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Original Contribution

SEXUAL DIMORPHISM OF FORAMEN MAGNUM: VALIDATION OF LENGTH AS A SINGLE MORPHOMETRIC PREDICTOR

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ABSTRACT
PURPOSE: Skull morphometrics is very important in archaeology and forensic sciences for sex identification, especially when only limited osteometric data are available. The foramen magnum (FM) and occipital condyles, appears to be the most permanently preserved region of the human skeleton. The FM length (FML) is the most frequently measured, and often, the single available parameter of the FM in dry skulls. METHODS: FM data for 2524 skulls were taken from the Howells craniometric dataset (HCD). The validation cohort consisted of data for 177 Greek adult non-pathological intact dried skulls (GRD) as provided by the Aristotle University and National and Kapodistrian University (Athens). Descriptive statistics, parametric and non-parametric tests were used. Logistic regression modelling with the derivation of predicted probabilities and receiver operating characteristic ROC curve analyses with 95% CI were applied. Two-tailed P<0.05 was considered significant. RESULTS: The results indicate that the mean of the HCD FML in male was 35.78mm while FML mean in GRD was 35.337mm. The original regression model had predicted correctly 65% of skulls. CONCLUSIONS: There was no significant difference between the predicted and observed values for sex in the Greek skulls validation set. FML, alone, can predict sex (male) with accuracy limit of 71%.

Key words: skull, morphometrics, forensic science, foramen magnum length, sex identification, validation, logistic regression modelling

INTRODUCTION

Skull morphometrics is very important in archaeology, forensic sciences and neurosurgery for precise anthropometric assessment of biological variability and sex identification, especially when only limited osteometric data are available (1-4).

The skull base, particularly the foramen magnum (FM) and occipital condyles (OCs) **(Figure 1A)**, appears to be the most permanently preserved region of the human skeleton. The FM length (FML), or *opening* (vertical line 1 on **Figure 1A**) is the most frequently measured, and often, the single available parameter in dry skulls. Skull-base radiology employs FML, in particular, as a "McRae's line" (horizontal line 2 in **Figure 1B**) as a standard reference tool to assess basilar impression. McRae's line is also part of the Power's ratio which is used as a ruleto estimate occipito-atlantal instability and dissociation (3-5).

Foramen magnum data for 2524 skulls (1368 male and 1156 female) were taken from the Howells craniometric dataset (HCD) which is freely accessible online at http://web.utk.edu/~auerbach/HOWL.htm as compiled between years 1965-1980 and described by Howells (1).

The validation cohort consisted of data for 177 (102 male and 75 female) Greek adult non-pathological intact dried skulls (GRD) as provided by the Aristotle University (Thessaloniki) and National and Kapodistrian University (Athens) as previously described elsewhere (2).

