Scaling children's waist circumference for differences in body size

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Abstract

Objectives: Both waist circumference and body size (~~stature~~height) increase with age throughout childhood~~.~~, Hence, there is ~~thus~~ a need to scale waist circumference ~~for differences in body size/stature~~ in children to detect differences in adiposity status (e.g., between populations and different age groups), independent of body size/height.

Methods: Using 2 culturally different samples, 1 English (10-15.9 years n = 9471) and ~~1~~2 Colombian (14-15 years, n = 37948), for waist circumference (WC) to be independent of ~~stature~~height (HT), a body shape index was obtained using the allometric power law WC=a.HT^b. The model was linearized with a log-transformation, and multiple regression/ANCOVA used to estimate the height exponents for waist circumference having controlled for age, sex and any other categorical/population differences.

Results in both samples the power-law height exponent varied systematically with age. In younger pre-pubertal children (age 10-11 years), the exponent was approximately unity, suggesting that pre-pubertal children might be geometrically similar. In older children, the height exponent declined monotonically to 0.5 (i.e., HT$^{0.5}$) in 15+ year olds, similar to the exponent observed in adults. UK children's height-adjusted WC revealed a 'u' shaped curve with age that appeared to reach a minimum at peak-height velocity, different for boys and girls. Comparing the WC of two populations (UK versus Colombian 14-15 year old children) identified that the gap in WC between the countries narrowed considerably after scaling for ~~stature~~height.

Conclusions: Scaling children's WC for differences in ~~stature~~height using allometric modelling reveals new insights in the growth and development of children's WC, findings that might well have ~~been~~ be overlooked if body size/~~stature~~height had been ignored.

Key words: Allometric modelling, power law, geometric similarity, waist circumference, ~~stature~~height

Introduction.

Excess adiposity is a key modifiable risk factor for cardiovascular disease in children and young people (Expert Panel on Integrated Guidelines for Cardiovascular Health and Risk Reduction in Children and Adolescents, 2011). It is also associated with a range of other negative health outcomes in children including type 2 diabetes mellitus, hypertension, non-alcoholic fatty liver disease, obstructive sleep apnea, and dyslipidemia (Kumar, and Kelly, 2017). With over a third of UK children aged 10-11 being classified as overweight and obese (Health and Social Care Information Centre, 2014) and similar trends being observed internationally (National Obesity Observatory, 2016), monitoring and assessment of ~~weight~~adiposity status in children and young people has become important to effectively target interventions aimed at preventing or treating diseases related to excess body fatness. As a consequence valid measures of assessing ~~weight~~adiposity status are crucial. Due to their ease of administration and relatively low cost, anthropometric measures remain popular for the assessment of ~~weight~~adiposity status (Prentice, and Jebb, 2001; Daniels, et al., 2009). Body mass index (BMI) has, despite its shortcomings, historically been widely used for this purpose, although more recently there has been an emphasis on anthropometric measures of ~~weight~~adiposity status such as waist circumference or waist-to-height ratio (Nevill et al. 2017, In Press). Meta analytical data has suggested that ~~centralised~~ measures of centralised obesity are superior to BMI in detecting cardiovascular and cardiometabolic disease (Lee, et al., 2008; Browning, et al., 2010) and studies suggest that greater abdominal obesity is an independent risk factor in addition to BMI (Zhu, et al, 2002; Jannsen, et al., 2004). Waist-to-Height ratio (WHTR) has specifically been identified as superior to both BMI and waist circumference (WC) alone in identifying adult cardiometabolic abnormality (Ashwell, et al., 2012). Thus, considering or normalising for ~~stature~~height may also be necessary to better refine the use of anthropometric indices of ~~weight~~adiposity status. It is also important to note that, depending on the adiposity index that is employed and on what cut-off values are used, the extent of obesity prevalence differs, with BMI particularly underestimating the extent of the issue (McCarthy, et al., 2003; Griffiths, et al., 2012). Refining and better understanding the utility of anthropometric measures for the estimation of ~~weight~~adiposity status, particularly of children is therefore important. ~~Furthermore, given the published international variation in weight status (National Obesity Observatory, 2016), understanding if a measure is a stable measure across different international groups is important. In order to do this there is a need to consider the utility of different measures in a range of populations where there are different cultural, behavioural and nutritional practices and contexts which may predispose children in one country to be more overweight or obese than others.~~

