Understanding the Cross Sectional Morphology of Flight Feather Shafts

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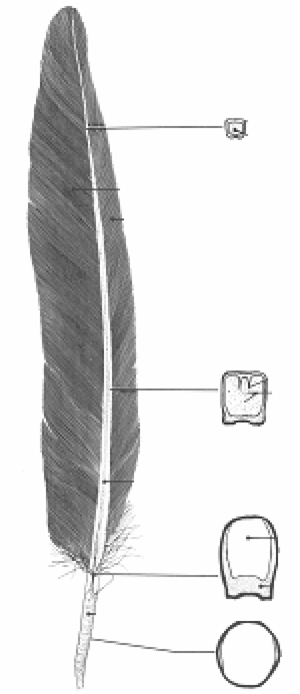
ABSTRACT **In the past, the cross sectional morphology of flight feather shafts was quantitatively non-existent, and any characterizations lacked explicit detail. The ability to mimic naturally found flight necessitates a full understanding of even the most perfunctory flight characteristics of flight feather shafts. Moreover, the onset of technology available today has provided a more accurate means of analysis for such applications. In this investigation flight feather shafts were cut and initially analyzed by means of a Charged Couple Device (CCD). A Computerized Tomography (CT) Scanner was later found to more accurately characterize the cross-sectional morphology of the flight feather shafts. Methods were devised to precisely and cautiously cut the feather flight feather shafts without destroying the specimen, all while minimizing kerf losses. As no methods by which flight feather shafts are cut into cross sections exist in literature, devising such a methodology became an assiduous procedure. Computerized tomography software was optimized to consider the varying characterization parameters along entire length of the flight feather shaft. The full flight feather shaft lengths were analyzed from calamus to tip. The two principle species analyzed in this research focus on the Anas platyrhynchos and the Archilochus colubris. Quantitative cross-sectional morphology data was gathered from reconstructed computerized tomography images. Specific surface ratios, x and y second moments of inertia, polar moments, and eccentricity measurements were determined from these cross sections. The accuracy of the results is somewhat dependant upon the analyst's interpretation of the region interest associated with the cross-sectional material. A study on the accuracy related to the methods in which the user collects data was done in effort to gauge the legitimacy of these findings.**

Prior to this investigation, previously conducted research revealed that the most detailed understanding of the cross-sectional morphology of flight feather shafts was found in hand-rendered drawings. Found to be the work of greatest relevancy, Purslow & Vincent[1] (1978), take a cursory delve into some understanding of the cross-sectional morphology of flight feather shafts. Modeling feathers in bending to determine the load response, being at the crux of their research; there is some geometric reference to the cross-sections of the circular calamus and the shaft's transitioning to a square cross-section throughout the rachis to the primary feathers' tips. The Columba livia bird species is of similar size to that of the Herring gull. Figure 1 (*Purslow & Vincent)* illustrates the bulk of what has been formerly accepted as the morphological characterization of flight feather shafts. The flight feather shaft shown in this image belongs to the pigeon species of the Columba livia. Most importantly and perhaps apparent, the shaft transitions from more of a circular cross section to a square along the rachis, beginning from the calamus to the tip of the shaft.

Fig. 1.



(Purslow & Vincent[1]) Formerly accepted as the extent of the knowledge associated with the cross sectional morphology of flight feather shaft.

Flight feather shafts have structural responsibilities for transmitting the lift and drag forces generated during flight to the organism's wing, transitively the organism's center of mass. Biomimetic flight vehicles, and micro aerial vehicles being a segment of biomimetics, lately are of increased curiosity. More specifically, this type of study has experienced an increased interest in the research of applications such as, surveillance and reconnaissance as a result of the agility advantages found in natural flight. Understanding natural flight vehicles from the ground up becomes essential to recreating and simulating natural flight artificially; and has caused some enthusiastic concern about the structural components associated with natural flight.