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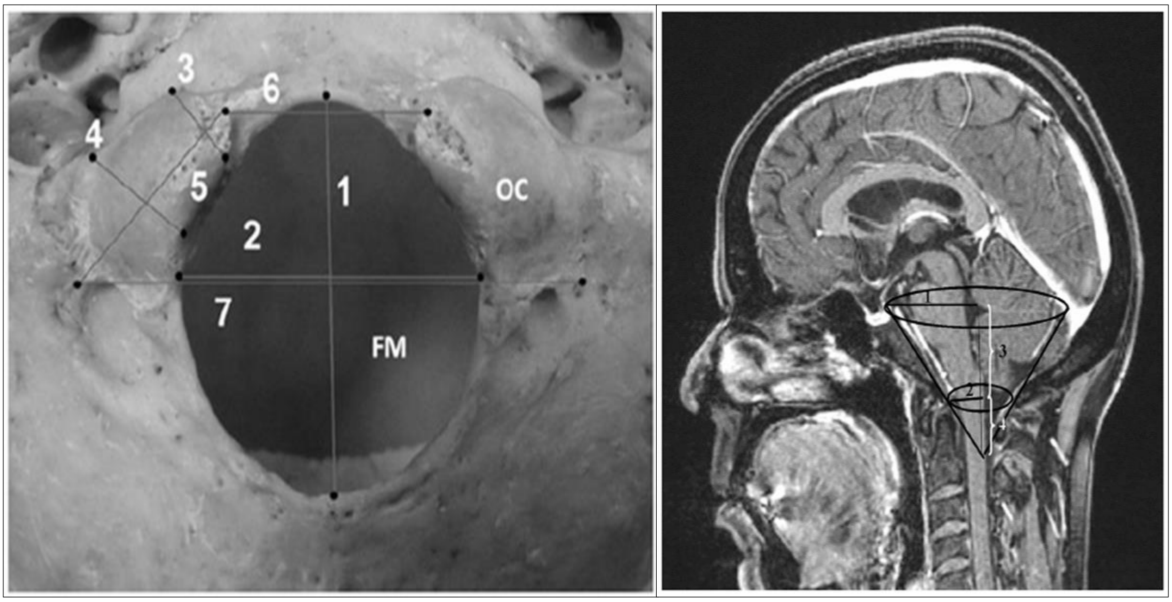
The aim of the study was to assess the classification performance and external validity of a univariate logistic regression model to estimate sex by foramen magnum length as a single available morphometric predictor.



1A. Foramen magnum (skull base) **1B.** Lateral (sagittal) view of MRI on skull

Figure 1. Foramen magnum length (FML)

MATERIALS AND METHODS

Foramen magnum data for 2524 (1368 male and 1156 female) skulls were taken from the Howells craniometric dataset (HCD) as compiled between 1965 and 1980 (Howells 1973, 1989, 1995). The validation cohort consisted of data for 177 (102 male and 75 female) Greek adult non-pathological intact dried skulls (GRD) as provided by the Aristotle University (Thessaloniki) and National and Kapodistrian University (Athens) as previously described elsewhere (Natsis, Piagkou, Skotsimara et al., 2013) (2).

Descriptive statistics, parametric and non-parametric tests for comparison and univariate analyses of the distributions were used. Logistic regression modelling of sex (category "1" = male) with the derivation of predicted probabilities and classification of each skull (at standard cut-off of 0.50) was performed. The receiver operating characteristic ROC curve analyses with 95% confidence interval (CI) were applied. Discrimination performance and models accuracy were measured by the area under the ROC curve with its 95% confidence intervals (6) while the marginal homogeneity between predicted and observed frequencies was confirmed by the McNemar test.

