ABSTRACT

Photography is widely accepted as a means of forensic case documentation and evaluation. In cases of criminal dismemberment, digital microscopy is commonly used to assess marks left on the bone. Reflectance transformation imaging (RTI) is a computational photography technique which documents and enhances the three-dimensional (3D) reflectance properties of the surface of an object. RTI has primarily been used in the cultural heritage sector but has recently transitioned into forensic science. This study examines the use of RTI for the documentation and presentation of cut surface characteristics on fully sectioned long bones. Juvenile pig radii were bisected using three different hand-saws, chosen as handsaws are the most common implement used in criminal dismemberments. The resulting 42 cut surfaces were then documented with a digital microscope and RTI. Four rendering modes were applied to the default RTI image, with diffuse gain being the most beneficial to accentuate cut surface features. Although great care must be taken when obtaining the photographic sequences necessary for detailed RTI analysis, RTI is relatively inexpensive, expeditious and easy to use, creating highly detailed, virtually interactive images RTI may not replace microscopy for analysis purposes, but could prove useful for documentation, image sharing and presentation.

KEYWORDS

Forensic Science; Forensic Anthropology; Reflectance Transformation Imaging; RTI; Digital Analysis; Saw Mark Analysis.

Saw mark analysis is focused on collecting data from microscopic features left by the sawing implement on cut bone (5). This information can indicate saw morphology, resulting in the narrowing of suspected weapons based on saw class (5). This analysis is most commonly completed under a microscope with oblique lighting, allowing the lighting direction to be altered during analysis to heighten specific features of note (2). Photography is also a standard approach for documenting forensic evidence (10). An accurate record of forensic evidence is essential for proper analysis, presentation of evidence in court and re-evaluation of evidence at a later date, however the 3D nature of human bone can make presenting clear and easily interpretable photographs of skeletal trauma difficult with traditional techniques (39).

Reflectance Transformation Imaging (RTI) is a computational photography technique which documents and enhances the 3D reflectance properties of the surface of an object (10,12). A series of digital photographs are taken from a stationary camera position while the light source is projected from a different known angle for each successive photograph, producing a series of images of the same object with different highlights and shadows. These photographic sequences are synthesized as Polynomial Texture Maps (PTM), which reproduce surface texture, color and reflective properties of the object (12). Utilizing the appropriate viewing software (RTIViewer), the PTM can be viewed much like a conventional 2D photographic image, however, unlike a traditional photograph, a PTM is derived from the 3D properties of the object, allowing the user to virtually alter the lighting direction. Furthermore, this interactive software allows the user to apply a variety of rendering modes to adjust the reflectance properties of the object while maintaining surface information. This can reveal details of the surface topography that may be impossible to view by other means, such as photography or direct visual examination (11,12,17-20).

RTI has only recently been used in forensic examination (10,11), however possesses the ability to render a 3D object into a 2D digital framework that retains its 3D reflective properties (12), allowing for an accurate and interactive digital record to be kept. Previous studies suggest that RTI is an inexpensive, portable and non-invasive technology that can greatly enhance normal photography and visual examination techniques of minute surface details, while also providing a digital record that can enable remote analysis and assist in the presentation of evidence in court (10,13-16). The ability of RTI to create an accurate, almost-3D digital rendering of the surface of an object suggests that RTI has the potential to enhance traditional analytical techniques of saw mark analysis by creating an interactive digital record that could be shared with other experts for remote analysis, retained for future examination or used for presentation of evidence in court. This study assesses the use of RTI for providing detailed images of completely sectioned bone cut surfaces that provide clear differentiation of saw mark characteristics.

Materials and Methods

Eleven defleshed juvenile pig (*Sus scrofa domestica*) radii were utilised for this study. Pig was chosen as a proxy for human bone as it is commonly used in experimental skeletal trauma analysis and has been proven to be of similar hardness to human cortical bone (9,21-27). Fleshed pig knuckles were purchased from Mckanna Meats, London, where the animals had been butchered the same day for consumption. No animals were slaughtered for the purposes of this experiment.

All specimens were macerated on the same day of purchase in the UCL Bioarchaeology Laboratory utilizing hot water enzyme maceration (28,29). The specimens were macerated prior to imparting trauma to enhance replicability and ensure that the cut surface characteristics remained undamaged for documentation and analysis (28,29).

