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Development of a body condition index to estimate adiposity in ponies and horses from morphometric measurements

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Abstract

Background: There is a high prevalence of obesity in ponies and pleasure horses. This may be associated with equine metabolic syndrome and an increased risk of laminitis. Body condition scoring (BCS) systems are widely used but are subjective and not very sensitive.

Objectives: To derive a body condition index (BCI), based on objective morphometric measurements, that correlates with % body fat.

Study design: Retrospective cohort study.

Methods: Morphometric measurements were obtained from 21 ponies and horses in obese and moderate body condition. Percentage body fat was determined using the deuterium dilution method and the BCI was derived to give the optimal correlation with body fat, applying appropriate weightings. The index was then validated by assessing inter-observer variation and correlation with % body fat in a separate population of Welsh ponies; and finally, the correlation between BCI and BCS was evaluated in larger populations from studies undertaken in Australia, the United Kingdom and the United States.

Results: The BCI correlated well with adiposity in the ponies and horses, giving a Pearson *r* value of 0.74 ($P < 0.001$); however, it was found to slightly overestimate the % body fat in leaner animals and underestimate in more obese animals. In field studies, the correlation between BCI and BCS varied particularly in Shetlands and miniature ponies, presumably due to differences in body shape.

Main limitations: Further work may be required to adapt the BCI to a method that is more applicable for Shetlands and miniature ponies.

Conclusions: This BCI was able to provide an index of adiposity which compared favourably with condition scoring in terms of accuracy of estimating adiposity; and was more consistent and repeatable when used by inexperienced assessors.

Samantha J. Potter and Madison L. Erdody contributed equally to this study.

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Therefore, this may be a useful tool for assessing adiposity; and may be more sensitive than condition scoring for tracking weight gain or weight loss in individual animals.

KEYWORDS
endocrine, equine metabolic syndrome, horse, obesity

1 | INTRODUCTION

Obesity is a major problem amongst ponies and some breeds of horses in many developed countries. Studies conducted in Australia, the United States and the United Kingdom have found the prevalence of obesity in horses and ponies in these countries to be in the range of 23%–33%.[1–4] Obesity is commonly associated with altered metabolic states, most commonly equine metabolic syndrome (EMS), and therefore an increased risk of laminitis.[5,6] Furthermore, many horse and pony owners perceive their animals as being an ideal/healthy weight when they may be obese or overweight.[1,7,8]

The most commonly used standardised practical field method of assessing adiposity in horses and ponies is by body condition scoring (BCS)[9–11]; however, it has become clear that these BCS systems have a number of limitations that may cause inaccuracy. From a practical perspective, additional inaccuracies may also be caused by the necessity to differentiate between condition scores by visual appraisal or manual palpation (both subjective). For example, during winter the horse's thicker coat can make visual appraisal difficult. Furthermore, the identification of a condition score, especially at higher BCS, based on the Henneke 1–9 BCS system provides rather vague descriptions which can make differentiating between condition scores difficult, especially for assessors with only basic horse knowledge. Measuring % body fat in live horses requires invasive, rather complex and often expensive methods, such as deuterium dilution.[12] Despite offering a good indication of total skeletal associated soft tissue and % body fat in animals at a stable BCS, decreased sensitivity in predicting total body fat was found in very obese animals on a weight loss regimen.[13,14] In a weight loss study where very obese ponies lost an average of 11.4% bodyweight, BCS was not significantly altered, although belly girth (an objective morphometric measurement) did decrease as it was suggested internal fat was lost.[13] Similarly the cresty neck score (CNS),[15] although it may correlate with measures of insulin dysregulation,[16] is subjectively assessed on a 6-point scale so is not as sensitive to small changes as a neck circumference measurement; and may be more of a feature in particular breeds.

A number of alternatives to the use of BCS, which use objective measurements, have been explored. Imaging methods such as ultrasound measurements of subcutaneous fat depth as a predictor of % body fat have not been shown to be very reliable.[17] The body mass index (BMI) is used widely in humans to determine whether an individual's weight is within the healthy range, using the equation: BW (kg)/height (m).[2] This, therefore, takes into account the size of the subject's frame. Applying the above formula to equate BMI to measure adiposity in horses has demonstrated only a moderate correlation ($r^2 = 0.60$) between BCS and BMI in horses.[18] In 2009, Carter et al. used the same principal and compared it to a method used in cats: BMI = BW (kg)/(length × height).[2,15,19] Again the correlation was rather poor. However, the validity of using these particular body mass indices, extrapolated from the human BMI, for estimation of body fat percentage in horses and ponies is questionable. The inclusion of bodyweight in a BMI for horses may be inadvisable for two reasons. First, horses and ponies vary a lot more in overall body size and conformation than humans do, and therefore the weight of the skeleton may differ considerably. Also, not only may muscle mass vary considerably with athletic training (which is also a problem in man, with the human BMI overestimating adiposity in well-muscled individuals),[20] but also the great size of the large intestine in horses means that gut fill also has a very big and variable impact on apparent bodyweight. Second, access to weigh scales would be a problem for the great majority of horse and pony owners; therefore, most would have to rely on heart girth measurements as an index of bodyweight, which can be rather inaccurate.[21]

Objective scoring methods have been developed to estimate bodyweight in various equine breeds.[22] However, for the reasons outlined above, bodyweight does not necessarily correlate with adiposity and it would be useful to have a body condition index (BCI) based on morphometric measurements (objectively measured) which can be used to estimate body fat percentage. The aims of the present study were to derive a BCI based on objective morphometric measurements that correlate well to % body fat as determined by a gold-standard method (deuterium dilution) in a university research herd of ponies and horses. Then to validate this index for inter-observer variation; assess the correlation with % body fat in a different population of animals; and determine the correlation with BCS assessments in larger populations from studies undertaken in Australia, the United Kingdom and the United States using experienced BCS assessors.

