Journal of Theoretical Biology 256 (2009) 343–350

Contents lists available at ScienceDirect

Journal of Theoretical Biology

journal homepage: www.elsevier.com/locate/yjtbi

Patterns of subcutaneous fat deposition and the relationship between body mass index and waist-to-hip ratio: Implications for models of physical attractiveness

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ARTICLE INFO

Article history:
Received 31 March 2008
Received in revised form
25 September 2008
Accepted 25 September 2008
Available online 21 October 2008

Keywords:
Anthropometric indices
Health outcomes
Fertility
Female attractiveness
Body shape
Curvaceousness
Body mass index
Waist-to-hip ratio
Fat

ABSTRACT

Body mass index (BMI) and waist-to-hip ratio (WHR) are two widely used anthropometric indices of body shape argued to convey different information about health and fertility. Both indices have also been shown to affect attractiveness ratings of female bodies. However, BMI and WHR are naturally positively correlated, complicating studies designed to identify their relative importance in predicting health and attractiveness outcomes. We show that the correlation between BMI and WHR depends on the assumed model of subcutaneous fat deposition. An additive model, whereby fat is added to the waist and hips at a constant rate, predicts a correlation between BMI and WHR because with increasing fat, the difference between the waist and hips becomes smaller relative to total width. This model is supported by longitudinal and cross-sectional data. We parameterised the function relating WHR to BMI for white UK females of reproductive age, and used this function to statistically decompose body shape into two independent components. We show that judgements of the attractiveness of female bodies are well explained by the component of curvaceousness related to BMI but not by residual curvaceousness. Our findings resolve a long-standing dispute in the attractiveness literature by confirming that although WHR appears to be an important predictor of attractiveness, this is largely explained by the direct effect of total body fat on WHR, thus reinforcing the conclusion that total body fat is the primary determinant of female body shape attractiveness.

1. Introduction

Anthropometric measures of body shape are widely used as indicators of nutritional status, fertility and predictors of future health outcomes (Molarius and Seidell, 1998; Willett, 1998). Such measures are particularly valuable for epidemiological studies because being cheap and easy to acquire they are often available for large samples of people. Many different measures of body shape have been proposed and used over the years. Of these, the two indices most widely used are body mass index (or BMI, weight in kg/height in m^2), and the ratio of the circumference of the waist to the circumference of the hips (waist-to-hip ratio, or WHR). In terms of shape, BMI can be conceived of as an index of the width of a body once height has been standardised. Given that the main source of variation in width is adiposity, BMI is usually thought of as an index of percentage total body fat. Indeed, BMI correlates well with more direct estimates of percentage body fat such as those obtained via densitometry or dissection of cadavers (e.g. Clarys et al., 2005). In contrast, WHR is usually conceived of as an index of fat distribution, with high WHR indicating a less curvaceous body shape with high abdominal (also referred to as central) adiposity, and low WHR indicating a more curvaceous body shape with low abdominal adiposity. Abdominal adiposity is assumed to reflect individual differences in physiology orthogonal to total body fat (Després and Lemieux, 2006), and has consequently been argued to be useful in predicting a range of health and fertility outcomes (Hu et al., 2007; Koning et al., 2007; Wang et al., 2005; Zaadstra et al., 1993).

One area of research in which the predictive strengths of BMI and WHR have been extensively explored and debated is the analysis of what makes a woman's body shape attractive. Singh (1993) hypothesised that because WHR provides information about youthfulness, reproductive endocrinologic status and long-term health risks, there are good evolutionary reasons to expect WHR to be used in mate choice, and hence attractiveness judgements. However, when considered individually, both BMI

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0022-5193/$ - see front matter
doi:10.1016/j.jtbi.2008.09.041

and WHR explain a high percentage of the variance in judgments of attractiveness, leading to a debate over which, if either of these cues is the primary determinant of attractiveness. This question has been hard to resolve because WHR and BMI tend to be positively correlated in both the synthesised and natural stimulus sets used in attractiveness research (Tovée et al., 1999; Tovée and Cornelissen, 1999). Our aim in this paper is to propose a model to explain why WHR and BMI are correlated, and to use this to unravel their relative contributions to attractiveness judgments in Western observers.

The role of WHR in attractiveness is supported by studies that have asked observers to rate sets of either line-drawn figures of women's bodies (Furnham et al., 1997; Henss, 1995; Singh, 1993) or altered photographic images (Henss, 2000; Rozmus-Wrzesinska and Pawlowski, 2005; Streeter and McBurney, 2003). In these studies WHR is manipulated by altering the width of the waist of the figures. The results from such studies have lead to the conclusion that a WHR of approximately 0.7 is most attractive with higher (i.e. less curvaceous) WHRs being rated less attractive by Western observers. However, altering the width of the waist not only changes WHR, but also apparent BMI. As WHR rises, so does apparent BMI, making it impossible to say whether changes in attractiveness are due to WHR, BMI, or both (Tovée et al., 1999; Tovée & Cornelissen, 1999). An additional problem with these studies is that some of the manipulations may result in images outside the natural range of variation, and as a result lack ecological validity (discussed by Bateson et al., 2007).

