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

Juan David Leongoméz[1*], Oscar R. Sánchez[1], Milena Vásquez-Amézquita[2], Eugenio Valderrama[1,#a], Andrés Castellanos-Chacón[1], Lina Morales-Sánchez [1,#b], Javier Nieto[3], Isaac González-Santoyo[4*]

[1]Human Behavior Lab, Faculty of Psychology, El Bosque University. Bogota, Colombia.

[2]Experimental Psychology Lab, Faculty of Psychology, El Bosque University, Bogota, Colombia.

[3]Laboratory of Learning and Adaptation, Faculty of Psychology, National Autonomous University of Mexico, Mexico City, Mexico.

[4]Neuroecology Lab, Faculty of Psychology, National Autonomous University of Mexico, Mexico City, Mexico.

[#a]Current Address: LH Bailey Hortorium, Plant Biology Section, School of Integrative Plant Science, Cornell University, Ithaca, NY, United States of America.

[#b]Current Address: Department of Psychology, Faculty of Social Sciences, Los Andes University, Bogota, Colombia.

*Corresponding authors

E-mail address: jleongomez@unbosque.edu.co (JDL), isantoyo.unam@gmail.com (IG-S)

Abstract

Body height growth 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 is poorly understood. Moreover, despite the association between height and attractiveness being extensively tested, whether immunity may be linking this relation is scarcely studied, particularly in non-Western samples. Here, we tested whether human height is related to health measured by both, self-perception, and relevant nutritional and health anthropometric indicators in three Latin-American populations that widely differ in socioeconomic and ecological conditions: two urbanized samples from Bogota (Colombia) and Mexico City (Mexico), and one isolated indigenous population (Me'Phaa, Mexico). Using Linear Mixed Models, our results show that, for both men and women, self-rated health is best predicted by an interaction between height and waist, and that the costs associated to a large waist circumference are differential for people depending on height, affecting taller people more than shorter individuals in all population evaluated. The present study contributes with information that could be important in the framework of human sexual selection. 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 its cognitive and behavioral effects, should be addressed in future research.

Introduction

In modern Western societies, it has been seen that while women usually show a marked preference for men significantly taller, over significantly shorter, than average [1,2], men are more tolerant in choosing women who are taller or shorter than average [3]. This is consistent with the idea that male height can be adaptive [4] and that sexual selection favors taller men, possibly because it provides hereditary advantages, such as genetic quality for the offspring [5,6], or direct benefits, provisioning resources and protection for women and their children [7]. This because height has been proposed as an indicator of resource holding potential (RHP), in terms of social dominance and deference [8,9], and socioeconomic status [5,10].

Supporting this idea, it has been found a direct linear relationship between male height and reproductive success, which would not apply to women, and suggest unrestricted directional selection, that would work to favor even very tall men, but not to very tall women [11]. 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 [12], while the maximum reproductive success of women is below female average height [13]. Furthermore, heterosexual men and women tend to adjust the preferred height of hypothetical partners depending on their own stature [14]. 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 [15].

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

One possibility can be addressed in the framework of the Life-History theory [16], and the immunocompetence handicap hypothesis (ICHH [17–19]). Body height growth is a life history component [1,20], that involves important costs for its expression and maintenance, which may originate trade-offs on other costly components such as reproduction [21] or immunity [22].

The costs in height can be measure in terms of survival and physiological expenditure [22]. 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 [22,23]. With some exceptions, we have a limited number of cell replications during our lifetimes. A minimal increment in body height necessary involves more cells, maybe trillions, and more replications during the life. This higher number of cell replications demands greater number of proteins to maintain taller, larger bodies [22], which together with an increase on free radicals generated by the corresponding energy consumption, may lead to greater likelihood of DNA damage [24], thus increasing the incidence of cancer and reducing longevity [22].

Trade-offs between these life-history components could be mediated by sexual hormones. Trade-off with reproduction occurs because at the beginning of sexual maturity sexual hormones are responsible to reallocate energetic and physiological resources to this function, instead of somatic growth. For instance, an increment in estrogen production leads to the onset of menstrual bleeding in women, but also slows the process of growth, and eventually causes it to cease [25]; estrogen 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 [26, see also 27]. In turn, trade-off with immunity occurs because the same increment in sexual steroids , usually has suppressive effects on several immune components [17]. For example, testosterone may increase the severity of malaria, leishmaniasis, amebiasis [28], and perhaps tuberculosis [see 29,30].