Analyzing the cross sections of flight feather shafts involves using a metric(s) to convey results related to a particular interest. For example, moments of inertia with regard to this investigation, yield biomechanical properties necessary for understanding the feather structurally. Moments of inertia can explain how the flight feather shaft will respond to various bending and twisting loads induced during flight. More pertinent for biological implications becomes the specific surface ration, or perimeter to area ratio. However, simple values for planar areas of the keratin cross sections of the flight feather shafts have the ability to be equally as important in a comparative sense. Of course there are many other metrics for characterizing planar areas as well, such as height to thickness ratios and eccentricity. Given the unexplored nature of the study, speculation as to the most critical metric is presumptuous.

Flight characteristics such wing beat frequency and paths are unique to all species, with some species sharing more similarities than others. Such a conceptual notion is thought to be true in structural terms as well. The Archilochus colubris species, also referred to as the Ruby-Throated Hummingbird, is of particular interest. This species was selected because not only do the physical size dimensions of the species exist as a bridge between insects and songbirds, but the species' flight characteristics are unique as well. The Anas platyrhynchos species, a duck species commonly referred to as the mallard, was selected for analysis because it is somewhat larger than a songbird, yet smaller than birds from larger categories, such as turkeys or geese. The species selected for this investigation were arbitrarily selected based upon this idea.

CCD technology enables images to be captured digitally. In basic terms, an array of coupled capacitors integrated into a circuit comprises a CCD unit. The principles of the photoelectric effect allow electrical charges to be converted into images. Thus, when incorporated with an optical microscope and a dimensioned grid slide, data can be gathered from viewing CCD images of cross sections. Such technology is helpful for delimiting the exact material to be quantified, yet is time intensive and seemingly less accurate than more advanced computerized approaches.

CT is a nondestructive technique that uses flat x-ray images to construct both two and three-dimensional images. A testing specimen is placed on a rotating stage located between an X-ray source and collector. Dimensions are only characteristic that can be obtained from CT image analysis. The accessibility of a CT scanner superseded the concept of using any CCD equipment late in the project. Figure 1A (Appendix) displays a simplified schematic further explaining CT.

At the onset of this project, no formal or accepted methods for cutting the flight feather shafts into cross-sections existed in literature. Lack of any accepted cross-sectioning method stipulated that one be devised. Henceforth from this realization, various cutting methods were explored and experimented upon. Thus the objective for devising a technique to cut the flight feather shaft is to do so without suffering any defects to the shaft itself, maintaining geometry. Such an idea encompasses minimizing the kerf loss effects as well. Cutting cross sections to be analyzed with a CCD necessitated the utmost level of precision, as cross sections were to be cut in 1 mm intervals or less along the lengths of the shafts analyzed. For cross sectional analysis conducted with the CT machine, cutting error was tolerated to be marginally more acceptable. However, the same method for cutting the cross sections of the flight feather shafts can be applied to both analytical methods, CCD and CT

MATERIALS & METHODS

Determining Suitable Specimen Preparation

Over 300 CT images were processed and used to carry out this investigation. Images were taken from species, Anas platyrhynchos and the Archilochus colubris. Testing images were also captured from Hearing gull cross sections in an effort to develop familiarization and methodology with the testing equipment. The images taken of the Hearing gull flight feather shafts were arbitrarily selected, and were found discarded in the organism's natural environment. The flight feathers of the Anas platyrhynchos were acquired locally at a craft store. The Archilochus colubris specimens were obtained academically.

The specific orientation of the flight feather shaft analyzed from the Anas platyrhynchos relative to the organism's wing is unknown; however is likely to be a more proximal primary flight feather. The size and shape of the flight feather taken from the Anas platyrhynchos possessed the size characteristic of a second flight feather, yet resembled the geometrical shape of a primary flight feather. The P10 and P9 primary feathers of the Archilochus colubris were analyzed by CT method. These are the outer two flight feathers on the wing of the organism. Figure 2 shows the position of these flight feathers relative to the wing of the Archilochus colubris. All bird species have 10 primary feathers. Note the location of the secondary flight feathers labeled S1 through S6 in the figure, and their distal position to the primary flight feathers. The flight feather shafts were scanned and analyzed via CT from the superior umbilicus to the tip of the shaft.