In a recent attempt to address the criticisms of the above studies Singh and Randall (2007) asked observers to rate the attractiveness of pre- and post-operative photos of women who had plastic surgery to redistribute fat from around the waist to the hip and buttock regions. According to their data, this manipulation reduced post-operative WHR without significantly changing BMI. Post-operative photographs were judged as more attractive than pre-operative photographs, leading Singh and Randall to conclude that, "WHR is a key determinant of female attractiveness, independent of BMI". However, this result is not as compelling as it may at first appear. The view of the women in the images was restricted to a back or oblique view of their lower torso and upper thighs only. So, given that the relative size of the waist and hips was the only information available to observers and height was impossible to assess, it is perhaps not surprising that their preferences were affected by WHR. The question remains as to how these women would have been rated if the whole body had been visible to observers.

To circumvent the above problems with unnaturalistic stimuli, a number of studies have used sets of unaltered photographs depicting the whole bodies of real women (e.g. George et al., 2008; Smith et al., 2007a; Swami and Tovée, 2006, 2007a, b; Swami et al., 2007a, b). Analysis of the attractiveness ratings of such image sets by Western observers shows that although individually, both WHR and BMI are significant predictors of attractiveness, when both factors are entered into a multiple regression model BMI explains the majority of the variance in attractiveness, with a BMI of around 20 kg/m^2 being optimally attractive. The proportion of the variance explained by WHR, once that due to BMI has been accounted for, is negligible.

However, even these analyses are difficult to interpret, because BMI and WHR are often correlated. This has been repeatedly shown in large-scale health surveys. For example, the Health Survey for England (Health Survey for England, 2003), which includes directly obtained measurements from 2429 Caucasian women of reproductive age (16–45) ranging in BMI from around 15–50, shows a correlation between BMI and WHR of 0.46. For studies of attractiveness, this correlation raises the problem of collinearity amongst explanatory variables, and begs the question of whether WHR or BMI is the primary cue used in attractiveness judgements.

We propose an explanation for why changes in total body fat would be expected to cause a correlation between WHR and BMI. Our explanation is based on a model of fat deposition that is supported by a range of empirical data. Finally, we use empirical data from the Health Survey for England (2003) to parameterise our model relating WHR to BMI, and use the resulting equation to separate out the effect of total body fat on body shape from any independent variation in body shape not attributable to total body fat.

2. Modelling fat deposition

Fig. 1 shows two grey schematic torsos (skeleton 1 and skeleton 2) with the subcutaneous fat removed. The two torsos vary in the proportions of their musculoskeletal configuration (exaggerated for the purposes of illustration). Skeleton 1 has a wider waist and narrower hips than skeleton 2, so that radius $Ws_1 >$ radius Ws_2, and radius $Hs_1 <$ radius Hs_2. Thus skeleton 1 is less curvaceous than skeleton 2 with a higher WHR. The thicker lines either side of each skeleton represent the visible torso profiles once subcutaneous fat has been overlaid using one of two models of fat deposition, either multiplicative or additive, explained in detail below.

Conceptually, the multiplicative model produces an equivalent effect to horizontally stretching a 2D image of a body, a technique frequently used to simulate versions of the same body with a range of different BMIs (e.g. Craig et al., 1999; Guaraldi et al., 1999; Winkler and Rhodes, 2005). In the multiplicative model, the radii (Ws'_1, Ws'_2, Hs'_1 and Hs'_2) of the visible waist and hip circumferences, are derived by multiplying the corresponding musculoskeletal waist and hip radii (i.e. Ws_1, Ws_2, Hs_1 and Hs_2) by a constant, k, assumed to increase linearly with total body fat. Fig. 2a demonstrates how waist and hip circumferences increase as a function of k under this multiplicative model. Both functions are linear, but the rate of increase of the hip circumference is higher than that of the waist circumference, resulting in the difference between the waist and hips increasing with increasing k. Under the multiplicative model,

$$\mathrm{WHR} = Ws_n.k/Hs_n.k \tag{1}$$

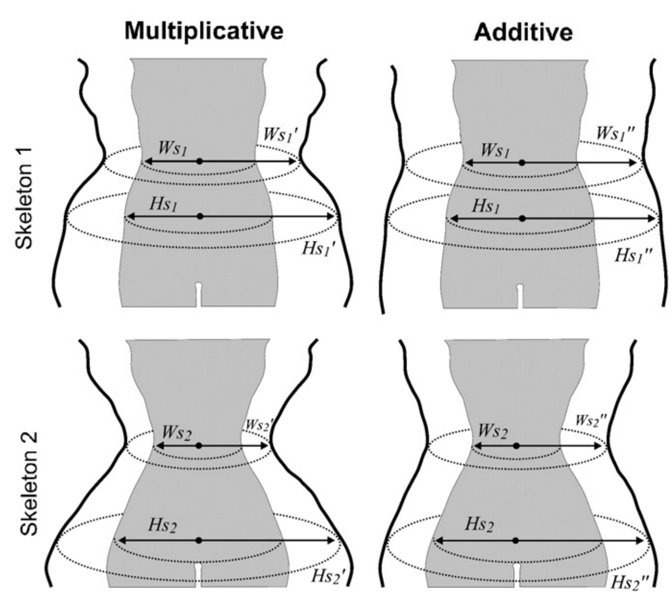

Fig. 1. A schematic to illustrate the multiplicative and additive models of fat deposition. See text for details.

