	0.441
50th	24.6 to 25.2	0.6 (0.3 to 0.9)	<0.001	23.4 to 24.8	1.4 (1.0 to 1.7)	<0.001	0.001
75th	27.1 to 28.5	1.4 (1.0 to 1.8)	<0.001	27.0 to 29.4	2.4 (2.0 to 2.9)	<0.001	0.001
95th	32.7 to 34.9	2.2 (1.3 to 3.1)	<0.001	35.3 to 38.8	3.5 (2.2 to 4.8)	<0.001	0.116

Note: Source (first and final year): Chile, Encuesta Nacional de Salud (ENS: 2003 and 2017); England, Health Survey for England (1997 and 2019); Mexico, Encuesta Nacional de Salud y Nutrición (ENSANUT: 2006 and 2018); Peru: Encuesta Demográfica y de Salud Familiar (ENDES: 2018 and 2020); United States, National Health and Nutrition Examination Survey (NHANES: 1999–2002 and 2015–2018). For estimates, data are predicted difference (final year minus the first year) at the 5th, 25th, 50th, 75th, and 95th percentiles of BMI, calculated using model coefficients from quantile regression analyses. All models adjusted for age and age^2 (age centered at 25 years) and included a two-way interaction term (sex-by-year) to examine whether change over time at the specified centiles varied by sex (*p* values in the final column).
Abbreviation: NH, non-Hispanic.

TABLE 2 Predicted values of WC (first and last) and difference (final minus first survey period) across centiles of WC by sex and country.

WC (cm)	Men			Women			Sex difference
	First, last	Change, β (95% CI)	*p* value	First, last	Change β (95% CI)	*p* value	*p* value
Chile (t_{2017} − t_{2003})							
5th	72.0 to 74.7	2.7 (−0.5 to 5.9)	0.096	64.4 to 69.6	5.2 (3.1 to 7.3)	<0.001	0.199
25th	80.0 to 82.8	2.8 (1.4 to 4.2)	<0.001	72.4 to 78.0	5.6 (3.8 to 7.5)	<0.001	0.016
50th	86.2 to 90.5	4.2 (2.9 to 5.6)	<0.001	81.5 to 86.7	5.2 (3.2 to 7.2)	<0.001	0.439
75th	93.0 to 96.6	3.6 (1.3 to 5.8)	0.002	89.2 to 95.6	6.4 (4.6 to 8.2)	<0.001	0.057
95th	104.3 to 111.1	6.8 (4.6 to 8.9)	<0.001	103.3 to 111.7	8.4 (3.9 to 12.9)	<0.001	0.523
Mexico (t_{2018} − t_{2006})							
5th	71.9 to 73.9	2.0 (0.8 to 3.2)	0.001	69.1 to 70.7	1.6 (0.6 to 2.6)	0.003	0.624
25th	81.3 to 83.9	2.5 (1.8 to 3.3)	<0.001	79.0 to 81.1	2.2 (1.5 to 2.8)	<0.001	0.487
50th	88.9 to 91.8	2.9 (2.1 to 3.6)	<0.001	87.3 to 89.5	2.3 (1.6 to 3.0)	<0.001	0.264
75th	97.2 to 100.3	3.1 (2.1 to 4.0)	<0.001	96.6 to 98.6	2.1 (1.3 to 2.9)	<0.001	0.119
95th	113.3 to 117.8	4.5 (1.9 to 7.0)	0.001	114.0 to 118.5	4.5 (2.6 to 6.4)	<0.001	0.995
Peru (t_{2020} − t_{2018})							
