Body mass index: a measure of fatness or leanness?

BY ALAN M. NEVILL

School of Sport and Exercise Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT

AND ROGER L. HOLDER

School of Mathematics and Statistics, University of Birmingham, Edgbaston, Birmingham B15 2TT

(*Received 8 December 1993 – Revised 20 May 1994 – Accepted 17 August 1994*)

The relationship between body fat and stature-adjusted weight indices was explored. Assuming the term height^2 is a valid indicator of a subject's lean body mass, height^2/weight was shown to be an accurate measure of percentage lean body mass and, as such, a better predictor of percentage body fat than the traditional body mass index (BMI; weight/height^2). The name, lean body mass index (LBMI), is proposed for the index height^2/weight. These assumptions were confirmed empirically using the results from the Allied Dunbar National Fitness Survey (ADNFS). Using simple allometric modelling, the term height^p explained 74% of the variance in lean body mass compared with less than 40% in body weight. For the majority of ADNFS subjects the fitted exponent from both analyses was approximately p = 2, the only exception being the female subjects aged 55 years and over, where the exponent was found to be significantly less than 2. Using estimates of percentage body fat as the dependent variable, regression analysis was able to confirm that LBMI was empirically, as well as theoretically, superior to the traditional BMI. Finally, when the distributional properties of the two indices were compared, BMI was positively skewed and hence deviated considerably from a normal distribution. In contrast, LBMI was found to be both symmetric and normally distributed. When height and weight are recorded in centimetres and kilograms respectively, the suggested working normal range for LBMI is 300–500 with the median at 400.

Regression models: Percentage body fat: Lean body mass

A number of studies have investigated the relationship between body fat and stature-adjusted weight indices, often with the aim of obtaining a simple but meaningful index that identifies the overweight or obese members of the community. A comprehensive and succinct review of stature-adjusted weight indices is given by Cole (1991).

Abdel-Malek *et al.* (1985) used weight and height to explain percentage body fat (BF%) with the following equation:

$$\mathrm{BF\%} = c \times W^{\mathrm{m}}/H^{\mathrm{k}}, \tag{1}$$

where W is body weight and H is height.

When model (1) was fitted to 458 individuals of different age groups and sex, using non-linear least squares, the authors concluded that the parameters m and k were common to all ages and both sexes (m = 1·2 and k = 3·3) but the constant c differed between the two sexes.

Deurenburg *et al.* (1991) also related BF% to weight, height, age and sex although the terms weight and height were combined in the form of the body mass index (BMI, also known as Quételet's index) BMI = W/H^2. They used multiple linear regression analysis to fit an implied model,

$$\mathrm{BF\%} = a + b_1 \times (W/H^2) + b_2 \times \mathrm{age} + b_3 \times \mathrm{sex}, \tag{2}$$

where sex was included as an indicator variable taking the values 0 and 1 for females and males respectively.

Since these models are not based on any biological principles, they can only be thought of as convenient for the purposes of both statistical calculation and ease of measurement, and may, fortuitously, approximate to the real relationship between the variables involved.

MODELS BASED ON BIOLOGICAL PRINCIPLES

Garrow & Webster (1985) related total body fat (BF), weight and height with the following model,

$$\mathrm{BF}/H^2 = b \times (W/H^2) - a. \tag{3}$$

There would appear to be a sound biological basis for their model if one starts with the equation,

$$W = \mathrm{BF} + \text{lean body mass (LBM)}. \tag{4}$$

If we assume that LBM is more stature-related than body weight and can be approximated by $\mathrm{LBM} = c \times H^2$ (an assumption that will be validated later), then by substituting this expression in (4) we obtain,

$$W = \mathrm{BF} + c \times H^2. \tag{5}$$

Hence, by dividing both sides of equation (5) by H^2, we obtain the equation (3) assumed by Garrow & Webster (1985) with $b = 1$ and $a = c$.