Therefore, as consequence of these life-history trade-offs, height could be considered as a reliable indicator of individuals' condition in terms of (1) the amount and quality of nutritional resources that were acquired until sexual maturity, (2) the RHP to obtain resources for the somatic maintenance in adult stage, and (3) the current immunocompetence to afford the immune cost imposed by sexual steroids. Thus, according 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 [18], which would result in increased sexual preference towards taller individuals.

Despite the association between height and attractiveness being widely tested, whether immunity might be linking this relation is poorly studied. Moreover, most studies have been done using high-income developed populations (often samples characterized as Western, Educated, and from Industrialized, Rich, and Democratic [WEIRD] societies [31]), which has led to a lack of information of what is occurring in other populations with important socio ecological differences. Considering these ecological pressures is important because although genetic allelic expression could be the main factor that determines individual height differences [25], height is also the most sensible human anatomical feature that respond to environmental and socioeconomic conditions [21,32]. For instance, variation in height across social classes is known to be greater in poorer countries [33], but much reduced where standards of living are higher [34]. Economic inequality not only affects population nutritional patterns, which are especially important during childhood to stablish adult height, but also the presence of infectious diseases [35]. Childhood disease is known to adversely affect growth: mounting an immune response to fight infection increases metabolic requirements and can thus affect net nutrition, and hence reduce productivity. Disease also prevents food intake, impairs nutrient absorption, and causes nutrient loss [36,37]. Therefore, comparing with high-income, 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, and in consequence could show a stronger sexual selective pressure over height, since it would more accurately signal growth rates, life-history trajectories, and health status. 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 [38]. In fact, during the last century, and given a general improvement in nutrition, height has increased around the world [39], but maintaining the level of dimorphism in favor of men.

Colombia and Mexico are two of the most socioeconomically heterogeneous countries in the world; although both countries have a high Human Development Index [40], and have relatively good health compared to global standards, attaining respective scores of 68 and 66 in the Healthcare Access and Quality (HAQ) Index [41], Colombia and Mexico have GINI coefficients of 50.8 and 43.4, respectively, making them the 12^{th} and 43^{th} 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, in Latin-America 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 42].

In addition to rural communities, in Latin-America, indigenous people tend to have high rates of poverty and extreme poverty [43], and have poorer health [44] less susceptible to improve by national income growth [45]. In Mexico, there are at least 56 independent indigenous peoples, whose lifestyle practices differ in varying degrees from the typical "urbanized" lifestyle. Among these groups, the Me'Phaa people, from an isolated region known as the "Montaña Alta" of the state of Guerrero, is one of the groups whose lifestyle most dramatically differs from the westernized lifestyle typical of more urbanized areas [46]. Me'Phaa communities are small groups, composed of fifty to eighty 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 fowl, but meat is consumed almost entirely during special occasions and is 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 Me'Phaa speak only their native language [47]. In consequence, these communities have some of the lowest income and economic development in the country, and the highest child morbidity and mortality due to chronic infectious diseases [46].

These three Latin-American populations can provide an interesting indication about how regional socioeconomic conditions, and the 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 both, self-perception, and relevant nutritional and health anthropometric indicators in three Latin-American populations that widely differ in socioeconomic and ecological conditions: two urbanized samples from Bogota (Colombia) and Mexico City (Mexico), and one isolated indigenous population (Me´Phaa, Mexico).

Materials and Methods

Ethics Statement

All procedures for testing and recruitment were approved by El Bosque University 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.

Participants

A total of 251 (120 women and 131 men) adults took part in the study. They were from three different samples: (1) Mexican indigenous population, (2) Mexican urban population, and (3) Colombian urban population. Me'Phaa indigenous participants from "La Montaña Alta" were recruited and participated in this study between January and March 2017, while Participants did it between May and June 2017. In Colombia, data collection took place between October and December 2018.

The first sample consisted of 75 subjects (mean age ± SD = 33.60 ± 9.51 years old) from the small Me'Phaa community – "*Plan de Gatica*" from a region known as the "*Montaña Alta*" of the state of Guerrero in Southwest Mexico. In this group, 24 participants were women (33.46 ± 8.61) and 39 were men (33.74 ± 10.41), who were participating in a larger study about immunocompetence. Both sexes were aged above 18 years old. In Mexico, people from this age are considered adults. We collected all measurements in the own community. Me'Phaa communities are about 20 kilometers apart, and it takes about three hours traveling on rural dirt roads to reach the nearest large town, about 80 km away. Mexico City is about 850 kilometers 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's age from 0 to 8 years old, which is the highest vulnerability and death risk age; [46]), and the lowest access to health services. These conditions were determined by last 10 years of statistical information obtained from the last record of the national system of access to health information in 2016 [46].