Fig. 2. Archilochus colubris Flight feather indicating the location of the primary and secondary flight feathers relative to the wing.

Various materials for cutting the flight feather shafts into cross sections were used in effort to either substantiate or disprove researched claims[2] thought to be relevant. A scalpel was used to remove the feathers' veins, in effort to isolate the feather shaft. Buehler Epo-Heat epoxy was injected via a syringe to maintain the integrity of the thin walled keratin structure of the flight feather shaft. Tempering with a Fisher Scientific Isotemp Furnace at 72°C for 15 minutes was experimented in parallel with the epoxy method, as was the soaking of the flight feathers in a 24 hour bath of water at room temperature (≈ 60°C). The central aim of the tempering was to harden the feather shaft to preserve its natural form while it is cut into cross sections. Several Hearing gull flight feather shafts were experimentally tempered and later cut. Prior to the three tempering methods experimented, the majority of the vanes were removed from each of the feather shafts. The vanes were delicately removed by scalpel. The entire vane could not be cut off due to its connection to the flight feather shaft. When the entire vane was cut off, the feather shaft split longitudinally as a result of the inherent shaft – vane connection.

A Buehler Isomet Low-Speed saw and scalpel were experimented with to establish an optimal cutting method for the entirety of the investigation. A new surgical scalpel blade was used for cutting each flight feather shaft. The low-speed saw was fitted with a Series 15-HC diamond wafering blade that was allowed to rotate at a setting of 6.5 units on the dial speed adjustment, which corresponds to angular velocity of approximately 200 rpm. A 75 gram mass induced the cutting action force when fitted upon the weight shaft stand and was countered with a counter weight balance. Figure 3 schematically illustrates the components of the Buehler Isomet Low-Speed saw.

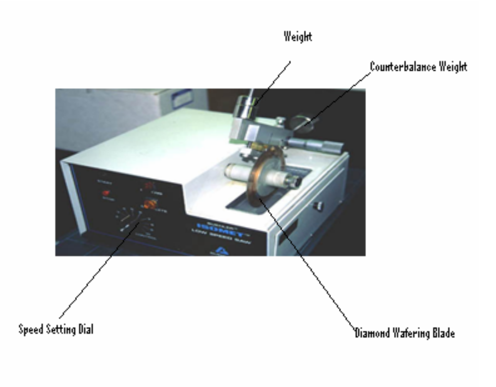


Fig. 3. Schematic illustration of the Buehler Isomet Low-Speed used to cut flight feather shafts into cross sections.

Use of the low speed saw proved superior to that of the scalpel, thus becoming the single means for cutting. A dial micrometer located between the weight and counterweight on the support arm of the saw accurately gauged the cuts. 1 millimeter cuts were made on hearing gull shafts and later cataloged for analysis with the CCD machine, while larger cuts were taken and cataloged for CT analysis.

Image Acquisition

A COHU CCD was used in conjunction with an Olympus BX60 optical microscope to gather images of the 1 millimeter cut cross sections. This method prefaced the CT method and served as more of a visual means of characterization. Figure 4 shows a digital image of an arbitrary Hearing gull's flight feather cross section captured with a CCD. Images were mounted on a 1 millimeter grid slide and viewed at 10x optical zoom setting. Note the ventral and dorsal positions of the shaft's cross section are indicated Due to the time intensive practice of cutting the 1 millimeter cross sections of the flight feather shafts and analyzing the CCD images manually, this methodology was abandoned for the more favorable and later CT technology.

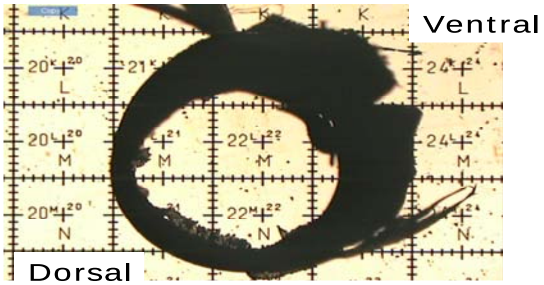


Fig. 4. CCD captured image of a Hearing gull's flight feather shaft found near the superior umbilicus.

