Self-reported Health is Related to Body Height and Waist Circumference in Rural Indigenous and Urbanised Latin-American Populations

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Abstract

Body height is a life-history component. It involves important costs for its expression and maintenance, which may originate trade-offs on other costly components such as reproduction or immunity. Although previous evidence has supported the idea that human height could be a sexually selected trait, the explanatory mechanisms that underlie this selection are poorly understood. Despite extensive studies on the association between height and attractiveness, the role of immunity in linking this relation is scarcely studied, particularly in non-Western populations. Here, we tested whether human height is related to health measured by self-perception, and relevant nutritional and health anthropometric indicators in three Latin-American populations that widely differ in socioeconomic and ecological conditions: two urbanised populations from Bogota (Colombia) and Mexico City (Mexico), and one isolated indigenous population (Me'Phaa, Mexico). Results of linear mixed models showed that self-rated health is best predicted by an interaction between height and waist circumference, and the costs associated with large waist circumference are height-dependent, affecting taller people more than shorter individuals. If health and genetic quality cues play an important role in human mate-choice, and height and waist interact to signal health, its evolutionary consequences, including cognitive and behavioural effects, should be addressed in future research.

Keywords: Self-reported health, body height, waist circumference, Linear Mixed Models, Latin-American populations, honest signals

Introduction

In modern Western societies, it has been seen that women usually prefer men who are significantly taller than average [1–3], while men are more tolerant in choosing women who are taller or shorter than average [4]. This is consistent with the idea that male height can be adaptive [5] and sexual selection favours taller men, possibly because height may represent a honest signal of individual quality, providing hereditary advantages, such as genetic quality for the offspring [6,7], or direct benefits, provisioning resources and protection for women and their children [8]. Following these last possible benefits, height has been also proposed as an indicator of resource holding potential (RHP), in terms of social dominance and deference [9,10] and socioeconomic status [6,11].

This idea is supported by evidence that the male height is directly correlated with reproductive success, which is not applicable to women, suggesting an unrestricted directional selection that favours very tall men but not to very tall women [12]. In fact, it has been reported that taller men (but not extremely tall men) are more likely to find a long-term partner and have several different long-term partners [13], while the maximum reproductive success of women is below the female average height [14]. Furthermore, heterosexual men and women tend to adjust their preferred height of hypothetical partners according to their own stature [15]. In general, heterosexual men and women prefer couples in which the man is taller than the woman, and women show a preference for facial cues that denote a taller man [16].

Although previous evidence has supported the idea that human height could be a sexually selected trait, the explanatory mechanisms underlying this selection are poorly understood.

One possibility can be addressed in the framework of the life-history theory [17], and the immunocompetence handicap hypothesis (ICHH) [18–20]. Growth in body height is a life-history component [1,21], that involves important costs for its expression and maintenance, which may originate trade-offs on other costly components such as reproduction [22] or immunity [23].

The costs in height can be measured in terms of survival and physiological expenditure [23]. For example, it has been shown that shorter people are more likely to be more longevous and less likely to suffer from age-related chronic diseases [23,24]. According to the Hayflick limit theory of ageing [25], our cells have a limited number of cell replications available in a lifetime. A minimal increment in body height involves more cells, maybe trillions, and large numbers of cell replications. These large numbers of cell replications demand a large pool of proteins to maintain taller, larger bodies [23], which together, with an increase of free radicals generated by normal cellular metabolism, may lead to a greater likelihood of DNA damage [26], thus increasing the incidence of cancer and reducing longevity [23].

Trade-offs between these life-history components could be mediated by sex hormones. The trade-off with reproduction occurs because sex steroids reallocate energetic and physiological resources to reproduction at the beginning of sexual maturity instead of somatic growth. For instance, increased oestrogen production leads to the onset of menstrual bleeding in women, but slows the process of growth, hence causing it to cease [27]. In addition, oestrogen stimulates mineral deposition in the growth plates at the ends of the long bones, thus terminating cell proliferation and resulting in the fusion of the growth plates to the shaft of the bone [28,29]. In turn, increased sex steroids trigger a trade-off with immunity, which usually exerts suppressive effects on several immune components [18]. For example, testosterone may increase the severity of malaria, leishmaniasis, amoebiasis [30] and perhaps tuberculosis [31,32].

Therefore, as a consequence of these life-history trade-offs, height could be considered as a reliable indicator of an individual's condition in terms of (1) the amount and quality of nutritional resources acquired until sexual maturity, (2) the RHP to obtain resources for the somatic maintenance in the adult stage, and (3) the current immunocompetence to afford the immune cost imposed by sexual steroids. Thus, in accordance with ICHH, height can be used for potential partners to receive information about the quality of potential mate; only high-quality individuals could afford to allocate resources to better immunity and attractive secondary sexual traits simultaneously [19], which would result in an increased sexual preference towards taller individuals.

Despite extensive studies on the association between height and attractiveness, the role of immunity in linking this relation is poorly studied. Moreover, most studies have been done using high-income developed populations such as Western, Educated, Industrialised, Rich and Democratic (WEIRD) societies [33], which has led to a lack of information of what is occurring in other populations with important socio-ecological differences. These ecological pressures are important because although genetic allelic expression could be the main factor that determines individual height differences [27], height is also the most sensible human anatomical feature that responds to environmental and socioeconomic conditions [22,34]. For instance, variation in height across social classes is known to be greater in poorer countries [35] but is much reduced in countries with higher standards of living [36]. Economic inequality not only affects the population's nutritional patterns, which are especially important during childhood to establish adult height, but also the presence of infectious diseases [37]. Childhood disease is known to adversely affect growth. For instance, mounting an immune response to fight against the infection requires concomitant increases in metabolic rate, which could affect the net nutrition, and hence reduces productivity. Disease also prevents food intake, impairs nutrient absorption and causes nutrient loss [38,39]. Therefore, compared with high-income and developed populations, habitants from sites with stronger ecological pressures imposed by pathogens or greater nutritional deficiencies would face greater costs to robustly express this trait, thereby showing stronger sexual selective pressure over height, as it signals signal growth rates, life-history trajectories and health status more accurately. This phenotypic variation is described as developmental plasticity, which is a part of the phenotypic plasticity related to growth and development, in response to social, nutritional and demographic conditions, among others [40]. During the last century, given a general improvement in nutrition, human height has steadily increased across the globe [41], but the level of dimorphism in favour of men is maintained.