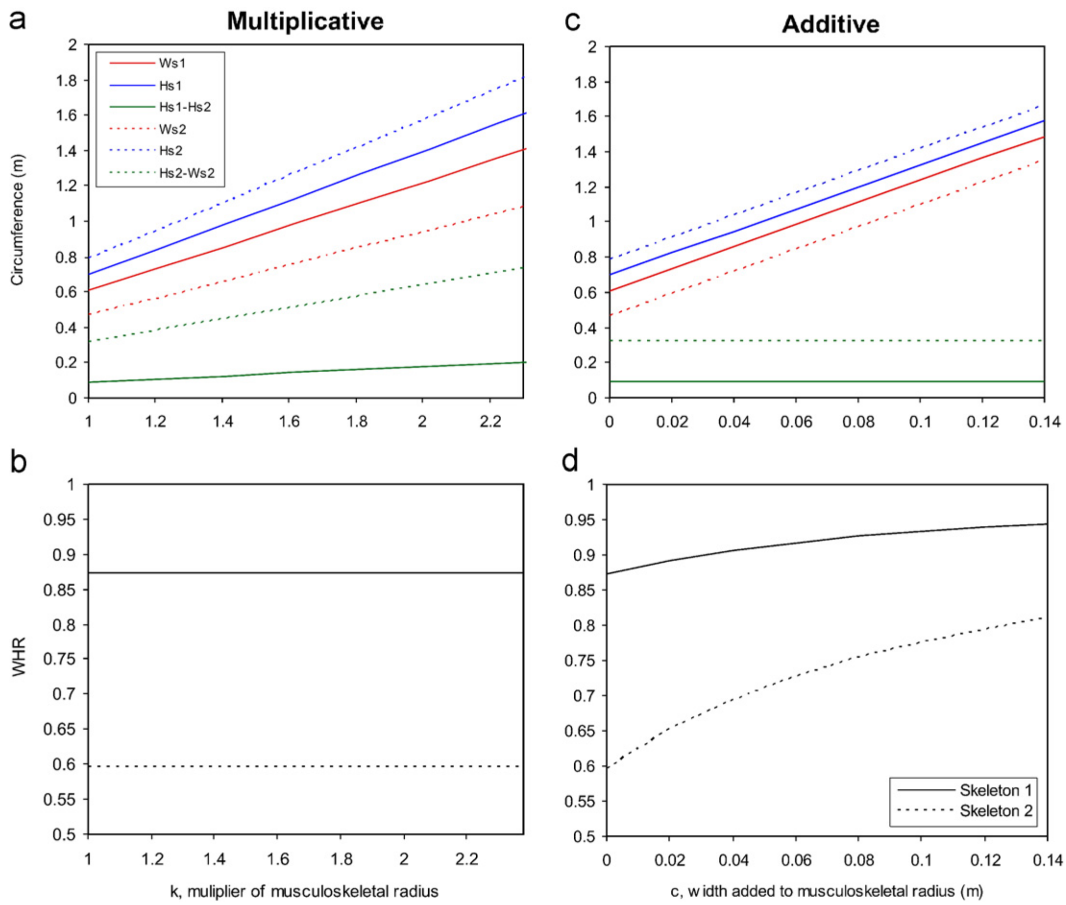

Fig. 2. Predictions from the multiplicative and additive models for the relationship between body weight (*x*-axes), waist and hip circumferences (a and c) and waist-hip ratio (b and d). The musculoskeletal waist and hip radii for Skeleton 1 and Skeleton 2 (i.e. Ws_1, Ws_2, Hs_1 and Hs_2) are: 0.0969, 0.0745, 0.111 and 0.125, respectively. These values were chosen to represent plausible extremes, and were measured from individuals with a body mass index (BMI) in the range 11–13, in whom we assume minimal total body fat (data reported earlier in Tovée et al., 1999). Parameter *c* took the range 0–0.14 m; these values were based the difference between the maximum and minimum waist/hip circumferences reported in the Health Survey for England (2003) dataset. Parameter *k* took the range 1.00–2.30; these values were chosen to give a similar range of circumferences to those given by parameter *c*.

and the functions relating WHR to k for skeletons 1 and 2 are shown in Fig. 2b. From these plots, it can be seen that WHR is independent of k for the multiplicative model, and is solely determined by the underlying musculoskeletal proportions.