5th	74.0 to 74.3	0.3 (−0.9 to 1.5)	0.620	72.3 to 72.4	0.1 (−0.8 to 1.0)	0.873	0.768
25th	81.2 to 81.4	0.2 (−0.5 to 0.9)	0.537	80.0 to 79.9	−0.1 (−0.7 to 0.4)	0.611	0.424
50th	88.1 to 88.0	−0.1 (−0.8 to 0.6)	0.759	86.8 to 87.1	0.3 (−0.4 to 0.9)	0.405	0.428
75th	95.2 to 95.2	0.0 (−0.8 to 0.7)	0.988	94.3 to 94.4	0.2 (−0.5 to 0.9)	0.628	0.736
95th	108.8 to 107.7	−1.1 (−2.8 to 0.7)	0.230	106.8 to 107.5	0.7 (−0.6 to 2.0)	0.268	0.105
US NH White ($t_{2015–2018}$ − $t_{1999–2002}$)							
5th	75.7 to 76.1	0.4 (−1.0 to 1.8)	0.600	66.4 to 69.5	3.1 (1.1 to 5.1)	0.002	0.028
25th	83.8 to 85.6	1.8 (0.5 to 3.1)	0.008	72.2 to 78.1	5.9 (4.5 to 7.4)	<0.001	<0.001
50th	92.2 to 95.0	2.8 (0.9 to 4.6)	0.003	82.8 to 88.3	5.4 (3.4 to 7.4)	<0.001	0.053
75th	101.5 to 106.1	4.6 (2.5 to 6.7)	<0.001	94.9 to 102.2	7.2 (4.2 to 10.3)	<0.001	0.158
95th	120.6 to 130.2	9.6 (4.6 to 14.6)	<0.001	115.3 to 124.5	9.2 (6.0 to 12.5)	<0.001	0.895
US NH Black ($t_{2015–2018}$ − $t_{1999–2002}$)							
5th	68.9 to 70.5	1.7 (−0.3 to 3.7)	0.105	68.2 to 70.9	2.6 (−0.7 to 5.9)	0.123	0.641
25th	76.8 to 81.5	4.7 (3.1 to 6.4)	<0.001	78.8 to 81.4	2.5 (0.4 to 4.7)	0.022	0.115
50th	87.1 to 92.0	4.9 (2.5 to 7.3)	<0.001	88.1 to 94.4	6.3 (3.8 to 8.8)	<0.001	0.424
75th	100.7 to 108.2	7.5 (4.0 to 11.0)	<0.001	103.8 to 111.5	7.7 (4.6 to 10.8)	<0.001	0.930
95th	122.1 to 130.5	8.4 (5.5 to 11.3)	<0.001	123.6 to 133.9	10.4 (4.3 to 16.4)	0.001	0.567
US Mexican-American ($t_{2015–2018}$ − $t_{1999–2002}$)							
5th	75.0 to 78.0	3.0 (0.2 to 5.8)	0.034	69.5 to 73.6	4.1 (1.4 to 6.8)	0.003	0.572
25th	85.3 to 88.9	3.6 (1.7 to 5.6)	<0.001	77.9 to 84.9	6.9 (4.9 to 9.0)	<0.001	0.023
50th	92.8 to 98.5	5.7 (3.8 to 7.6)	<0.001	86.9 to 94.6	7.8 (5.5 to 10.0)	<0.001	0.172
75th	103.3 to 110.3	7.0 (5.1 to 8.9)	<0.001	100.6 to 107.7	7.1 (3.6 to 10.6)	<0.001	0.961
95th	120.0 to 131.6	11.6 (7.1 to 16.2)	<0.001	119.5 to 129.3	9.8 (3.2 to 16.5)	0.004	0.659
England (t_{2019} − t_{1997})							
5th	75.4 to 75.6	0.1 (−0.8 to 1.1)	0.778	62.5 to 64.6	2.1 (1.0 to 3.3)	<0.001	0.011
25th	82.6 to 83.3	0.7 (−0.2 to 1.6)	0.136	68.4 to 72.2	3.8 (2.8 to 4.7)	<0.001	<0.001
50th	87.8 to 89.9	2.1 (0.9 to 3.4)	0.001	73.9 to 80.2	6.4 (5.2 to 7.5)	<0.001	<0.001
75th	94.3 to 97.7	3.4 (2.3 to 4.5)	<0.001	82.5 to 90.2	7.7 (6.3 to 9.1)	<0.001	<0.001
95th	108.1 to 113.3	5.2 (3.3 to 7.1)	<0.001	100.5 to 110.3	9.8 (7.7 to 11.9)	<0.001	0.002