The second sample consisted of 66 subjects (20.67 ± 2.32) over 18 years old of general community from Mexico City, of whom 36 were women (20.2 ± 2.27) and 30 were men (21.13 ± 2.36). Participants from both Mexican populations were aged 18 to 60 years old. Finally, the third sample consisted of 122 undergraduate students with ages ranging from 18 to 30 years old (30.23 ± 4.27), 60 were women (20.2 ± 2.27) and 62 were men (21.13 ± 2.36) from Bogota, Colombia. All urban participants were recruited through public advertisements.

Participants from both urban population samples were taking part in two different, 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, odor samples, and facial photographs, were also collected as part of a separate project. Additionally, for women in the Colombian sample 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 female 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 o chronic disease, these health issues were also considered as exclusion criteria.

Given that 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 habiting in the same community. Nevertheless, the total of Me’Phaa people habiting in the region called “Montaña Alta” is comprised of 20-30 communities with almost the same number of families than “Plan de Gatica”. Therefore, our sample size cannot be considered representative of the total “Me’Phaa” people habiting in the region “Montaña Alta”, but from the specific “Plan de Gatica” community. Most participants from the “Mexico City” and “Bogota” samples, however, were recruited at the National Autonomous University of México, and El Bosque University campuses, respectively. Therefore, these samples are comprised mostly of bachelor and graduate students, and cannot be considered representative of a larger population from their respective whole city, which is comprised of about 12 million adult persons in the case of 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 community, and participants from the urban population attended a university laboratory from each country on individual appointments.

Participants from Mexico City and Bogota were recruited through public advertisements in social media, and poster boards located along the central campus of National Autonomous University and El Bosque University. While in Mexico City, participants received either 1 partial course credit or a payment equivalent to $5 dollars as compensation for their participation, in Bogota all participants were given academic credits for their participation.

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

The Interpreters provided by Xuajin Me'Phaa organization administered the SF-36 Health survey in the Me'Phaa Language. Interpreters use Spanish as second language, and are thoroughly proficient in speaking and reading Spanish. We used the validated SF-36 survey for urban and rural Mexican populations [50] for interpreters to translate from Spanish to the Me'Phaa language. Given the ethnical customs of Me'Phaa culture, and to avoid bias in participant responses, participants were always interviewed by an interpreter of their same sex; i.e. men were interviewed by a male interpreter and women by a female interpreter. The same interpreter interviewed all participants of its corresponding sex.

Indigenous participants only answered items that define dimension of general health (i.e. Item number 1, 33, 34, 35, 36) with the exception of the item 35. This item informs about the expectation of future health. However, because grammatical compositions of Me'Phaa language does not consider "infinitive" and "future" as verbal tense [51], interpretation of this question was not possible for Me'Phaa people, and this item was excluded.

In Colombia, we used a Spanish language validated version of the SF-36 questionnaire [52], which was validated in Colombia [53]. The SF-36 produces eight factors, 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).

To calculate this factors, all items were recoded following the instructions on how to score SF-36 [52].We calculated final factor averaging the recoded items. To make this data compatible with the Mexican database, and because item 35 cannot be answered by the Mexican Indigenous population, this item was excluded and the health factor was calculated averaging only items 1, 33, 34, and 36.

Anthropometric measurements

All anthropometric measurements were measured three times, consecutively, and then averaged (for agreement statistics between the three measurements of each characteristic, see section 1.3 on S1 File). All participants were in light clothes and had their shoes removed. The same observer repeated the three measurements.

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

Anthropomorphic measurements also included waist circumference (cm), weight (kg), fat percentage, visceral fat level, muscle percentage, and BMI. Circumference of waist was measured in centimeters using a flexible tape, midway between the lowest rib and the iliac crest, and was recorded to the nearest millimeter. These anthropomorphic measures 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 [57]. 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 presence of the features of metabolic syndrome [58,59]. Hence, In the presence of the clinical criteria of metabolic syndrome, an increased waist circumference does provide relevant pathophysiological information insofar as it defines the prevalent form of the syndrome resulting from abdominal obesity [55].

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

Statistical analysis

To test the association between height and health, we fitted general a Linear Mixed Model (LMM). The dependent variable in this model were the self-reported health factor and the predictor variables included participant sex, age, population (indigenous, urban), height and waist as fixed, main effects, as well as anthropometric measurements (hip, weight, fat percentage, BMI and muscle percentage). Interactions between height and population, height and sex, and height and waist circumference were also included. Country was always included as a random factor, with random intercepts.

Although allowing slopes to vary randomly is recommended [60], we only included random intercepts in the models because there is only one data-point per subject. Population (indigenous, 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, while no such differences were expected by country. General LMM were fitted to test residual distribution. In all cases, residuals were closer to a normal or gamma (inverse link) distribution, for each population/country. Models was fitted using the *lmer* function from the *lmerTest* package [61; https://www.rdocumentation.org/packages/lmerTest] in R, version 3.5.2 [62].