2 | MATERIALS AND METHODS

2.1 | Part A: Derivation of the BCI

2.1.1 | Animals

Seven Standardbred horses, seven mixed breed ponies and seven Andalusian horses were used in the derivation of the BCI. Further details and phenotypic information have been provided previously.[23] These were all adult animals (age range 4–15 years) and included 10 mares and 11 geldings. Height measurements (to the withers) varied between 117 and 167 cm, and length between 115 and 178 cm.

Initially, all animals began in moderate body condition. Then animals were placed on a high-calorie ration (∼200% of maintenance energy requirements) for 20 weeks until the animals had reached between BCS

7 and 8 out of 9.[23] This was followed by a weight loss phase, which concluded once animals reached moderate body condition (BCS 5/9) or the 12-week period ended.[24] BCS was conducted using the Henneke scoring system, as modified by Kohnke.[25] Weight was measured weekly using calibrated weigh scales (Horseweigh Ltd, UK).

2.1.2 | Morphometric measurements

Morphometric measurements including heart girth circumference (HG), belly girth circumference (BG), mid-neck circumference (NC), body length (*L*) and height to the withers (*H*) were obtained using measuring tapes. The exact placement of the tape measure (important for accuracy) is shown in Figure S1. Measurements were taken at the beginning and end of the weight gain and weight loss periods, and were always taken by the same investigator.

2.1.3 | Body fat estimation by deuterium dilution

The deuterium dilution method was used as a gold standard technique for estimating % body fat. Briefly, animals were weighed on calibrated weigh scales and then an initial blood sample was taken. Then deuterium oxide (Cambridge Isotope Laboratories) was administered intravenously at a dose of 0.12 mL/kg bodyweight.[12] Four hours after administration, once the deuterium had equilibrated within all body water compartments, a second blood sample was taken. Samples were analysed for deuterium using isotope mass spectrometry (Iso-Analytical Ltd), and the fat-free mass was calculated. Percentage body fat was then calculated by subtraction from total body mass. This procedure was undertaken before and after each weight gain or weight loss period. Therefore there were 68 data sets with morphometric measurements together with concurrent % body fat measurements by deuterium dilution, used to derive the BCI equation (2 phases of weight gain and weight loss, each with 17 animals and 4 animals set aside as controls).

2.1.4 | Development of the BCI

The BCI formula expresses the overall outer circumference of the animal (weighted average of neck circumference, heart girth and belly girth) for a given size of animal (i.e., divided by height and length). The length measurement was included to give a more accurate estimation of the size of the frame/skeleton of the animal. To assess the appropriate weighting for each of these measurements, these regression coefficients were derived by the principle of Newton's method. This method, used to find the roots of a nonlinear equation, was conducted using the SOLVER function in MS Excel. For each iteration, the difference between the BCI and % body fat (deuterium dilution) was recorded for each horse and the sum of the squares of the differences (SSD) was calculated. More than 1000 iterations were performed to derive the regression coefficients that resulted in the lowest possible SSD value (i.e., BCI values as close as possible to the body fat percentage).

2.2 | Part B: Validation of the BCI

2.2.1 | Correlation of BCI with % body fat

A plot of BCI versus % body fat was constructed, and the data points were fitted to both linear and nonlinear regression equations, to determine which gave the best fit. The goodness of fit was assessed by comparing the sum of the squares. The BCI value was correlated with % body fat and BCS using Pearson's correlation (GraphPad Prism software version 5.0; GraphPad Software Inc.). Sample size calculations indicated that this number of data sets was clearly able to determine whether the correlation coefficient differed significantly from zero, with an alpha value of 0.05 and a power of >90% (https://sample-size.net/correlation-sample-size/). The BCI was also compared to % body fat using Bland–Altman analysis, to examine the distribution of the differences across the range of adiposity.

2.2.2 | Comparing accuracy and variability of BCI with BCS values obtained by trained but inexperienced investigators

A study was undertaken to compare the accuracy and variability of the BCI (an objective measure) with the BCS (a subjective assessment) when undertaken by less experienced evaluators. The inexperienced participants consisted of five final year Doctor of Veterinary Medicine students. Although the students were used to observing and handling horses, these observers were all inexperienced in BCS of horses using the modified Henneke method (equivalent to typical horse owners). Participants were provided with an instructional sheet visually demonstrating how to take measurements and conduct BCS. Researchers also demonstrated the measurements and areas of observation before participants commencing; thereafter, they were unassisted while they were actually taking their measurements. Eight Ponies, 8 Andalusians and 8 Standardbreds were available for assessment, and each student measured and assessed between 13 and 23 of these animals using both methods (students were not available to measure all 24 animals for logistical timetabling reasons). Values for BCS and BCI (calculated in a Microsoft Excel spreadsheet from the input measurements) obtained by the students were analysed to give a coefficient of variation, derived by expressing the SD as a % of the mean. Therefore, the variability could be compared between the two methods of assessment. Scores given by participants were then also compared to those reported by two experienced observers, assessing during the same week.

2.2.3 | Validation in a separate population of ponies

Morphometric measurements and % body fat were obtained from a group of 16 Welsh ponies, as part of a separate study (investigators PKM and CMcA).[26] Measurements were obtained before and after an 11-week weight loss protocol, starting with obese body condition (>7 out of 9) and losing ~6% of bodyweight. Percent body fat was calculated using the deuterium dilution method in the same way as described in Part A.

The BCI was calculated and correlated with the % body fat as described above, giving a Pearson's correlation coefficient *r* value (GraphPad Prism software version 5.0; GraphPad Software Inc.).

To determine ranges of the BCI that equate to certain levels of adiposity, receiver operating characteristic (ROC) curve analysis was undertaken from this data. This was based on an animal being considered 'fat' if its estimated body fat was >20% (which equated to a BCS on the Kohnke-modified Henneke scale of 6.83)[17] and 'over-conditioned' if the estimated body fat was >15%.