Note: Source (first and final year): Chile, Encuesta Nacional de Salud (ENS: 2003 and 2017); England, Health Survey for England (1997 and 2019); Mexico, Encuesta Nacional de Salud y Nutrición (ENSANUT: 2006 and 2018); Peru, Encuesta Demográfica y de Salud Familiar (ENDES: 2018 and 2020); United States, National Health and Nutrition Examination Survey (NHANES 1999–2002 and 2015–2018). For estimates, data are predicted difference (final year minus the first year) at the 5th, 25th, 50th, 75th, and 95th percentiles of WC, calculated using model coefficients from quantile regression analyses. All models adjusted for age and age^2 (age centered at 25 years) and included a two-way interaction term (sex-by-year) to examine whether the change over time at the specified centiles varied by sex (*p* values in the final column).
Abbreviations: NH, non-Hispanic; WC, waist circumference.

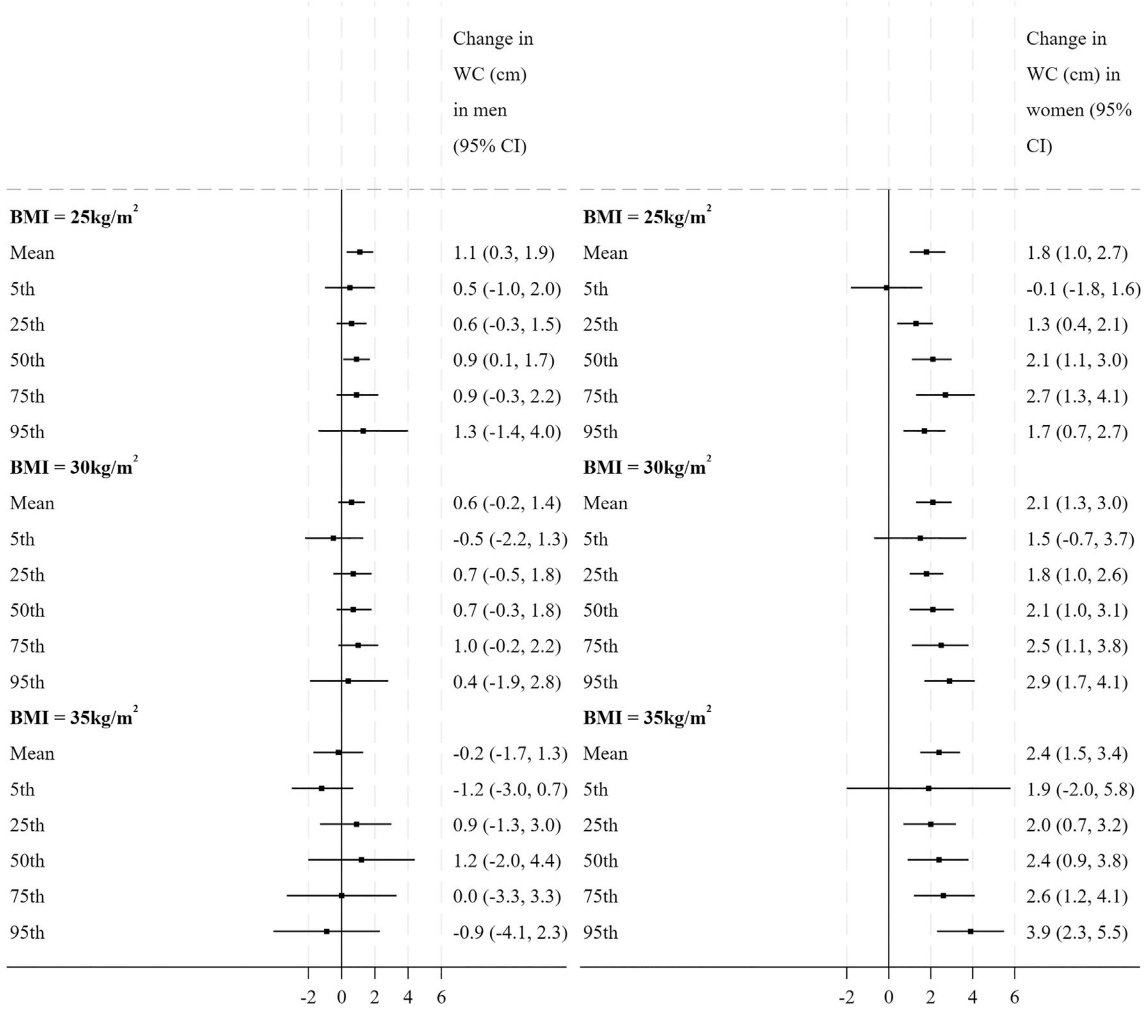

FIGURE 1 Estimated secular change (2003–2017) in mean waist circumference (WC) and at various percentiles of the WC distribution relative to BMI at 25, 30, and 35 kg/m^2 by sex in Chile.

In both sexes in Peru, WC at the 50th and 75th percentiles decreased between 2018 and 2020 at both BMI cut-points. In men, at BMI = 25 kg/m^2, increases at the 50th WC percentile were observed in Chile and in Mexico. At BMI = 30 kg/m^2, increases at the 50th and 75th WC percentiles were observed in Mexico and in England.

Increases in WC relative to BMI were more evident in women, with larger increases at higher levels of BMI, especially in US NH White individuals and in England (Figures 4 and 5). At BMI = 25 kg/m^2, increases at the 50th WC percentile ranged from 2.3 cm in US Mexican-American individuals (1999–2002 vs. 2015–2018; 95% CI: 1.6–3.1; $p < 0.001$) to 3.0 cm in England (1997 vs. 2019; 95% CI: 2.4–3.5; $p < 0.001$). Increases at the 75th WC percentile ranged from 1.9 cm in US Mexican-American individuals (95% CI: 0.8–3.1; $p = 0.013$) to 3.3 cm in England (95% CI: 2.8–3.9; $p < 0.001$).

At BMI = 30 kg/m^2, increases at the 50th WC percentile ranged from 0.7 cm in Mexico (2006 vs. 2018; 95% CI: 0.2–1.2; $p = 0.045$, but with a larger increase in men than in women) to 3.9 cm in England (1997 vs. 2019; 95% CI: 3.0–4.8; $p < 0.001$). Increases at the 75th WC percentile ranged from 1.4 cm in US Mexican-American individuals (1999–2002 vs. 2015–2018; 95% CI: 0.6–2.2) to 4.1 cm in England (1997 vs. 2019; 95% CI: 3.4–4.8; $p < 0.001$).

DISCUSSION

Using nationally representative HES data from the United States, Mexico, Chile, Peru, and England, we quantified changes between 1997 and 2020 in BMI, WC, and WC relative to BMI and explored differences by sex. Except for Peru, BMI and WC means increased in each country and US race and ethnicity group in both sexes, with larger increases in women than in men in England (BMI and WC), Chile (WC), and US NH White individuals (WC). Except for Peru, BMI and WC each upwardly shifted in each country and US race and ethnicity group in both sexes, with larger increases at the upper-tails. Increases in BMI and WC at the 50th and 75th percentiles were larger in women than in men in England.