Colombia and Mexico are two of the most socioeconomically heterogeneous countries in the world with a high Human Development Index [42]. Colombia and Mexico attain respective scores of 68 and 66 in the Healthcare Access and Quality Index [43], indicating that the populations are in relatively good health compared to global standards. Also, Colombia and Mexico have GINI coefficients of 50.8 and 43.4, respectively, making them the 12th and 43rd most unequal countries in the world (GINI index – World Bank estimate; https://data.worldbank.org/indicator/SI.POV.GINI). These national-level statistics, however, hide important within-country differences. In particular, Latin-American people in rural areas tend to be poorer and have less access to basic services such as health and education than people in urban areas.

According to data from the World Bank and the Colombian National Administrative Department of Statistics, in 2017 Colombia was the second most unequal country in Latin-America after Brazil. In rural areas, 36% of people were living in poverty and 15.4% in extreme poverty, while in urban areas, these values were only 15.7% and 2.7%, respectively [for a summary, see 44].

In addition to rural communities, in Latin-America indigenous people tend to have high rates of poverty and extreme poverty [45], and poorer health [46], which is less susceptible to improve by the national income growth [47]. In Mexico, there are at least 56 independent indigenous peoples whose lifestyle practices differ in varying degrees from the typical 'urbanised' lifestyle. Among these groups, the Me'Phaa people, from an isolated region known as '*Montaña Alta*' of the state of Guerrero, is one of the groups whose lifestyle most dramatically differs from the typical Westernised lifestyle of more urbanised areas [48]. Me'Phaa communities are small groups of indigenous people, composed of 50 to 80 families, each with five to ten family members. Most communities are based largely on subsistence farming of legumes such as beans and lentils, and the only grain cultivated is corn. Animal protein is acquired by hunting and raising some fowls, and meat is only consumed during special occasions but not part of the daily diet. There is almost no access to allopathic medications, and there is no health service, plumbing or water purification system. Water for washing and drinking is obtained from small wells. Most of the Me'Phaa speak only their native language [49]. In consequence, these communities have the lowest income and economic development in the country, and the highest child morbidity and mortality due to chronic infectious diseases [48].

These three Latin-American populations can provide an interesting indication about how the regional socioeconomic conditions and intensity of ecological pressures by pathogens may modulate the function of height as an informative sexually selected trait of health and individual condition. Therefore, the aim of the present study was to evaluate whether human height is related to health measured by self-perception, and relevant nutritional and health anthropometric indicators in three Latin-American populations that widely differ in socioeconomic and ecological conditions: two urbanised populations from Bogota (Colombia) and Mexico City (Mexico), and one isolated indigenous population (Me´Phaa, Mexico).

Materials and Methods

Participants

A total of 477 adults (238 women and 239 men) participated in this study. They were from three different samples: (1) Mexican indigenous population, (2) Mexican urban population and (3) Colombian urban population. In Mexico, Me'Phaa indigenous participants from 'La *Montaña Alta*' were recruited and participated in this study between January and March 2017, while data from participants from Mexico City was collected between May and June 2017. In Colombia, data collection was carried out between October and December 2018.

The first sample consisted of 63 subjects (mean age ± standard deviation [SD] = 33.63 ± 9.69 years old) from the small Me'Phaa community – '*Plan de Gatica*' from a region known as '*Montaña Alta*' of the state of Guerrero in Southwest Mexico. In this sample, 24 participants were women (33.46 ± 8.61 years old) and 39 participants were men (33.74 ± 10.41 years old), who participated in a larger study on immunocompetence. Both sexes were aged above 18 years old. In Mexico, people above 18 years old are considered adults. All measurements were collected in the participants' own community. Me'Phaa communities are about 20 km apart, and it takes about three hours of travel on rural dirt roads to reach the nearest large town, about 80 km away. Mexico City is about 850 km away, and the trip takes about twelve hours by road. This community has the lowest income in Mexico, the highest index of child morbidity and mortality by gastrointestinal and respiratory diseases (children aged 0 to 8 years had the highest vulnerability and death risk [48]), and the lowest access to health services. These conditions were recorded in the National Health Information System 2016 [48].

The second sample consisted of 60 subjects of over 18 years old (30.27 ± 8.56 years old) from the general community in Mexico City, of whom 30 were women (37.47 ± 5.61 years old) and 30 were men (23.07 ± 3.22 years old). Finally, the third sample consisted of 354 undergraduate students with ages ranging from 18 to 30 years old (20.39 ± 2.10 years old), 184 were women (20.16 ± 2.08 years old), and 170 were men (20.64 ± 2.10 years old) from Bogota, Colombia. All urban participants were recruited through public advertisements.

Participants from both urban population samples were taking part in two separate, larger studies in each country. In Colombia, all data were collected in the morning, between 7 and 11 am, because saliva samples (for hormonal analysis), as well as voice recordings, body odour samples, and facial photographs were also collected as part of a separate project. Additionally, women in the Colombian and Mexican samples were not hormonal contraception users, and all data were collected within the first three days of their menses.

Participants who were under allopathic treatment and hormonal contraception users from both countries were excluded from data collection. All participants completed a sociodemographic data questionnaire, which included medical and psychiatric history. No women were users of hormonal contraception. Although no participant reported any endocrinological or chronic disease, these health issues were also considered as exclusion criteria.

Given that the indigenous community of '*Plan de Gatica*' consists of 60–80 families, each with five to seven members, the final sample for this study could be considered as semi-representative of a larger Me'Phaa population inhabiting in the same community. Nevertheless, the total population of Me'Phaa people inhabiting the '*Montaña Alta*' is comprised of 20–30 communities with almost the same number of families as '*Plan de Gatica*'. Therefore, it is important to mention that our sample size cannot be considered representative of the total Me'Phaa people inhabiting the '*Montaña Alta*' region, but from the specific '*Plan de Gatica*' community. Similar condition occurs for participants from the Mexico City and Bogota samples. These participants were recruited at the National Autonomous University of México and Universidad El Bosque campuses, respectively. Therefore, these samples are comprised mostly of bachelor and graduate students, and cannot be considered as representative of a large population of the whole city, which is comprised of about 12 million adult persons in Mexico and about 5 million adults in Bogota.

Procedure

All participants signed the informed consent and completed the health and background questionnaires. For participants from the indigenous population, the whole procedure was carried out within their own communities, and participants from the Mexican and Colombian urban population attended a laboratory at either the National Autonomous University of México or Universidad El Bosque respectively, on individual appointments.

Participants from Mexico City and Bogota were recruited through public advertisements on social media and poster boards located along the central campus of the National Autonomous University and Universidad El Bosque. While in Mexico City, participants received either one partial course credit or a payment equivalent to $5 dollars as compensation for their participation, all participants in Bogota were given academic credits for their participation.