As with Deurenberg *et al.* (1991) and Abdel-Malek *et al.* (1985), most observers estimate BF% rather than record BF itself. Since $\mathrm{BF} = W \times \mathrm{BF}\%/100$, equation (5) becomes,

$$W = W \times \mathrm{BF}\%/100 + c \times H^2. \tag{6}$$

Rearranging equation (6), the appropriate model for BF% becomes,

$$\mathrm{BF}\% = 100 - (100 \times c \times H^2/W). \tag{7}$$

Hence, rather than using the stature-adjusted weight index BMI to predict BF%, as assumed by most authors, model (7) would suggest the term H^2/W as a predictor variable. Since BF% is (100 − LBM%), where LBM% denotes percentage lean body mass, equation (7) is simply restating the assumption that $\mathrm{LBM} = c \times H^2$ (as $\mathrm{LBM}\% = 100 \times \mathrm{LBM}/W = 100 \times c \times H^2/W$). Acknowledging this relationship, we suggest the term H^2/W, be referred to as the lean body mass index (LBMI).

VALIDATION USING MEASUREMENTS FROM THE ALLIED DUNBAR NATIONAL FITNESS SURVEY

In the previous section it was suggested that there will be a stronger association between LBM and height than between body weight and height. As a consequence, theoretically, LBMI should be a better predictor of BF% than BMI. These assumptions need to be validated using a large representative data set, randomly drawn from a population, and the Allied Dunbar National Fitness Survey (1992; ADNFS) was ideal for this purpose. The survey selected 4316 subjects, aged 16 years and over, at random from thirty English parliamentary constituencies; each subject being interviewed by Office of Population Censuses and Surveys (OPCS) trained employees about their health, lifestyle and physical activity. Of these subjects, a sub-sample (*n* 3024) took part in a physical appraisal that was conducted in one of three mobile laboratories in the thirty selected sites.

Estimates of BF%, taken for the ADNFS, were determined using the methods of Durnin & Womersley (1974), based on skinfold thicknesses at four sites; the biceps, triceps,

Table 1. *Number of subjects by age group and sex*

Age (years)...	16–24	25–34	35–44	45–54	55–64	Total
Male	176	252	272	264	199	1163
Female	194	274	267	240	228	1203
Total	370	526	539	504	427	2366

subscapular and supra-iliac. Other factors known to be associated with body fat and weight include the age and sex of the subject. The numbers of male and female subjects included in the subsequent analyses from different age groups are given in Table 1.

STATURE-RELATED WEIGHT OR STATURE-RELATED LEAN BODY MASS?

Based on the work of Quételet (1869), the implicit allometric model relating weight and height would appear to be

$$W = a \times H^2, \tag{8}$$

suggesting a linear relationship between $\log(W)$ and $\log(H)$ with slope = 2. A generalization of this model, based on the term W/H^{p} introduced by Benn (1971), would be

$$W = a_1 \times H^{\mathrm{p}_1}, \tag{9}$$

where p_1 is chosen to suit best the population under study.

In line with Benn (1971), one might reasonably argue that the relationship between LBM and height can be generalized as follows:

$$\mathrm{LBM} = a_2 \times H^{\mathrm{p}_2}. \tag{10}$$

Nevill & Holder (1994) were able to offer reasons, other than for statistical convenience, why log-linear models are likely to be the most appropriate models for variables such as body weight and LBM. When both weight and LBM are plotted against height the vertical scatter of points is likely to expand as the variables increase in magnitude. This feature in data, clearly present in the results from the ADNFS (see Figs 1 and 2 respectively), is known as heteroscedasticity and contravenes an important assumption usually made in linear and non-linear regression, i.e. the error variation about the regression model should remain constant throughout the range of observations.

Fortunately, this characteristic of data can be accommodated by a log transformation of the dependent variable, provided the standard deviation of observations at a given value of the independent variable is proportional to the mean at that value.