2.3 | Part C: Comparison of BCI with BCS in large cohorts of ponies and horses

Data from three large field studies were used to examine the correlation between the BCI and BCS. The first study, conducted by the Royal Veterinary College, London (investigators EK, PH and NMG),[27] involved 245 ponies of mixed breeds, including Irish, cob, Welsh, Shetland, miniature and others. The second study was conducted across 10 Pony clubs across Victoria, Australia.[1] This cohort of 233 animals included a mix of ponies (various breeds and crosses including Shetlands, miniature ponies, Australian riding ponies and British native breeds) and also horses, mostly including Standardbreds and Thoroughbreds.[1] The third study, conducted in the United States by investigators BJM, PH and KK obtained morphometric measurements from 115 horses and 11 ponies aged between 1 and 26 years.[28] The horse breeds included various Warmblood breeds (92 Warmbloods; the tallest 182 cm in height to the withers) and also 23 Thoroughbreds, and Thoroughbred crosses; and the ponies included Welsh, Shetland and Welsh/Connemara crosses.

The BCI values were calculated from the morphometric data using the BCI equation and BCS was assessed by the Kohnke modified Henneke method. All investigators were very experienced in BCS. BCI values were plotted against the body condition scores. The correlation between BCI and BCS was assessed by calculating the Pearsons *r* value, using GraphPad Prism software (Version 5.0; GraphPad Software Inc.).

3 | RESULTS

3.1 | Part A: Derivation of the BCI

3.1.1 | Body fat estimation by deuterium dilution

The deuterium dilution method gave values for % body fat in the University of Melbourne research herd of ponies and horses that ranged from 4.1% to 12.8% in animals in moderate body condition, to 11.9% to 20.2% in obese animals (BCS 7–8 out of 9). No animals had a BCS >8 out of 9. These body fat values (undertaken by experienced investigators) correlated very well with body condition scores (Pearson *r* value 0.82; $P < 0.0001$; Figure S2a).

3.1.2 | Development of the BCI

To assess the appropriate weighting for each of the morphometric measurements used in the BCI equation, >1000 iterations were performed to derive the regression coefficients that resulted in the lowest possible SSD value (i.e., a single BCI equation which gives values as close as possible to the body fat percentage, based on a range of individual subjects, both at moderate and obese body condition). This provided the final equation below:

$$\mathrm{BCI} = \left(\frac{\left(\mathrm{HG}^{1.18} + \mathrm{BG}^{0.98} + \mathrm{NC}^{1.31}\right)}{\left(H^{1.23} + L^{1.01}\right)} \right)^{5.10}$$

3.2 | Part B: Validation of the BCI

3.2.1 | Correlation of BCI with % body fat

Applying this equation to 68 measurements from 21 different animals, the BCI value correlated well with the % body fat, giving a Pearson *r* value of 0.74 ($P < 0.0001$; Figure 1). Fitting the data points to both linear and nonlinear regression equations, the goodness of fit assessed by the sum of the squares was very similar for the two methods (148.9 for the straight line fit vs. 149.8 for the curve). The BCI also correlated well with the body condition score values (Pearson *r* value 0.74; $P < 0.0001$; Figure S2b).

The Bland–Altman analysis, comparing the BCI results with % body fat in animals in moderate and obese body conditions, showed a very small bias overall, of just 0.23 (±SD 3.25). However, the 95% limits of agreement ranged from −6.14 to 6.60, and the plot indicated that the BCI overestimated the % body fat in leaner animals and underestimated the % body fat in more obese animals (Figure 2).

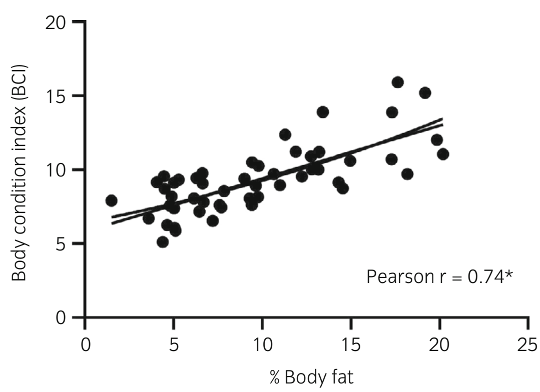

FIGURE 1 Correlation between BCI and % body fat, measured by deuterium dilution, in ponies and horses from Study 1 (University of Melbourne) from which the BCI equation was initially derived, including animals in moderate and obese body condition. The data points were fitted to a linear and nonlinear regression equation, and the goodness of fit assessed by the sum of the squares was very similar for the two methods (148.9 for the straight line fit vs. 149.8 for the curve). The Pearson *r* correlation value was 0.74 ($P < 0.0001$).

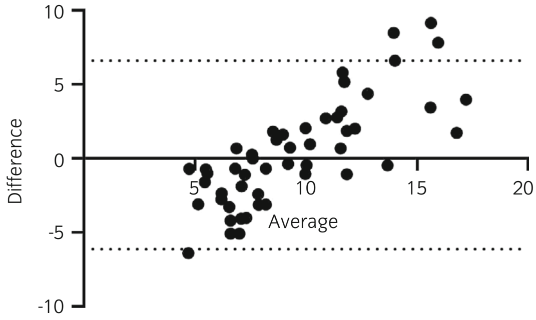

FIGURE 2 Bland–Altman plot comparing body fat assessed by deuterium dilution and estimated by the BCI method, in ponies and horses from Study 1 (University of Melbourne) from which the BCI equation was initially derived, including animals in moderate and obese body condition. The bias was 0.23 (±SD 3.25), however the 95% limits of agreement (dotted lines) ranged from −6.14 to 6.60, and the plot indicated that the BCI over-estimates the % body fat in leaner animals and under-estimates the % body fat in more obese animals.

