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MORPHOMETRIC ANALYSIS OF THE HUMAN STERNUM FOR SEX ESTIMATION: A QUANTITATIVE APPROACH IN FORENSIC MEDICINE

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ABSTRACT

Background: Sex estimation is a fundamental step in the identification process during medico-legal investigations, particularly when dealing with fragmented or decomposed remains. The sternum, owing to its resilience and anatomical variability between sexes, serves as a valuable skeletal element for this purpose. **Aim:**This study aims to evaluate the reliability of various sternal measurements in determining sex in an Indian population. **Methods:** An observational cross-sectional study was conducted at the Department of Forensic Medicine and Toxicology, VMMC & Safdarjung Hospital, New Delhi, from January 2020 to June 2021. A total of 110 autopsied individuals aged between 10 and 70 years were included. Exclusion criteria comprised cases with fractured, deformed, or diseased sterna. After removal and maceration of the sternum, six osteometric parameters were recorded: length of manubrium, body of sternum, total sternum, and breadths of the manubrium and body, along with the sternal index. Receiver Operating Characteristic (ROC) curve analysis was used to evaluate the discriminative power of each parameter. **Results:** The study population comprised 84 males (76.36%) and 26 females (23.64%). All sternal parameters, except the sternal index (higher in females), were significantly greater in males ($p < 0.0001$). ROC analysis revealed that the length of the body of sternum was the most reliable predictor of sex, with an Area Under the Curve (AUC) of 0.906, sensitivity of 85.71%, specificity of 88.46%, and diagnostic accuracy of 86.36%. A cut-off value of >86 mm for males and ≤86 mm for females was established. The total sternal length and other parameters also showed acceptable to excellent diagnostic performance. **Conclusion:**Sternal measurements, particularly the length of the body of the sternum (86.36%), are reliable indicators for sex estimation in forensic settings. This study provides population-specific cut-off values for an Indian cohort, enhancing the utility of sternal morphometry in forensic anthropology and medico-legal practice.

INTRODUCTION

Identification is the process of establishing the individuality of a person, living or deceased. In medico-legal investigations, skeletal examination is essential for identifying unknown individuals, particularly for estimating sex, age, and stature (1,2). Other features such as race, scars, moles, and professional marks also aid in identification (3).Mass disasters such as plane crashes or fires often result in fragmented or decomposed remains, complicating identification (4). In such cases, forensic experts rely heavily on bones, particularly when soft tissues are destroyed.

The sternum is a flat, elongated bone forming the central anterior thoracic wall, protecting the mediastinal organs, especially the heart (5,6,7). Being subcutaneous and relatively resilient to decomposition, it is often preserved in forensic contexts.

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Sex determination is a critical first step in biological profiling, as it immediately halves the potential pool of identities (8). Reliable sex estimation requires high accuracy (correct identification within a sample) and reliability (performance on independent samples). Legal standards demand at least 95% accuracy(9). Skeletal sex differences become marked after puberty, typically around 15–18 years, with the pelvis, skull, sternum, and long bones providing the most reliable indicators (10,11).

Krogman reported 100% accuracy with complete skeletons, 95% using the pelvis alone, and 80% with long bones. The sternum shows about 80% accuracy in sex estimation (10). Since Wenzel (1788), the sternum has been studied as a single indicator, showing proportionally longer mesosterna in males (12). Dwight found a manubrium-to-body length ratio of 49:100 in males and 52:100 in females (10,13). The sternal index, calculated as (manubrium/body) × 100, averages 46.2 in males and 54.3 in females (14). Hyrtl's Law states this ratio is >1:2 in females and <1:2 in males (15). Ashley's "149 rule" suggests that a combined manubrium and body length ≥149 mm indicates male sex, with ~80% accuracy (16-18).

This study aims to evaluate the sternum for sex estimation, as it often remains intact even in severely decomposed bodies.

METHODOLOGY

Study Design and Participants

This study is an prospective observational Cross-Sectional study carried out in the Department of Forensic Medicine and Toxicology, Vardhman Mahavir Medical College & Safdarjung Hospital's, New Delhi, from Jan 2020 to June 2021 after obtaining hospital ethical committee approval (**IEC/VMMC/SJH/Thesis/2019-10/157**). Dead bodies of Indian population brought for autopsy to the Mortuary wing were the source population.