Recently, Nevill et al (2017) used an allometric scaling approach in a sample of 4763 adults aged 20-69 years to explore the utility of WC and WHTR in explaining cardiometabolic risk. Their work identified a need to scale WC in adults to provide a better index associated with cardiometabolic risk in adults. They proposed a new anthropometric index: WC/height$^{0.5}$ which was found to be a stronger predictor of cardiometabolic risk compared to a range of other anthropometric indices of ~~weight~~adiposity status including BMI, WC and WHTR. The results of Nevill et al's recent work identify a need to scale waist ~~girth~~circumference to more accurately understand the association between ~~weight~~adiposity status and health related variables. The present study sought to extend this work and explore the applicability of the proposed WC/height$^{0.5}$ ratio in a pediatric sample. Children's WC grow~~s~~ naturally with ~~stature~~height and age so it is imperative to be able to scale their WC for differences in body size. This will then enable more accurate identification of factors associated with excessive waist ~~girth~~circumference as children grow into adulthood. This could then be used as a key tool in the assessment of ~~weight~~adiposity status for prevention and treatment purposes in instances where ~~weight~~adiposity status is important. The aim of this study was to examine the utility of allometric modelling to identity the most appropriate method of scaling waist ~~girth~~circumference in childhood to facilitate a comparison of ~~size~~height-adjusted waist ~~girth~~circumference between different age groups and across different populations known to vary in ~~stature~~height.

Materials and Methods

Study design and participants.

This study is based on secondary data analysis from two separate and independent samples drawn from two different countries; these being the United Kingdom and Colo~~u~~mbia that have contrasting levels of affluence, social economic status, nutrition as well as genetic factors that may well explain the differences in ~~and hence stature~~height. In both cases, institutional ethics approval and written informed consent were provided prior to any data collection. The Colombian sample consisted of children aged 14 to 15 years, whereas the UK sample was aged between 9 and 18 years.

Sample 1 comprised data taken from East of England Healthy Hearts Study. Comprehensive detail regarding the methods used are presented elsewhere (Voss and Sandercock, 2010). Following approval by the University of Essex ethical review committee, 9471 (10.0–15.9 year olds; Boys=5041, Girls= 4430) children were recruited from a structured convenience sample of 23 state schools. All data collection occurred between

2007 and 2009. Only state-run, comprehensive schools were sampled. Letters were sent to schools in the East of England region inviting them to participate in this study. Purposeful sampling was then used to select a representative mix of volunteer schools to take part in the study. The sample was selected to ensure that it had characteristics similar to the East of England in terms of rural (30%) or urban location (70%) and area-level deprivation. In England, 80% of the population live in urban areas, whereas the East has more rural areas. The East of England itself is also relatively affluent with a deprivation score of ~10% below the national average. Physical education (PE) is compulsory for all English school pupils until age 16. All pupils normally attending PE were potentially included in the study; exclusion criteria were the presence of known illness (such as underlying cardiomyopathy) and lack of parental or pupil consent. Schools provided consent for pupils to be tested and we used an additional opt-out approach to parental consent. Finally, verbal consent was required from each participant at a point of testing. This approach resulted in response rate of 98.2%.

Sample 2 consisted of data drawn from the combined 'Curriculum 40 x 40' and 'Prueba Ser' surveys administered by Bogota's District Secretary of Education in November 2015. These were cross-sectional surveys of 9th grade students recruited from public and private schools in all 20 'localidades' (municipalities) within the District Capital of Bogota (Cundinamarca Department, Andean Region of Colombia). The Study was approved by the Review Committee for Research in Human Subjects at the University of Rosario (Code N° CEI-ABN026-000262). All 9th Grade students attending participating schools were eligible for inclusion. The nature and purpose of the study were given to potential participants and their parents or guardians explaining that data would be available to the Colombian Health Authorities in accordance with the Law of Data Protection (Resolution 8430/93).