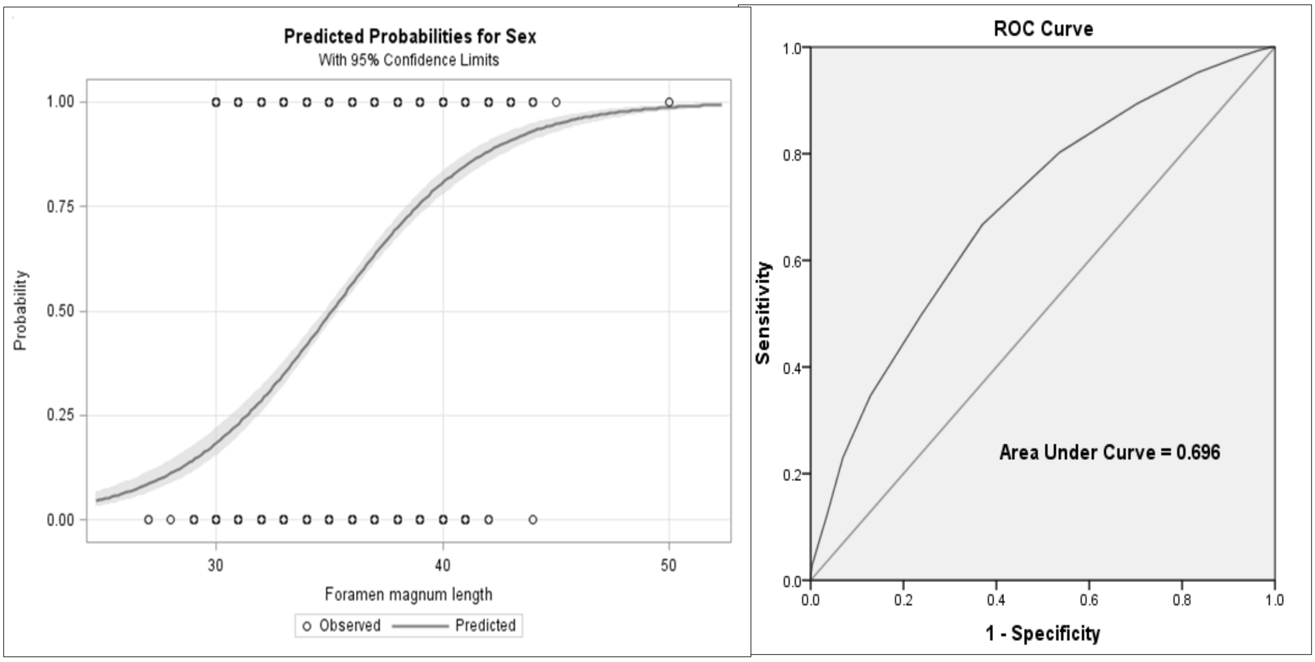
Calibration performance of the models was evaluated by Hosmer and Lemeshow test. Calibration was also assessed by fitting of predicted probabilities to observed frequencies, according to FML deciles. Two-tailed $P<0.05$ was considered significant. All analyses were completed in SPSS, Stata and SAS packages.

RESULT 1: DERIVATION

Equation 1: Probability of male sex [0.0-1.0] = (exp(-10.264+FOL*0.292)) / (1+exp(-10.264+FOL*0.292))

The values of mean±SD of foramen magnum length in Howells craniometric dataset (HCD) were 35.78±2.64 mm (male: 36.60±2.53 and female: 34.81±2.42, $P<0.05$) while foramen magnum length in Greek adult non-pathological intact dried skulls (GRD) were respectively 35.337±3.082 mm (male: 36.018±3.312 and female: 34.411±2.473).

The original regression model (derivation model) in HCD (see Equation 1) had predicted sex correctly an average of 65% of skulls **(Figure 2)** from both sexes (area under ROC curve = 69.6%, with 95% CI 67.5-71.6%, $P<0.001$) and best cut-off of 35.50 mm (maximum expected "shrinkage" of 2.605%).