Secular changes in WC relative to BMI showed mixed patterns. Decreases in mean and median WC relative to BMI between

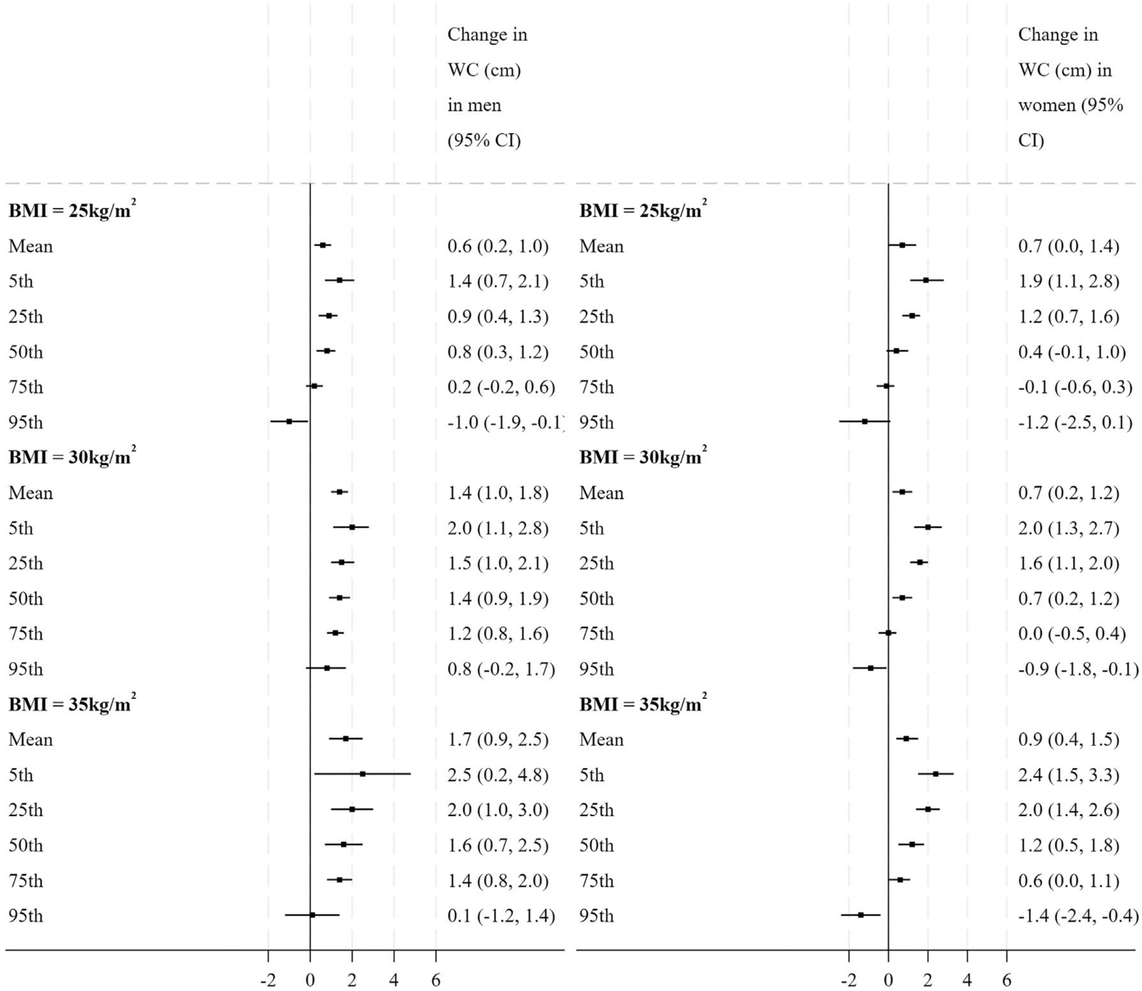

FIGURE 2 Estimated secular change (2006–2018) in mean waist circumference (WC) and at various percentiles of the WC distribution relative to BMI at 25, 30, and 35 kg/m^2 by sex in Mexico.

2018 and 2020 were observed in both sexes in Peru. Increases at the 50th and 75th WC percentiles relative to BMI were more pronounced in women than in men, with larger increases at higher BMI levels, especially in US NH White individuals and in England. Mexico was a noteworthy exception: secular change in WC relative to BMI was larger in men than in women.

Comparisons with other studies

Precise comparisons with the few global studies on secular changes in mean WC relative to BMI [9, 14] or body weight [13] are difficult due to differences in study populations, time period, analytical sample (including age range and sex), and statistical techniques. Nevertheless, our findings agree with previous studies that have shown increases in WC in both sexes and the recent shift to higher WC independent of BMI, especially, but not exclusively, in women. Most of the secular increase in mean WC between 1999 to 2000 and 2011 to 2012 in the United States was independent of increases in BMI in women, but not in men, with no reported differences between race and ethnicity groups [6]. Albrecht et al. reported disproportionate increases in mean WC relative to BMI in US, Mexican, Chinese, and English populations, particularly in women aged 20 to 29 years [14].