Radii were sectioned using three new, hand-powered saws: (1) a handsaw (7 teeth per in.), (2) a tenon saw (15 teeth per in.), and (3) a junior hacksaw (32 teeth per in.). The proximal and distal epiphyses were removed from each specimen, ensuring the retention of saw marks in the cortical bone of the diaphysis (1), and the resulting diaphyseal segment was held between two bench vices (Irwin TV150 Woodcraft Vice) with 20mm thick padding attached to the jaws. Two bisecting cuts were made through each diaphyseal segment, with each cut inflicted manually by the same right-handed female researcher to maintain regularity of force. The saw was held perpendicular to the long axis of the bone for the entirety of each cut, minimizing the creation of directional changes. Upon cut completion the saw was then removed from the bone in a single upward stroke, facilitating the creation of pull-out striae. A speed of 60 beats per minute was chosen to control the pace of saw motion (9) with the power stroke occurring on each beat until the bone was completely sectioned. Seven cuts were made with each saw, resulting in 14 cut surfaces per saw and 42 cut surfaces in total.

Photographs were taken of each cut surface with a Dino-Lite Pro HR Digital Microscope (AM7000/AD7000 Series) with a handheld light source (Apple iPhone 6s torch) providing directional lighting to heighten surface detail. The microscope was set to 10X magnification with each cut surface placed perpendicular to the scope so the entire cut surface of the bone could be visualized in one image. This method was used to create a singular microscopic image with directional lighting to compare to the final RTI images.

Following guidelines for RTI photography (10-12), a Canon Sigma with a 70mm macro lens was set on a Macro 2000 adjustable camera stand with tilting stage. Each specimen was placed on the stage with the cut surface perpendicular to the camera lens. The camera was manually set to an ISO of 200, with an aperture setting of F11, a shutter speed of 1/60th of a second and set to shoot in sRAW format. A single reflective black ball bearing was set on a coupler nut to raise the sphere to the height of each specimen. Additional material (white corrugated plastic) was used to ensure the sphere and scale remained on the same plane as each specimen. The camera was manually focused upon the cut surface of each specimen, ensuring that both the specimen and the sphere were within the field of view. The camera focus was then set with tape, ensuring that the images remained in focus throughout the photography process. A Speedlite YN560III handheld flash (set to a power of 1/128) was used to illuminate the specimen.

Photographs were taken with the flash positioned at eight intervals around the specimen, set at three angles (20º, 45º and 70º), until a 360º sequence of photographs had been taken. This process created a sequence of obliquely lit images recorded by the black sphere as known Directional Lighting (Fig. 1). This resulted in an average of 22 photographs per specimen and took between 5 and 10 minutes. The sRAW images were opened with Adobe Bridge (CC 2018) and saved as JPEG files. The PTM was then created with PTMFitter and RTIBuilder, and the finished file was opened with RTIViewer (32). The software utilized to create and view the PTM (PTMFitter, RTIBuilder and RTIViewer) is available for free online. All three applications were operated on a 2016 MacBook Air (Apple Inc.).

Lighting direction was altered in RTIViewer and four rendering modes were used to assess the PTM of each specimen: Diffuse Gain, Specular Enhancement, Normal Unsharp Masking, and Luminance Unsharp Masking. These rendering modes were chosen due to their use in previous literature (10,16,17). Specular Enhancement heightens perception of the surface shape and Diffuse Gain is used to manipulate the surface sensitivity to light, enhancing the perception of surface shape features. Both Normal and Luminance Unsharp Masking are sharpening modes used to enhance high frequency details and the edge contrast of an object. Normal Unsharp Masking enhances surface contrast, while Luminance Unsharp Masking amplifies depth without affecting color (32).

Results

The difficulty in presenting the results of RTI is presenting the images without demonstrating the interactive nature of the software. Using RTIViewer to digitally alter the Directional Lighting heightens visibility of surface characteristics (Fig. 2). The ability to alter Directional Lighting in RTIViewer allows for a dynamic analysis to be completed digitally. Applying rendering modes provided even greater visibility of surface characteristics by digitally enhancing the 3D features of the cut surface (Fig. 3). The default RTI image presents the 2D PTM with direct lighting, causing the surface characteristics to become obscured and flattened into 2D space. The tooth hop can be viewed with slightly greater clarity in the image with Directional Lighting, however upon adding the rendering modes the tooth hop and general surface features are further accentuated. Diffuse Gain provided the most heightened visibility of cut surface features, while Specular Enhancement was the only rendering mode which resulted in occasional loss of edge detail, resulting in a lack of visibility of exit chipping. The heightened visibility obtained with the RTI images is particularly notable when compared to the microscopic images (Figs. 4,5). Although all cut surfaces are visible in both images of Fig. 4, the tooth hop and exit chipping are more clearly defined within the enhanced RTI image. No differences in cut surface feature visibility were seen between saw types.