Sample Size

In the study of **Goksin Nilufer Yonguc et al** (19)., observed that correlation coefficient of total sternal length and stature was 0.806. Taking this value as reference, the minimum required sample size with 80% power of study and 5% level of significance is 10 study subjects. Also, sensitivity and specificity of total sternal length for predicting gender was 89.2% and 80% respectively. Taking this value as reference, the minimum required sample size with desired precision of 10%, 80% power of study, and 5% level of significance is 108 study subjects. To reduce margin of error, total sample size taken is 110.

Inclusion & Exclusion Criteria

Cases of both sexes where identity is known and Age greater than 10 years and less than 70 years were included in the study. Whereas, fracture of sternum, Unclaimed dead bodies, Skeletal deformities, diseased or deformed bones that affects sternum were excluded from the study.

Procedure and technique for the Removal of the Sternum

After obtaining informed consent from the deceased's relative, the body was placed in the supine position with arms by the sides, and an I-shaped incision was made from the chin to the symphysis pubis. The chest muscles were dissected with the knife directed inward towards the ribs, extending laterally to the mid-axillary line and over the clavicles. The chest cavity was opened by cutting the costal cartilages close to the costochondral junctions, starting from the second cartilage. The sternoclavicular joint was identified by shoulder movement, and its capsule was divided using a vertical, circular motion of the knife. The sternum was detached from the diaphragm and removed completely, with each specimen labelled. Maceration of soft tissues was performed by boiling the sternum in a solution of 7–8 grams of sodium hydroxide per litre of water, using 2 litres of solution in an aluminium vessel for 60–75 minutes. The specimens were monitored to prevent over-boiling and achieve optimal maceration. After boiling, the specimens were thoroughly rinsed, and residual soft tissue was removed using forceps and a soft brush. The cleaned bones were dried on a clean cloth for 2–3 days and then sealed in airtight zip-lock bags for preservation as shown in Figure 1.

Osteometric Parameters Used for Analysis

Measurements were taken using vernier callipers as shown in Figure 2,

1. Total length of sternum: Straight distance from the deepest point of the suprasternal notch to the point on the lower margin of the corpus Sterna in the mid-sagittal plane. When the sternum was not united as a single piece due to lack of fusion, individual segments were measured independently, and the total length is calculated by adding all.
2. Length of body of sternum: Straight distance from the point on the lower margin of manubrium to the point on the lower margin of the body in the mid-sagittal plane.
3. Length of manubrium: Straight distance from the suprasternal notch to the point on the lower margin of the manubrium in the mid-sagittal plane.
4. Breadth of manubrium: Straight distance between the most laterally placed points on the lateral margins of the manubrium, taken at right angles to the length of the manubrium.
5. Breadth of body of sternum: The straight distance between the most laterally placed points on the lateral margins of the body taken at right angles to the length of the body.
6. Sternal index:

$$\frac{\text{Length of manubrium}}{\text{Length of body}} \times 100$$

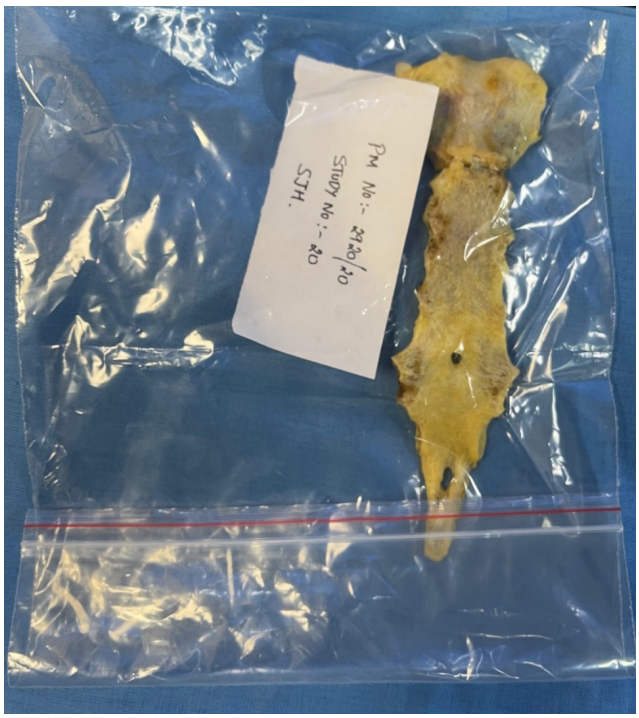
Statistical Analysis

Categorical variables will be presented in number and percentage (%) and continuous variables will be presented as mean ± SD and median. Normality of data will be tested by Kolmogorov-Smirnov test. If the normality is rejected, then non parametric test will be used. Pearson correlation coefficient/ Spearman Rank correlation coefficient (when the data sets are not normally distributed) will be used to correlate quantitative parameters. Receiver operating characteristic curve will be