For the indigenous groups, recruitment was done through the Xuajin Me'Phaa non-governmental organisation, which is dedicated to the social, environmental and economic development for the indigenous communities of the region (see video from this organisation, http://youtu.be/In4b9_Ek78o). Xuajin Me'Phaa has extensive experience in community-based fieldwork and has built a close working relationship with the community authorities. The trust and familiarity with the community customs and protocols have previously led to successful academic collaborations [48, 49]. Therefore, Xuajin Me'Phaa served as a liaison between the Mexican research group the and communities for the present study, offering mainly two important factors in data collection: the informed consent of community members and participants, and two trained interpreters of Me'Phaa and Spanish language of both sexes.

First, participants were asked to complete the health and sociodemographic data questionnaires. Subsequently, the anthropometric measurements were taken.

Self-reported health

In order to obtain a standardised value of self-perception of health, we implemented in all three populations the Short Form (36) health survey (SF-36; RAND Corp.). The SF-36 produces eight dimensions, calculated by averaging the recoded scores of individual items: (1) Physical functioning (items 3 to 12), (2) Role limitations due to physical health (items 13 to 16), (3) Role limitations due to emotional problems (items 17 to 19), (4) Energy/fatigue (items 23, 27, 29 and 31), (5) Emotional well-being (items 24, 25, 26, 28 and 30), (6) Social functioning (items 20 and 32), (7) Pain (items 21 and 22) and (8) General health (items 1, 33, 34, 35 and 36).

The interpreters provided by the Xuajin Me'Phaa organisation administered the SF-36 Health survey in Me'Phaa language. Interpreters used Spanish as the second language and are thoroughly proficient in speaking and reading Spanish. We used the validated SF-36 survey for urban and rural Mexican populations [52] for interpreters to translate Spanish to Me'Phaa language. Given the ethnical customs of Me'Phaa culture, the participants were always interviewed by an interpreter of the same sex to avoid bias in participant responses; for instance, men were interviewed by a male interpreter and women by a female interpreter. The same interpreter interviewed all participants of his/her corresponding sex.

For the present study, both urban and indigenous participants only answered items corresponding to the dimension defined as general health (i.e. Item numbers 1, 33, 34, 35 and 36), except for item 35. This item informs about the expectation for future health. Since the grammatical compositions of

Me'Phaa language do not consider 'infinitive' and 'future' as verbal tenses [53], an interpretation of this question was not possible for the Me'Phaa people, therefore, this item was excluded.

In Colombia, we used a Spanish version of the SF-36 questionnaire [54], that was previously validated in the same country[55].

To obtain the self-reported health rate, all items were recoded following the instructions on how to score SF-36 [54]. We calculated the final factor by averaging the recoded items. To make this data compatible with the Mexican database, item 35 was excluded because it cannot be answered by the Mexican Indigenous population, and the general health dimension was calculated by averaging only items 1, 33, 34 and 36.

Anthropometric measurements

All anthropometric measurements were measured thrice and subsequently averaged to obtain the mean value (for agreement statistics between the three measurements of each characteristic, see section 1.3 in the Supplementary Material). All participants wore light clothing and had their shoes removed. The same observer repeated the measurements thrice.

We measured the body height in cm, to the nearest mm, by using a 220 cm Zaude stadiometer, with the participant's head aligned according to the Frankfurt horizontal plane, and feet together against the wall.

Anthropomorphic measurements also included waist circumference (cm), weight (kg), fat percentage, visceral fat level, muscle percentage and body mass index (BMI). The waist circumference was measured midway between the lowest rib and the iliac crest in cm by using a flexible tape and was recorded to the nearest mm. These anthropomorphic measurements have been used as an accurate index of nutritional status and health, especially waist circumference. Metabolic syndrome is associated with visceral adiposity, blood lipid disorders, inflammation, insulin resistance or full-blown diabetes and increased risk of developing cardiovascular disease [54,55, for a review, see 56], including Latin-American populations [59]. Waist circumference has been proposed as a crude anthropometric correlate of abdominal and visceral adiposity, and it is the simplest and accurate screening variable used to identify people with the features of metabolic syndrome [60,61]. Hence, in the presence of the clinical criteria of metabolic syndrome, increased waist circumference provides relevant pathophysiological information insofar as it defines the prevalent form of the syndrome resulting from abdominal obesity [57].

Weight, fat percentage, visceral fat level, muscle percentage and BMI were obtained using an Omron Healthcare HBF-510 body composition analyser, which was calibrated before each participant's measurements were obtained.

Statistical analysis

We used linear mixed models (LMM) to test the association between height and health. The dependent variable in this model was the self-reported health factor and predictor variables included participant sex, age, population (indigenous or urban), height and waist and anthropometric measurements (hip, weight, fat percentage, BMI and muscle percentage) as fixed, main effects. Interactions between height and population, height and sex and height and waist circumference were also included. The country was always included as a random factor, with random intercepts.

Although allowing slopes to vary randomly is recommended [62], we only included random intercepts in the models because there was only one data-point per subject. Population (indigenous or urban) was always included as a fixed effect because while there are important differences in health (and self-reported health) between indigenous and urban populations in Latin-America, no such differences were expected by country. LMM were fitted to test the residual distribution. In all cases, residuals were closer to a normal or gamma (inverse link) distribution, for each population/country. Models were fitted using the *lmer* function from the *lmerTest* package [63; https://www.rdocumentation.org/packages/lmerTest] in R, version 3.5.2 [64].

The most parameterised initial model was then reduced based on the Akaike Information Criterion (AIC) and the best-supported model (i.e. the model with the lowest AIC with a ΔAIC higher than two units from the second most adequate model) is reported [see 65]. To accomplish this, we implemented the *ICtab* function from the *bbmle* package [66; http://www.rdocumentation.org/packages/bbmle]. Once a final model was selected, model diagnostics were performed (collinearity, residual distribution and linearity of residuals in each single term effect; see section 3 in the Supplementary Material).

Results

All data and code used to perform these analyses are openly available from the Open Science Framework (OSF) project for this study (https://osf.io/5rzfs/).

Figure 1 shows the distribution of age, waist, hip, height, weight, fat percentage, visceral fat, BMI, muscle percentage and self-reported health. Age, waist, height, visceral fat and self-reported health, strongly varied in both women (Fig 1A) and men (Fig 1B) between samples from each population (indigenous or urban) and country (Colombia, Mexico).