Discussion

RTI is an emerging technology that has recently transitioned into the forensic science community, however this study suggests that it could be a useful tool to document the microscopic features of the cut surface of a bone. RTI captured the 3D properties into a single image that could be altered digitally. Although all rendering modes assisted in the enhancement of cut surface features, particularly useful in this study was Diffuse Gain. Digitally altering the lighting direction proved to heighten surface characteristics. Although this can be accomplished with traditional oblique lighting techniques, RTI allows for a wide range of Directional Lighting to be manipulated at the touch of a button and on a single image.

Furthermore, RTI is relatively inexpensive, accessible and easily employable. The specialist software (RTIBuilder, PTMFitter, and RTIViewer) required is free for download and can be utilised on any computer. The equipment necessary for image acquisition (camera, camera stand or tripod, adjustable light source, and reflective ball bearing) should also be available in most anthropology laboratories as photography is a common method of recording forensic evidence (10). While specialist RTI kits can be purchased from the Cultural Heritage Imaging website (from USD$370 at the time of writing) and multi-day training courses are available (12), these are unnecessary to capture accurate RTI image sequences.

The maximum time commitment necessary in this study was 45 minutes, from set-up to final product available for digital alteration. Along with the low time commitment this study required an average of 25 megabytes of storage capacity per specimen. Although digital storage capacity is an important consideration when assessing the applicability of various digital recording techniques, it is becoming increasingly more common to store large quantities of digital data while taking up less physical space. The advantage of digital storage is the ability to easily share and analyse data while not requiring large storage facilities, and possibly making the collation and comparison of data easier and more efficient than cataloguing physical specimens (40). The advantage of storing a digital PTM is the ability to virtually alter the image as you would the physical specimen. Although the storage requirement may initially seem like a disadvantage, the wider range of digital options available with RTI compensates for this.

The accurate digital record and enhanced viewing capabilities of RTI could allow for expert analysis without the examiner having to be on location, or physically handle the bone specimen, allowing for experts around the world to share their expertise (16-18). Obtaining the RTI image sequences is also non-invasive and requires a low level of specimen handling, ideal in instances where the bone may be damaged or easily friable (17,35). Presenting clear and easily interpretable photographs of skeletal trauma can be difficult due to the 3D nature of bone (39), and the reflective properties of the bone may cause trauma to become partially obscured and difficult to interpret from traditional photographic or microscopic evidence. The enhanced clarity and definition of RTI images could prove useful in presenting saw mark trauma evidence in an easily understandable manner (10). Additionally, criminal evidence may need to be re-evaluated in the future due to the discovery of new circumstances or evidence, or the availability and development of new research methods and technologies (37,38). In some cases, evidence may have disappeared, for instance in cold cases, or have been returned for burial. An accurate record of the trauma as it was in its original state allows for proper evaluation even after the evidence has ceased to exist (39).

The majority of difficulties encountered in this study occurred during image acquisition. If the specimen is moved slightly, or the camera comes out of focus during image acquisition the resulting PTM is blurry. Large areas of shadow or glare upon the specimen due to inappropriate light placement also result in a tainted final image that is difficult to see clearly. Great care must be taken during the image acquisition process and any unclear, over- or under-exposed images must be deleted prior to PTM creation. If the resulting PTM is inadequate a new image sequence should be photographed.

Conclusion

RTI is an inexpensive, easily accessible, and easy to use technology that accurately records the 3D properties of the cut surface of a bone and allows for virtual examination similar to that of traditional microscopic analysis with oblique lighting. However, RTI allows the viewer to alter lighting direction and add enhancements to a single digital image with the touch of a button. While

RTI may not replace traditional analytical methods of saw mark analysis, this study suggests that RTI could prove useful for the presentation of forensic evidence. RTI can be utilised by experts and untrained observers alike, and allows for an accurate, interactive digital record to be shared with other experts for remote analysis or retained for future examination and presentation of evidence in court.

