Introduction
Increasingly, computed tomography (CT) imaging has become an accepted and more utilized non-invasive method in skeletal biological sex estimation and classification. CT data have been used to generate 3D skeletal models (3DCT) from which morphological features of the skull have been assessed. Furthermore, 3DCT is one method that may be used in conjunction with discrete 3D coordinate data points, which are commonly employed for craniometric assessment of sex.

Several studies have assessed the precision of 3DCT acquisition of landmarks as compared to traditional caliper measurements and coordinate data collected by use of a digitizer on actual skulls, and no significant differences were found (Hildebrand et al. 1990; Williams & Richtsmeier 2003). Additionally, no significant differences were found when using the method of observation for landmark designation (Richtsmeier et al. 1995), suggesting that coordinate data from CT scans can be reliably used for sex estimation.

The purpose of this study was to assess the validity of craniometric landmark generation from 3DCT scans for sex determination. Both size and shape differences between the sexes were explored with 2D craniometrics and also with 3D geometric morphometric analysis (GMA).

Materials and Methods
The present analysis was conducted on a sample of 104 (M=50, F=54) post-mortem CT scans collected by the Department of Forensic Medicine, University of Copenhagen. These data contain adult individuals of documented sex. Individuals were scanned at a voltage peak of 120 kVP with slice thickness varying between 0.5mm and 2.0mm.

Segmentation and rendering of the data was done using Materialise Mimics medical imaging software to create 3DCT models of the skull for each individual. From the 3DCT, 21 landmarks of the skull, as outlined in Moore-Jansen et al. (1994) (Table 1), were designated on each cranium in Mimics (Figure 1). The coordinate data for each landmark and for each individual were then exported from Mimics to PAST (Paleoanthropological Statistics) software (Hammer et al. 2001) and SPSS statistical software programs for further analyses.

From the 3D coordinate data, inter-landmark distances (ILD) were used to generate 22 traditionally used 2D, linear craniometric measurements (Table 2). An independent samples t-test was used to test for significant differences between males and females in mean measurements. The ILD measurements of the skull predominantly capture size differences and to a lesser extent, shape differences. To investigate overall shape, independent of size, in the sample, GMA was conducted to analyze specific shape differences between the sexes. Generalized Procrustes Analysis was done to separate size and shape by rotating, scaling, and translating the raw coordinates of each cranium to the same relative position known as the Procrustes Coordinates. Individuals with missing values were supported by column average substitution. Discriminant function analysis (DFA) was then performed using leave-one-out cross validation (LOOCV) and a forward Wilks’ lambda stepwise selection on both the 2D and 3D data to determine how well the individuals within the sample correctly classified into the appropriate sex group. Finally, the DFA results were then visualized for the GMA using MorphoJ (Klingenberg 2011).

Results
Six ILDs were significantly different between males and females in this sample (Table 3; Figure 2). These two variables were used in stepwise selection of all 22 ILD in DFA. Using these two variables produced 74.0% cross-validated combined classification accuracy with males classifying slightly better than females (Table 4; Figure 2).

The Procrustes Coordinates produced 71.2% cross-validated, combined classification accuracy with males again classifying slightly better than females (Table 4; GMA) (Figure 3). Five coordinates were selected in the stepwise analysis: FMBR_Y, FMXR_X, L_Z, EUR_Z, GOR_Y. Males had markedly larger shape differences than females in specific regions (in order of extent of differences): prosthion, bregma, infradentale, foramen magnum left, foramen magnum right, euron left, euron right, zygion left, and zygion right (Figures 4-6; females represented by red dots & males represented by blue lines).

Discussion and Conclusions
Using traditional 2D measurements, biconal width (GO-GO) and upper facial height (N-PR) best separated males and females based predominantly on size. Interestingly, these areas were not the areas of greatest differences between males and females in the shape analysis. Based on the greater displacement of the landmarks shown in Figures 4 to 6, males were generally more prognathic in the mouth region (PR & ID). They also tended to have larger shape differences in the width of the foramen magnum (FMB left & right) and in cranial breadth (EU left & right) than females.

References

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Table 1. Independent mean test for sex differences between cranial variables.

Table 2. Independent mean test for sex differences between cranial variables.

Table 3. Independent sample t test for sex differences between cranial variables.

Table 4. LOOCV correct classification count for ILD.

Figure 1. Mean landmark points for males and females after GMA in lateral view (photo from Williams & Williams 2001).

Figure 2. Two-way LOOCV DFA result for sex using two important selected variables.

Figure 3. Procrustes Coordinates produced 71.2% cross-validated, combined classification accuracy with males again classifying slightly better than females (Table 4; GMA) (Figure 2). Five coordinates were selected in the stepwise analysis: FMBR_Y, FMXR_X, L_Z, EUR_Z, GOR_Y. Males had markedly larger shape differences than females in specific regions (in order of extent of differences): prosthion, bregma, infradentale, foramen magnum left, foramen magnum right, euron left, euron right, zygion left, and zygion right (Figures 4-6; females represented by red dots & males represented by blue lines).

Figure 4. Mean landmark points for males and females after GMA in lateral view (photos from Williams & Williams 2001).