The log-linear models implied by equations (9) and (10) are,

$$\log(W) = \log(a_1) + \mathrm{p}_1 \times \log(H) + \epsilon_1, \tag{11}$$

$$\log(\mathrm{LBM}) = \log(a_2) + \mathrm{p}_2 \times \log(H) + \epsilon_2, \tag{12}$$

where the residual errors ϵ_1 and ϵ_2 are assumed to be normally distributed with constant variance.

The methods of Box & Cox (1964) can be used to confirm the most appropriate power transformation required to remove heteroscedasticity and provide normally distributed errors. Those authors suggest transforming the dependent variable (Y) using either $Y' = (Y^\lambda - 1)/\lambda$ if $\lambda \neq 0$ or $Y' = \log(Y)$ if $\lambda = 0$; the value of the parameter λ being chosen to

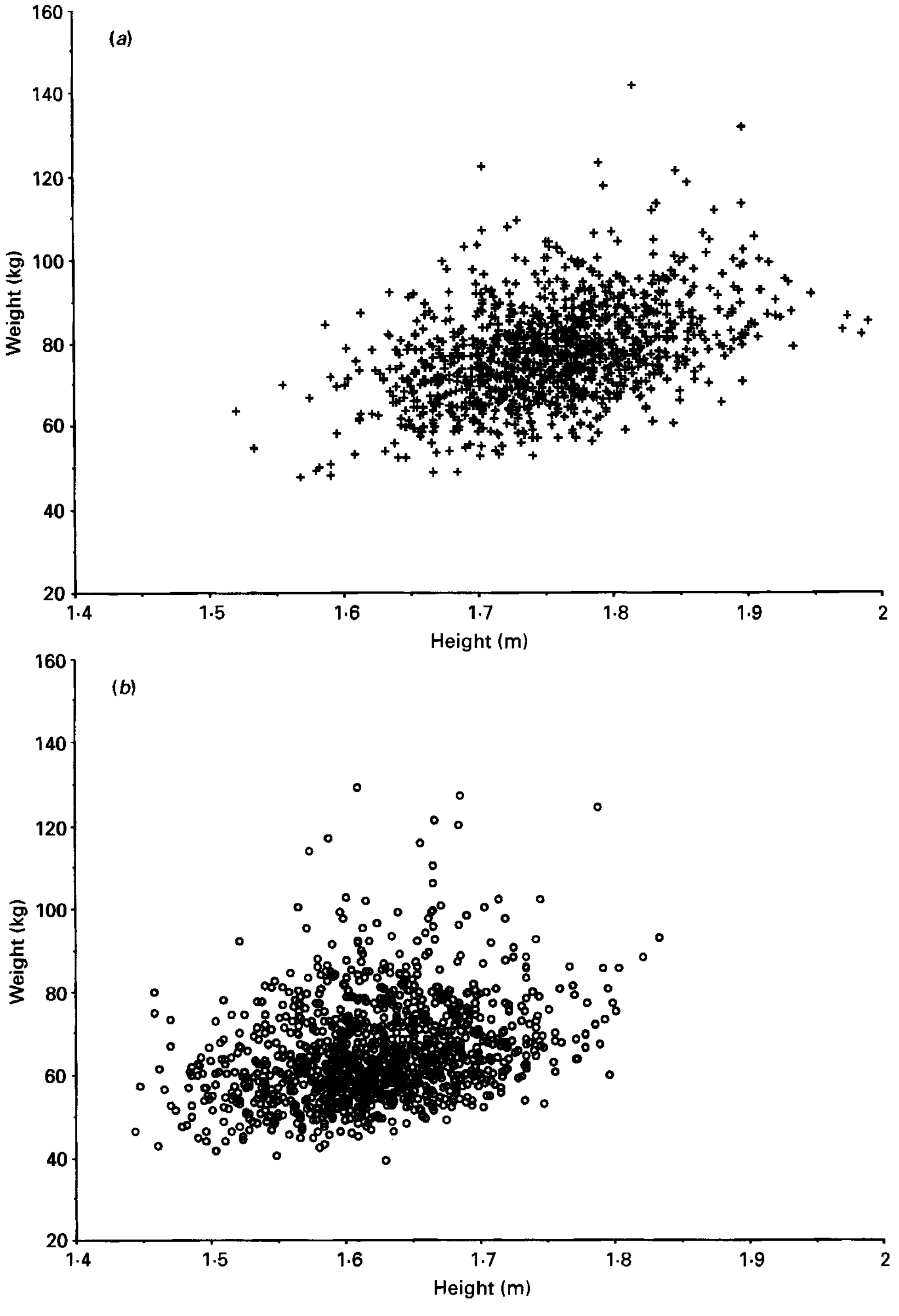

Fig. 1. Body weight (kg) *v*. height (m) for (*a*) male and (*b*) female subjects from the Allied Dunbar National Fitness Survey (1992).