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Figure Legends

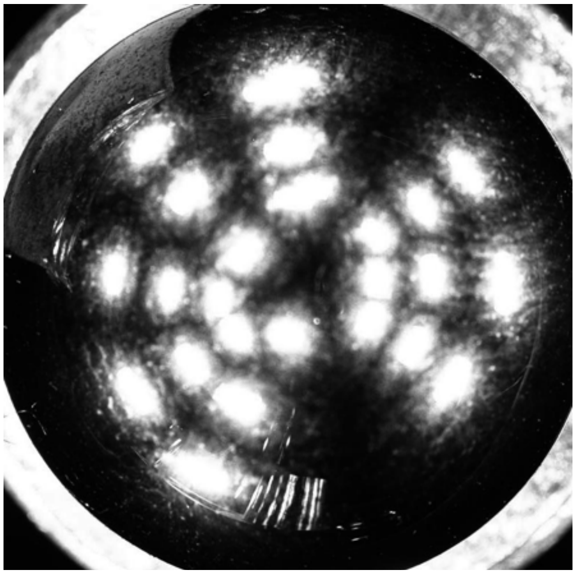

FIG. 1 – *An example of the RTIBuilder highlight blend created from the sequence of photographs. The central dark area represents the camera lens and placement of the specimen. The bright spots represent the flash placement when each photograph was taken around the specimen.*