Procedures

The procedures used for data collection in both samples were identical and employed the same measurement techniques.

Anthropometric body-size measures

Participants' body mass and statureheight were measured to the nearest 0.1 kg (Seca Digital Scales Model 813; Seca Ltd. Hamburg, Germany) and 0.1 cm (Seca Portable

Stadiometer Model 213; Seca Ltd. Hamburg, Germany), respectively while wearing light clothing (T-shirts and shorts) and without shoes. Typical error measurement for mass and ~~stature~~height were <1%. WC was also assessed (to nearest 0.1 cm) using non-elastic anthropometric tape (Bodycare Products, Ltd. Southampton, UK for Sample 1 (UK), Ohaus 8004-MA for Sample 2 (Colombia)) at the midpoint between the last rib and the iliac crest. All anthropometric measures were made by trained, researchers who were the same sex as the participants. Intra-tester agreement of WC measures was ensured in training and typical error of measurements for WC was 1-2%. Anthropometric details are reported in Table 1 and Table 2 below for English and Colombian children respectively.

Table 1 and 2 about here

Statistical Methods

In adults, a simple body shape index for WC to be independent of ~~stature~~height (HT) was proposed (Nevill et al. 2016) using the allometric power law

$$WC = a.HT^b.\varepsilon, \qquad\qquad (1)$$

where a and b are the scaling constant and scaling exponents for the waist ~~girth~~circumference respectively, and ε is the multiplicative error ratio. Note that the multiplicative error ratio 'ε' assumes that the error will increase in proportion to body size, a characteristic in data known as heteroscedasticity that can be controlled by taking logarithms. Age and sex were incorporated into the model by allowing 'a' to vary for either sex and each age group (age categories 20-29, 30-39, …, 60+) to accommodate the likelihood that waist ~~girth~~circumferences may rise and then peak sometime during adulthood.

In children, the same model (1) is unlikely to be entirely satisfactory, due to the well-known changes in body shape that occur as children go through puberty. For this reason, we introduced the additional flexibility that the parameters 'a' AND 'b' were allowed to vary for both sex and each age group (≤10 y, 11, 12, 13, 14, ≥15 y). The model can be linearized with a log-transformation, and multiple regression/ANCOVA can be used to estimate the height exponent for WC having controlled for both age and sex.

Results: UK children

The mean (SE) WC (cm) for boys and girls by age groups are given in Figure 1. As children get older and taller, their WC increases monotonically although there is evidence that in girls, WC begins to plateau at the age of 14 y.

Figure 1 about Here

However, when we scale WC to accommodate for differences in the children's body size/height (Eq.1), the story appears to be quite different. The mean (SE) waist ~~girth~~circumference (log transformed) for boys and girls by age are given in Figure 2, having controlled for ~~stature~~height (also log transformed).

Figure 2 about Here

The allometric power-law model for WC (Eq. 1) identified significant height exponent associated with WC that varied with age groups (identified by a significant age group-by-~~stature~~height interaction; P<0.001), suggesting that to identify a body-shape index for WC to be independent of ~~stature~~height (HT), the ~~stature~~height exponent should vary systematically with age. Table 3 gives the ~~stature~~height (HT) exponents by age groups (also illustrated in Figure 3). Note that there was no sex-by-~~stature~~height interaction (P>0.05).

Figure 3 about Here

Results: Comparing UK and Colombian Children's waist ~~girth~~circumferences aged 14 and 15 years old

The mean (SE) WC (cm) for boys and girls for the UK and Colombian children aged 14 and 15 years old are given in Figure 4. UK children have greater WC (light grey) than their Colombian counter parts (dark grey). Also, boys have greater WC than girls irrespective of their country of origin.

Figure 4 about Here

However, when we scale WC to accommodate for differences in the children's body size/~~stature~~height (Eq.1), once again this conclusion needs to be modified. Because the Colombian children are shorter, in particular the girls, the WC (log transformed) for the Colombian boys and girls increases relative to their UK counterparts, and in the case of the Colombian girls' their adjusted WC ~~are~~ is now greater than the Colombian boys' adjusted WC.