In contrast, for the additive model, the radii (Ws''_1, Ws''_2, Hs''_1 and Hs''_2) of the visible waist and hip circumferences are calculated by adding a constant, c, to the corresponding musculoskeletal waist and hip radii. As with the k above, c is assumed to increase linearly with total body fat. Fig. 2c demonstrates how waist and hip circumferences increase as a function of c under this additive model. As with the multiplicative model, both functions are linear, but the rate of increase of the waist and hip circumferences are identical, resulting in the difference between the waist and hips being constant and thus independent of c. Under the additive model,

$$\mathrm{WHR} = (Ws_n + c)/(Hs_n + c) \tag{2}$$

and the resulting relationships between WHR and c for skeletons 1 and 2 are shown in Fig. 2d. Under the additive model, WHR increases as a monotonic, decelerating function of c. Thus, with simple assumptions about how subcutaneous fat is deposited, the additive model can account for why BMI and WHR are correlated. Indeed, this model predicts that changes in BMI will result in correlated changes in WHR given a fixed underlying frame. The additive model additionally predicts that the form of the function relating WHR to BMI should be monotonically increasing and decelerating.

The two models presented above are in fact just two special cases from a whole family of models describing how the circumferences of the waist and hips increase with overall weight gain. Longitudinal studies of individuals gaining and losing weight show that the thickness of subcutaneous fat is well described as a linear function of weight that is independent of the direction of weight change (Garn and Harper, 1955; Garn et al., 1987). However, the regression equations derived for different body areas differ in both slope and intercept. Our multiplicative model describes the case in which the slopes for the waist and hips differ (slope is higher for the hips) and both intercepts are zero; whereas our additive model describes the case for which the slopes for the waist and the hips are identical, but the intercepts differ (the intercept for the hips is higher). Clearly any combination of slopes and intercepts is theoretically possible, and in the Appendix we derive the general conditions under which different relationships between WHR and weight (BMI) are expected. A positive relationship between WHR and weight is predicted in approximately half of the parameter space, whereas the flat relationship occurs only under a much more restricted range of parameter values of which the multiplicative model is one particular case.

3. Empirical support for the additive model

In order to establish whether the multiplicative or additive model is a better description of fat deposition ideally we need longitudinal data on how subcutaneous fat thickness in different body areas (specifically hips and waist) changes as a function of individual body weight. These data have been obtained by Garn et al. (1987), who report skinfolds for different body sites, including abdominal and iliac, in women gaining and losing weight. However, sadly the published report gives only the slopes of the regressions relating skinfold thickness to weight, and although these slopes are very similar (1.03 and 1.08 for abdominal and iliac, respectively), supporting our additive model, without the intercepts there is insufficient information to allow us to predict the relationship between WHR and BMI (see Appendix for details). Caan et al., 1994 report waist circumference, hip circumference and WHR as a function of weight change in white women gaining or losing weight. As above, they report similar slopes for the regressions relating waist and hip circumference to weight change (0.86 and 0.81, respectively). Additionally, as predicted by our additive model, their data confirm a weak, but significant positive correlation between weight change and WHR.