used to find out the cut-off point of sternal lengths and breadths for predicting gender. Diagnostic test will be used to calculate sensitivity, specificity, NPV and PPV. A p value of less than 0.05 will be considered as significant. The data will be entered in MS EXCEL spreadsheet and analysis will be done using Statistical Package for Social Sciences (SPSS) version 21.0.

RESULTS AND OBSERVATIONS

In the present study, 26.36% of patients belonged to age group of 31-40 years followed by 21-30 years (23.64%), 41-50 years (21.82%), 51-60 years (12.73%), 11-20 years (8.18%) and 61-70 (7.27%). Mean value of age(years) of study subjects was 38.22 ± 13.7 with median (25th-75th percentile) of 35.5(29-47.75) as shown in figure 3.



In present study, 76.36% of patients were males and 23.64% of patients were females as shown in Figure 4.

Mean value of length of manubrium (mm), length of body of sternum (mm), length of total sternum (mm), breadth of manubrium (mm), breadth of body of sternum (mm) and sternal index of study subjects was 163.29 ± 8.16, 51.43 ± 5.19, 90.99 ± 11.77, 166.46 ± 19.24, 57.37 ± 7.25, 37.24 ± 6.47 and 57.49 ± 8.07 with median (25th-75th percentile) of 163(158-169), 51(48-54.95), 91.85(84.5-99.375), 167.5(154-180.375), 57(52-61), 37(32-42) and 57.06(52.65-62.092) respectively as shown in table 1.

ROC curves above the diagonal line are considered to have reasonable discriminating ability to predict sexual dimorphism. All the parameters had significant discriminatory power to predict male. Interpretation of the area under the ROC curve showed that the performance of length of body of sternum (mm) (AUC 0.906; 95% CI: 0.836 to 0.954) was outstanding. Discriminatory power of length of total sternum (mm) (AUC 0.894; 95% CI: 0.821 to 0.945) was excellent and discriminatory power of length of manubrium (mm) (AUC 0.75; 95% CI: 0.658 to 0.827), breadth of manubrium (mm) (AUC 0.782; 95% CI: 0.693 to 0.855), breadth of body of sternum (mm) (AUC 0.769; 95% CI: 0.679 to 0.844) and sternal index (AUC 0.739; 95% CI: 0.646 to 0.818) was acceptable. Among all the parameters, Length of body of sternum (mm) was the best predictor of male at cut off point of >86 with 90.60% chances of correctly predicting gender sex as male.

Length of body of sternum (mm) had sensitivity of 85.71% followed by breadth of body of sternum (mm) (84.52%), length of total sternum (mm) (82.14%), breadth of manubrium (mm) (79.76%). In prediction of male, Length of manubrium (mm) had lowest sensitivity of 52.38%. On the other hand, length of body of sternum (mm), length of manubrium (mm) had specificity of 88.46% each followed by length of total sternum (mm) (84.62%), breadth of body of sternum (mm)

Table 1. Descriptive statistics of measurements of study subjects.

Measurements	Mean ± SD	Median (25th-75th percentile)	Range
Length of manubrium (mm)	51.43 ± 5.19	51(48-54.95)	37.5-67.5
Length of body of sternum (mm)	90.99 ± 11.77	91.85(84.5-99.375)	66-119
Length of total sternum (mm)	166.46 ± 19.24	167.5(154-180.375)	115.5-216
Breadth of manubrium (mm)	57.37 ± 7.25	57(52-61)	40-83.5
Breadth of body of sternum (mm)	37.24 ± 6.47	37(32-42)	24-56
Sternal index	57.49 ± 8.07	57.06(52.65-62.092)	39.61-85.07