Figure 5 about Here

The allometric power-law model for waist ~~girth~~circumference (Eq. 1) of the combined UK and Colombian children identified significant height exponent associated with waist ~~girth~~circumference that varied with age groups (identified by a significant age group-by-~~stature~~height interaction; P=0.004), suggesting that to identify a body-shape index for waist ~~girth~~circumference (W) to be independent of ~~stature~~height (HT), the ~~stature~~height exponent should vary with age. Table 4 gives the ~~stature~~height (HT) exponents by the two age groups.

Table 4 about here*

Discussion

The developmental growth in Children's absolute WC (cm) increases monotonically up to 14-15 years (see Figure 1). However, in relation to their body size/~~stature~~height, the ~~stature~~height adjusted differences in WC over this age range appears to follow a "u" shaped curve, with the minimum adjusted WC occurring at 12 years for girls and 14 years for boys (see Figure 2). We speculate that these minimums occur at an approximate age when the children's peak height velocity is likely to occur (Malina, et al., 2004).

In adults, the ~~stature~~height exponent required to render WC independent of ~~stature~~height (fitted using Eq. 1) was found to be b=.528 (SEE=.04) having controlled for both age and sex (Nevill et al. 2016). This appeared to be appropriate for all age groups (the analysis failed to identify an "age group"-by-"Log(height)" interaction). As a result, the most appropriate waist-to-~~stature~~height ratio to be independent of body size was confirmed to be WC divided by ~~stature~~height (HT$^{0.5}$) abbreviated to WHT.5R (Nevill et al., In Press). The new ratio WHT.5R was not only independent of body size but it was also the best anthropometric predictor of cardiometabolic risk (CMR), a single composite score derived from log

transformed z-scores of: Triglycerides + average blood pressure ((diastolic + systolic)/2) + glucose + HDL (*-1).

In children, the ~~stature~~height exponent varied significantly with age (see Table 1 and Figure 3). As with adults, the ~~stature~~height exponent was close to .5 in the older 15 year old children. However, in younger children, the exponent was greater, found to be approximately unity at age 11. These findings suggest that in younger children (11 y or less), the WC divided-by-~~stature~~height (HT) ratio (WHTR) is likely to be independent of body size, but in older children (15 or older) the waist divided by ~~stature~~height ($HT^{0.5}$) (WHT.5R) is a more appropriate ratio.

This systematic decline (from 11 to 15 years) in the ~~stature~~height exponent required to render waist ~~girth~~circumference independent of body size, is similar to that observed by Cole (1986) when exploring the most appropriate Mass (M)-to-~~stature~~height ratio (M/HT^{p}) associated with adiposity. Cole (1986) identified the height exponent to peak at age 11 (p=3, the Ponderal index (M/HT^{3})), but then to systematically decline to p=2 after puberty (i.e., BMI= M/HT^{2}).

Taking these findings together (i.e., the ~~stature~~height exponent of b=1 for waist in the current study and ~~stature~~height exponent of p=3 for body mass in Cole 1986), it would appear that pre-pubertal children aged 11 years are approximately geometrically similar, that is, when individual body components such as homologous muscles, hearts, lungs should have masses proportional to body mass (M), cross-sectional or surface areas proportional to $M^{0.67}$ and linear dimensions, such as heights or limb ~~girth~~circumferences, proportional to $M^{0.33}$. In somatotype terms, the 11 year old children's body shape could be described as "ectomorphic", that is, relatively tall, lean and linear since the reciprocal ponderal index (RPI=$height^{3}$/mass), is a key component used to calculate the somatotype "ectomorphy" (see Duquet and Carter (1996)). As children get older, go through puberty and reach adulthood, their body shape diversifies growing into a variety of different proportions of adiposity, bone and muscle mass, making ~~stature~~height a less reliable predictor of waist and body mass resulting in less steep ~~stature~~height exponents for waist (b=0.5) in Eq. 1 (see Figure 3) and body mass (p-=2) in Cole 1986.