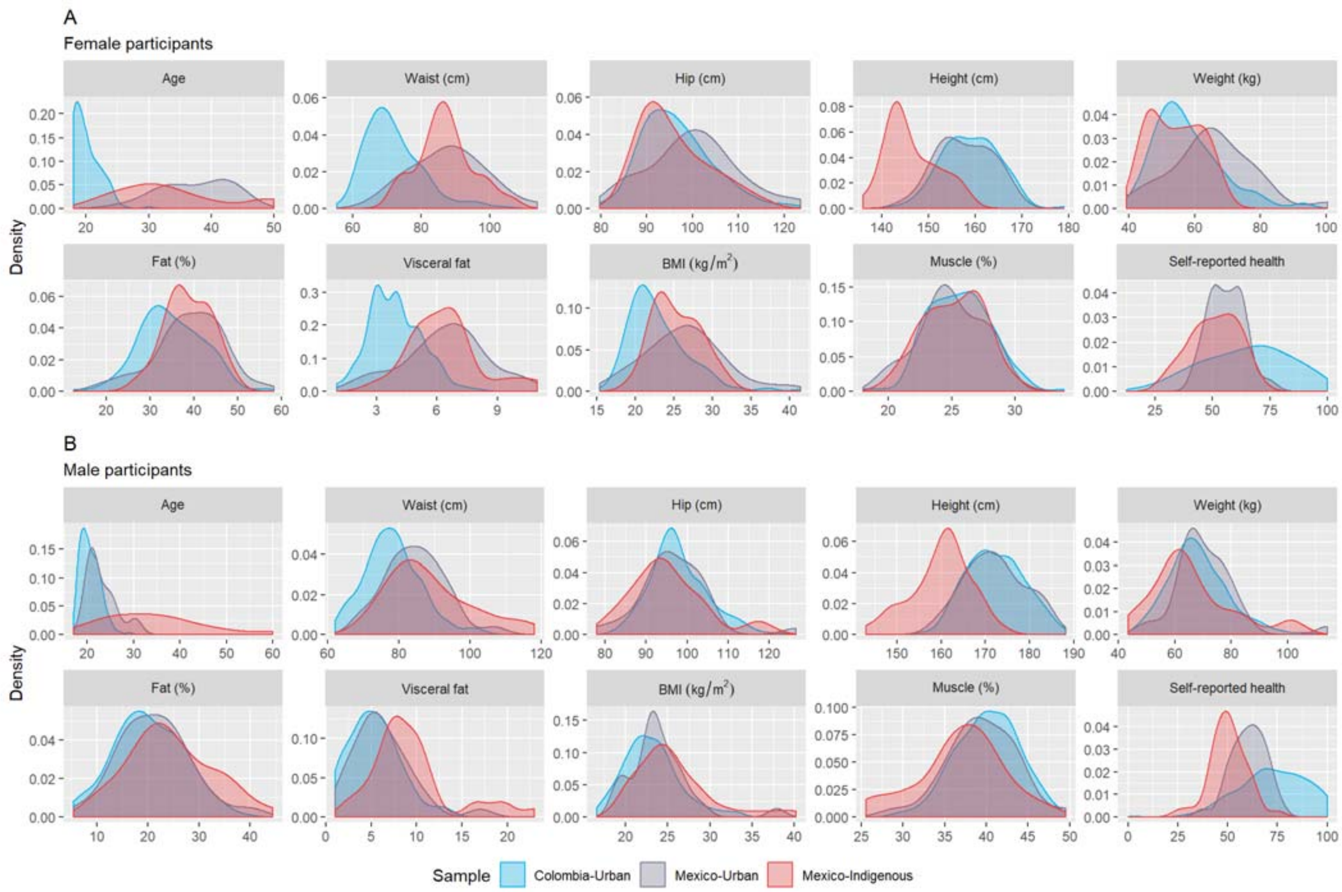

Figure 1. **Distribution of all measured variables by sex, population and country.** (A) Male participants. (B) Male participants. For descriptives (mean, SD, median, minimum and maximum values), see Table S2 (female participants) and Table S3 (male participants) in the Supplementary Material.

To establish the relationship between height and self-reported health, we fitted three mixed models (Table 1).

Table 1. Results of separate LMMs testing effects of independent variables on self-reported health.

	Model 1			**Model 2**			**Model 3**		
	Estimate	***df***	***p***	**Estimate**	***df***	***p***	**Estimate**	***df***	***p***
(Intercept)	-47.33	458.96	0.723	-205.97	466	0.057	-223.02	466.91	0.036
Age	0.13	424.47	0.444	0.15	382.15	0.37	.	.	.
BMI (kg/m^2)	1.2	458.03	0.501	.	.	.	.	.	.

Fat (%)	-0.19	458	0.653	.	.	.	.	.	.
Height (cm)	0.73	458.79	0.392	1.7	465.54	0.011	1.82	466.04	**0.005**
Height:PopulationUrban	0.59	458.03	0.05	.	.	.	.	.	.
Height:SexMale	-0.25	458.23	0.258	.	.	.	.	.	.
Height:Waist	-0.01	458.62	0.479	-0.02	465.54	0.02	-0.02	466.09	**0.01**
Hip (cm)	-0.28	458.08	0.219	.	.	.	.	.	.
Muscle (%)	0.12	458.95	0.81	.	.	.	.	.	.
PopulationUrban	-83.95	458	0.073	7.85	438.81	**0.021**	7.65	376.41	**0.023**
SexMale	40.82	458.54	0.267	6	465.02	**0.008**	5.87	466.04	**0.01**
Waist (cm)	1.33	458.32	0.493	2.94	465.38	0.034	3.23	466.29	0.017
Weight (kg)	-0.32	458.09	0.622	.	.	.	.	.	.

Note. The indigenous population and females were used as reference for categorical predictors. Significant effects are in bold. For a full version of this table, including standard errors and *t*-values, see Table S7, and for an ANOVA-like table of random effects, see Table S8 in The Supplementary Material available online.

In the first model, we included as predictors all measured variables as main effects, as well as the interactions between height and population, height and sex, and height and waist. In the second model, we included age, height, population, sex, waist, and the interaction between height and waist. For the final, third model, we removed age since this predictor did not have any influence on the self-reported health factor in the previous models.

These three models were compared using the AIC, Akaike weights (w_i AIC) and ΔAIC (Table 2). The analyses revealed that Model 3 is not only the most parsimonious model, but has a lower AIC and higher Akaike weight [see 65] than the previous two models. In fact, Model 3 is 4.56 times more likely to be the best model compared with Model 2, and more than 400 times compared with Model 1 (in comparison with Model 1, Model 2 is close to 90 times more likely to be the best model).

Table 2. Performance criteria of *LME* models.

Model	**AIC**	**ΔAIC**	***df***	**w_i(AIC)**
Model 3	4006.985	.	8	0.8185
Model 2	4010.019	3.0342	9	0.1795
Model 1	4019.03	12.0447	16	0.002

Note. Models are in descending order from the best to the worst fitting. ΔAIC is the change in AIC between each model and the previous model. Akaike weights w_i(AIC) are conditional probabilities for each model being the best model [65].