A SKYSCAN 1074 Portable X-Ray Microtomograph was used to capture images for CT processing. Images were acquired with a maximum x-ray production power of 40 watts, comprised of 40 kilovolts and a 1,000 milliamps current. Depending upon shaft size, images were scanned at exposure times of 60 and 120 microseconds. The shafts of the Anas platyrhynchos were scanned a larger exposure time, as they are larger and easier for the x-ray collector to resolve. The flight feather shafts of the Archilochus colubris were scanned at an exposure time of 60 microseconds. The images were acquisitioned with the smallest rotating step angle interval allowable at 0.90° over 180° of rotation. Images were fitted into molding putty fixed upon the rotating stage of the x-ray microtomograph. The images were oriented such that cross section of the flight feather shafts existed in the cervical plane (abscissa and ordinate section), while the shaft length existed in the occlusal plane (z coordinate direction) of the CT scanner. Such configuration logically increased the amount of cross section to be analyzed in one scan, thus decreasing the number of cuts, conceivably yielding greater accuracy. It is from the cervical plane that the CT analysis was conducted, and the metric data was obtained. Figure 5 schematically shows the setup for the x-ray microtomograph, and the flight feather shaft's orientation within the apparatus. For the Anas platyrhynchos species, the flight feather shaft was cut into five segments for analysis, while the P10 and P9 feathers of the Archilochus colubris species did not need to be cut.

Image Reconstruction

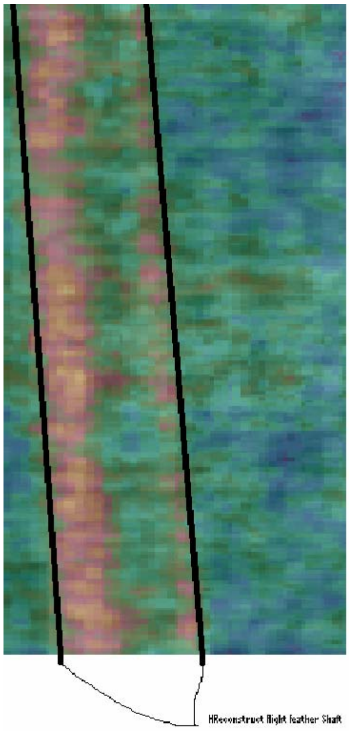


Fig. 5. Image viewed in NReconstruct Application. Outlined is the rachis section of a flight feather shaft from an Archilochus colubris to be reconstructed into cross section intervals of 0.062mm.

Upon the acquisitioning of the specimen, the images captured were reconstructed via the SKYSCAN NReconstruct application. Within this application the images captured during acquisitioning are compiled for three-dimensional rendering of the specimen. It is here that the first CT calculations are processed to indirectly arrive at the desired results. Within this application the user has ability to define the region of the occlusal plane that is of interest. The entire acquisitioned specimen was selected for every flight feather shaft analyzed in this investigation. In addition it is here that the user selects the intervals of cross sectional cuts to be computed by the software. Cut interval sizes, or steps, were selected at 3 units, corresponding to 0.062 millimeters per cross sectional cut along the length of the flight feather shaft. The same reconstruction settings were applied to the analyzed flight feather shafts of the Anas platyrhynchos and Archilochus colubris species. This computerized reconstruction was expeditious relative to the lengthy acquisition process, requiring approximately 5 minutes per rendering, and required the accessibility of host server. Figure 2A of the appendix displays the application screen with the various user controls highlighted.

CT Binary Image Processing

After the reconstruction rendering occurred, the images were cross sectioned and ready for CT processing and analysis. Reconstructed files created within the NReconstruct application were opened within the SKYSCAN CT-Analyzer version 1.4.0.0 application. In order for the desired dimensioning and subsequent calculations to be made, the reconstructed and complied images must be converted to the binary view mode within the application and the millimeter length preference selected for calculation. Once in binary viewing mode, the desired metrics were allowed to be processed.