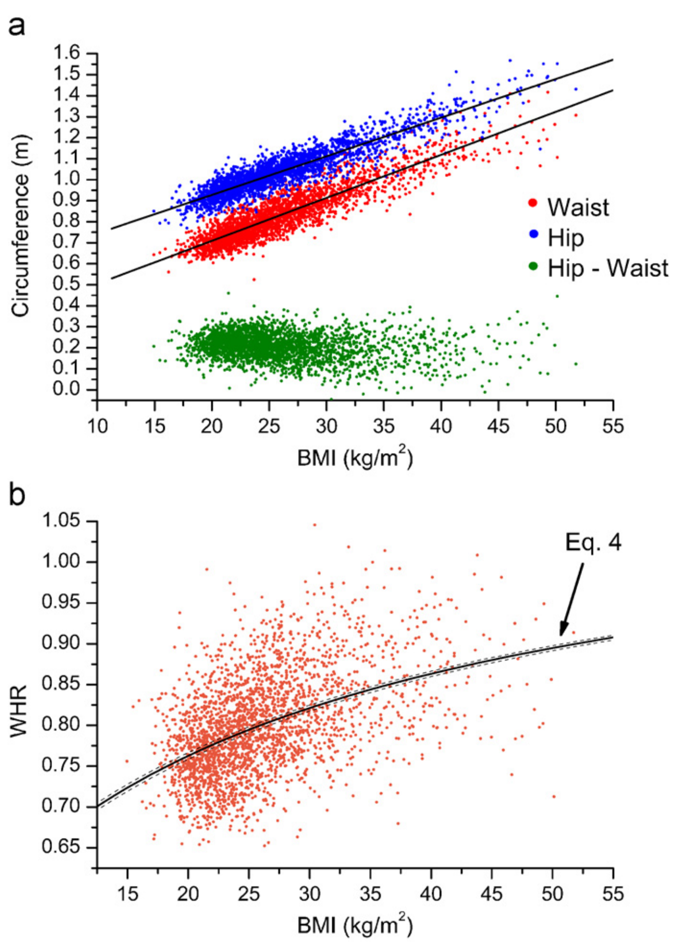

Fig. 3. (a) Overlaid scatterplots of waist and hip circumference and the difference between them as a function of body mass index (BMI). Solid lines represent simple regressions expressing waist and hip circumferences as functions of BMI. The respective equations are: Waist = 2.045.BMI+30.041 and Hip = 1.839.BMI+56.107. The data were obtained from the Health Survey for England (2003) and represent 2429 white women of reproductive age (16–45) with BMI < 55; (b) scatterplot of waist hip ratio (WHR) as a function of BMI from the above HSE 2003 data set. The solid line represents the values of WHR that we would expect for each value of BMI, based on the additive model, according to the equation: $\mathrm{WHR_{BMI}}$ = (2.057.BMI+29.670)/(1.842.BMI+56.004). The dashed lines represent the 95% confidence limits for the model.

A less direct approach to distinguishing the multiplicative and additive models is to use biometric data from individuals of different BMIs. As predicted by the additive model, data from the Health Survey for England (2003) demonstrate that over the full BMI range the difference between waist and hip circumferences is approximately constant (Fig. 3a). We can express waist and hip circumferences in terms of their respective regressions on BMI; R-square values for the regression equations are 0.81 and 0.84, respectively. An estimate of the relationship between WHR and BMI can therefore be expressed as follows:

$$\mathrm{WHR} = (m_{\mathrm{waist}} \cdot \mathrm{BMI} + c_{\mathrm{waist}})/(m_{\mathrm{hip}} \cdot \mathrm{BMI} + c_{\mathrm{hip}}) \tag{3}$$

Using the Health Survey for England (2003) data to parameterise Eq. (3) gives the following function for white UK women of reproductive age:

$$\mathrm{WHR} = (2.057 \cdot \mathrm{BMI} + 29.670)/(1.842 \cdot \mathrm{BMI} + 56.004) \tag{4}$$

95% confidence intervals for the regression coefficients and intercepts are: $m_{\mathrm{waist}} = 2.036–2.077$; $c_{\mathrm{waist}} = 29.133–30.207$; $m_{\mathrm{hip}} = 1.826–1.858$; $c_{\mathrm{hip}} = 55.570–56.438$.

The curve corresponding to Eq. (4), with its 95% confidence limits, is shown overlaid on the empirical data in Fig. 3b. In support of the additive model, and contrary to the predictions of the multiplicative model, WHR is a monotonically increasing, decelerating function of BMI.

Therefore, in summary both longitudinal and cross-sectional data support our additive model: as BMI increases waist and hip circumferences grow linearly with similar slopes, and WHR grows non-linearly as a decelerating function.

4. Application to attractiveness research

Tovée et al. (1999) asked 40 undergraduates to rate the attractiveness of unaltered colour photographs of 50 women ranging in BMI from approximately 11–47 and WHR from 0.68 to 0.90. The Pearson correlation between BMI and WHR in this image set is $r = 0.62$, $p < 0.0001$ (Fig. 4a).

If the additive model of fat deposition described above is correct, then in order to separate out the contributions of total body fat and curvaceousness to attractiveness judgements in this data set, it is necessary to statistically separate the effects on body shape and lower body curvature due to total body fat ($\mathrm{WHR_{BMI}}$) from those which are not attributable to total body fat ($\mathrm{WHR_{NONBMI}}$). $\mathrm{WHR_{NONBMI}}$ will reflect individual differences in underlying musculoskeletal proportions, hormonally mediated patterns of fat deposition and possibly genetically determined individual variation in fat deposition across different body compartments. The values of WHR given by Eq. (4) correspond to $\mathrm{WHR_{BMI}}$, whereas the residuals from this model correspond to $\mathrm{WHR_{NONBMI}}$. For the Health Survey for England (2003) dataset, the fitted values ($\mathrm{WHR_{BMI}}$) and residuals ($\mathrm{WHR_{NONBMI}}$) are extremely well decorrelated ($r = 0.02$, $p = 0.3$), and therefore ideal for multivariate analysis.

To apply this approach to the reanalysis of the data from Tovée et al. (1999), we used Eq. (4) to compute $\mathrm{WHR_{BMI}}$ for each image using the known BMI of the woman in the photograph. We then subtracted $\mathrm{WHR_{BMI}}$ from the measured WHR of each woman to compute $\mathrm{WHR_{NONBMI}}$. Fig. 4b confirms that $\mathrm{WHR_{BMI}}$ and $\mathrm{WHR_{NONBMI}}$ are uncorrelated. In order to stabilise the variance of $\mathrm{WHR_{BMI}}$, $\mathrm{WHR_{NONBMI}}$ and mean attractiveness values for multivariate analysis, we converted these variables to z-scores (Altman, 1991). The relationship between attractiveness and $\mathrm{WHR_{BMI}}$ as well as between attractiveness and $\mathrm{WHR_{NONBMI}}$ is