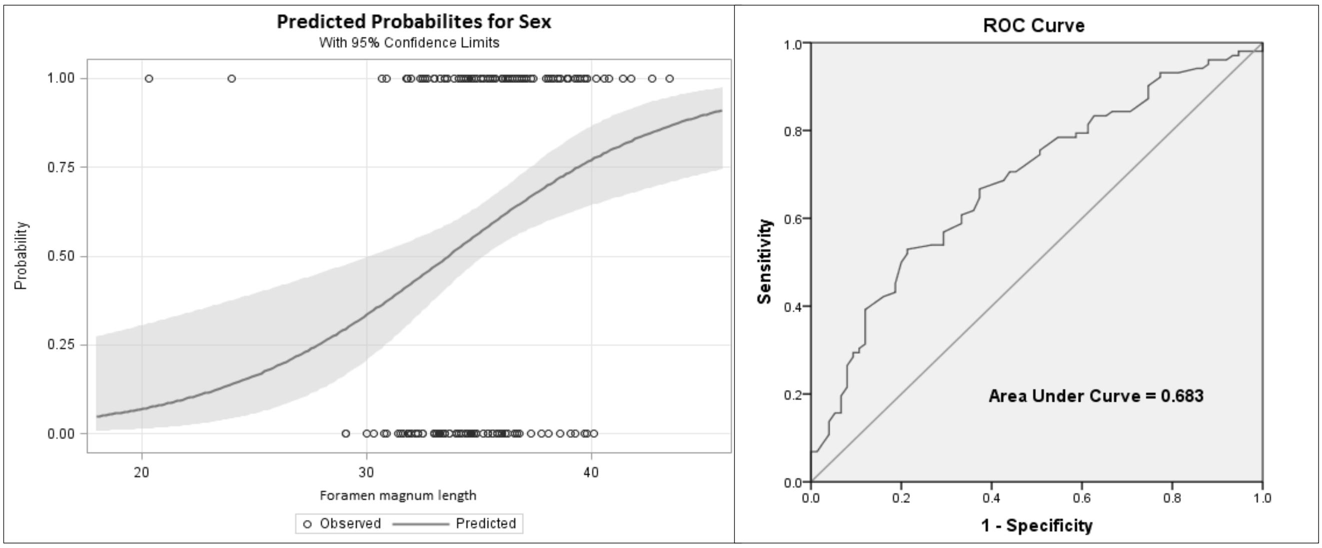
2A. Logistic regression model (1, male; 0, female) **2B.** Accuracy of sex classification (AUC_{ROC})
Figure 2. Derivation model to predict sex by foramen magnum length (FML) on Howells data.

RESULT 2: VALIDATION

Further, by employing the foramen magnum length from Greek dataset and sex data, the foramen magnum length from Howells dataset (derivation) model was assessed for calibration (validated) internally (p_{H-T}=0.72) and externally by:

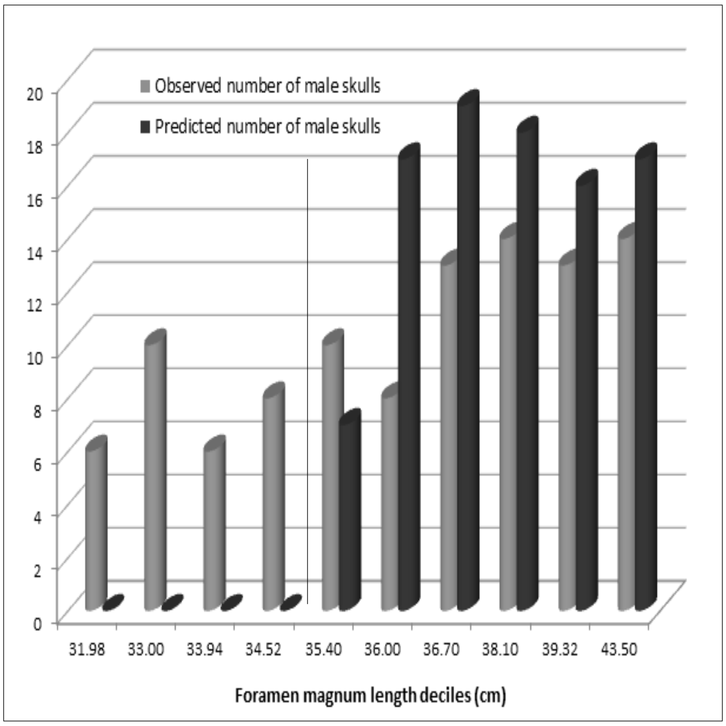
(1) applying its coefficients (see equation
(2) predicting probabilities and
(3) classifying the Greek skulls as "male" or "female" (cut-off of 0.50).