Nevertheless, for Model 3 (the minimum adequate model), Variance Inflation Factors (VIF) revealed extreme collinearity for height, waist, and the interaction between height and waist (VIF > 68 in those cases; Table S9). This problem, however, was solved after centring and rescaling both height and waist measures (VIF < 2.4 in all cases; Table S10). In addition, this centred and rescaled version of Model 3 had no issues regarding its residual distribution (i.e. for all samples it resembled a normal distribution) and linearity of residuals (see Fig S2); each single term predictor was linearly related to self-rated health (see Fig S3).

Furthermore, the final, centred and rescaled version of Model 3 had a lower AIC than model 3 (3988 vs. 4007) and was over 10000 times more likely to be the best model, as revealed by Akaike weights (see Table S11).

The final model (Table 3; Fig 2) showed a significant, negative main effect of waist circumference (t = -3.23, β = -2.93, p = 0.001), a significant effect of population (urban samples rated their health 7.65 points higher than indigenous participants; t = 2.28, p = 0.02) and sex (men rated their health 5.87 points higher than women t = 2.60, p = 0.010). In addition, this model (Table 3) revealed that Colombians reported better heath than Mexicans (Fig 2B).

Table 3. Results of the final LMM testing effects of independent variables on self-reported health

	Estimate	***SE***	***df***	***t***	***p***
(Intercept)	53.74	5.02	2.66	10.7	**0.003**
Height_cs	1.53	1.2	466.25	1.27	0.204
Waist_cs	-2.93	0.91	432.99	-3.23	**0.001**
SexMale	5.87	2.26	466.04	2.6	**0.01**
PopulationUrban	7.65	3.36	376.41	2.28	**0.023**
Height_cs:Waist_cs	-2.2	0.85	466.09	-2.6	**0.01**

Note. The indigenous population and females were used as reference for categorical predictors. Significant effects are in bold. Both waist and height were centred and rescaled (identified by the suffix _cs).

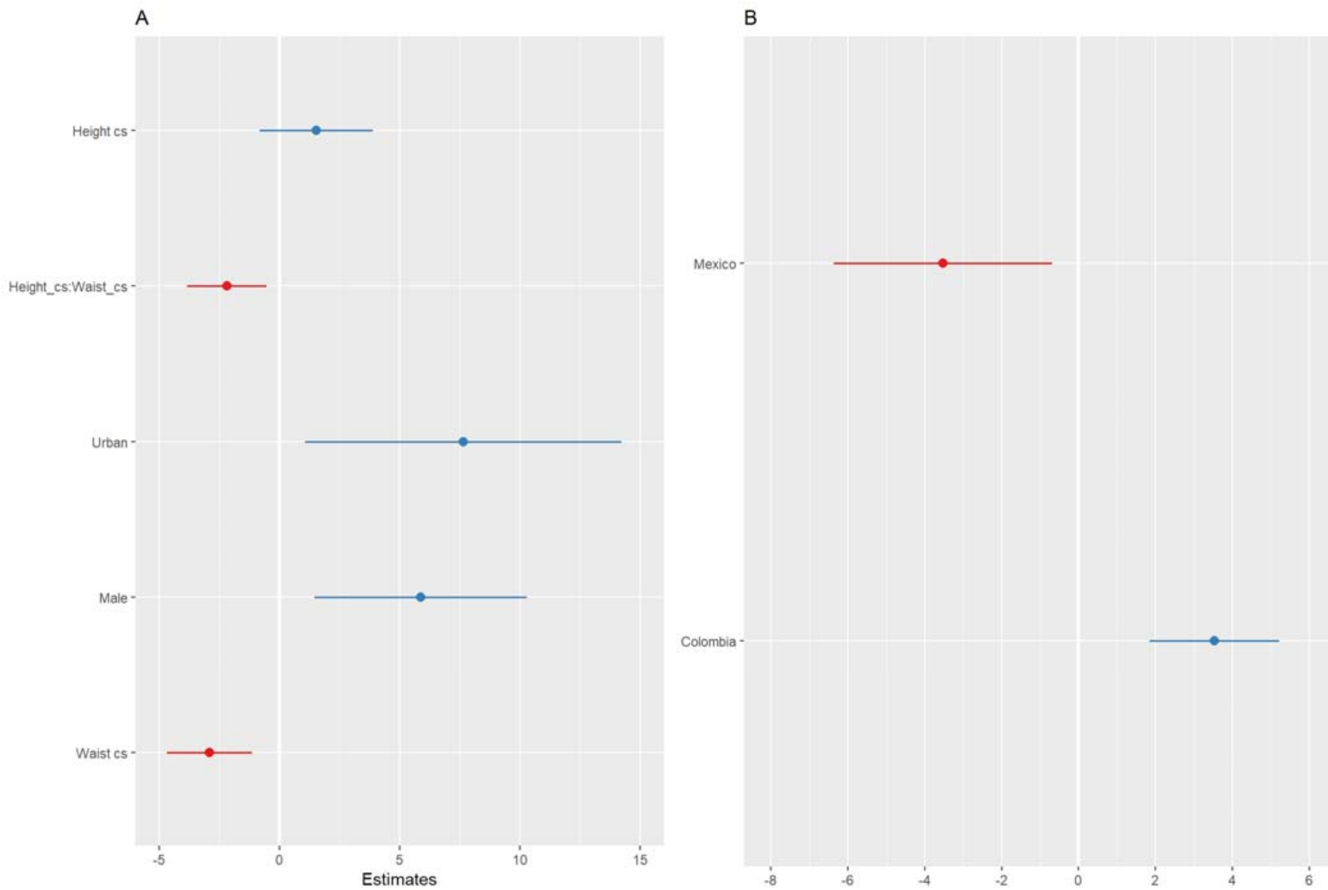

Figure 2. **Final model estimates.** Forest-plot of estimates for each fixed factor with 95% confidence interval [CI]. (A) Fixed effects. (B) Random effects. For categorical fixed predictors, indigenous population and female participants were used as reference. Both waist and height were centred and rescaled (identified by the suffix _cs).

Moreover, a significant interaction between waist and height (Table 3; $t = -2.06$, $p = 0.041$) was exposed, indicating that the associated health costs of a larger waist circumference were height-dependent (Fig 3); the best predicted self-rated health was for tall participants with small waists, and the worst was for (again) tall participants but with large waist circumferences. The model also revealed that for shorter people, there are no predicted significant associated costs of having a large waist. In other words, the association between height and self-rated health is positive for people with small waist circumferences, but negative for people with large waists.