Before any metrics are calculated the region of interest was determined by the user. A toggle bar within the binary viewing component of the application facilitates a toggle switch to control region of interest associated with half-tone binary image. This metrics data that resulted were heavily dictated by this method step. This step proved useful for removing the excess vanes that could not be entirely cut away. However, deciphering what was the most accurate selection of the cross sections to be analyzed was not rudimentary, and required a great deal of care. Figure 6 display the CT-Analyzer's user interface window, showing a cross section and its corresponding position along the length in the occlusal plane of the scanned specimen taken 3 millimeters above the bottom of the specimen. This Figure was taken from the raw image mode and not the binary image viewing mode. Notice the slight existence of veins that occurs on the sides of the image.

Such defects were minimized in the CT-Analyzer application.

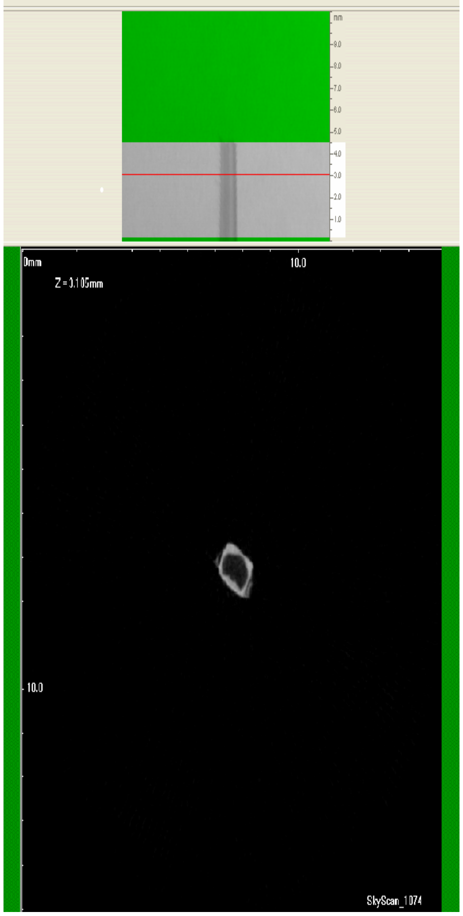


Fig.6. CT-Analyzer raw image shown after the reconstruction of the acquired images. The cross section (bottom) and its corresponding interval (top) on the length of the flight feather shaft are shown.

Image analyses

Seven of the 9 specimens scanned were analyzed for the following metrics: x and y second moments of area, polar moments of inertia, specific surface ratios, and eccentricity. The CT-Analyzer Program calculated the x and y second moments of area as following:

$$I_X = \int y^2 dA$$

$$I_y = \int x^2 dA$$

Where y is the distance from the x axis as determined by the application to some infinitesimally small area ad, and x is the distance from y axis as determined by the application to again, some infinitesimally small area da. The polar moment of inertia (J_z), or the moment about the z-axis is calculated from the perpendicular axis theorem

$$J_Z = \int \left(x^2 + y^2\right) dA$$

where y is the distance from the x axis as determined by the application to some infinitesimally small area dA, and x is the distance from y axis as determined by the application to again, some infinitesimally small area dA. Perimeter and area values were obtained directly from measurements made the application. The values for these metrics were collected at intervals slightly greater than 0.4 mm along the length of the flight feather shafts. This interval sectioning was held constant for all specimens analyzed.

Once the images are processed the images then contain the data for these metrics. Image by image, this data was transferred to an excel file, where the metrics could be displayed as a function of shaft length. This allowed for comparison between the two species.

In an effort to gauge the precision involved with selecting the appropriate half-tone of the binary image of the cross section, a small comparative inquiry study was completed. Two users knowledgeable of this investigation selected what they considered to be the region of interest associated with the cross-sectional images processed for data extraction. Planar area was the metric calculated and compared against the two users for deviation to gain some understanding of the accuracy of this method.