Table 2. Receiver operating characteristic curve of measurements to predict gender sex as male.						
Male	Length of manubrium (mm)	Length of body of sternum (mm)	Length of total sternum (mm)	Breadth of manubrium (mm)	Breadth of body of sternum (mm)	Sternal index
Area under the ROC curve (AUC)	0.75	0.906	0.894	0.782	0.769	0.739
Standard Error	0.0476	0.0342	0.0373	0.0488	0.059	0.0543
95% Confidence interval	0.658 to 0.827	0.836 to 0.954	0.821 to 0.945	0.693 to 0.855	0.679 to 0.844	0.646 to 0.818
P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cut off	>51.5	>86	>159	>52	>32	≤60.5
Sensitivity(95% CI)	52.38%(41.2 - 63.4%)	85.71%(76.4 - 92.4%)	82.14%(72.3 - 89.6%)	79.76%(69.6 - 87.7%)	84.52%(75.0 - 91.5%)	79.76%(69.6 - 87.7%)
Specificity(95% CI)	88.46%(69.8 - 97.6%)	88.46%(69.8 - 97.6%)	84.62%(65.1 - 95.6%)	61.54%(40.6 - 79.8%)	65.38%(44.3 - 82.8%)	65.38%(44.3 - 82.8%)
PPV(95% CI)	93.6%(82.5 - 98.7%)	96%(88.8 - 99.2%)	94.5%(86.6 - 98.5%)	87%(77.4 - 93.6%)	88.7%(79.7 - 94.7%)	88.2%(78.7 - 94.4%)
NPV(95% CI)	36.5%(24.7 - 49.6%)	65.7%(47.8 -80.9%)	59.5%(42.1 - 75.2%)	48.5%(30.8 - 66.5%)	56.7%(37.4 - 74.5%)	50%(32.4 - 67.6%)
Diagnostic accuracy	60.91%	86.36%	82.73%	75.45%	80.00%	76.36%

Table 3. Receiver operating characteristic curve of measurements to predict gender sex as female.						
Female	Length of manubrium (mm)	Length of body of sternum (mm)	Length of total sternum (mm)	Breadth of manubrium (mm)	Breadth of body of sternum (mm)	Sternal index
Area under the ROC curve (AUC)	0.75	0.906	0.894	0.782	0.769	0.739
Standard Error	0.0476	0.0342	0.0373	0.0488	0.059	0.0543
95% Confidence interval	0.658 to 0.827	0.836 to 0.954	0.821 to 0.945	0.693 to 0.855	0.679 to 0.844	0.646 to 0.818
P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cut off	≤51.5	≤86	≤159	≤52	≤32	>60.5
Sensitivity(95% CI)	88.46%(69.8 - 97.6%)	88.46%(69.8 - 97.6%)	84.62%(65.1 - 95.6%)	61.54%(40.6 - 79.8%)	65.38%(44.3 - 82.8%)	65.38%(44.3 - 82.8%)
Specificity(95% CI)	52.38%(41.2 - 63.4%)	85.71%(76.4 - 92.4%)	82.14%(72.3 - 89.6%)	79.76%(69.6 - 87.7%)	84.52%(75.0 - 91.5%)	79.76%(69.6 - 87.7%)
PPV(95% CI)	36.5%(24.7- 49.6%)	65.7%(47.8 - 80.9%)	59.5%(42.1 - 75.2%)	48.5%(30.8 - 66.5%)	56.7%(37.4 - 74.5%)	50%(32.4 - 67.6%)
NPV(95% CI)	93.6%(82.5 - 98.7%)	96%(88.8 - 99.2%)	94.5%(86.6 - 98.5%)	87%(77.4 - 93.6%)	88.7%(79.7 - 94.7%)	88.2%(78.7 - 94.4%)
Diagnostic accuracy	60.91%	86.36%	82.73%	75.45%	80.00%	76.36%

Table 4. Comparative statistics of manubrial and body of sternal lengths, mm (mean±3SD) of sternum studied by different workers (21-22, 25-34).