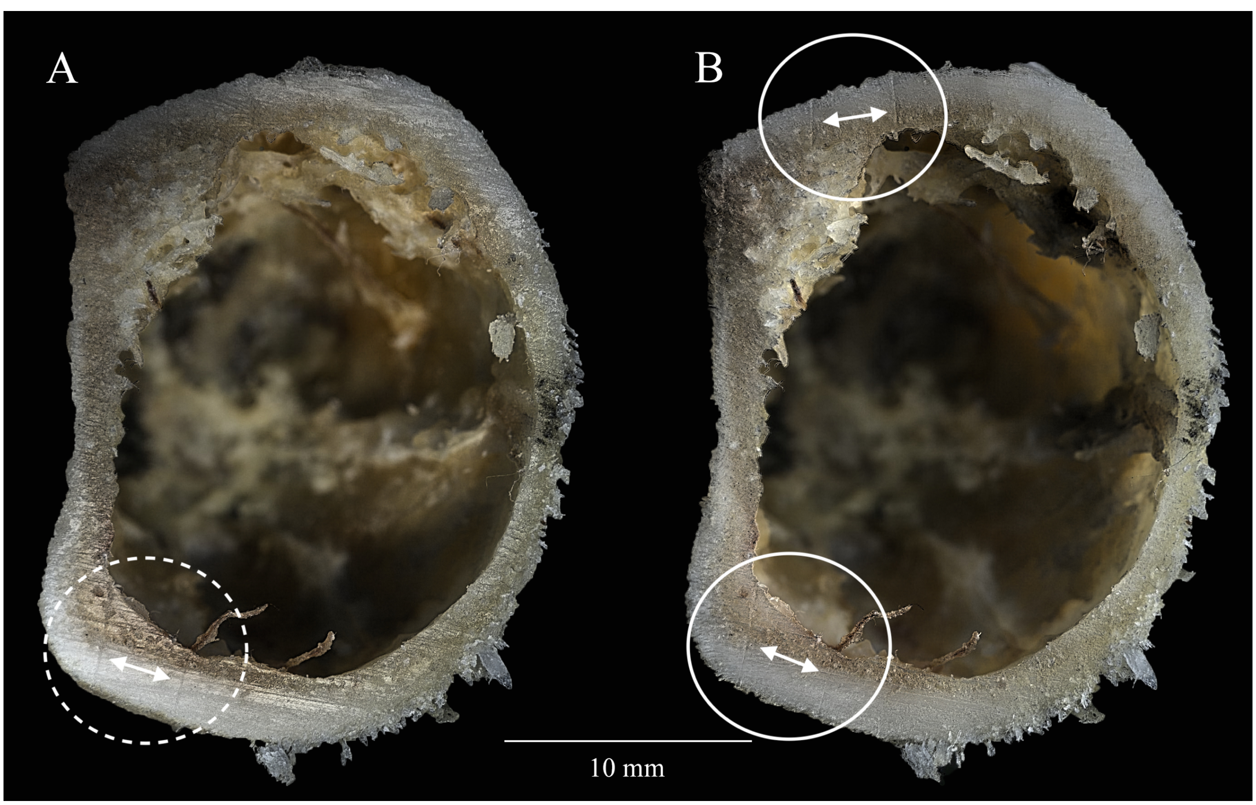

FIG. 2 – *Two RTI images of Specimen 002 7A, with Luminance Unsharp Masking and Directional Lighting coming from the bottom of the image (A) and the top of the image (B). With Directional Lighting from the bottom of the image (A) only one incidence of pull-out striae is seen (dashed circle). When Directional Lighting is changed to light the specimen from the top of the image (B) two incidences of pull-out striae are able to be seen (solid circles).*