In addition, age, waist circumference, height, fat percentage, visceral fat, BMI and muscle percentage, were significantly correlated with self-rated health ($r > 0.10$, in all cases) in men and women (bivariate Pearson correlations between all measured variables in all participants are shown in the Table S4, women in Table S5 and men in Table S6).

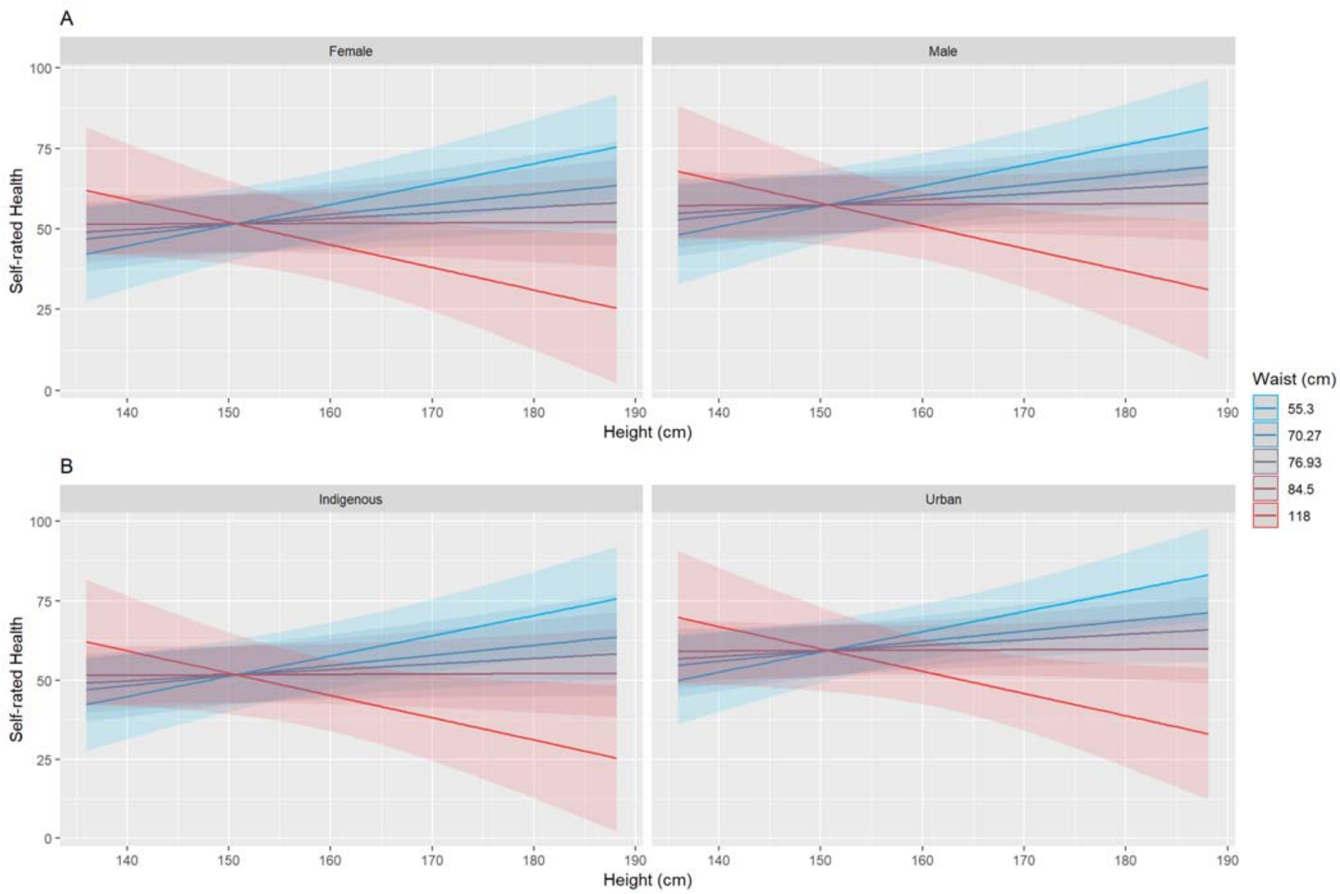

Figure 3. **Interaction between height and waist**. Model predictions were split by (A) sex, and (B) population. To simplify the interpretation, raw (instead of centred and rescaled) values of height and waist were used. Waist reference, minimum, quartiles (lower, median and upper) and maximum waist circumference values were used, shown on a blue to red colour scale. For an interactive 3D and animated plot of the interaction between height and waist, see Fig. S4 in the Supplementary Material.

Discussion

The present study provides new insights into the relationship between height and health in men and women by studying three Latin-American populations, which included urban and indigenous populations with marked differences in access to basic needs and services like food and health.

Contrary to our initial hypothesis, height was not a significant predictor of self-perceived health but interacted with waist circumference in all populations studied. Most results in favour of a direct relationship between height itself and health were carried out in small modern populations and specific Western ethnic groups more than twenty years ago. New studies with non-traditional population groups have failed to verify the positive relationship between height and health, especially associated with cardiovascular and autoimmune diseases [67,68]. For example, studies on Native Americans, Japanese, Indians and Pakistanis showed that shorter people had a lower prevalence of cardiovascular disease than the tallest people in each population [68]. These findings were similar in Sardinian inhabitants, a European population with the lowest physical stature recorded in Europe in recent years [67].

Interestingly, our results suggest that although there is a main effect of waist circumference on self-perceived health, the associated costs of large abdominal circumference are differential depending on stature; this is, waist circumference predicted self-reported health differently for people of different heights: while being taller predicts better self-rated health for taller people with relatively small waists, being taller was found to be associated with poorer perceptions of their health in people with larger waist circumferences. Furthermore, while there is a cost of abdominal and visceral adiposity for tall people, there is no predicted cost for shorter persons. Therefore, these results argue the importance of considering a phenotypic integration of different human features that could be involved in health or physiological conditions, when a possible sexually selected trait is being evaluated as a signal of immunocompetence.

On the other hand, given that height is the most sensible human anatomical feature to environmental and socioeconomic conditions [22,34], we expected stronger association between health and height for the indigenous population where the cost to produce and maintain this costly trait is greater than for inhabitants from urbanised areas. Nevertheless, we did not find inter-population differences in the magnitude of this relation. Urban populations reported better health than the indigenous population, and the shortest participants tended to be from the indigenous Me'Phaa sample. These results could, in fact, suggest different life-history strategies. Compared with modern Western societies, different life strategies could take place in harsh environments,[69], for instance, investing relatively less energy in growth and reallocating it towards reproduction [22]. In addition, a relative increase in the intensity or number of infectious diseases (including paediatric diseases in Me'Phaa) and higher tendency to early sexual maturity could negatively impact growth, resulting in a lower average height [70,71]. These trends could be compensations between life-history components [27]. Finally, fast and prolonged growth imply high costs for the organism [1]. Rapid growth may influence mortality risk [72] and growing for a longer time delays the onset of reproduction, increasing the risk of death and producing fewer offspring [1]. This perspective of life strategies allows us to understand the relationship between height, health and reproduction. This suggests the importance of addressing factors such as ethnicity, socioeconomic status, level of urbanisation in populations where there is great heterogeneity in access to food, health and pressure resources for pathogens, for instance, in Latin-American populations in which this relationship has barely been directly explored.