The most parameterized 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 2 units from the second most adequate model) is reported [see 63]. To accomplish this, we implemented the *ICtab* function from the *bbmle* package [64; 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 S1 File).

Results

All analysis, data manipulation, tables and figures, as well as the code to produce them, can be reproduced and explored in more detail using *R* scripts in *Markdown* format (S2 File) using the are available as Supplementary Files, as well as the output, S1 File (in HTML format), where all Supplementary tables and figures can also be found. All data are available at the Open Science Framework (https://doi.org/10.17605/OSF.IO/KGR5X).

Figure 1 shows the distribution of age, waist, height, visceral fat and self-reported health, which strongly varies in both women (Fig 1A) and men (Fig 1B), sex, population (indigenous, urban) and country (Colombia, Mexico).

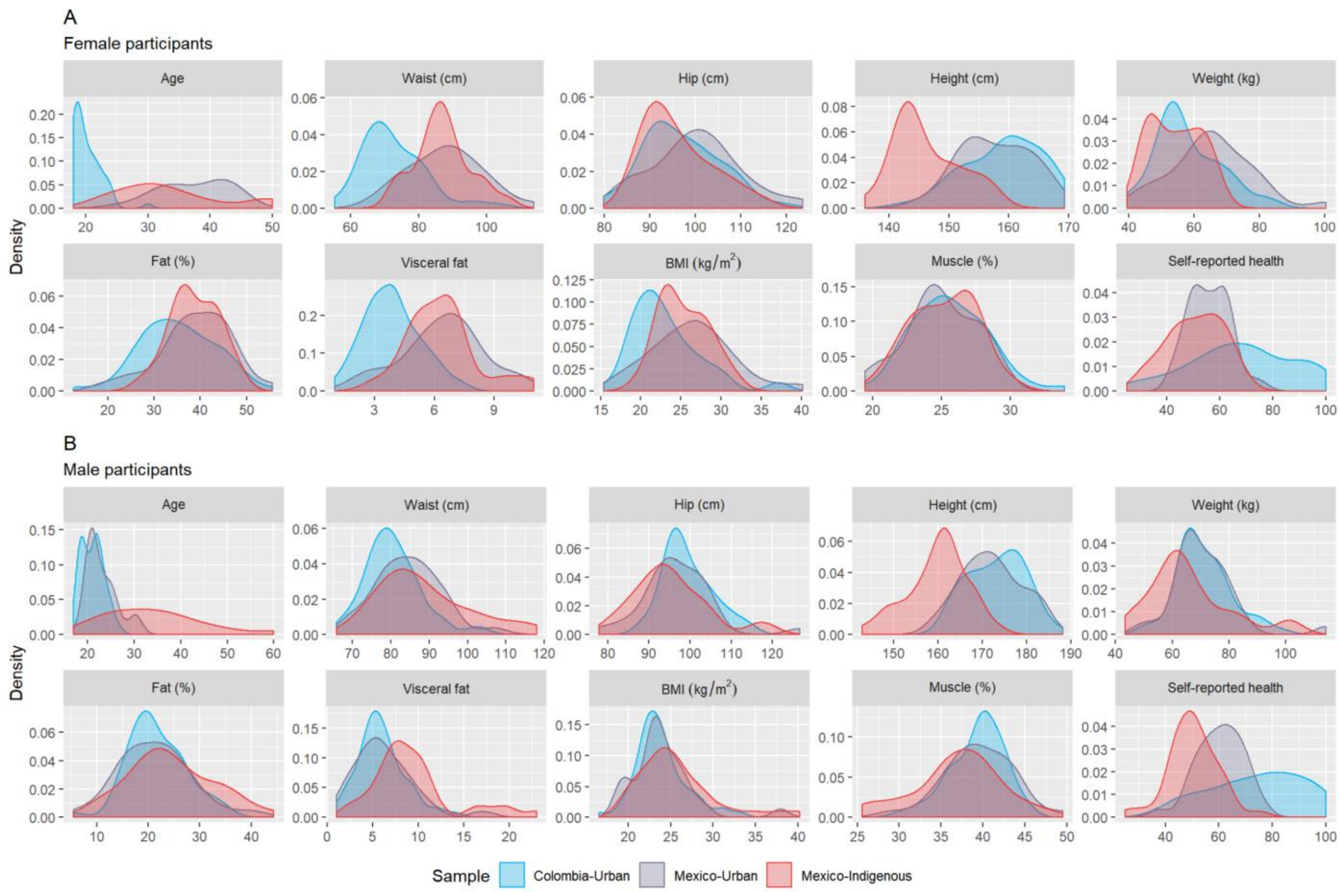

***Fig 1.* Distribution of all measured variables by sex, population and country.** (A) Female participants. (B) Male participants. For descriptives (mean, SD, median, minimum, and maximum values), see S2 Table (female participants) and S3 Table (male participants), of the Supplemental Material.