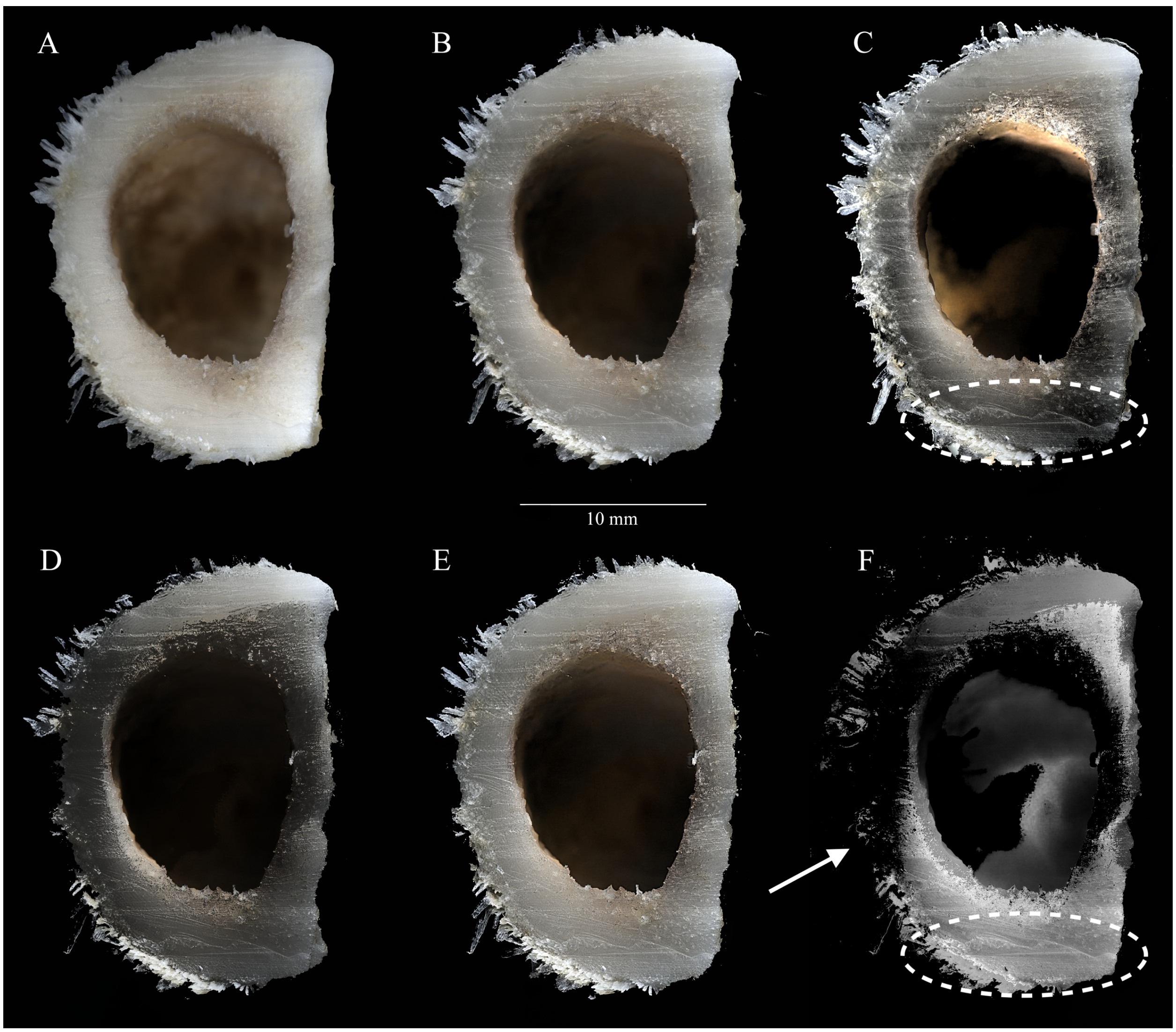

FIG. 3 – *A series of RTI images of Specimen 002 2B with different RTI rendering modes: (A) Default with direct lighting, (B) Default with oblique lighting, (C) Diffuse Gain, (D) Normal Unsharp Masking, (E) Luminance Unsharp Masking, and (F) Specular Enhancement.*

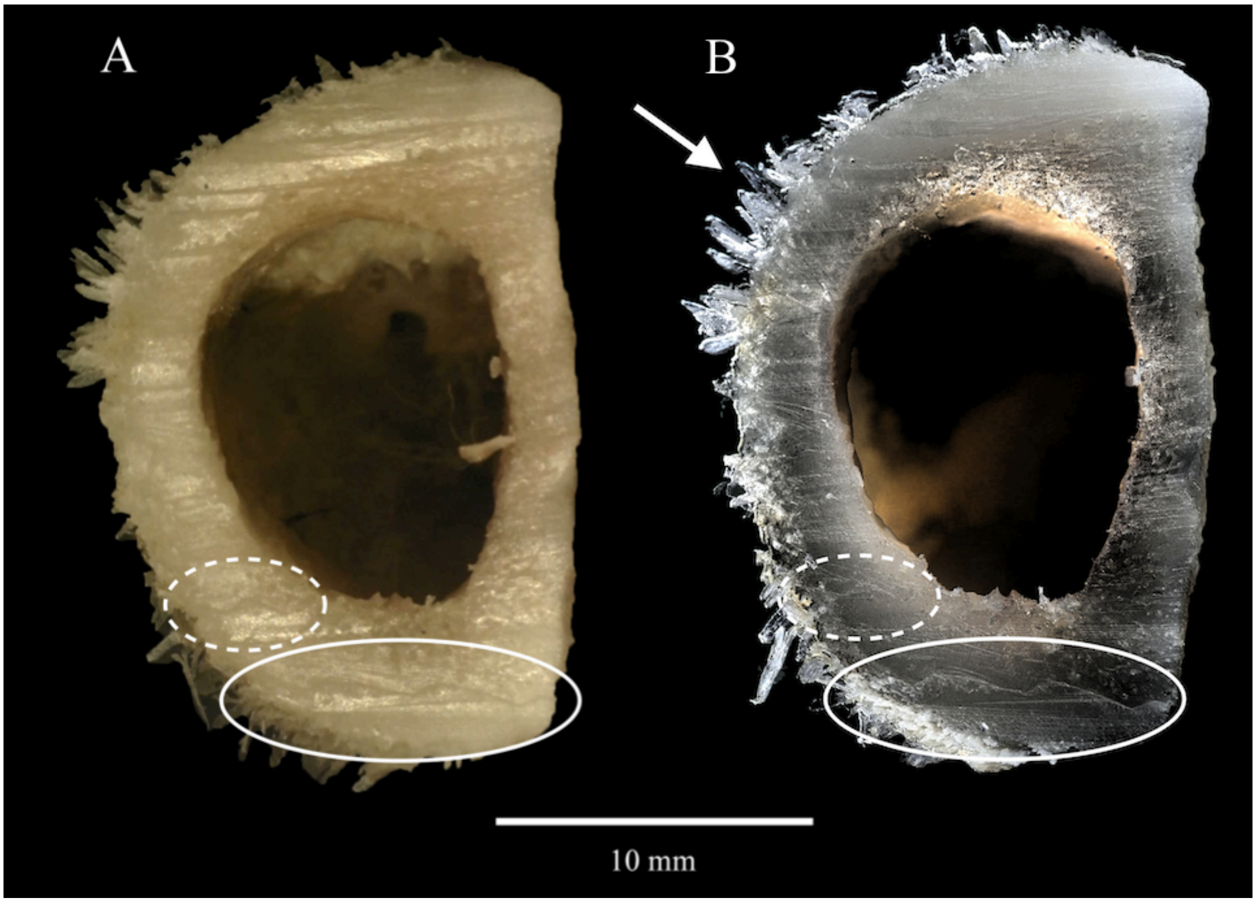

FIG. 4 – *A series of images illustrating Specimen 002 2B: A) digital micrograph and B) RTI image rendered with Diffuse Gain. Both images demonstrate clear visualisation of exit chipping, although RTI demonstrates heightened contrast (solid arrow). Two instances of tooth hop are visible on both images (solid ovals), although more clearly defined in the RTI image.*