The proposed method of scaling WC of children from different populations becomes particularly insightful when comparing the WC of UK and Colombian children. In absolute terms, the WC of UK children appear considerably greater than that of Colombian 14 and 15 year old children (see Figure 4). However, because Colombian children, in particularly the girls, are considerabl~~e~~y shorter than their UK counterparts and Colombian boys, the gap between the ~~stature~~height adjusted WC is considerably less (see Figure 5). Indeed the

Colombian girls' adjusted WC has increased to the extent that their mean exceeds the Colombian boys, having controlled for their relative differences in body size/~~stature~~height. The current study uniquely compared a sample of UK and Colombian children where data were collected using comparable methods. However, we acknowledge that the age range of the Colombian sample is narrower than that of the UK sample. This lack of alignment reflects the difficulty in collating identical samples from relatively large geographically and culturally diverse samples and should be considered when interpreting the findings of the present study.

In conclusion, as children grow into adults, their WC will also grow relative to their body size/~~stature~~height. Using allometric modelling, the power law $WC=a.HT^{b}$ identified the most appropriate ~~stature~~height exponent required to remove/adjust chidren's WC to be independent of body size/~~stature~~height, varied systematically with age. In younger pre-pubertal children (age 10-11 years), the exponent was approximately unity, suggesting that pre-pubertal children might be geometrically similar, but in older children the ~~stature~~height exponent declines monotonically to 0.5 (i.e., $HT^{0.5}$) in 15 year olds and older, similar to the exponent observed in adults (Nevill et, al. 2016). UK children's the ~~stature~~height-adjusted WC revealed a 'u' shaped curve with age, that would appear to reach a minimum at peak-height velocity, but different for boys and girls. Comparing the WC of two populations (UK versus Colombian 14-15 year old children) with contrasting levels of affluence, social economic status, nutrition and hence ~~stature~~height, identified that the gap in the ~~stature~~height adjusted WC narrowed considerably between the two countries. Indeed the much shorter Colombian girls' ~~stature~~height-adjusted WC were found to exceed the Colombian boys, having controlled for their relative differences in body size/~~stature~~height. Unlike Nevill et al (2016), this paper did not examine if the scaling approach presented here was associated with any health related risk factors. Given the findings presented in the current study a logical next step is to examine is allometrically scaling WC in pediatric populations is more strongly associated with health related risk factors than WC alone. In summary, scaling children's WC using allometric modelling reveals new insights in the growth and development of this important anthropometric indicator of ~~weight~~adiposity status that might otherwise be overlooked.

Perspectives

Recently, Nevill et al (In press) used allometric scaling and reported that the WC/height $^{0.5}$ ratio was more strongly related to cardiometabolic risk than BMI, or other anthropometric measures of centralised obesity in adults. WC grows naturally with ~~stature~~height and age in children. As a consequence scaling WC for difference in body size is important to enable

more accurate identification of factors associated with excessive waist ~~girth~~circumference as children grow into adulthood.

Using an allometric scaling approach in two, culturally distinct samples we identified the most appropriate method of scaling waist ~~girth~~circumference in childhood to facilitate a comparison of ~~size~~height-adjusted waist ~~girth~~circumference between different age groups and across different populations known to vary in ~~stature~~height. In younger pre-pubertal children (age 10-11 years), the exponent suggested that pre-pubertal children might be geometrically similar. In older children the ~~stature~~height exponent declined monotonically to 0.5 (i.e., $HT^{0.5}$) in 15 year olds and older, similar to the exponent observed in adults (Nevill et al., in press). When comparing the WC of the UK and Colombian populations, using the allometric scaling approach. Using such an approach is useful in better understanding the influence of growth and development on WC as an indicator of ~~weight~~adiposity status.

Conflict of Interest: None

Author Contributions: AMN, MJD, IL, GS analyzed the data and drafted the manuscript. AM, PD, GS, RR-V designed the study, directed implementation and data collection. AMN, MJD, IL, PD, RR-V and GS edited the manuscript for intellectual content and provided critical comments on the manuscript.