Author	Region	Sex	N	Length of Manubrium	t-test	Length of body of sternum	t-test
Dwight et al.	-	M	142	53.70	-	110.40	-
		F	86	49.40	-	91.90	-
Paterson et al.	-	M	310	52.00	-	103.70	-
		F	126	47.30	-	91.00	-
Ashley et al.	Africa	M	85	45.90	-	96.50	-
		F	13	44.20	-	82.90	-
Ashley et al.	Europe	M	378	52.20	-	104.70	-
		F	168	47.90	-	90.80	-
Selthofer et al.	Croatia	M	55	55.2±3.6	-5.25**	109.7±14.4	-7.59**
		F	35	52.4±4.5	-5.55**	94.2±14.0	-5.95*
Jit et al.	Chandigarh (India)	M	312	51.73±5.22	0.83	95.35±9.88	-1.52
		F	88	48.42±5.28	-1.60	78.60±9.31	-0.04
Dahiphale et al.	Maharashtra (India)	M	96	48.46±5.59	5.50**	94.43±9.43	-0.31
		F	47	43.78±5.24	3.60**	70.19±8.54	5.03**
Gautam et al.	Gujarat (India)	M	56	53.00	-	95 . 00	-
		F	44	48.00	-	76.00	-
Torwalt et al.	Canada	M	89	54.43±6.10	-3.20**	109.41±12.48	-10.42**
		F	41	48.79±4.92	-1.71	93.55±8.99	8.41**
Queiroz et al.	Brazil	M	50	-	-	88 .87±10.04	3.32**
		F	50	-	-	82.44±10 .05	-2.17*
Vella et al.	Italy	M	20	52.60±5.50	-0.38	97.7±7.70	-1.94
		F	20	43.20±4.90	3.18**	85.70±10.30	-2.76*
Fernandez et al.	Spain	M	36	51.56±5.63	0.54	101.13±7.69	-4.59**
		F	40	45.00±5.51	2.10*	82.71±8.40	-2.32*
Hunnargi et al.	Maharashtra (India)	M	75	51.99±4.96	0.17	89.17±10.63	1.32
		F	40	44.8810.63	3.53**	72.38±9.85	3.63**
Atal et al.	Delhi (India)	M	50	45.75±2.99	11.76**	100.28±6.25	-5.68**
		F	50	41.20±3.31	8.32**	78.35±6.26	0.14
Present study (2021)	Delhi (India)	M	84	52.42±5.21	-	94.92±9.65	-
		F	26	48.23±3.65	-	78.27±8.62	-

**Significant at 0.01 level. *Significant at 0.05 't'-Values for comparison with present study.

(65.38%). In prediction of male, Breadth of manubrium (mm) had lowest specificity of 61.54%. Highest positive predictive value was found in length of body of sternum (mm) (96.00%) and highest negative predictive value was found in length of body of sternum (mm) (65.70%). There is always a trade-off between sensitivity and specificity (any increase in sensitivity will be accompanied by a decrease in specificity) so we choose that variable as best in which combination of sensitivity and specificity gives the maximum predictive value i.e., maximum diagnostic accuracy.So overall length of body of sternum (mm) was best predictor of gender as shown in table 2.

ROC curves above the diagonal line are considered to have reasonable discriminating ability to predict female. All the parameters had significant discriminatory power to predict female. Interpretation of the area under the ROC curve showed that the performance of length of body of sternum (mm) (AUC 0.906; 95% CI: 0.836 to 0.954) was outstanding. Discriminatory power of length of total sternum (mm) (AUC 0.894; 95% CI: 0.821 to 0.945) was excellent and discriminatory power of length of manubrium (mm) (AUC 0.75; 95% CI: 0.658 to 0.827), breadth of manubrium (mm) (AUC 0.782; 95% CI: 0.693 to 0.855), breadth of body of sternum (mm) (AUC 0.769; 95% CI: 0.679 to 0.844) and sternal index (AUC 0.739; 95% CI: 0.646 to 0.818) was acceptable.Among all the parameters, Length of body of sternum (mm) was the best predictor of female at cut off point of ≤86 with 90.60% chances of correctly predicting female.