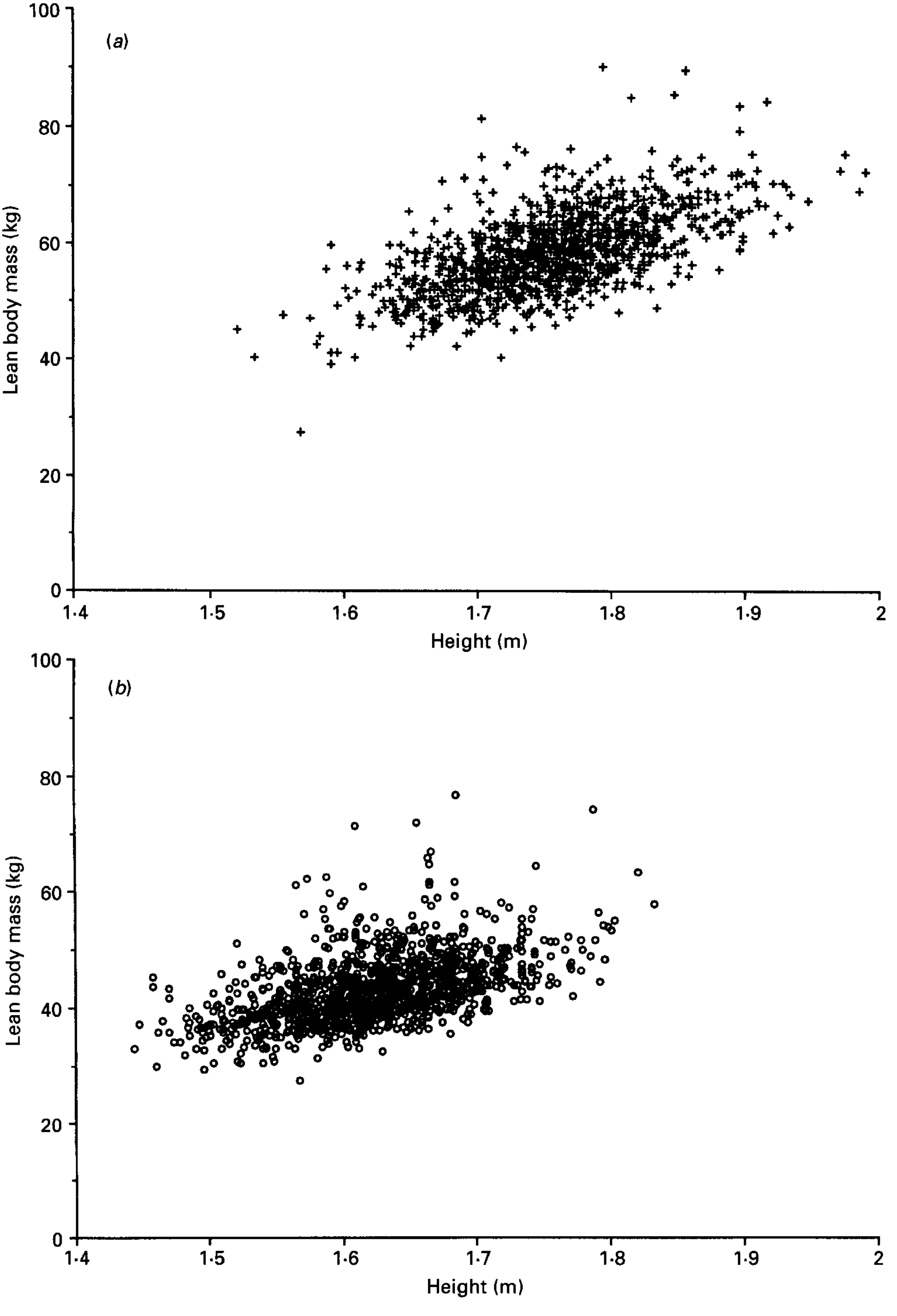

Fig. 2. Lean body mass (kg) *v*. height (m) for (*a*) male and (*b*) female subjects from the Allied Dunbar National Fitness Survey (1992).

Table 2. *The height exponent parameters for the weight and lean body mass* v. *height models by age group and sex*

Age (years)...	16–24	25–34	35–44	45–54	55–64
Weight *v.* height model (R^2 39·5, SE 0·144 log (kg))					
Male	2·52	1·71	1·66	1·72	2·08
Female	1·93	1·89	1·66	1·46	1·42
Lean body mass *v.* height model (R^2 73·7, SE 0·101 log (kg))					
Male	2·31	1·82	1·88	1·76	1·81
Female	1·94	1·89	1·93	1·63	1·29

maximize the log-likelihood function. The transformation will then provide residuals which best approximate to a normal distribution with constant variance. As expected, the transformation parameter required to maximize the log-likelihood function for both dependent variables, weight and LBM, was close to $\lambda = 0$, implying the necessity of a log transformation and the appropriateness of the log-linear model and accompanying assumptions.

Having verified that the transformation parameter λ is close to zero, the parameters in equations (11) and (12) can be fitted directly to the ADNFS data using linear least-squares. Allowing separate parameters to be fitted to each sex and age group, the model (11) relating body weight to height explained R^2 39·5% of the variation together with a standard error of 0·144 log (kg). However, the model (12) relating LBM to height explained R^2 73·7% of the variation together with a standard error of 0·101 log (kg). These