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Table 1 Sample size and anthropometric details (mean ±sd) of boys and girls from the East of England Healthy Hearts Study

Boys	N	WC (cm)	SD	~~Stature~~Height (cm)	SD	Mass (kg)	SD
age10	363	64.52	9.06	142.04	7.24	37.53	9.00
age11	1137	67.76	9.71	148.03	7.42	43.05	10.41
age12	1155	69.17	10.42	152.95	8.81	47.48	11.58
age13	979	71.81	10.02	160.50	9.41	53.40	12.23
age14	842	72.91	10.30	166.40	9.16	57.99	12.49
Age15	565	75.75	9.98	172.20	8.14	65.65	12.95
Total/means	5041	70.39	10.46	156.92	12.39	50.71	14.08
Girls							
age10	342	63.05	8.11	142.09	7.26	37.75	8.85
age11	1033	65.88	9.51	149.78	7.51	44.66	10.51
age12	1119	67.44	9.70	154.51	7.09	49.18	11.22
age13	902	69.50	9.83	158.10	7.04	52.94	10.88
age14	679	70.38	9.90	160.60	6.66	55.82	10.49
Age15	355	70.33	7.94	162.30	6.74	57.10	9.50
Total/means	4430	67.84	9.71	154.74	8.98	49.57	11.88

Table 2. Sample size and anthropometric details (mean ±sd) of boys and girls from the District Capital of Bogota, Colombia

Boys	N	WC (cm)	SD	~~Stature~~Height (cm)	SD	Mass (kg)	SD
age14	7667	69.075	6.9551	163.488	7.3197	163.488	7.3197
Age15	9959	69.931	6.7552	165.868	6.9071	165.868	6.9071
Total/means	17626	69.559	6.8559	164.831	7.1871	164.831	7.1871
Girls							
age14	9641	68.265	7.1620	156.221	5.6540	52.727	8.4900
Age15	10681	68.810	7.1295	156.524	5.7241	53.604	8.4298
Total/means	20322	68.551	7.1500	156.380	5.6928	53.187	8.4695

Table 3. The ~~stature~~height (HT) exponents ('b') and their 95% confidence intervals (CI) for the UK children by age groups.

	N	Baseline 'b'	Δb	SE	95% CI Lower	95% CI Upper	'b'
Age 10	704		.759	.131	.502	1.016	1.19
Age 11	2159		.648	.106	.440	.855	1.08
Age 12	2266		.531	.104	.326	.735	0.96
Age 13	1874		.239	.106	.030	.447	0.67
Age 14	1511		.284	.112	.065	.503	0.71
Age 15	918	.430	0	.091	.251	.608	0.43

Children age 15 years was used to estimate the baseline height scaling exponent b, and all other height exponents for different age groups were compared with it, indicated by Δb. The different height exponent values were obtained by introducing a height-by-age group interaction term into the ANCOVA (see statiatical methods).

Table 4. The ~~stature~~height (HT) exponents ('b') and their 95% confidence intervals (CI) for the combined UK and Colombian children by age groups.

	N	Baseline 'b'	Δb	SE	95% CI Lower	95% CI Upper	'b'
Age 14	18819		.059	.020	.019	.098	.627
Age 15	21450	.569	0	.015	.539	.598	.569