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

Table 1. Results of separate linear mixed models 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)	-97.01	226.83	0.520	-166.17	233.81	0.198	-181.41	234.65	0.153
Age	0.07	224.16	0.660	0.11	231.11	0.488	.	.	.
BMI (kg/m^2)	-0.03	226.02	0.990	.	.	.	.	.	.
Fat (%)	-0.21	226.00	0.650	.	.	.	.	.	.
Height (cm)	1.13	226.58	0.240	1.49	233.27	0.064	1.59	234.01	**0.043**
Height:PopulationUrban	0.30	226.00	0.300	.	.	.	.	.	.
Height:SexMale	0.02	226.01	0.930	.	.	.	.	.	.
Height:Waist	-0.02	226.37	0.180	-0.02	233.25	0.064	-0.02	234.00	**0.041**
Hip (cm)	-0.05	226.98	0.830	.	.	.	.	.	.
Muscle (%)	-0.32	226.81	0.570	.	.	.	.	.	.
PopulationUrban	-38.67	226.02	0.400	8.42	233.98	**0.009**	8.24	234.38	**0.010**
SexMale	3.18	226.09	0.940	6.01	233.07	**0.034**	5.82	234.00	**0.039**
Waist (cm)	2.60	226.19	0.220	2.66	233.18	0.094	2.91	234.01	0.061
Weight (kg)	0.03	226.06	0.970	.	.	.	.	.	.

Note. 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 S7 Table, and for an ANOVA-like table of random effects, see S8 Table in the Supplemental 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 self-reported health factor in the previous models.

These three models were compared using the Akaike Information Criterion (AIC) as well as 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 63] than the previous two models; in fact, Model 3 is 5.66 times more likely to be the best model compared to Model 2, and more than 4000 compared to Model 1 (in comparison to Model 1, Model 2 is close to 750 times more likely to be the best model).

Table 2. Performance criteria of *LME* models.

Model	AIC	ΔAIC	*df*	w_i(AIC)
Model 3	1981.4	.	8	0.85
Model 2	1984.87	3.47	9	0.15
Model 1	1998.09	16.69	16	<0.001

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. Akaike weights w_i(AIC) are conditional probabilities for each model being the best model [63].

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 > 75 in those cases; S9 Table). This problem, however, has solved after centering and rescaling both height and waist measures (VIF < 3 in all cases; S10 Table). In addition, this centered and rescaled version of Model 3 had no issues regarding its residual distribution (i.e. for all samples it resembled a normal distribution) or linearity of residuals (see S2 Fig), and each single term predictor was linearly related to self-rated health (see S3 Fig).

Furthermore, the final, centered and rescaled version of Model 3, had a lower AIC than model 3 (1962 vs 1981), and was over 1400 times more likely to be the best model, as revealed by Akaike weights (see S11 Table).

The final model (Table 3; Fig 2) showed a significant, negative main effect waist circumference ($t = -3.01$, $\beta = -3.27$, $p < 0.001$), as well as a significant effect of population (urban samples rated their health 8.24 points higher than indigenous participants; $t = 2.60$, $p = 0.01$), and sex (men rated their health 5.82 points higher than women $t = 2.07$, $p = 0.039$). In addition, this model (Table 3) revealed that Colombians reported better heath than Mexicans (Fig 2B).

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

	Estimate	***SE***	***df***	***t***	***p***
(Intercept)	53.64	6.2	1.88	8.65	**0.016**
Height_cs	-0.17	1.57	234.16	-0.11	0.914
Waist_cs	-3.27	1.08	234.29	-3.01	**0.003**
SexMale	5.82	2.81	234	2.07	**0.039**
PopulationUrban	8.24	3.17	234.38	2.6	**0.01**
Height_cs:Waist_cs	-2.28	1.11	234	-2.06	**0.041**