Length of manubrium (mm) and length of body of sternum (mm)had sensitivity of 88.46% each followed by length of total sternum (mm) (84.62%), breadth of body of sternum (mm) (65.38%). In prediction of female, Breadth of manubrium (mm) had lowest sensitivity of 61.54%. On the other hand, length

of body of sternum (mm) had specificity of 85.71% followed by breadth of body of sternum (mm) (84.52%), length of total sternum (mm) (82.14%), sternal index (79.76%). In prediction of female, Length of manubrium (mm) had lowest specificity of 52.38%. Highest positive predictive value was found in length of body of sternum (mm) (65.70%) and highest negative predictive value was found in length of body of sternum (mm) (96.00%). So we choose that variable as best in which combination of sensitivity and specificity gives the maximum predictive value i.e. maximum diagnostic accuracy so overall length of body of sternum (mm) was best predictor of female as shown in table 3.

DISCUSSION & CONCLUSION

It was obvious from the foregoing observations that all parameters measured have a higher value in males except sternal index which is greater in females. This is in total agreement with previously studies (10, 20-24). Table 4 shows the comparative statistics of manubrial and body of sternal lengths, mm (mean±3SD) of sternum studied by different workers in various parts of world including India.

All the parameters of the sternum i.e., the length, breadth of the body, breadth of the manubrium, sternal index and total length showed significant statistical difference between males and females. The sternal index is found characteristically high in all the studies in females (10, 14, 35, 36). This is reflected in the higher mean values obtained for females (62.11 ± 6.67) in this study, when compared to that of males (56.06 ± 7.95). Sternal index is calculated from the formula: Length of manubrium X 100/ Length of body. The reason for the higher value of sternal index in females may be attributed to the following: The length of manubrium exceeds half the length of body of the sternum in females; while in males, the length of body of sternum is at least twice the length of manubrium. This view which had been put forward by many authors and workers has also been noticed in the present study (35, 36). This observation could also explain the reason for the statistically significant difference in the measurements of length of manubrium in males and females. One author is of the view that the manubrium is somewhat smaller in males while bigger in females (37). Jit et al., have opined that manubrium corpus index is not useful in sexing a given sternum (23). Dwight et al., stated that variations in the length of manubrium in the two sexes are minimal but an individual sternum is usually found to lie in the overlapping zone (26). Only a negligible percentage of sternums could be sexed accurately in the present study, as well as by Jit et al., using demarking points for length of manubrium(22). Using limiting point for this variable while the present study could estimate sex with an accuracy of 60.91%, whereas in study by Hunnargi et al., this variable achieved an accuracy of around 77% (29).

The mean length of body of the sternum was found to be significantly higher in males (94.92mm) than females (78.27 mm). This observation is in close agreement with those of Wenzel et al., Krogman et al., Paterson et al., and Jit et al., have all suggested that length of body of the sternum is greater in males (10, 20-22). The accuracy for sex estimation based on limiting point for length body of the sternum in the present study (86.36%) closely match that found by Hunnargi et al(29).

The mean total length of sternum is also significantly higher in males (172.7mm) than in females (146.31mm). This finding again is in concordance with the observation of Jit et al (22). The accuracy of sex estimation derived from combined length of manubrium and sternum using either Ashley's 'rule 149' (by Jit et al., and Hunnargi et al.) or using limiting point (by Hunnargi et al.; and present study) happens to be almost similar ranging between 82.1 and 94.5% and was in concordance with the present study (accuracy: 82.73%) (22, 29).

ROC curves above the diagonal line are considered to have reasonable discriminating ability to estimate sex. All the parameters had significant discriminatory power to predict male. Length of body of sternum (mm) had sensitivity of 85.71% and length of manubrium (mm) had lowest sensitivity of 52.38%. On the other hand, both the length of body of sternum (mm) and the length of manubrium (mm) had specificity of 88.46% and breadth of manubrium (mm) had lowest specificity of 61.54%. Present study had mentioned a definite cut off value above or below which the sternum can be sexed. Therefore, a subject is likely **male** if:

- Sternal body > 86 mm
- Manubrium length > 51.5 mm
- Sternal body breadth > 32 mm
- Manubrium breadth > 52 mm
- Sternal index ≤ 60.5
- Total sternum length > 159 mm

Likely **female** if these values are equal to or below the above thresholds, where was , it vice versa for sternal index.

There is always a trade-off between sensitivity and specificity (any increase in sensitivity will be accompanied by a decrease in specificity) so we choose that variable as best in which combination of sensitivity and specificity gives the maximum predictive value i.e., maximum diagnostic accuracy. So, overall the length of body of sternum (86.36%) was best predictor of Sex.

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