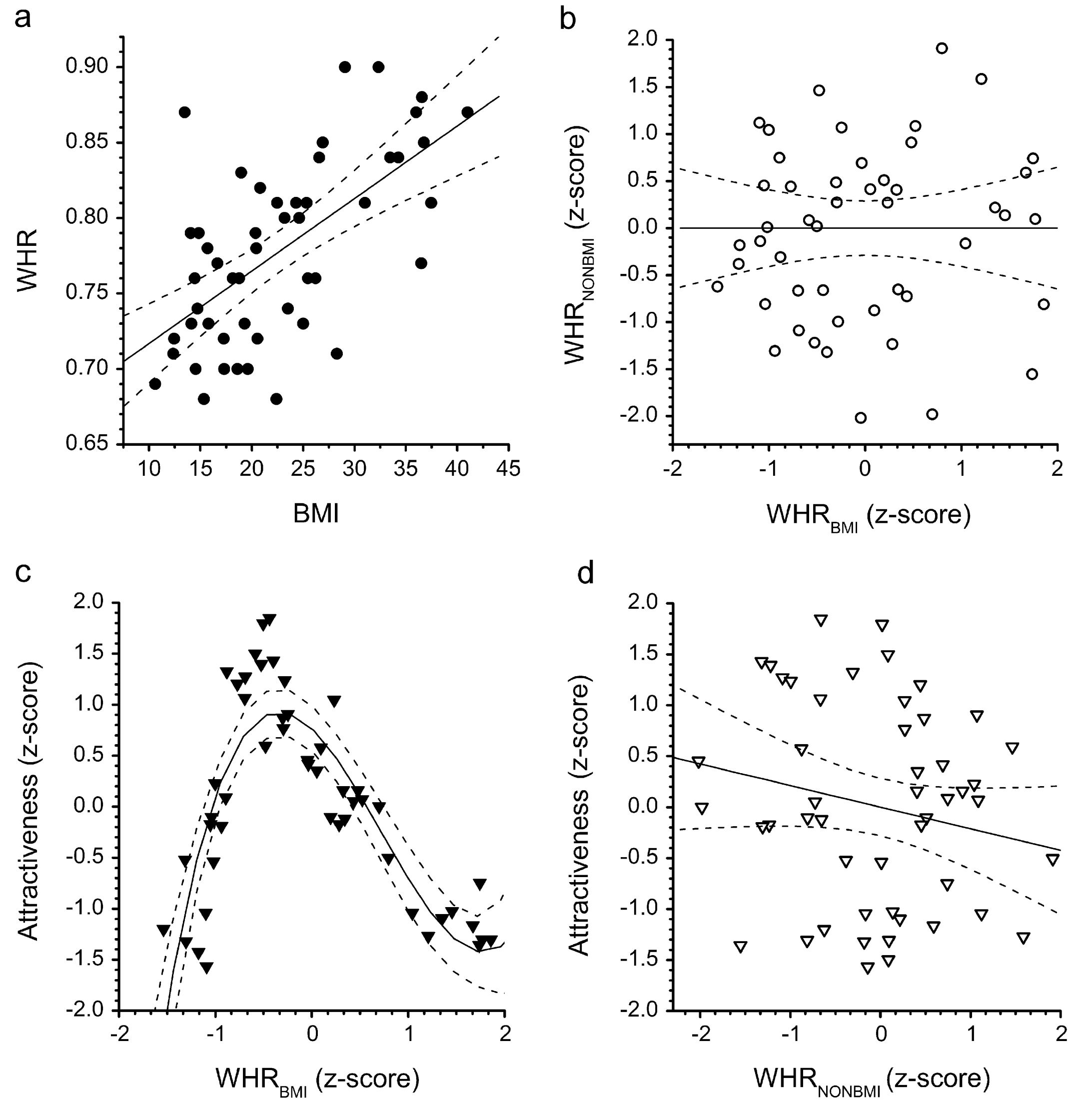

Fig. 4. Scatterplots of: (a) waist hip ratio (WHR) as a function of body mass index (BMI), (b) WHR_{NONBMI} as a function of WHR_{BMI}, (c) attractiveness as a function of WHR_{BMI}, and (d) attractiveness as a function of WHR_{NONBMI}. Solid lines represent regression between *x*- and *y*-axis variables. Dotted lines represent 95% confidence intervals.

shown in Figs. 4c and d. We used multiple polynomial regression to model the contributions of WHR_{BMI} and WHR_{NONBMI} to the prediction of attractiveness ratings. The full model explained 73.35% of the variance in attractiveness ratings ($F_{4,45} = 31.8$, $p < 0.0001$). It is: $y = -0.16x_1 + 189.9x_2 - 357.6x_3 + 167.6x_4$, where y is predicted attractiveness and x_1, x_2, x_3 and x_4 are WHR_{NONBMI}, WHR_{BMI}, WHR^2_{BMI} and WHR^3_{BMI}, respectively. The unique variance accounted for by WHR_{BMI} is 68.00%, while that for WHR_{NONBMI} is 2.33% and was not significant at $p < 0.05$.