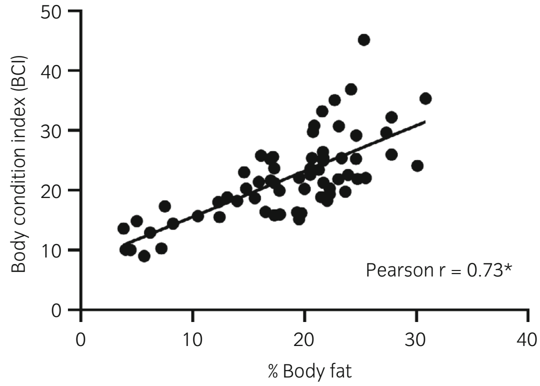

FIGURE 3 Correlation between BCI and % body fat, measured by deuterium dilution, in ponies and horses from Study 2 (SRUC) from which the BCI equation was subsequently validated, including animals in moderate and obese body condition. The data points were fitted to a linear and nonlinear regression equation, and the goodness of fit assessed by the sum of the squares was very similar for the two methods (1459 for the straight line fit vs. 1477 for the curve). The Pearson *r* correlation value was 0.73 ($P < 0.0001$).

3.2.2 | Comparing accuracy and variability of BCI with BCS values obtained by trained but inexperienced investigators

Considering the average values for the body condition scores and BCI obtained from the morphometric measurements taken by the trained but inexperienced assessors (mean ± SD BCS 6.09 ± 0.82 out of 9; BCI 12.12 ± 3.08), these values were very similar to those obtained by the experienced assessors (mean ± SD BCS 6.16 ± 0.78 out of 9; BCI 11.95 ± 3.59). Therefore, over a large number of animals, the inexperienced assessors were achieving a reasonably correct assessment on average. However, when the coefficient of variation was calculated, by expressing the SD as a % of the mean, the variability in the BCS scoring values arrived at by the inexperienced assessors was greater than the variability for the BCI values (paired *t*-test; $P = 0.002$). The mean coefficient of variation for body condition scores between assessors was 13.9% (±7.4 SD); whereas the mean coefficient of variation for the BCI was 10.9% (±6.0 SD).

3.2.3 | Validation in a separate population of ponies

Using the morphometric measurements and % body fat data from a group of 16 Welsh ponies in both moderate and obese body condition, separate from the initial study (investigators PKM, PH and CMcA), also showed a good correlation between the BCI index (calculated using the same equation as above) and the % body fat (calculated by deuterium dilution; Figure 3). The Pearson *r* correlation value was 0.73 ($P < 0.0001$) and fitting the data points to both linear and nonlinear regression equation again gave a very similar goodness of fit (sum of the squares was 1459 for the straight line fit vs. 1477 for the nonlinear curve fit).

The correlation between BCI and BCS in these Welsh ponies was also very good, giving a Pearson *r* correlation value of 0.79 ($P < 0.0001$; Figure S3). However, in this case the goodness of fit assessed by the sum of the squares was slightly better for the nonlinear equation (1077) than for the straight line fit (1165).

ROC curve analysis suggested that a cut-off BCI value of 21.7 would be most appropriate for designating an animal as 'obese' (estimated body fat >20%), with a test sensitivity of 79.4 and specificity of 81.3 (Figure S4a). Designating a % body fat of >15% as being 'overconditioned', this would correspond to a BCI greater than 18.0 (sensitivity 84.0% and specificity 87.5%; Figure S4b).

3.3 | Part C: Comparison of BCI with BCS in large cohorts of ponies and horses

Because of differences that became apparent in the relationship and correlation of the BCI values with BCS values in the data from different types of animals (particularly in Shetlands and miniature ponies vs. other pony breeds; and a weaker correlation in larger horse breeds), the data from the three large field studies (measured in exactly the same way) were pooled and categorised to allow evaluation separately of the data from the horses (>14.2 h), pony breeds (excluding Shetlands and miniature ponies) and Shetlands plus miniature ponies.

3.3.1 | Pony breeds (excluding Shetlands and miniature ponies)

Accurate morphometric data for the BCI, plus BCS assessment by experienced assessors using the same modified Henneke method, was

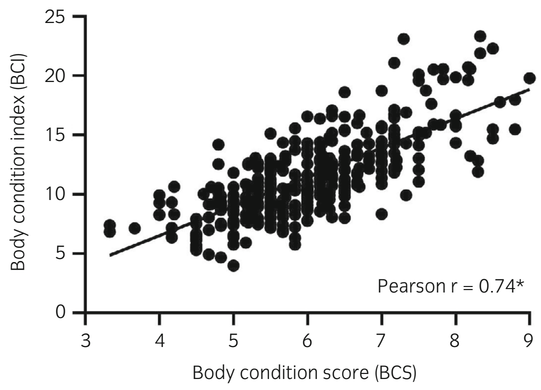

FIGURE 4 Correlation between BCI and BCS in pony breeds (excluding Shetlands and miniature ponies) from Studies 3–5. The data points were fitted to a linear and nonlinear regression equation, and the goodness of fit assessed by the sum of the squares was not significantly different comparing the nonlinear equation (1836) with the straight line fit (1861). The Pearson *r* correlation value was 0.74 ($P < 0.0001$).

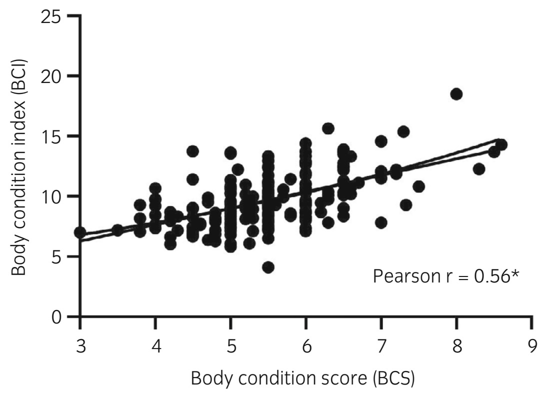

FIGURE 5 Correlation between BCI and BCS in horse breeds from Studies 3–5. The data points were fitted to a linear and nonlinear regression equation, and the goodness of fit assessed by the sum of the squares was not significantly different comparing the nonlinear equation (694) with the straight line fit (702). The Pearson *r* correlation value was 0.56 ($P < 0.0001$).

available from 341 mixed breed ponies. The correlation between BCI and BCS was highly significant (Pearson *r* correlation value 0.74; $P < 0.0001$; Figure 4). The goodness of fit assessed by the sum of the squares was not significantly different comparing the nonlinear equation (1836) with the straight line fit (1861), suggesting a linear relationship.