Children age 15 years was used to estimate the baseline height scaling exponent b, and the height exponents of children age 14 are compared with it, indicated by Δb. The different height exponent values were obtained by introducing a height-by-age group interaction term into the ANCOVA (see statiatical methods).
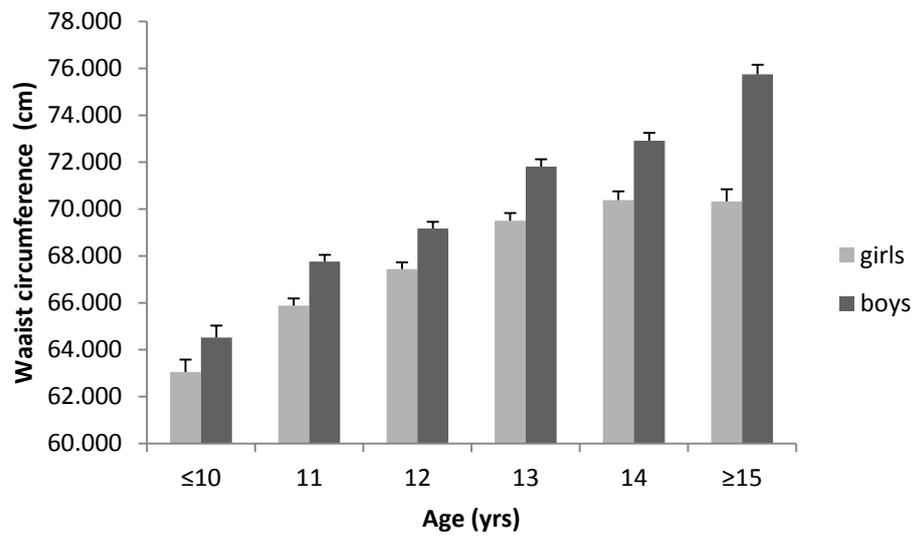
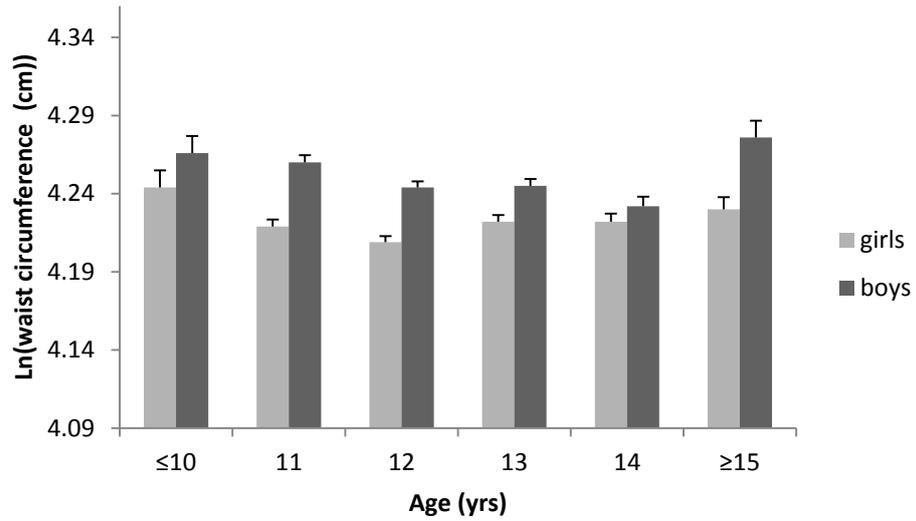Figure 1. The mean (±SE) waist circumference (WC) (cm) for the UK boys and girls by age groups