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

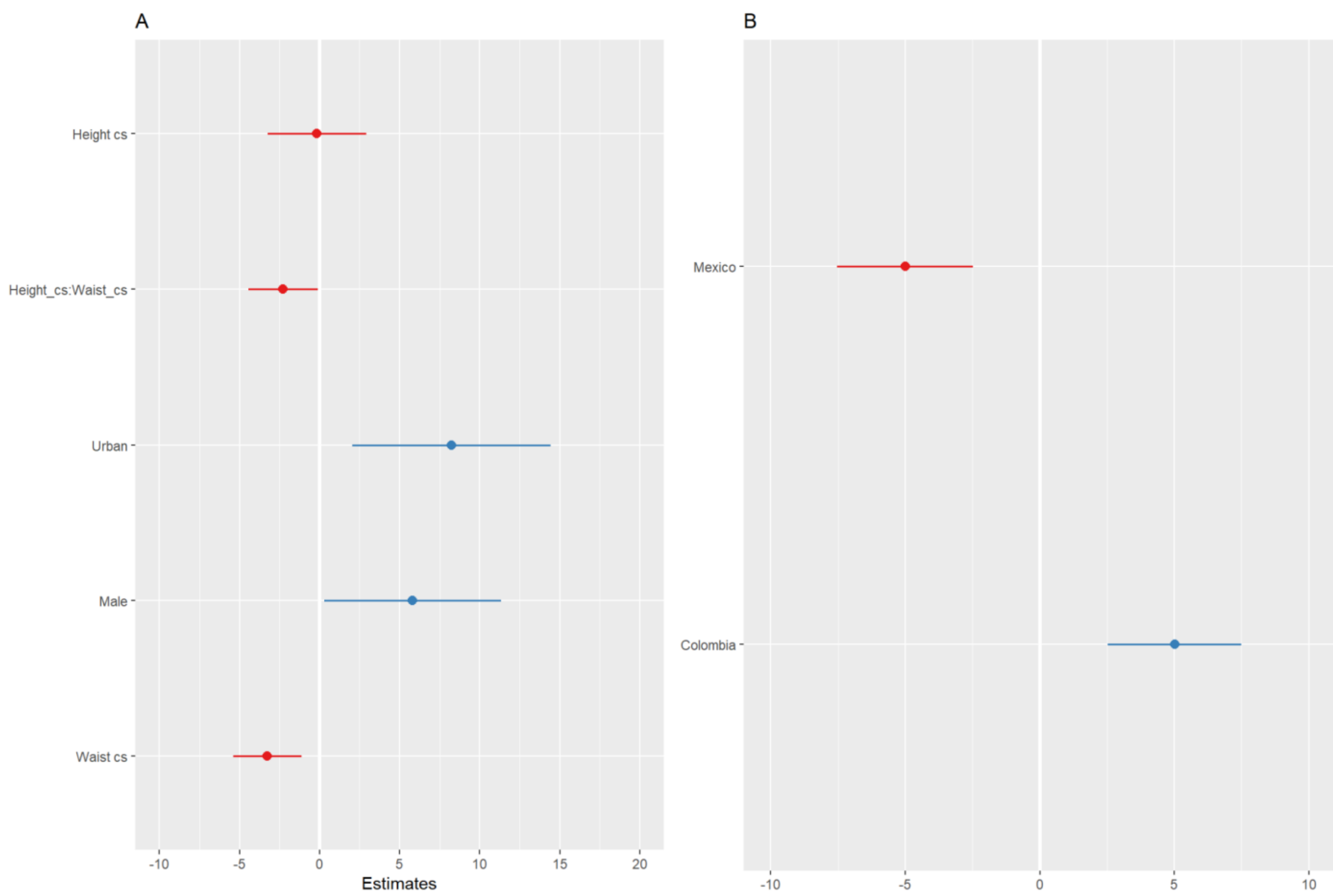

Fig 2. **Final model estimates.** Forest-plot of estimates for each fixed factor with 95% CI. (A) Fixed effects. (B) Random effects. For categorical fixed predictors, indigenous population and female participants were used as reference. Both waist and height were centered and rescaled (identified by 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 different for people of different heights (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, visceral fat, BMI, and muscle percentage, were significantly correlated with self-rated health ($r > 0.20$, in all cases), for men and women (for bivariate Pearson correlations between all measured variables see S4 Table for all participants combined, S5 Table for women, and S6 Table for men).