Table 1 compares the outcome of fitting a multiple regression with WHR_{BMI} and WHR_{NONBMI} as predictors (described above) with that of the previously used approach of fitting a multiple regression with BMI and WHR as predictors. In addition to the Tovée et al. (1999) data set, we also include the results of applying these two approaches to data from three other previously published image sets. Although the correlation between BMI and WHR is much higher in the Tovée et al. (1999) data set than the other three, in all four data sets the two techniques for modelling attractiveness produce similar results with the component of shape attributable to BMI explaining more of the variance in attractiveness ratings. It is interesting to note that in all cases WHR_{BMI} explains more of the variance than BMI.

5. Discussion

We have proposed an explanation for the observed positive relationship between WHR and BMI based on a biologically plausible additive model of fat deposition. This model assumes that fat is deposited at a constant rate on fixed musculoskeletal frames whose waist-to-hip proportions vary from one individual to the next. The assumptions underlying this additive model are supported by both longitudinal and cross-sectional measurements from real bodies showing that, on average, waist and hip circumferences are linearly related to BMI, and that the difference between waist and hip circumference is approximately constant over a wide BMI range. The additive model of fat deposition predicts a positive (albeit decelerating) relationship between WHR and BMI, because as bodies become wider (i.e. higher BMI), the constant difference between the waist and hips becomes smaller relative to total width, and thus bodies become less curvaceous (i.e. higher WHR). As expected, this relationship between WHR and BMI is also seen in data from real bodies. We used the data from real bodies to parameterise our model, and yield an equation that allows us to predict the expected WHR for white UK women of reproductive age.

Table 1
Comparison of two different approaches to modeling the effects of BMI and WHR on attractiveness judgments for four different data sets.

Study	Number of images	BMI range	WHR range	Correlations		Multiple regression					
						With BMI and WHR			With WHR_{BMI} and WHR_{NONBMI}		
				BMI v WHR	WHR_{BMI} v WHR_{NONBMI}	Total variance	Unique % variance for BMI	Unique % variance for WHR	Total variance	Unique % variance for WHR_{BMI}	Unique % variance for WHR_{NONBMI}
Tovée et al., 1999	50	11.00–47.00	0.68–0.90	0.62	−0.22	75.63	62.50	1.61	73.35	68.00	2.33
Akira Gomi images	93	16.60–24.2	0.62–0.87	0.17	−0.10	18.36	14.75	1.51	17.87	17.25	1.48
Tovée et al., 2002	60	18.00–25.80	0.66–0.84	0.14	−0.22	29.05	24.58	1.98	29.02	28.98	1.94
Smith et al., 2007a	43	18.42–26.60	0.64–0.84	0.14	−0.23	56.69	48.62	3.29	55.84	55.83	3.11

An important consequence of our model is that it suggests a novel, theoretically justifiable method for statistically decomposing measured WHR into two independent components: WHR explained by overall fatness (WHR_{BMI}) and residual curvaceousness not explained by overall fatness (WHR_{NONBMI}). We used this method to revisit the question of the relative contributions made by BMI and WHR to the attractiveness of female body shape (Singh and Randall, 2007; Tovée et al., 1999). To partial out the contributions to attractiveness judgements of WHR_{BMI} from WHR_{NONBMI}, we used our model (Eq. (4)) to decompose the WHR measurements from the dataset in Tovée et al. (1999) into WHR_{BMI} and WHR_{NONBMI}, and explored the relationship between each of these variables and the reported attractiveness ratings. We found that while WHR_{BMI}, which corresponds to the effects on body shape due to additive addition of body fat, explains a significant proportion of the variance in attractiveness judgements, WHR_{NONBMI}, which corresponds to other effects on body shape not attributable to overall fatness, has no significant role in accounting for attractiveness. We therefore conclude that WHR has little explanatory value in attractiveness judgments over and above what it reveals about total body fat. This conclusion is strengthened by our demonstration that the same pattern is found for three other previously published data sets based on different sets of images.

Although the above conclusion is the same regardless of whether BMI and WHR or WHR_{BMI} and WHR_{NONBMI} are used as predictors (see Table 1) we believe that the latter approach is preferable for the following reasons. First, because we have shown that there are underlying reasons to expect WHR and BMI to be correlated, it makes sense to use a method that eliminates this potential source of colinearity among explanatory variables. Second, it clarifies the source of the dispute about whether BMI or WHR is the primary determinant of attractiveness: WHR is an important predictor of attractiveness judgments but only that component of it that is directly attributable to overall body fat; residual curvaceousness not attributable to BMI has little or no role in predicting attractiveness judgments.