RESULTS

Preparation of Flight Feather Shafts for CT Analysis

It was resolved that tempering the flight feather shafts in a water bath for 24 hours was the most effective means of tempering. This served to make the feather shaft stiffer and easier to cut with the low-speed saw. Length and diameter measurements of the flight feather shafts tempered in water were taken prior to and following the tempering, as they were for all tempering experimentation. Conclusively, no geometrical variation was experienced by the flight feather shafts.

Tempering with Buehler's Epo-Heat proved troublesome. After mixing the epoxy, it was quick to harden and difficult to inject into the follicle end of the flight feather shaft. Further experimentation with the epoxy showed that it performed well to preserve the geometry of the shafts, though only with the most delicate care and attention to timing and application.

The method involving tempering with the furnace proved to be of no value. The heat prescribed caused discoloration in the shaft. Moreover, this method hardened the flight feather shafts so much that they became too brittle. When cutting the feathers tempered with the low-speed saw, it was difficult to even allow them to be cut. Most of the feathers tempered by this method cracked when fitted gently into the saw's chuck.

It was unnecessary to cut the shafts of the Archilochus colubris to analyze their cross sections as the entire shaft was able to be captured from x-ray microtomograph. When weighted properly (*Materials and Methods)* the low speed proved it could work well to cut cross sections.

Fig 7 graphically represents the data procured from the method described above. This data shows the morphology taken over a 1 cm section of the rachis of an Archilochus colubris. On primary y-axis of the graph the specific surface ratio is shown as a function of length. On the secondary y-axis, both the x and y second moments of inertia are shown as a function of length. Notice that the specific surface ratio decreases subtly with length, while the second moments of area stay relatively constant across the length space analyzed by the CTAnalysis software. The data for Figure 7 is presented as Figure 1in Appendix B.

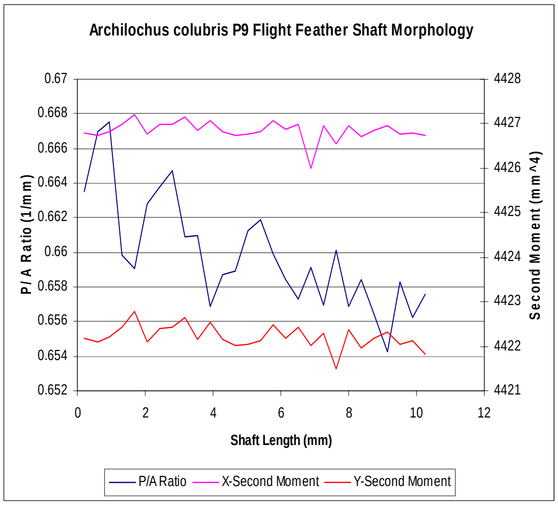


Fig.7. Graphical representation of over a 1cm scan from the 9th primary flight feather of the Archilochus colubris, displaying specific surface and the x and y second moments of area as a function of length.

Shown in Figure 8 are the same data classifications, but for the flight feather shaft of a male Anas platyrhynchos.

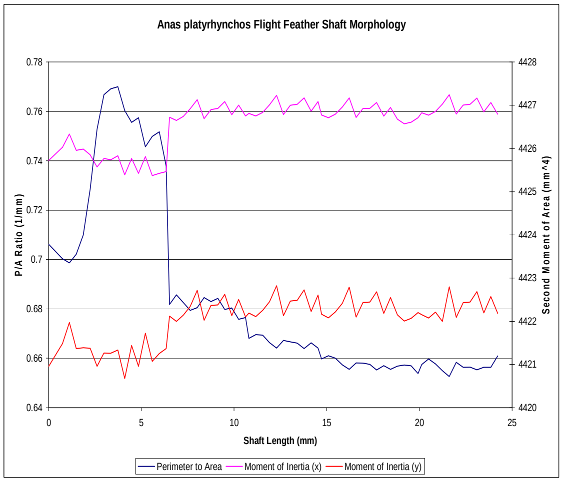


Fig.8. Graphical representation of over a 2cm scan from a primary flight feather of the Anas platyrhynchos, displaying specific surface and the x and y second moments of area as a function of length.