statistics confirm the assumption that height is more strongly related to LBM than body weight. The estimates of the height exponent parameters p_1 and p_2 taken from the fitted models (11) and (12), are given in Table 2. The interpretation of these values will be considered in the discussion.

PREDICTING PERCENTAGE BODY FAT FROM HEIGHT AND WEIGHT

The proposition that LBMI may be, theoretically, a better predictor of BF% than BMI may now be investigated using the BF% measurements from the ADNFS. The two possible models to consider are

$$\mathrm{BF\%} = a_1 + b_1 \times \mathrm{BMI} + \epsilon_1, \tag{13}$$

$$\mathrm{BF\%} = a_2 + b_2 \times \mathrm{LBMI} + \epsilon_2, \tag{14}$$

where the residual errors ϵ_1 and ϵ_2 are normally distributed with constant variance.

To accommodate differences due to age and sex, both models were fitted, allowing for different constant parameters for each of the ten groups described in Table 1. When model (13) was fitted, where BMI is used as a predictor variable, the solution explained R^2 80·0% of the variance (SE 3·52 BF%). This compares with R^2 81·5% of the variance (SE 3·37 BF%) when BF% was predicted using model (14) with LBMI as the predictor variable. Although the use of LBMI provides a marginally superior fit to the data, the real value of model (14) lies in its biological plausibility, as demonstrated earlier. The parameter estimates for both models (13) and (14) (not shown) identify a clear increase in BF% with age and a difference of approximately 10% body fat between male and female subjects.