Public health implications

The epidemiological literature suggests various reasons for recent secular increases in WC relative to BMI. First, population-level trends in anthropometric data must be carefully interpreted considering the strengths and limitations of the indicators used. It is increasingly recognized that WC is a more sensitive anthropometric indicator than BMI to detect changes in body adiposity. Because BMI is only based on weight and height, it does not take body composition into account, e.g., it cannot distinguish between lean mass and fat mass and does not capture information on body fat distribution [8]. Population-level trends in BMI thereby indicate either changes in muscle mass and/or changes in fat mass; therefore, using BMI alone can only serve as an approximate measure of secular changes in the amount of fat mass [2, 8, 25]. To provide more precise estimates of population-level

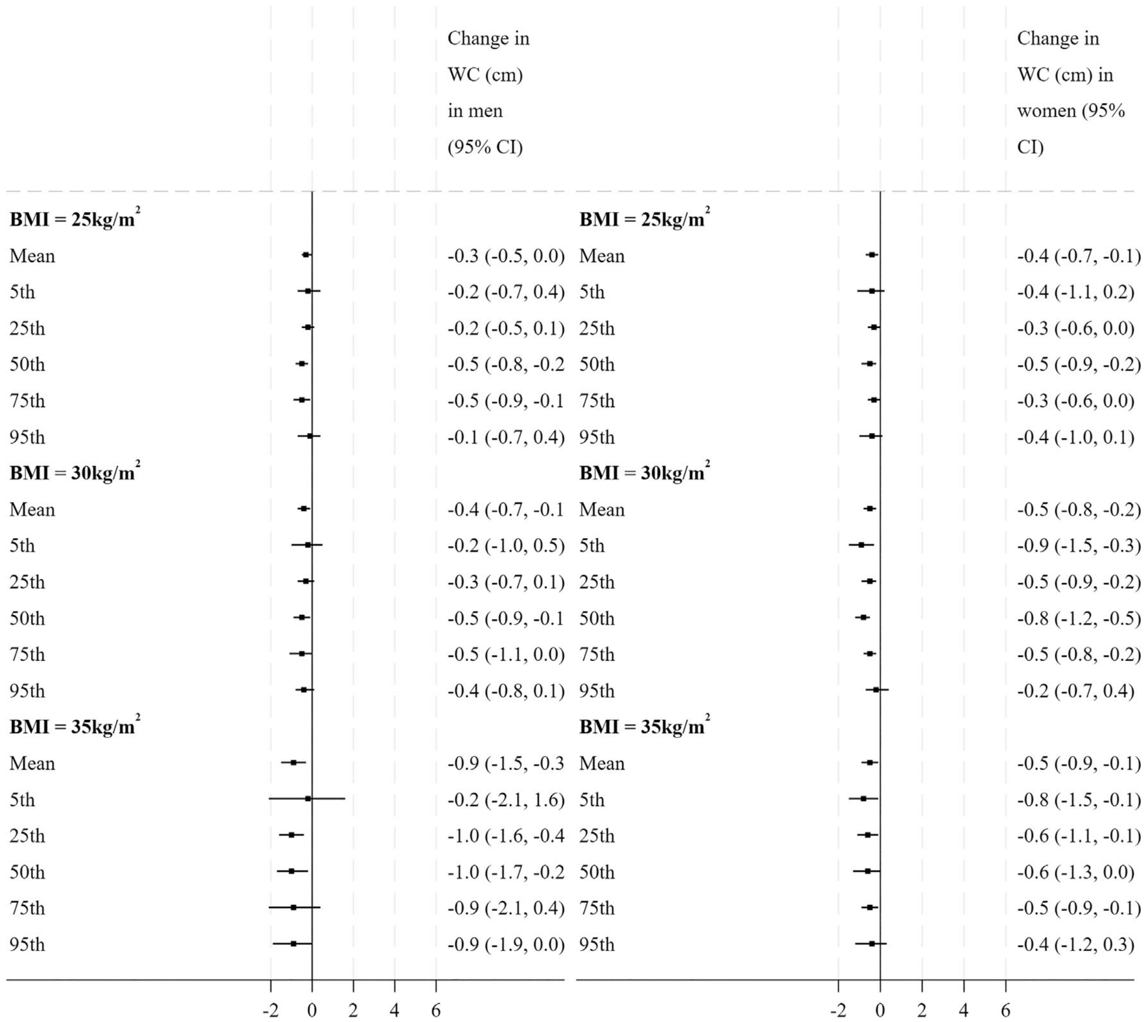

FIGURE 3 Estimated secular change (2018–2020) in mean waist circumference (WC) and at various percentiles of the WC distribution relative to BMI at 25, 30, and 35 kg/m^2 by sex in Peru.

changes in fat mass and their association with cardiometabolic risk, measurements of WC, used alone or in combination with hip and height measurements, are needed.