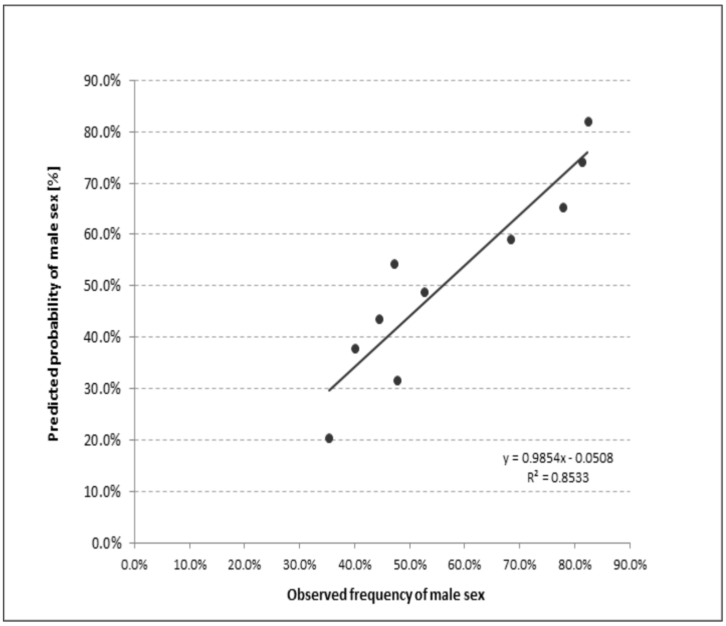
For comparison, same type of univariate logistic regression model was developed by using foramen magnum length on validation data (Greece) **(Figure 3A)**



3A. Logistic regression model (1, male; 0, female) **3B.** Accuracy of sex classification (AUC_{ROC})
Figure 3. Models to predict sex by foramen magnum length on validation data (Greece).

The HCD FML (derivation) model was validated in GRD by using above regression coefficients (a=-10.264, b=0.292) and classifying the Greek skulls as male or female according to the calculated (predicted) probabilities. Using the predicted probabilities, the area under ROC curve, AUC_{ROC} was 68.3%, 95% CI (60.5; 76.2%), **(Figure 3B)** with best cut-off of 0.489 and corresponding to best cut-off FML of 35.10 mm (the straight line, **Figure 4A**). Model test accuracy (correctness) in GRD was 63.8% with 95% CI (56%; 71%). There was no significant difference between the predicted and observed values for sex (McNemar test P=0.525) in the Greek skulls validation set. Predicted and observed sex frequencies were homogeneous ($p_{McNemar}$=0.525) as was significant the calibration plot fit (P<0.01, **Figure 4B**).





4A. Frequency of male sex by FML deciles **4B.** Calibration plot (predicted *vs.* observed probabilities)

Figure 4. Predicted and observed frequencies in validation skull data (Greece).

DISCUSSION

Our derivation model to predict sex by foramen magnum length (OR=1.34, Fig. 2A) is very simple yet with very high power of 99.7% at P<0.00001. If validated in independent data from Greece where 57.6% were male skulls, a correct classification of 63.84% was achieved.

When additional foramen magnum dimension, e.g., width (breadth, line 2 on Fig. 1A), was also considered in a sequential algorithm (i.e., after foramen magnum length) in a way similar to that for end-stage renal disease (7), the average accuracy increased to 68.36% (with upper 95% limit of 75.2%).

CONCLUSION

- ✓ Length (opening) is often the most precise but, frequently, the single existing measure of the foramen magnum, especially on a sagittal view by CT or MRI.
- ✓ Foramen magnum length (FML) and its variability are very important parameters in craniometry (anthropology), identification (forensic science) and skull-base surgery.
- ✓ Foramen magnum length (FML), alone, can predict sex (male) with an upper 95% accuracy limit of 71%.
- ✓ There was no significant difference between the predicted and observed values for sex in the Greek skulls validation set.

ABBREVIATIONS

CT - Computed tomography
FM - Foramen magnum
FML - Foramen magnum length
GRD - Greek adult non-pathological intact dried skulls
HCD - Howells craniometric dataset
MRI - Magnetic resonance imaging
ROC (curve) - Receiver operating characteristic

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