3.3.2 | Horse breeds

BCI values were calculated from morphometric data from 216 horses and correlated with BCS assessment (Figure 5). The relationship was again linear, with the goodness of fit assessed by the sum of the squares not significantly different comparing the nonlinear equation (694) with the straight line fit (702). The Pearson *r* correlation value (0.56) was still highly significant ($P < 0.0001$), although weaker than the pony data.

3.3.3 | Shetlands and miniature ponies

Data were available from a total of 48 Shetlands and miniature horses from the three studies (Figure 6). The relationship was linear (goodness of fit assessed by the sum of the squares not significantly different comparing the nonlinear equation [1538] with the straight line fit [1624]) and the Pearson *r* correlation value was 0.71 ($P < 0.0001$). However, on closer inspection of the data on the graph, there appeared to be several individual animals with BCI values indicating a body fat % around 30%–35% (over a range of body condition scores between 4 and 9) and one >50%. Furthermore, although the overall Pearson correlation was significant, the slope of the line was quite different compared to the other pony breeds (the line was close to 40% body fat at BCS 9, compared to 20% body fat for other pony breeds).

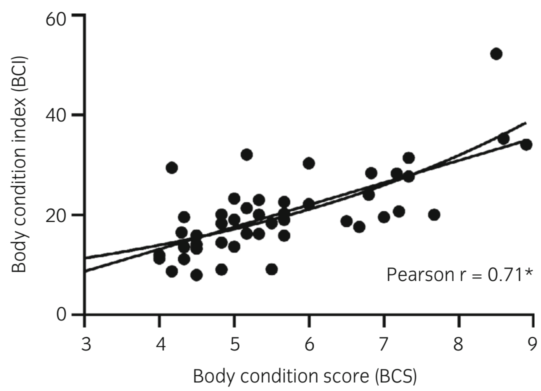

FIGURE 6 Correlation between BCI and BCS in Shetland and miniature pony breeds from Studies 3–5. The data points were fitted to a linear and nonlinear regression equation, and the goodness of fit assessed by the sum of the squares was not significantly different comparing the nonlinear equation (1538) with the straight line fit (1624). The Pearson *r* correlation value was 0.71 ($P < 0.0001$).

4 | DISCUSSION

The current work developed an objective index, based on simple morphometric measurements, which can be used to estimate body fat percentage in ponies and horses within 3–8 on the Henneke BCS scale. A version of the BCI was first developed by Potter et al. but it did not include body length and was developed using empirical rather than mathematical methods.[29] The current BCI, including body length, used mathematical methods to optimise the correlation to % body fat as determined by a gold-standard method (deuterium dilution). The correlation was optimised as far as possible, given that: (1) it was based upon external body measurements, and (2) that it was designed to be applied to both ponies and horses.

The deuterium dilution method gave values for % body fat in the research herd of ponies and horses that correlated well with body condition scores (assessed by experienced investigators). It has previously been shown that, up to a BCS of 7, this method (BCS) can be very good at predicting total body fat when undertaken by experienced assessors and with animals at a stable bodyweight; but is not so accurate for monitoring weight loss in very obese animals.[12] It should be noted that unlike some other studies in obese equids, where a significant proportion were >BCS 8 out of 9, the animals in the present study were not intended to exceed BCS 7 out of 9, although a number of them achieved condition scores between 7 and 8. This was part of a broader diet study where the rate of increase of adiposity was being compared in different breeds, and the effects on insulin sensitivity. Therefore the study protocol was dictated by the requirements of that study. Furthermore, the animal ethics requirements were such that supplementary feeding with the high-calorie diet had to be discontinued once the animals reached BCS 7/9. Therefore severely obese animals were not included in the derivation of the BCI formula. Internal body fat has been shown to increase in a nonlinear relationship with BCS, with the slope steepening further up the BCS scale; and therefore the difference in body fat change between BCS 8 and BCS 9 may be considerable.[14] For the current BCI formula, based upon external morphometric measurements, it was not expected that it would necessarily accurately reflect changes in internal body fat. Therefore, focussing on the range up to BCS 8 was considered reasonable. Furthermore, the slight overlap in % body fat (determined by deuterium dilution) between animals with a moderate BCS and those with an obese BCS almost certainly reflects the potential discrepancy between the degree of internal adiposity and the amount of subcutaneous adiposity assessed by the BCS.

The BCI formula expresses the overall outer circumference of the animal (weighted average of neck circumference, heart girth and belly girth) for a given size of animal (i.e., divided by height and length). The inclusion of the belly girth measurement in the BCI may partially help to reflect the amount of internal abdominal fat (although it will also change with subcutaneous fat around the belly area and also any change in muscle tone of the abdominal muscles, e.g., in pituitary pars intermedia dysfunction). The heart girth measurement is familiar to those owners estimating weight using a weight tape; and also is intended to assess the subcutaneous fat which may accumulate behind the shoulder. Regional adiposity, characteristic of EMS, would be expected to include a cresty neck (increased neck circumference) and also regional fat behind the shoulder.[15] However, generalised over-conditioning would tend to increase both the heart girth and belly girth measurements, and therefore this BCI was intended to be applicable to both EMS-prone breeds and breeds that do not typically exhibit this phenotype.

To assess the appropriate weighting for each of these measurements, these regression coefficients were derived by the principle of Newton's method, used to find the roots of a nonlinear equation. The final equation gave a fairly equal weighting to each of the morphometric parameters, suggesting that no one parameter was more important than the others. This contrasted slightly with the findings of Dugdale et al.[13] who found that the belly girth measurement correlated better with changes in adiposity than heart girth or neck circumference; however, they were using ponies that were originally in a more obese condition than those used to derive the equation in the present study.