However, use of WC in national surveillance efforts also has recognized limitations, including being unable to distinguish between visceral and subcutaneous adipose tissue [26]. Debates are ongoing regarding the most appropriate indicator of excess adiposity. The current recommended WC cutoffs used herein to define abdominal obesity [22] consider differences by sex, but race and ethnicity-specific and BMI category-specific thresholds are also available [8]. Such WC thresholds do not adjust for between-individual differences in height; thresholds based on absolute or unadjusted WC have been criticized for penalizing taller individuals, who have, on average, higher WC than shorter individuals but may not necessarily be at greater health or cardiometabolic risk [27]. Because evidence suggests the ratio of WC to height correlates more strongly with intra-abdominal fat than an index based on WC alone, monitoring population-level trends in abdominal obesity using height-adjusted WC indices such as waist-height ratio with a global boundary value of 0.5 [28, 29] and a proposed modification (waist-by-height$^{0.5}$) [30] offers important avenues for future epidemiological surveillance.

Second, at an etiological level, increasing sedentarism, sleep deprivation, diets high in sugar and refined carbohydrates/energy-dense foods, endocrine disruptors, and certain medications have been proposed as potential explanatory factors for recent increases in WC relative to BMI [26, 31]. Such increases may partly explain concomitant increases in diabetes and prediabetes among individuals with class II/III obesity in the United States [32] and metabolic syndrome in Asian individuals [33]. In a recent systematic review by Jung et al. [34], causes such as metabolic syndrome, physical inactivity, inadequate nutrition, congenital and perinatal factors, vitamin D deficiency, endocrine disease, gut microbiota dysbiosis, neuromuscular disease, organ failure, cancer, and other inflammatory conditions have been linked with decreases in skeletal muscle mass in young populations. Speculative reasons for the greater increase in WC relative to BMI in women compared with men include higher levels of percentage body fat [35] and physiological differences pronounced at older ages (mainly after menopause), because the deposits of subcutaneous

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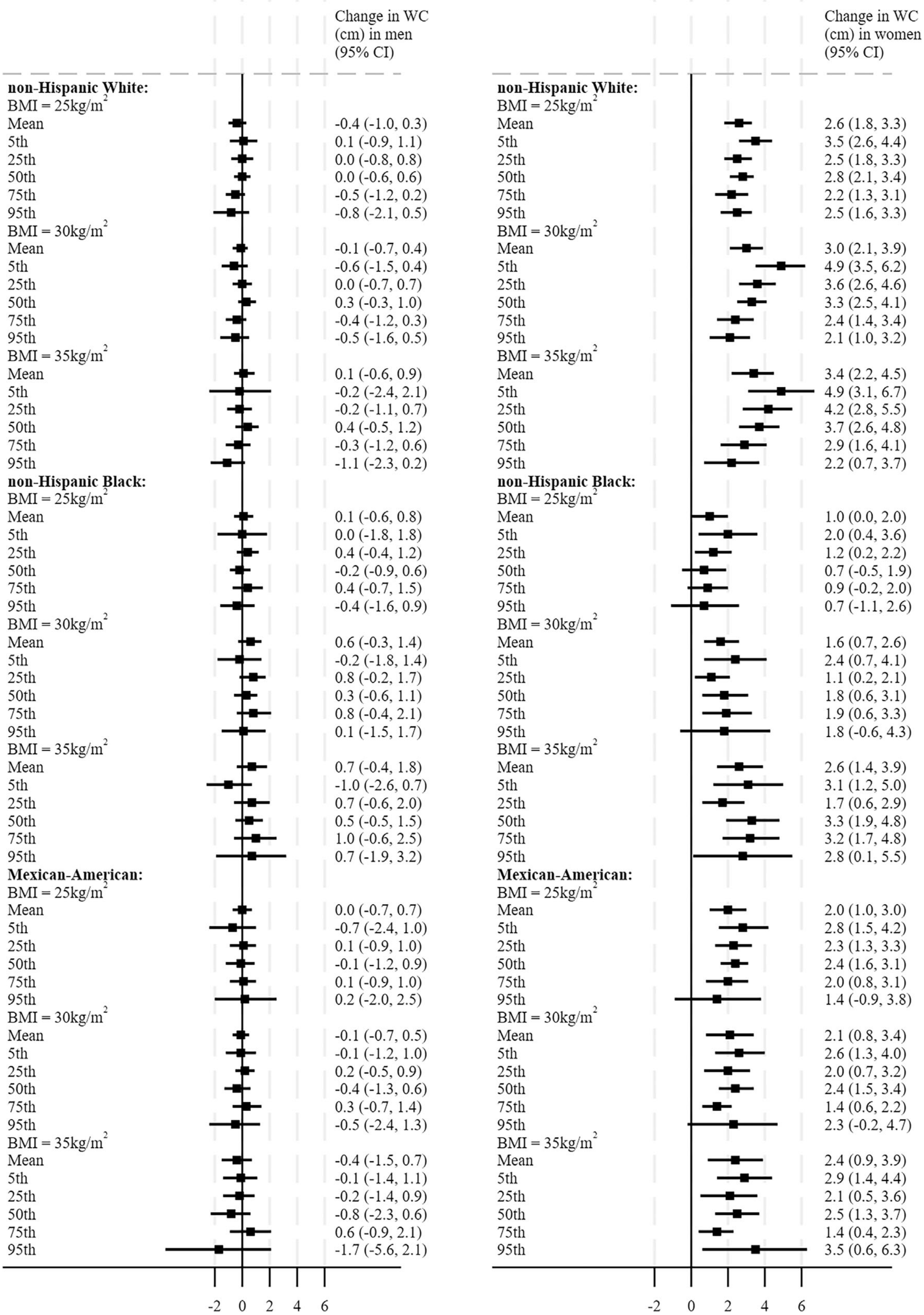