Figure 2. The mean (SE) waist circumference (WC, log transformed) for UK boys and girls by age group, having controlled for ~~stature~~height (also log transformed).
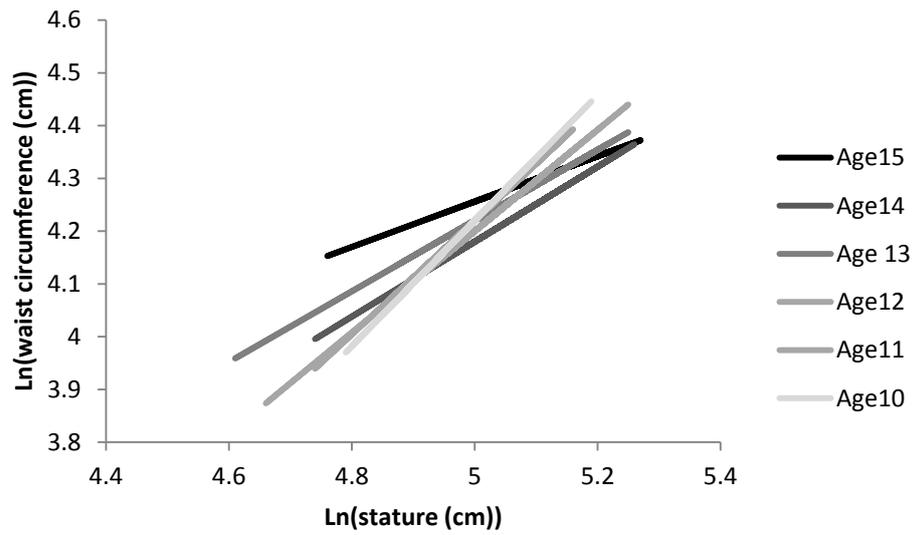
Figure 3. The fitted slope parameter for the ~~stature~~height exponents 'b' associated with waist ~~girth~~circumference (Eq. 1) by age group.
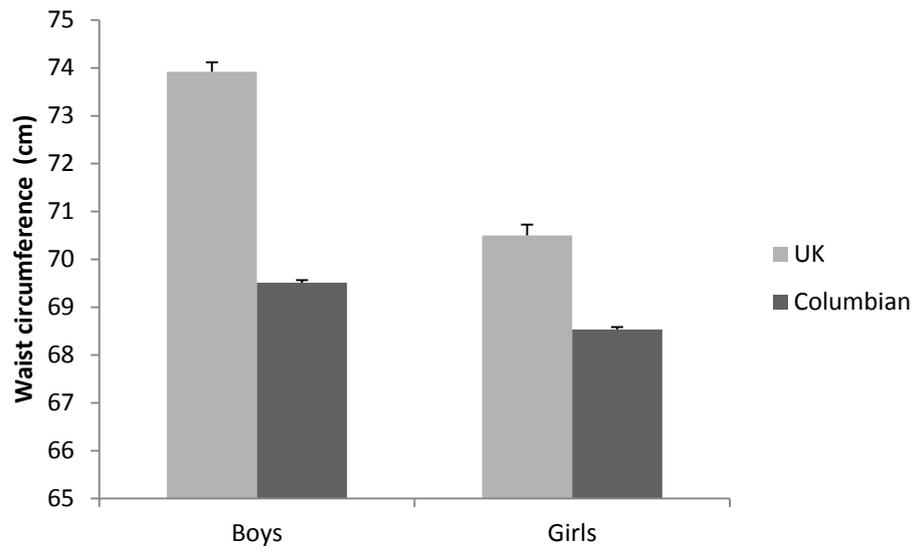
Figure 4. The mean (±SE) waist circumference (WC) (cm) comparing UK and Colombian boys and girls (unadjusted) aged 14 and 15 years old
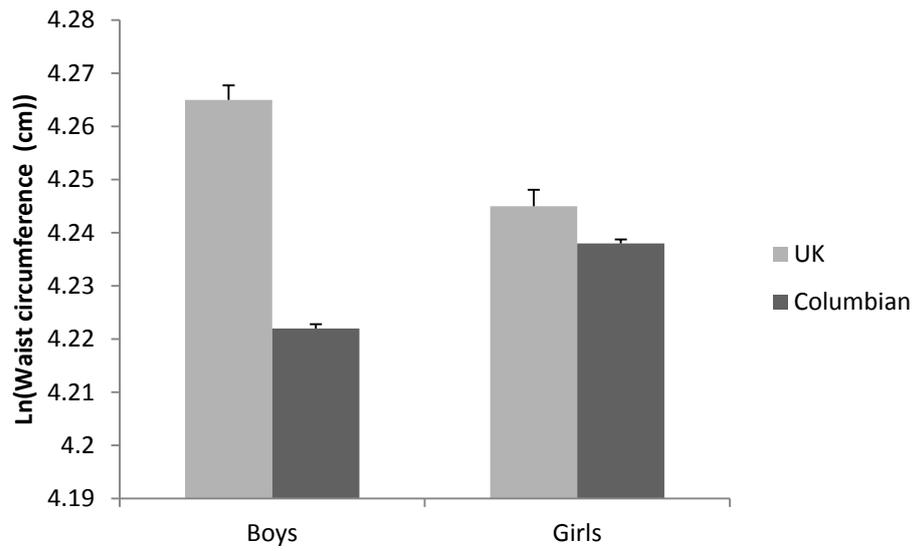
Figure 5. Comparing UK and Colombian Children's waist ~~girth~~circumferences (adjusted for ~~stature~~height) aged 14 and 15 years old