Although our study did not directly evaluate any immunological marker but a self-perception of health, the implementation of a physiological immune indicator of the adaptive immune system appears to be consistent with our results. It has been found that men, but not women, show a curvilinear relationship between antibody response to a hepatitis-B vaccine and body height, with a positive relationship up to a height of 185 cm, but an inverse relationship in taller men [20]. In our three populations, the maximum height was lower than 185 cm, which could explain the linear but not curvilinear association that we found. In addition, the fact that self-perception in our study and antibody response in previous studies are both positively associated with body height could contribute to the knowledge about the reliability of self-perception of health as an indicator of an immunological condition.

Finally, in relation with sex differences, women reported lower average health than men in all communities, which is concordant with reports and normative SF-36 data in other populations, especially in younger people [73,74]. These results could consolidate the idea that height is a reliable signal of health in men [27], while it could reflect reproductive success in women [75] in terms of labour and birth, and to a lesser extent, function as an indicator of health [76]. It has been seen that taller women experience fewer problems during the labour process due to a lower risk of mismatch between foetal head size and size of the birth canal [76]. Nevertheless, this speculative idea warrants further studies on comparing health, reproductive success and female height.

It is important to take into account that the mode of survey administration might be a limitation in our study, and it could have led to confounding effects. For example, it is possible that indigenous people have different understanding and thresholds about their general health perception, which we were unable to evaluate without previous validation of translated items, and it could have explained the lowest values of general health reported by indigenous people. Nevertheless, it could also reflect the real health conditions in Me’Phaa communities and not a misunderstanding of the survey. Other national indicators of health, such as morbidity and mortality by gastrointestinal and nasopharyngeal infectious diseases, have reported that Me'Phaa communities also present the lowest values in Mexico [48], which is consistent with our results. In fact, items for the dimension of general health perception have the lowest standard deviation and coefficient of variation in the entire SF-36 survey, in both validated Spanish [52,55] and English versions [77], which makes this dimension the most understandable one.

In addition, in order to consider obvious differences in language and perception of health, statistical models in this study assumed these inter-population variations *a priori*. Random effects for countries were considered in all performed LMM. We found that although urban populations differ considerably from the indigenous population, the relations between height, waist circumference and self-perceptions of health were observed in the same direction for all populations.

The present study contributes information which could be important in the framework of human sexual selection. If health and genetic quality cues play an important role in human mate-choice [e.g. 78], and height and waist interact to signal health, its evolutionary consequences, including cognitive and behavioural effects, should be addressed in future research. This could be done by studying the interaction between waist circumference and height, in relation to reproductive and/or mating success, as well as mate preferences and perceived attractiveness, in populations with both Westernised and non-Westernised lifestyles.

Data accessibility

All data used for this article are openly available at the OSF [79]. Code to perform all analyses, data manipulation, tables and figures is available in both HTML ('Supplementary_Material.html') and *R Markdown* ('Supplementary_Material.Rmd') formats, so that it can be fully reproduced and explored in depth [80].

Ethics

All procedures for testing and recruitment were approved by Universidad El Bosque Institutional Committee on Research Ethics (PCI.2017-9444) and National Autonomous University of Mexico Committee on Research Ethics (FPSI/CE/01/2016). All participants read and signed a written informed consent.

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Competing interests

The authors declare that they have no competing interests.

Authors' contributions

JDL, ORS, MV-A, EV and I.G-S. conceived and designed this study. JDL, ORS, AC-C, LM-S, and IG-S collected data. JDL and IG-S analysed all data. JDL, ORS, MV-A and IG-S wrote the first draft. All authors contributed to writing, approved the final version of the manuscript and gave approval for publication.