The BCI value correlated well with the % body fat, and also correlated well with the BCS values. Also the body condition scores correlated well with the % body fat; but it should be noted that the BCS was undertaken by experienced investigators. However, it was important also to directly compare the BCI results with % body fat in animals using Bland–Altman analysis to evaluate bias and the pattern of mean difference. While there was a very small bias overall, the 95% limits of agreement were larger and the plot indicated that the BCI tended to overestimate the % body fat in leaner animals and underestimate the % body fat in more obese animals. As discussed above, this is entirely to be expected, because more obese animals would be expected to put on considerable amounts of intra-abdominal fat, and any index using external morphometric measures cannot completely account for this fat. However, the correlation between BCI and % body fat and Bland–Altman parameters did not improve even when an increased weighting was applied to the belly girth measurement. A range of increased weightings (exponents of 1 up to 3) were applied to the belly girth measurement, but none of those values gave any improvement in correlation between BCI and % body fat, and 0.98 was found to be optimal.

The average values for the BCS (a subjective measurement) and BCI (objective measurement) obtained from the morphometric measurements taken by the trained but inexperienced assessors were similar to those obtained by the experienced assessors, which showed that the inexperienced assessors (albeit with some anatomic knowledge) were achieving a reasonably correct assessment on average, even with the BCS; but this was *on average* over a large number of animals. However, it should be acknowledged that the inexperienced assessors did vary between each other when determining the BCS in some individual horses and ponies, and some individual assessors differed considerably from the experienced assessors. The coefficient of variation demonstrated that the variability in the BCS scoring values arrived at by the inexperienced assessors was greater than the variability for the BCI values (13.9% vs. 10.9%). This suggests that the BCI index, being an objective measure, should be more consistent and reproducible than the BCS when performed by the majority of horse and pony owners. It has been shown that many horse and pony owners tend to significantly underestimate their animals' body condition.[1,7] This may be for various reasons, including being exposed to images of ‘show condition’ animals in magazines/websites and also not being able to identify subtle changes in condition of their animals over time as they increase in adiposity. Therefore an objective measure that changes incrementally with small changes in body circumference may have significant advantages over BCS in some situations.

For further validation of the BCI, we were fortunate to have morphometric measurements and % body fat data (also obtained by deuterium dilution) available from a group of 16 Welsh ponies in both moderate and obese body condition, that represented a different cohort of animals from those used to derive the index. Applying the

BCI to this cohort also showed a good correlation between this index and the % body fat, with a linear relationship. As a sense-check, the correlation between BCI and BCS in these Welsh ponies was also very good. However, because breeds vary so much in size and shape, it was necessary to evaluate the BCI in larger cohorts, including as wide a range of body sizes and types as possible.

The relationship and correlation of the BCI values with BCS values in the data from Shetlands and miniature ponies appeared to vary from the other breeds when they were included in the analysis of mixed breed populations. Therefore, the Shetlands and miniature ponies were evaluated separately and the data from the other pony breeds and the horses from the three large field studies (measured in exactly the same way) were pooled. There was a highly significant correlation between BCI and BCS in the large cohort of mixed breed ponies, with an apparently linear relationship. A similar relationship was found in the horse breeds, although the Pearson *r* correlation value (0.56) was weaker than the pony data. However, the fact that most of these animals were in the moderate BCS range of 4.5–6.5, with very few at BCS 7 or above, meant that most of the points were centred in the middle of the graph, therefore any correlation was going to be more difficult to establish accurately. More studies including more horses with obese and/or very low body condition score would be warranted to determine whether that would give an increased r correlation value. Another consideration with horses is that they are more likely to be used for athletic purposes, and fit horses are likely to have more muscle and much less body fat. This may affect any index of adiposity based on morphometric measurements and could also affect body condition score.[11] The 9-point Henneke body condition score was originally developed for the assessment of Quarterhorse broodmares[9]; and although widely used it has been recognised that it may not be appropriate for other types of horses (a version has also been developed for warmblood horses).[10] A separate subjective muscle scoring system, or objective index based on morphometric measurements or ultrasonographic or impedance measurement, would be more appropriate for horses undergoing athletic training.[30–32] And a muscle scoring system has also recently been developed for animals exhibiting muscle atrophy.[33]

There may also be differences in body shape causing differences in relative morphometric measurements between heavy vs. light horse breeds. Therefore, measurements may not reflect the same degree of adiposity. For example, Andalusian horses tend to be heavier in frame than Thoroughbreds, Standardbreds or Arabian horses. Also, they are more likely to develop a cresty neck and exhibit regional adiposity (similar to ponies), because they commonly tend to exhibit insulin dysregulation and signs of EMS.[34] Specific morphometric measurements and their relationships have been determined for the Andalusian horse breed.[35] It was important in the present study that Andalusian horses as well as Standardbreds were included in the original cohort from which the BCI was derived, representing both types. However, potential differences in breed characteristics need to be considered when interpreting the BCI, and ultimately may require an optimisation for particular breeds.

The development of a cresty neck is typical of EMS-prone breeds, including ponies, Andalusian horses and other Spanish originating breeds; and as such it may be predictive of insulin dysregulation.[15] However, the cresty neck score, developed by Carter et al.,[15] is associated with similar issues to condition scoring, in that it is subjectively evaluated and may not reduce very much in early weight loss. Again it is a very effective tool for experienced evaluators, but may not be as accurate when performed by horse or pony owners. Since the BCI does incorporate the neck circumference, neck adiposity is taken into account. In the present study, the BCI significantly correlated with the cresty neck score, with an *r* value of 0.67 (Figure S6a). There was a slightly better correlation between BCS and cresty neck score ($r = 0.8$; Figure S6b), although all of these assessments were carried out by an experienced investigator.