The above conclusions are supported by two other recent studies from our lab. The first described the subtle variations in body shape not captured by BMI and WHR in 60 front-view, whole-body photographs of real women by conducting a principal components analysis on the waveforms generated by plotting the width of the bodies at 31 equally spaced anatomical positions from the hips to the shoulders (Tovée et al., 2002). This analysis shows that female body shape is described by four independent principal components, the first of which (PC1) represents body width, and corresponds almost exactly to the shape changes assumed by our additive fat deposition model (see Smith et al. (2007b); Fig. 1). PC1 is highly correlated with both BMI and attractiveness ratings, but not significantly correlated with WHR. PCs 3 and 4 both correlate significantly with WHR, but neither explains significant variance in attractiveness ratings (Tovée et al., 2002). The second study used skinfold thickness measures from 43 women to estimate percentage body fat, and found this to be the best predictor of attractiveness judgements made on colour video clips showing the whole body rotating through 360° (Smith et al., 2007a). Again, there is no significant correlation between WHR and attractiveness ratings in this study. In summary therefore, studies using full-length, unaltered bodies of real women show that the primary determinant of physical attractiveness is overall body fat, and there is no evidence that WHR has any additional role in explaining attractiveness judgments.

It is important to mention a limitation of the specific model presented in this paper. The equation we derive relating WHR to BMI (Eq. (4)) is based on white, Western women of reproductive age included in the Health Survey for England (2003). Since patterns of fat deposition are known to differ substantially between people of different age, sex and race (e.g. Wells et al., 2008) Eq. (4) should only be used to derive WHR_{BMI} and WHR_{NONBMI} for white Western women of reproductive age. To extend our method for use with data from subjects not within this group it would be necessary to re-parameterise Eq. (3) with anthropometric data from an appropriate sample.

Although our primary concern in this paper has been the clarification of the relationship between WHR, BMI and attractiveness judgements, the technique we propose for decomposing measured WHR into the WHR explained by overall fatness and residual curvaceousness potentially has much wider applications. Due to their ease of measurement, anthropometric indices such as BMI, WHR and waist circumference (WC) are widely used in medicine to assess risk factors for a range of common medical problems including infertility, cardiovascular disease and diabetes. However, there is still considerable debate over which single index is the best predictor, and specifically whether WHR or WC provides the better estimate of abdominal adiposity (Molarius and Seidell, 1998; Sargeant et al., 2002; Wang et al., 2005; Zhou, 2002). It would be interesting to explore whether the predictive power of either WHR or WC could be improved by using the techniques we have described to partial out the effects of abdominal adiposity from overall obesity.

Acknowledgements

We thank the Wellcome Trust (PLC) and the Royal Society (MB) for financial support.

Appendix

The relationships between hip (h) and waist (w) circumferences and weight (x) can both be described by straight-line functions of the form

$$h = ax + b \tag{A1}$$

$$w = cx + d \tag{A2}$$

where a, b, c and d are constants representing the slopes and intercepts.

Thus, waist hip ratio can be written

$$\frac{w}{h} = \frac{cx + d}{ax + b} \tag{A3}$$

The slope of Eq. (A3) can be found by differentiating with respect to x

$$\frac{d(w/h)}{dx} = \frac{c(ax+b) - a(cx+d)}{(ax+b)^2} = \frac{bc - ad}{(ax+b)^2} \tag{A4}$$

Function (A3) is independent of x when

$$\frac{bc - ad}{(ax+b)^2} = 0 \tag{A5}$$

For expression (A4) to equal zero, the numerator ($bc-ad$) must equal zero, which will only be true when the condition $bc = ad$ is met. This situation is captured by our multiplicative model in which b and d are both equal to zero, and thus $bc-ad = 0$. The denominator of Eq. (A4) is a squared term and will therefore always be positive, meaning that the sign of the slope will be determined by the sign of numerator, and specifically the relative magnitudes of bc and ad. If $bc>ad$, then the function relating WHR to weight will be positive. This situation is captured by our additive model in which because $c = a$ and $b>d$ the slope is positive. Alternatively, if $bc<ad$, then the function relating WHR to weight will become negative (a situation not captured by either of our models, but nonetheless theoretically possible). These conditions are summarised graphically in Fig. 5.

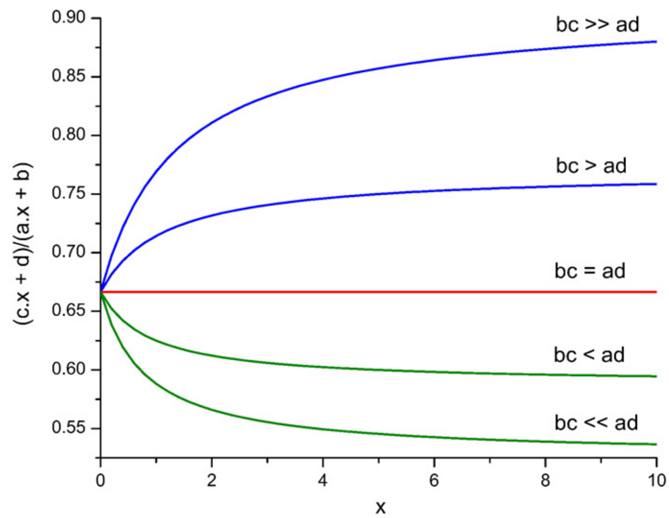

Fig. 5. Series of curves illustrating $(w/h) = (cx+d)/(ax+d)$ (Eq. (A3)) as a function of x for fixed values of c, b and d, and varying parameter a.

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