FIGURE 4 Estimated secular change (1999–2002 and 2015–2018) in mean waist circumference (WC) and at various percentiles of the WC distribution relative to BMI at 25, 30, and 35 kg/m^2 by sex and race and ethnicity group in the United States.

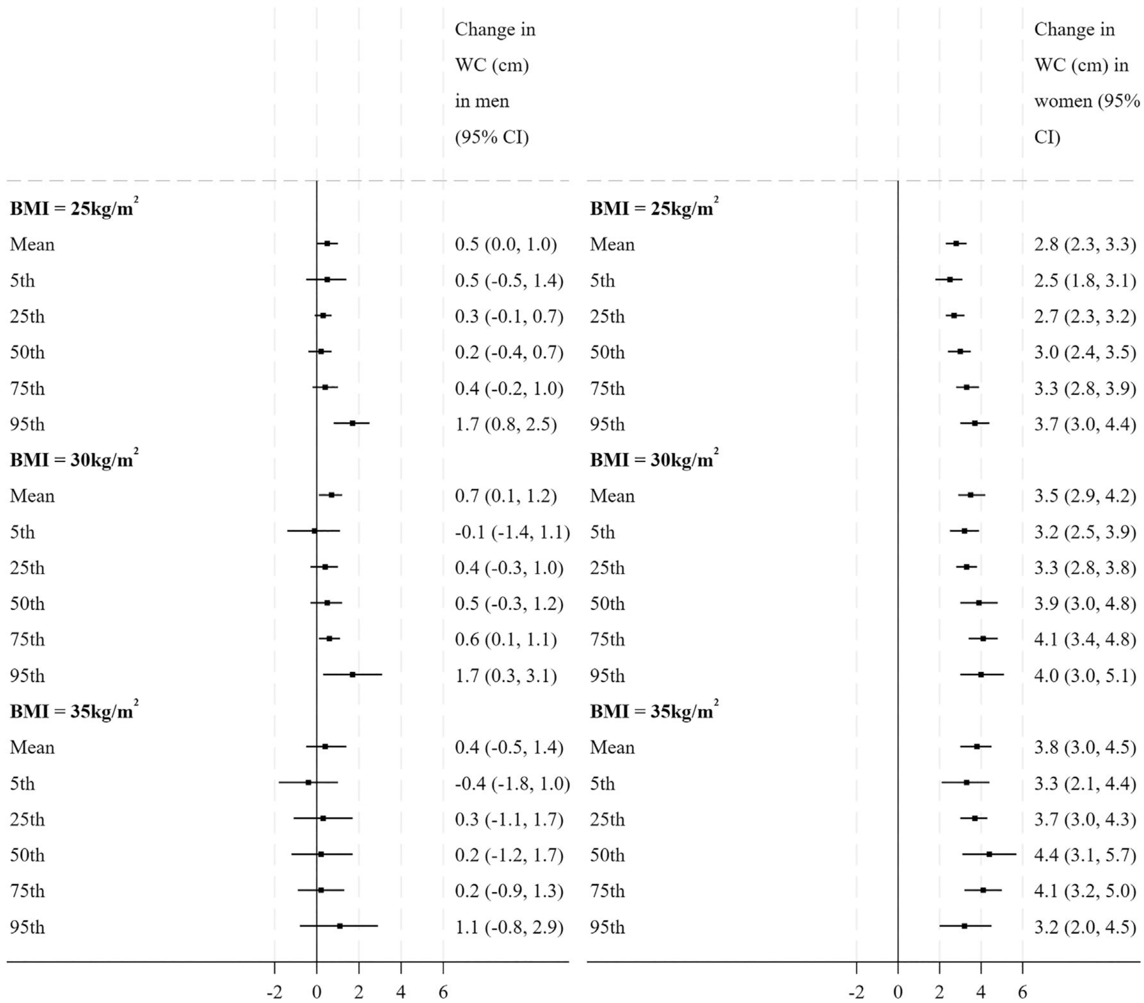

FIGURE 5 Estimated secular change (1999–2017) in mean waist circumference (WC) and at various percentiles of the WC distribution relative to BMI at 25, 30, and 35 kg/m^2 by sex in England.

adipose tissue surrounding hips and thighs decrease with increasing age, and visceral adipose tissue increases [36]. This sex disparity is an important issue because WC has been shown to more strongly associate with health risk than BMI, especially in women [37].