Shetlands and miniature horses appeared to demonstrate quite a different relationship between the BCI and BCS values. Noting the scale of the *Y* axis of the graph, the slope of the line was quite different compared to the other pony breeds and the BCI values indicated very high-body fat percentages for the equivalent BCS values. Although Shetlands and miniature horses can get quite obese, it is unlikely that for a particular body condition score these breeds would have a dramatically higher % body fat than other pony breeds. It is more likely that other factors of body shape affected the BCI. These breeds clearly exhibit shorter limbs and therefore reduced height in relation to their body circumference. However, the reason for the increased BCI values that appeared as obvious outliers compared to other pony breeds could not be attributed to height alone. The relative proportion of neck, heart girth and belly circumference to each other, and to length, differed in these breeds; and it is likely that a separate BCI would need to be derived specifically for them. There were no purebred Shetland or miniature ponies in the research herd from which our BCI was derived; and performing additional deuterium dilution experiments on a separate cohort of Shetlands or miniature ponies was outside the scope of the current study.

Regarding the interpretation of the BCI, since it does not necessarily equate to the % body fat in all circumstances, it may be useful to consider some ranges for the index that equate to a certain level of adiposity. One definition of a horse being 'fat' is if its estimated body fat is >20% (which equated to a BCS on the Kohnke-modified Henneke scale of 6.83).[17] There were few animals in the first study (Part A) with a deuterium dilution % body fat value of >20%, and therefore the Welsh pony cohort from Part C was used. The values from the ROC curve analysis provide practical cut-off values for indicating to owners when animals may be considered obese or 'over conditioned'; however, these values would be for guidance only, due to individual variation.

5 | LIMITATIONS OF THE STUDY

Single measurements for the BCI were taken by an experienced investigator in each section of the project. However, repeatedly taking measurements to make an average might have improved accuracy. In many cases, the tape was repositioned several times to get it absolutely in the right orientation and location. However, we did not formally record multiple values to obtain an average and therefore we cannot say whether this would have improved the accuracy in a significant way. Furthermore, it was not possible to calculate a coefficient of variation for comparing BCI and BCS measurements by experienced assessors, because only two expert personnel were available at the one time.

The significant increase in internal body fat that occurs between BCS 8 and 9 may be metabolically important, but it may need to be accepted that no condition index or scoring system based on external measurements could accurately reflect the degree of internal body fat at that extreme end of the scale. Therefore, from a practical perspective, determining 'cut-off' values using ROC curve analyses (see above and Figure S6a,b) to indicate a BCI value above which an animal would be considered obese (so that appropriate dietary countermeasures can be taken) was thought to be the best approach.

6 | CONCLUSION

The BCI derived in the present study was able to apply objective morphometric measurements to correlate with % body fat, as determined by a gold-standard method (deuterium dilution) in a primary cohort of ponies and horses. This index compared favourably with BCS in terms of accuracy of estimating adiposity; however, being based on objective measurements it was more consistent and repeatable than BCS when used by inexperienced assessors. Therefore the BCI may be a useful measure to use when horse owners are assessing body condition or adiposity in their animals, and it may also be more useful and sensitive than condition scoring for tracking weight gain or weight loss in individual horses or ponies. However, it should be acknowledged that the index appeared to overestimate % body fat in Shetlands and miniature ponies, perhaps due to their different body shape, and further work may be required to adapt the BCI to one that is more applicable for these breeds.

AUTHOR CONTRIBUTIONS

The studies were designed by Simon R. Bailey, Patricia A. Harris and Nicholas J. Bamford; Samantha J. Potter, Madison L. Erdody, Nicholas J. Bamford, Edward J. Knowles, Philippa K. Morrison, Katelyn Kaufman, Bridgett J. McIntosh and Simon R. Bailey all contributed to data collection. All authors contributed to the data interpretation and manuscript preparation. Simon R. Bailey had access to all data in the study and takes responsibility for the integrity of the data and accuracy of the data analysis.

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CONFLICT OF INTEREST STATEMENT

P. Harris is employed by the funder, MARS Petcare UK; other authors have declared no competing interests.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICAL ANIMAL RESEARCH

Studies at the University of Melbourne were conducted under Ethics Committee approval ID 1011918. The UK Welsh Mountain pony studies were conducted under Home Office project licence number: PPL 70/8475. Other studies were approved by the Royal Veterinary College Animal Welfare and Ethical Review Board (2015-5128) with UK Home Office Licence (PPL 70/8195/PED 1AA054).

INFORMED CONSENT

Owner informed consent was obtained for all client-owned animals.

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REFERENCES

1. Potter SJ, Bamford NJ, Harris PA, Bailey SR. Prevalence of obesity and owners' perceptions of body condition in pleasure horses and ponies in South-Eastern Australia. Aust Vet J. 2016;94:427–32.
2. Thatcher CD, Pleasant RS, Geor RJ, Elvinger F, Negrin KA, Franklin J, et al. Prevalence of obesity in mature horses: an equine body condition study. J Anim Physiol Anim Nutr. 2008;92:222 (abstract).
3. Giles SL, Rands SA, Nicol CJ, Harris PA. Obesity prevalence and associated risk factors in outdoor living domestic horses and ponies. PeerJ. 2014;2:e299.
4. Robin CA, Ireland JL, Wylie CE, Collins SN, Verheyen KLP, Newton JR. Prevalence of and risk factors for equine obesity in Great Britain based on owner-reported body condition scores. Equine Vet J. 2015;47:196–201.
5. Frank N. Equine metabolic syndrome. Vet Clin North Am Equine Pract. 2011;27:73–92.
6. Harris PA, Bamford NJ, Bailey SR. Equine metabolic syndrome: evolution of understanding over two decades: a personal perspective. Anim Prod Sci. 2020;60:2103–10.
7. Morrison PK, Harris PA, Maltin C, Grove-White D, Argo CM, Barfoot C. Perceptions of obesity in a UK leisure-based population of horse owners. Acta Vet Scand. 2015;57(Suppl 1):O6 (abstract).
8. Jensen RB, Danielsen SH, Tauson A-H. Body condition score, morphometric measurements and estimation of body weight in mature Icelandic horses in Denmark. Acta Vet Scand. 2016;58(Suppl 1):59.