Model (2), proposed by Deurenberg *et al.* (1991), differs from model (13) in that the effects of age and sex are incorporated by the addition of extra terms in the former, whereas the parameters a_1 and b_1 are varied for different ages and sexes in the latter. In order to compare LBMI and BMI as predictors of BF%, two models were fitted, (*a*) model (2) as proposed by Deurenberg *et al.* (1991), incorporating BMI, age and sex, and (*b*) the same as Deurenberg *et al.* (1991) but replacing BMI with LBMI. The fitted models are as follows:

(*a*) $\text{BF}\% = 1{\cdot}01 \times \text{BMI} + 0{\cdot}11 \times \text{age} + 9{\cdot}15 \times \text{sex} - 5{\cdot}81$ $\quad R^2$ 75·7 (SE 3·82),
(*b*) $\text{BF}\% = 47{\cdot}9 - 0{\cdot}069 \times \text{LBMI} + 0{\cdot}10 \times \text{age} + 9{\cdot}5 \times \text{sex}$ $\quad R^2$ 77·8 (SE 3·65).

Thus, even with the Deurenberg model formulation, LBMI is a better predictor of BF% than BMI. However, this formulation is less satisfactory than the fitted models (13) and (14). It is interesting to note that the above models (*a*) and (*b*) could be improved by incorporating an age^2 term acknowledging the eventual decline in BF% with advancing years.

The error structure of the preferred model (*b*) for BF% was investigated using the methods of Box & Cox (1964). The transformation parameter, required to maximize the log-likelihood function, was found to be $\lambda = 1{\cdot}3$ with a 95% confidence interval of $\lambda = 1{\cdot}1$–$1{\cdot}5$. (Note that a value of $\lambda = 1$ implies making no transformation of the dependent variable.) Hence, based on the ADNFS data, the assumption made by Abdel-Malek *et al.* (1985) and Deurenberg *et al.* (1991) that BF% was normally distributed with constant variance was incorrect although not entirely unreasonable.

DISTRIBUTIONAL PROPERTIES OF THE BMI AND LBMI

Cole (1991) recognized the distributional limitations of BMI when reviewing stature-adjusted weight indices. He observed that the distribution of BMI was skewed, especially for children and young adults, and recommended that the index was transformed as either H^2/W or $H/W^{1/2}$, since these inverted indices were likely to be symmetric and approximately normally distributed. As anticipated, the distribution of BMI, taken from the results of the ADNFS, is positively skewed (see Fig. 3). In contrast, the distribution of LBMI was found to be both symmetric and bell shaped (see Fig. 4).

A test of normality was conducted on BMI and LBMI using the probability plot correlation test for normality (Filleben, 1975) as implemented in MINITAB (1989). The correlation between the ordered BMI scores and the corresponding normal equivalent deviates was found to be r 0·977, suggesting that BMI deviated considerably from a normal distribution ($P < 0{\cdot}001$). When the ordered LBMI scores were correlated with the corresponding normal equivalent deviates, the correlation was found to be r 0·999, indicating that LBMI was approximately normally distributed. Even when the scores were subdivided according to age and sex, the probability plot correlation test confirmed that LBMI remained approximately normally distributed within each sub-group. This has important implications for tests of significance such as the t test, ANOVA and regression analysis when applied to BMI. As such procedures are only valid for normally distributed measurements, their use on BMI must be questionable. However, if LBMI is used instead of BMI, no such problem arises.

The centiles of LBMI, taken from the ADNFS, have been calculated and are presented in Table 3. A convenient and fairly accurate approximation to a normal range for LBMI would therefore appear to be 300–500 with a median value of 400. Variation between males and females in LBMI is minimal. (Note that the number of subjects given in Table 3 differs from those given in Table 1; the ages of subjects in Table 1 were restricted to 16–64 years.)