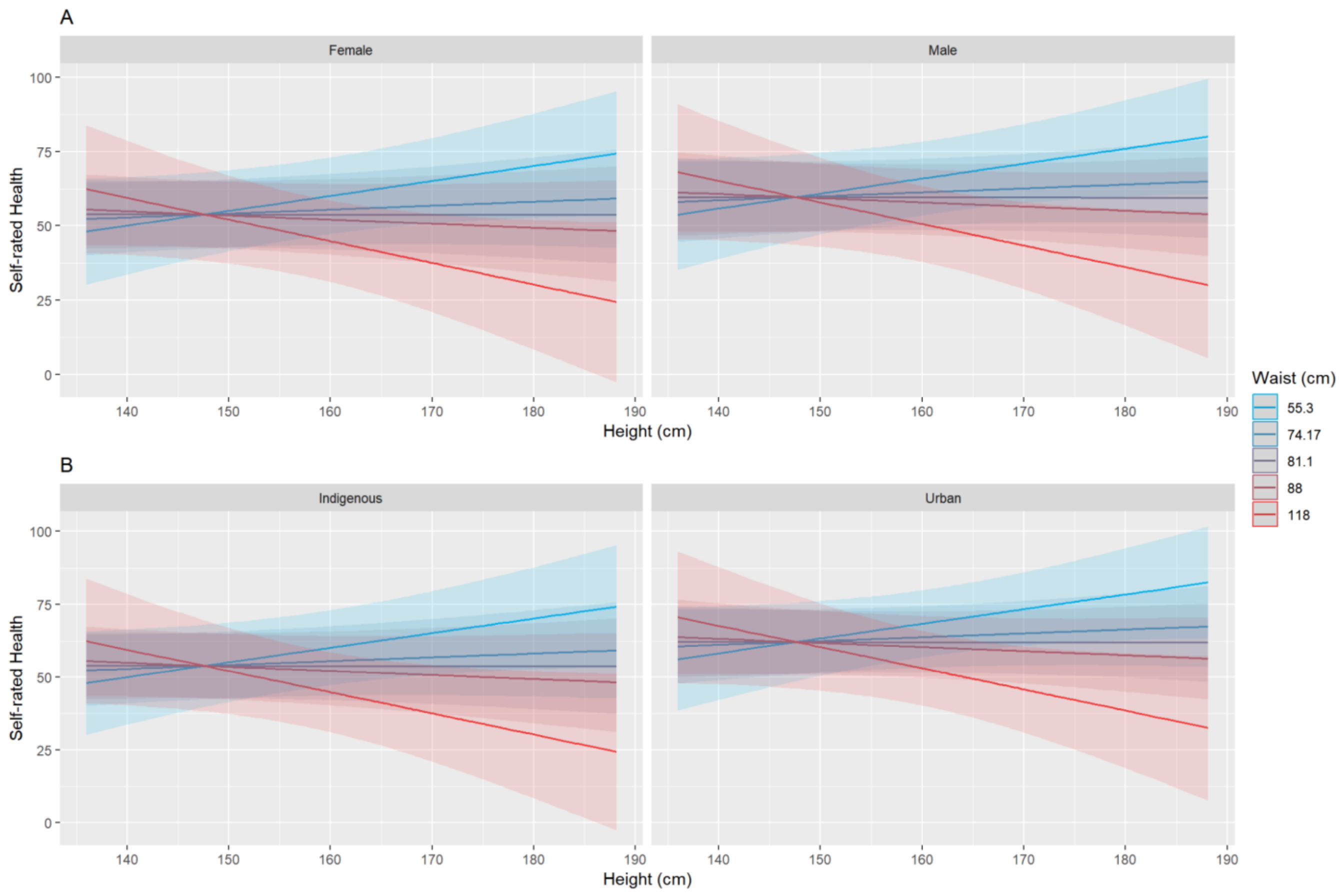

Fig 3. **Interaction between height and waist**. Model predictions were split by (A) sex, and ((B) population. To simplify interpretation, raw (instead of centred and rescaled) values of height and waist were used. As waist reference, minimum, quartiles (lower, median and upper), and maximum waist circumference values were used, showed on a blue to red colour scale. For an interactive 3D plot of the interaction between height and waist, see S4 Fig, or the 3D animated version contained in S1 File.

Discussion

The present study provides new insights into the nature of the relationship between height and health, in both men and women, by studying three Latin American samples, 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, we did not find height by itself to be a significant predictor of self-perceived health but by an interaction with waist circumference in all populations studied. Most results in favor of a direct relationship between height itself and health were carried out more than twenty years ago, in small samples, from modern societies, and in specific Western ethnic groups. 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 [65,66]. For example, studies in groups of Native Americans, Japanese, Indians and Pakistanis showed that lower people had a lower prevalence of cardiovascular disease than the highest people in each group [66]. These findings were similar in a group of inhabitants of Sardinia, a European population with the lowest physical stature recorded in Europe in recent years [65].