Similarly to Figure 7, the morphology data presented in Figure 8 shows that the x and y second moments of area stay constant relative to the specific surface ratio, which decreases with length. The data for Figure 8 is presented as Figure 2 in Appendix B.

Figure 9 offers some understanding of the error present in the method used to attain the data presented in Figures 7 and 8.

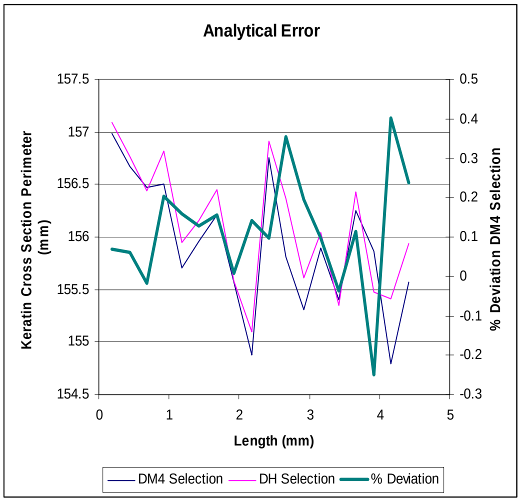


Fig.9. Error discovered when method for attaining data is performed by two separate parties. Two participants (DM4 & DH) attained data to plot cross section perimeter as a function of length, the percent deviation is shown.

This deviation is due to the user's selection of the cross section to be analyzed in the binary mode viewed in the CTAnalysis Software Application. Consequently different grayscale interpretations were selected, thus the deviation witnessed in Figure 9. Over 4mm of the rachis section was analyzed at the same interval for each selection. An Anas platyrhynchos flight feather shaft was analyzed to produce an understanding of this error. The data for this study is presented as Figure 1 in Appendix B.

DISCUSSION

The trends presented in Figures 7 and 8 show some evidence of morphological similarity. For both species, the second moment of area values appears to remain constant regardless of length. The specific surface ratio seems to decrease as the length is increased, moving in the direction towards the tip of the flight feather shaft.

The error presented in Figure 9 is rather minimal, and the figure serves to prove that the morphological trend in the data appear to be rather similar, as denoted by the two selections. Figure 8 shows the only evidence relating the success of the flight feather shaft cutting methodology executed. Figure 8 is the result of independently analyzing 5 cut flight feather shaft segments from the Anas platyrhynchos. From Figure 8 there appears to be a sudden drop in the specific surface ratio around 7mm. This disconnect is most likely symbolic of the cutting technique effecting the natural geometry of the flight feather shaft. However, there are 3 other jointed segments represented in the analysis which Figure 8 displays. There appear to be no other sever e disconnect anomaly, besides the location around 7 mm.

However, in particular regards to Figure 9, it does make sense that the perimeter of the keratin cross section decreases as the tip of the flight feather shaft is approached. Figures 7 and 8 somewhat portray this concept as well. The specific ratio decreases, as a result of the perimeter shrinking in value relative to the cross sectional

CONCLUSION

In retrospection, the formulated methods developed to conduct this investigation appear to be sound. It was learned that the accuracy of quantifying the cross-sectional morphology of flight feather shafts is largely dictated upon specimen preparation and equipment software tuning.

The results obtained are representative of one method for quantifying the cross sectional morphology of flight feather shafts. The results produced serve to validate the method formulated in this investigation.

This investigation fell short of a comparative study among species and inter-species. To further understand and make conclusions about the cross-sectional morphology of flight feather shafts, more data and analysis would be required to reinforce any such claims.

ACKNOWLEDGMENTS

Dr. Andrew J. Rapoff provided guidance for this investigation, and further contributed the accessibility of his laboratory facilities.

Mathew Roginsky played a roll in the initial setup of the interface between the CT software and x-ray microtomograph.

Dave Hodgson (DH) assisted by being an auxiliary view selector for the

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