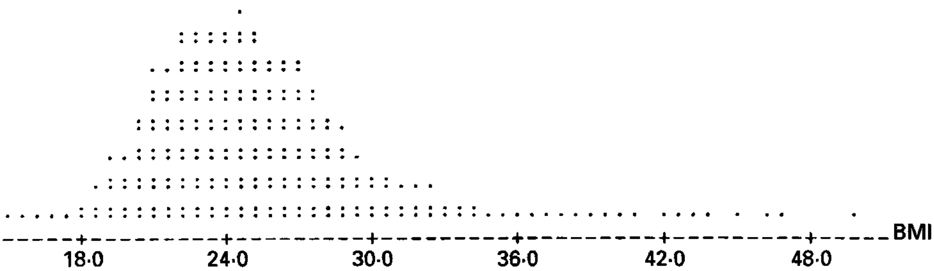

Fig. 3. Dotplot of body mass index (BMI) from the Allied Dunbar National Fitness Survey (1992). Each dot represents fifteen subjects.

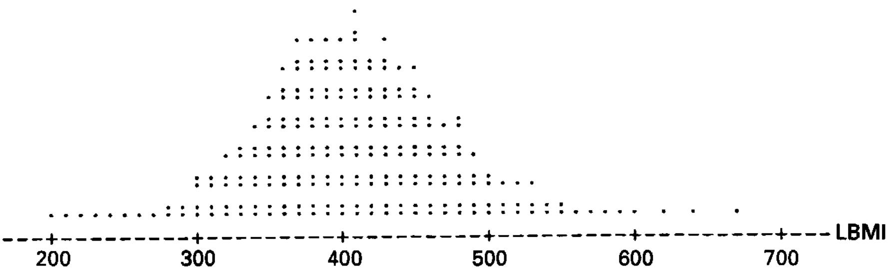

Fig. 4. Dotplot of lean body mass index (LBMI) from the Allied Dunbar National Fitness Survey (1992). Each dot represents fifteen subjects.

Table 3. *The centiles of the lean body mass index* (H (*cm*)^2/W (*kg*))

Age (years)...	16–24	25–34	35–44	45–54	55–64	65–74	75+	All
Centiles								
2·5%	313	282	298	295	284	281	271	289
5·0%	329	318	309	314	294	298	300	306
50·0%	443	425	404	398	384	387	400	406
95·0%	543	520	497	482	483	483	528	509
97·5%	556	530	520	493	500	512	547	530
n (subjects)	370	527	541	505	430	383	247	3003

DISCUSSION AND CONCLUSIONS

For many years stature-adjusted weight indices have been studied since it was assumed that such indices would help identify the overweight or obese members of the community. The majority consensus from such studies (e.g. Cole, 1991 and Garrow & Webster, 1985) was that the BMI (Quételet's index) was the best stature-adjusted weight index available. However, if we assume that LBM is more stature-related than body weight, then theoretically, based on simple biological principles, a better linear model (7) to predict BF% was shown to involve LBMI $= H^2/W$ rather than the traditionally adopted BMI $= W/H^2$. Because the model (7) is based on biological principles, it might be expected to be applicable over a wider range than an empirically derived model.

The above assumptions were validated, empirically, using the results from ADNFS (1992). First, when both LBM and weight were modelled, using the allometric model $Y = c \times H^p$, the predictor height (H) accounted for 73·7% of the variation in LBM compared with only 39·5% of the variation in body weight. Both models show a very similar pattern of parameter estimates with the height exponent close to $p = 2$ for both the male subjects and female subjects aged 16–54 years. However, in the last decade, from 55 to 64 years, the female height parameter appears to be considerably less than 2, possibly reflecting events such as the menopause and associated Ca depletion. Hence, with the possible exception of female subjects aged 55 years and over, these findings support the proposition that H^2 will reflect accurately the subjects' LBM and, therefore, the H^2/W value will correlate highly with LBM%.