Interestingly, our results suggest that although there is a main effect of waist size on self-perceived health, the associated costs of a 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 consider a phenotypic integration of different human features that could be involved in health or physiological condition, 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 [21,32], we expected stronger relation between health and height for indigenous population, where the cost to produce and maintain this costly trait is greater than for habitants from urbanized areas. Nevertheless, we did not find inter-population differences in the magnitude of this relation; urban populations reported better health than the indigenous sample, and the shortest participants tended to be from the indigenous Me'Phaa sample. These results could in fact suggests different life history strategies. In harsh environments, compared to modern Western societies, different life strategies could take place [67], like investing relatively less energy in growth and reallocating it towards reproduction [21]. In addition, a relative increase in the intensity or number of infectious diseases (including child disease, like in the case of the Me'Phaa) and a tendency to early sexual maturity, could have negative effects on growth, resulting in lower average height [68,69]. These trends could be a compensation between life history components [25]. Finally, fast and prolonged growth imply high costs for the organism [1]; rapid growth seems to influence mortality risk [70], and growing for a longer time, delays the onset of reproduction, increasing the risk of dying and producing fewer offspring [1]. This perspective of life strategies allows us to understand the relationship between height, health, and reproduction. It suggests the importance of addressing factors such as ethnicity, socio-economic status, level of urbanization, especially in populations where there is great heterogeneity of access to food, health and pressure resources for pathogens, as 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 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 [19]. In our three populations, the maximum height was lower than 185 cm, which could explain the linear but not curvilinear association 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 immunological condition.

Finally, in relation with sex differences, women reported lower health in average than men in all communities, which is concordant with reports and normative SF-36 data in other populations, and especially in younger people [e.g. 71,72]. These results could add support to the idea that height is a reliable signal of health in men [25], while for women it could reflect reproductive success [73] in terms of labor and birth, and to a lesser extend function as an indicator of health [74]. It has been seen that taller women experience fewer problem during this process, because of a lower risk of a mismatch between fetal head size and the size of the birth canal [74]. Nevertheless, this idea is only speculative and more studies comparing health, reproductive success and female height need to be done.

It is important to take into account that the mode of survey administration might be a limitation in our study, and it could have lead 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 of indigenous people. Nevertheless, it could also be reflecting the real health conditions in these 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 [46], 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 of the entire SF-36 survey, in both validated Spanish [50,53], and English versions [75], 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 linear mixed models. We found that although urban populations differ considerably from indigenous populations, the relations between height, waist circumference and self-perceptions of health were observed in the same direction for all populations.

The present study contributes with information that 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. 76], and height and waist interact to signal health, its evolutionary consequences, including its cognitive and behavioral 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 samples with both Westernized and non-Westernized lifestyles.

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Supporting Information

S1 File. HTML output for R Markdown. This file contains the script and output for all analyses, data manipulation and compilation, tables and figures. This file was created using R scripts in Markdown format (Rmd file) to promote transparency and ensure reproducibility.

S2 File. R Markdown source file for HTML output. R Markdown file used to generate S1 File.

S1 Table. Intraclass correlation of anthropometric characteristics measurements.

S2 Table. Descriptive statistics of measured variables of female participants.

S3 Table. Descriptive statistics of measured variables of male participants.

S4 Table. Correlations between measured variables for all participants

S5 Table. Correlations between measured variables for female participants

S6 Table. Correlations between measured variables for male participants

S7 Table. Results of separate linear mixed models testing effects of independent variables on self-reported health. Full table including standard errors and *t*-values.

S8 Table. ANOVA-like table with tests of random-effect terms.

S9 Table. Variance Inflation Factors of Model 3 predictors.

S10 Table. Variance Inflation Factors of the Final Model (Model 3 centered and rescaled) predictors.

S11 Table. Information criteria for Model 3 and Model 3 (centered and rescaled).

S1 Fig. Sexual dimorphism of height, waist and health for all samples (A) Self-perceived health. (B) Height. (C) Waist. Comparisons between female and male participants for each sample, were performed using *t*-tests, adjusted for multiple tests. **** $p < 0.0001$.

S2 Fig. Model diagnostics. (A) Residual distribution for each sample. (B) Linearity in each (single term) fixed factor. Centered and rescaled variables are identified by the suffix _cs.

S3 Fig. Single term predictor slopes. Slope of coefficients for each (single term) fixed predictor, against self-rated health (linear relationship between each model term and response). For Population, 1 = Indigenous, and 2 = Urban. For sex, 1 = female, and 2 = male. For simplicity, raw (instead of centered and rescaled) values of height and waist were used.

S4 Fig. Interaction between height and waist (interactive, animated 3D version). For simplicity, raw (instead of centered and rescaled) values of height and waist were used. Click and drag the plot to change its orientation. Scroll to zoom. In S1 File, where this figure is also included, you can also use the buttons below the figure to control the animation.