9. Henneke DR, Potter GD, Kreider JL, Yeates BF. Relationship between condition score, physical measurements and body fat percentage in mares. Equine Vet J. 1983;15:371–2.
10. Kienzle E, Schramme S. Beurteilung des ernährungszustandes mittels body condition scores und gewichtsschätzung beim adulten warmblutpferd. Pferdeheilkunde. 2004;20:517–24.
11. Carroll CL, Huntington PJ. Body condition scoring and weight estimation of horses. Equine Vet J. 1988;20:41–5.
12. Dugdale AHA, Curtis GC, Milne E, Harris PA, Argo CM. Assessment of body fat in the pony: part II. Validation of the deuterium oxide dilution technique for the measurement of body fat. Equine Vet J. 2011;43:562–70.
13. Dugdale AHA, Curtis GC, Cripps PA, Harris PA, Argo CM. Effect of dietary restriction on body condition, composition and welfare of overweight and obese pony mares. Equine Vet J. 2010;42(7):600–10.
14. Dugdale AHA, Curtis GC, Harris PA, Argo CM. Assessment of body fat in the pony: part 1. Relationships between the anatomical distribution of adipose tissue, body composition and body condition. Equine Vet J. 2011;43(5):552–61.
15. Carter RA, Geor RJ, Staniar WB, Cubitt TA, Harris PA. Apparent adiposity assessed by standardized scoring systems and morphometric measurements in horses and ponies. Vet J. 2009;179:204–10.
16. Ragno VM, Klein CD, Sereda NS, Uehlinger FD, Zello GA, Robinson KA, et al. Morphometric, metabolic, and inflammatory markers across a cohort of client-owned horses and ponies on the insulin dysregulation spectrum. J Equine Vet. 2021;105:103715.
17. Dugdale AHA, Grove-White D, Curtis GC, Harris PA, Argo CM. Body condition scoring as a predictor of body fat in horses and ponies. Vet J. 2012;194:173–8.
18. Donaldson MT, McFarlane D, Jorgensen AJR, Beech J. Correlation between plasma alpha-melanocyte-stimulating hormone concentration and body mass index in healthy horses. Am J Vet Res. 2004;65(11):1469–73.
19. Hoenig M, Ferguson DC. Effects of neutering on hormonal concentrations and energy requirements in male and female cats. Am J Vet Res. 2002;63:634–9.
20. Gavarry O, Lentin G, Pezery P, Delextrat A, Chaumet G, Boussuges A, et al. A cross-sectional study assessing the contributions of body fat mass and fat-free mass to body mass index scores in male youth Rugby players. Sports Med Open. 2018;4(1):17.
21. Catalano DN, Coleman RJ, Hathaway MR, McCue ME, Rendahl AK, Martinson KL. Estimation of actual and ideal bodyweight using morphometric measurements and owner guessed bodyweight of adult draft and warmblood horses. J Equine Vet. 2016;39:38–43.
22. Martinson KL, Coleman RC, Rendahl AK, Fang Z, McCue ME. Estimation of body weight and development of a body weight score for adult equids using morphometric measurements. J Anim Sci. 2014;92:2230–8.
23. Bamford NJ, Potter SJ, Harris PA, Bailey SR. Effect of increased adiposity on insulin sensitivity and adipokine concentrations in horses and ponies fed a high fat diet, with or without a once daily high glycaemic meal. Equine Vet J. 2016;48:368–73.
24. Bamford NJ, Potter SJ, Baskerville CL, Harris PA, Bailey SR. Influence of dietary restriction and low-intensity exercise on weight loss and insulin sensitivity in obese equids. J Vet Intern Med. 2019;33:280–6.
25. Kohnke J. Feeding and nutrition: the making of a champion. Pymble, Australia: Birubi Pacific; 1992. p. 371–2.
26. Morrison PK, Newbold CJ, Jones E, Worgan HJ, Grove-White DH, Dugdale AH, et al. The equine gastrointestinal microbiome: impacts of weight loss. BMC Vet Res. 2020;16:78.
27. Knowles EJ, Elliott J, Harris PA, Chang YM, Menzies-Gow NJ. Predictors of laminitis development in a cohort of nonlaminitic ponies. Equine Vet J. 2022;55:12–23. https://doi.org/10.1111/evj.13572
28. DeLano K, McIntosh BJ, Kaufman K, Harris PA. Evaluation of body condition index in comparison with body condition score in horses and ponies. J Anim Sci. 2017;95:33 (abstract)–4.
29. Potter SJ, Harris PA, Bailey SR. Derivation of a new body condition index to estimate body fat percentage from morphometric measurements: comparison with body condition score. J Equine Vet. 2015;35(5):410–1. (abstract).
30. Fonseca RG, Kenny DA, Hill EW, Katz LM. The relationship between body composition, training and race performance in a group of Thoroughbred flat racehorses. Equine Vet J. 2013;45(5):552–7.
31. Harrison AP, Elbrønd VS, Riis-Oleson K, Bartels EM. Multi-frequency bioimpedance in equine muscle assessment. Physiol Meas. 2015;36:453–64.
32. Walker V, Tranquille C, Dyson S, Spear J, Murray R. Association of a subjective muscle score with increased angles of flexion during sitting trot in dressage horses. J Equine Vet. 2016;40:6–15.
33. Herbst AC, Johnson MG, Gammons H, Reedy SE, Urschel KL, Harris PA, et al. Development and evaluation of a muscle atrophy scoring system (MASS) for horses. J Equine Vet. 2022;110:103771.
34. Martin-Gimenez T, de Blas I, Aguilera-Tejero E, Diez de Castro E, Aguirre-Pascasio CN. Endocrine, morphometric, and ultrasonographic characterization of neck adiposity in Andalusian horses. Domest Anim Endocrinol. 2016;56:57–62.
35. Martin-Gomenez T, Aguirre-Pascasio CN, De Blas I. Beyond scoring systems: usefulness of morphometry considering demographic variables, to evaluate neck and overall obesity in Andalusian horses. Animal. 2018;12(3):597–605.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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