Strengths and limitations

Our analyses allowed examination of secular changes in WC relative to BMI across countries with different levels of income (high income: Chile, England, and the United States; upper-middle income: Mexico; middle income: Peru) but with a focus on the Americas region. Our study adds to the global evidence base by adding the most recent HES data from England and the United States and including data, for the first time, to our knowledge, from Chile and Peru and from men in Mexico. Each country's national survey was used, enabling nationally representative inference with high-quality data: height, weight, and WC were directly measured by trained staff using standardized protocols; therefore, our findings avoid known biases associated with self-reported measures [38]. The time period covered spanned more than a decade in four of the five countries, allowing us to account for the potential effects of any obesity prevention-related policies implemented during this time. Furthermore, we used all available data to produce model-based estimates of secular change and employed linear and quantile regression to examine changes over time in means and across the WC distributions independent of BMI.

Several limitations should be considered when interpreting our results. Our study made no attempt to directly compare the magnitude of secular changes across countries due to differences in survey periods. Instead, we highlight similarities and differences in overall patterns, including differences by sex. Although WC measurement was consistent within each survey, comparisons between the United States and the other countries should be additionally treated with caution because the former measured WC at the top of the iliac crest rather than at the midpoint between the iliac crest and the costal wall. Evidence suggests that WC measurements at the top of the iliac crest versus the midpoint are larger, especially in women [39, 40]. Peruvian data could only be presented from 2018 to 2020;

therefore, these findings on secular changes should be treated with caution. Survey nonresponse is an increasing problem. Participants in HES tend to be healthier than nonparticipants; conditional on survey participation (e.g., data on sociodemographics), less healthy participants, including groups with higher BMI values, may be less likely to agree to direct measurements of height, weight, and WC [6, 38]. Although nonresponse weights are available (and were used herein), such weights do not necessarily adjust for potential bias in anthropometric data collection. Our findings may thereby have underestimated secular increases in WC relative to BMI to some extent. Combining adjacent 2-year cycles in NHANES to produce estimates based on 4 years of data ensured greater precision; however, doing so makes the inherent assumption of no trend in the estimate over the time period being combined [24]. We acknowledge that the observed sex differences presented herein could be due to potential confounding factors not included in the models, including modifiable factors such as socioeconomic status, physical activity, and diet. Finally, apart from NHANES, the other HES do not routinely collect body composition data; therefore, anthropometric indicators potentially more sensitive to adiposity (e.g., total or percentage body fat, skinfold thickness) were not available. Likewise, analyses using other anthropometric measures commonly collected in HES, such as hip circumference, were not included in our study due to data not being available in all countries.

CONCLUSION

Our analyses of 20 years of anthropometric data support emerging evidence of increasing WC relative to BMI, especially, but not exclusively, in women. Routinely collecting WC data in health surveys strengthens national efforts of disease risk surveillance and potentially contributes to reduced disparities across BMI groups for detection and disease treatment. More investigation is needed to identify the key modifiable factors underlying recent increases in WC relative to BMI.O

AUTHOR CONTRIBUTIONS

Luz M. Sánchez-Romero and Shaun Scholes conceptualized the study. Luz M. Sánchez-Romero, Janine Sagaceta-Mejía, Antonio Bernabé-Ortiz, Shaun Scholes, and Álvaro Passi-Solar were responsible for collecting information, generating the data sets, and conducting the analyses. Luz M. Sánchez-Romero, Janine Sagaceta-Mejía and Shaun Scholes interpreted the results and wrote the manuscript. Jennifer S. Mindell, Antonio Bernabé-Ortiz, Lizbeth Tolentino-Mayo, and Alison Moody critically revised the manuscript. All authors have read and approved the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declared no conflict of interest.

DATA AVAILABILITY STATEMENT

Source data were openly available before the initiation of the study. Chile: National health survey databases are freely available on the Ministry of Health website (https://www.gob.cl/en/ministries/ministry-of-health/). Mexico: The data underlying this study were generated by the National Institute of Public Health and are freely available (https://ensanut.insp.mx/). Peru: The data underlying this study can be found in the repository National Open Data Platform (https://www.datosabiertos.gob.pe/) and are freely accessible. United States: National Health and Nutrition Examination Survey (NHANES) datasets are publicly available at the Centers for Disease Control and Prevention (CDC) website (https://www.cdc.gov/nchs/nhanes/index.htm). England: The Health Survey for England datasets generated and analyzed during the current study are available via the UK Data Service (UKDS; https://ukdataservice.ac.uk/), subject to their end-user license. All reproducible code is openly accessible via GitHub (https://github.com/shauns11/Secular-change-in-waist-circumference-relative-to-body-mass-index-).

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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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