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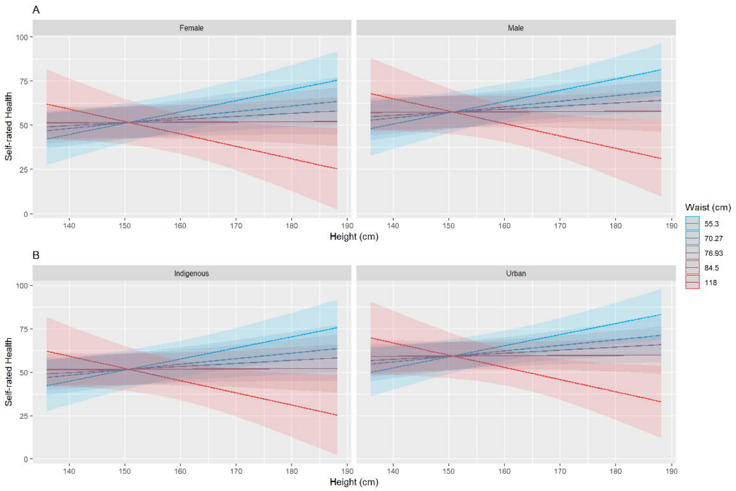
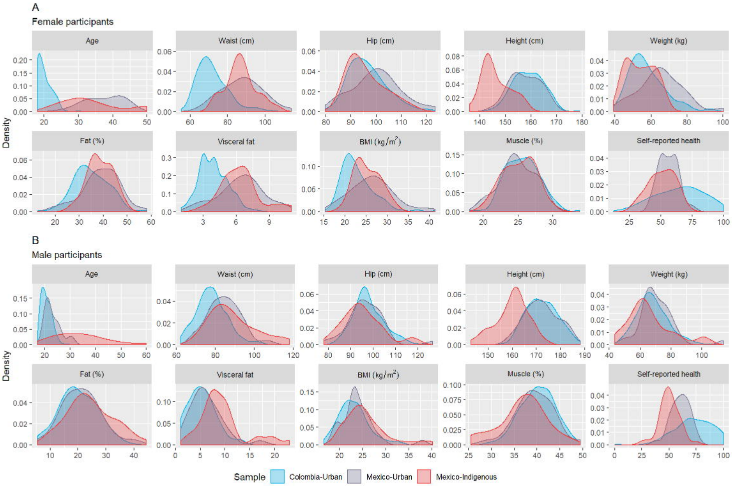
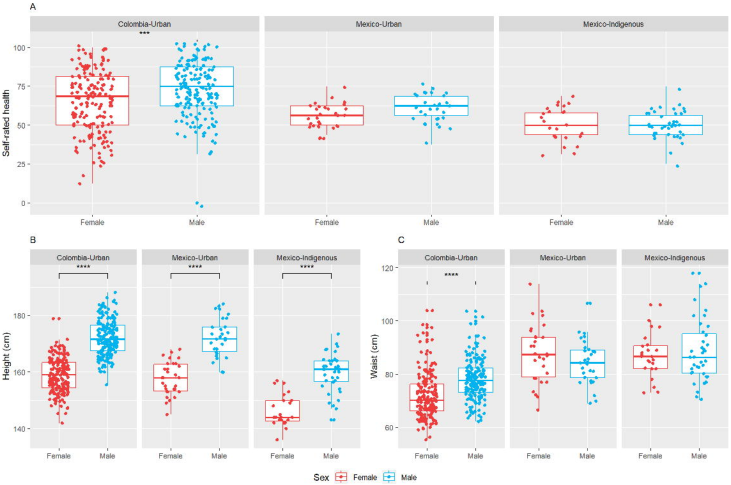
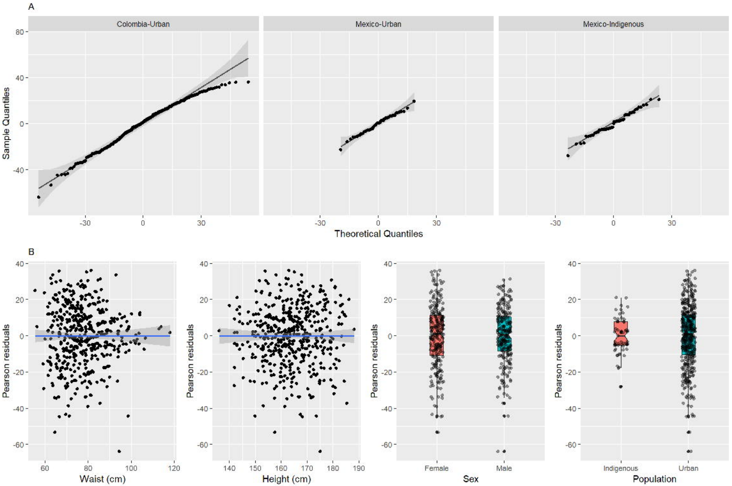
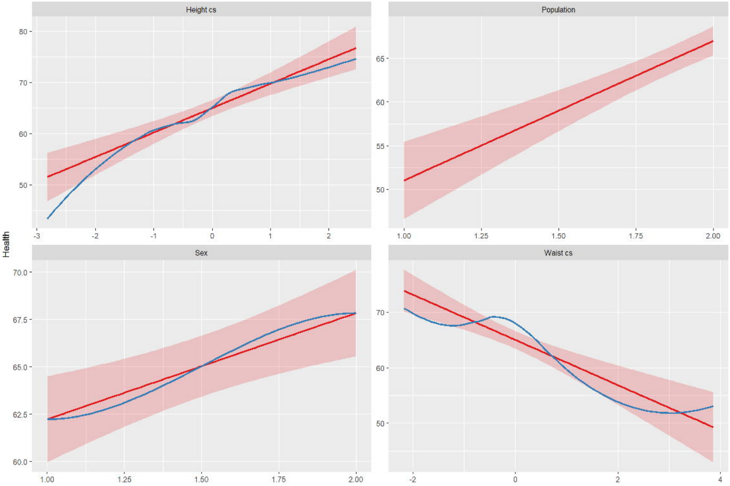

A
Female
Male
Self-rated Health
Height (cm)
B
Indigenous
Urban
Waist (cm)
55.3
70.27
76.93
84.5
118
100
75
50
25
0
140
150
160
170
180
190


A
Female participants
Age
Waist (cm)
Hip (cm)
Height (cm)
Weight (kg)
Fat (%)
Visceral fat
BMI (kg/m²)
Muscle (%)
Self-reported health
Density
B
Male participants
Age
Waist (cm)
Hip (cm)
Height (cm)
Weight (kg)
Fat (%)
Visceral fat
BMI (kg/m²)
Muscle (%)
Self-reported health
Density
Sample
Colombia-Urban
Mexico-Urban
Mexico-Indigenous

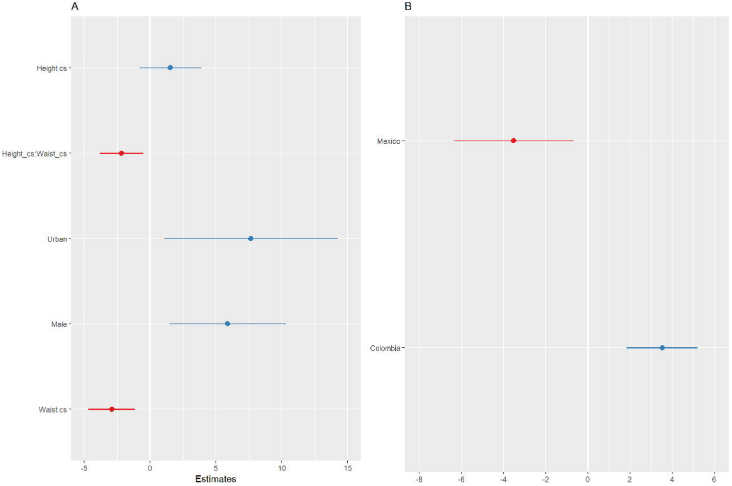

A
Colombia-Urban
Mexico-Urban
Mexico-Indigenous
***
Self-rated health
100
75
50
25
0
Female
Male
B
Height (cm)
180
160
140
****
C
Waist (cm)
120
100
80
60
Sex
Female
Male



A
Colombia-Urban
Mexico-Urban
Mexico-Indigenous
Sample Quantiles
Theoretical Quantiles
80
40
0
-40
-30
0
30
B
Pearson residuals
Waist (cm)
Height (cm)
Sex
Female
Male
Population
Indigenous
Urban
40
20
0
-20
-40
-60
60
80
100
120
140
150
160
170
180
190



Height cs
Population
Sex
Waist cs
Health
80
70
60
50
-3
-2
-1
0
1
2
65
60
55
50
1.00
1.25
1.50
1.75
2.00
70.0
67.5
65.0
62.5
60.0
1.00
1.25
1.50
1.75
2.00
70
60
50
-2
0
2
4


A
Height cs
Height_cs:Waist_cs
Urban
Male
Waist cs
-5
0
5
10
15
Estimates
B
Mexico
Colombia
-8
-6
-4
-2
0
2
4
6