The second assumption, that LBMI was theoretically a better predictor of BF%, was confirmed empirically when both BMI and LBMI were used to predict the estimates of BF% taken from the ADNFS. Acknowledging the limitations of estimating BF% using the methods of Durnin & Womersley (1974), the predictor LBMI explained 1·5 percentage points more of the variance in the BF% measurements than the traditional BMI ratio. The analysis identified the expected sex difference in BF% between male and female subjects, together with the expected increase with age.

These findings were incorporated into regression models, originally proposed by Deurenberg *et al.* (1991). The model incorporating LBMI provided the better solution that explained over 2 more percentage points of the variance in BF% than the model originally proposed by Deurenberg *et al.* (1991). This supports the proposition that LBMI is a more accurate measure of BF% but confirms the necessity that it must be subtracted from a large positive constant rather than being inverted to best reflect BF%.

Further support for LBMI comes from Cole (1991) when reviewing stature-adjusted weight indices to identify the underweight, overweight and obese. Cole observed that the distribution of BMI is skewed, especially in children and young adults. For this reason he suggested transforming the index to either H^2/W or $H/W^{1/2}$, since these indices were more likely to be close to the normal distribution, a finding that was confirmed using the data from the ADNFS. Hence, not only does LBMI have a sound biological interpretation as a measure of LBM%, but its distribution will be a better approximation to a normal distribution than BMI for subsequent statistical analyses, e.g. investigating categorical differences such as social class or ethnic origin. Clearly, by analysing the index H^2/W the overweight will be identified simply by observing the groups with low measurements of the index, implying a low LBM% and therefore indicating a high BF%. An easily memorized approximation to a normal range for LBMI would be 300–500 with a median value of 400 when height and weight are measured in centimetres and kilograms respectively.

The authors wish to thank the Sports Council and the Health Education Authority for access and permission to publish the findings from the Allied Dunbar National Fitness Survey. The authors would also like to thank the statistical editor for her valuable suggestions when revising the manuscript.

REFERENCES

Abdel-Malek, A. K., Mukherjee, D. & Roche, A. F. (1985). A method of constructing an index of obesity. *Human Biology* **57**, 415–430.

Allied Dunbar National Fitness Survey (1992). *Main Findings*. London: Sports Council and the Health Education Authority.

Benn, R. T. (1971). Some mathematical properties of weight-for-height indices used as measures of adiposity. *British Journal of Preventive and Social Medicine* **25**, 42–50.

Box, G. E. P. & Cox, D. R. (1964). An analysis of transformations (with discussion). *Journal of the Royal Statistical Society B* **26**, 211–252.

Cole, T. J. (1991). Weight-stature indices to measure underweight, overweight and obesity. In *Anthropometric Assessment of Nutritional Status*, pp. 83–111 [J. H. Himes, editor]. New York: Wiley-Liss.

Deurenberg, P., Weststrate, J. A. & Seidell, J. C. (1991). Body mass index as a measure of fatness: age- and sex-specific prediction formulas. *British Journal of Nutrition* **65**, 105–114.
Durnin, J. V. & Womersley, J. (1974). Body fat assessed from total body density and its estimation from skinfold thickness measurements on 481 men and women aged 16 to 72 years. *British Journal of Nutrition* **32**, 77–85.
Filliben, J. J. (1975). The probability plot correlation coefficient test for normality. *Technometrics* **17**, 111–117.
Garrow, J. S. & Webster, J. (1985). Quételet's index (W/H^2) as a measure of fatness. *International Journal of Obesity* **9**, 147–153.
MINITAB (1989). *Reference Manual.* Minitab Inc., 3081, Enterprise Drive, State College, PA 16801.
Nevill, A. M. & Holder, R. L. (1994). Modelling maximum oxygen uptake: a case study in non-linear regression formulation and comparison. *Applied Statistics* **43**, 653–666.
Quételet, L. A. (1869). *Physique Sociale*, vol. 2. Brussels: C. Muquardt.

Printed in Great Britain