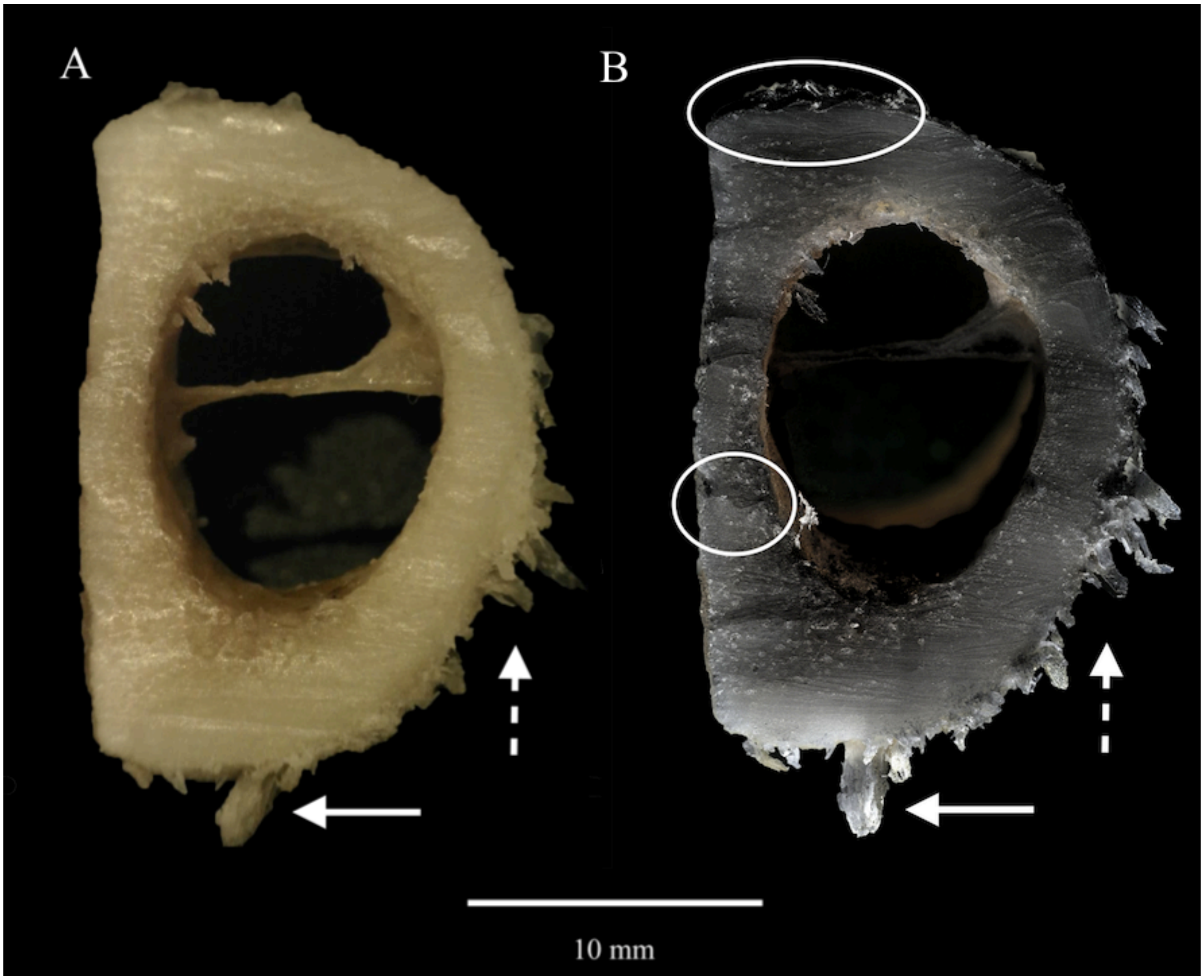

FIG. 5 – *A series of images illustrating Specimen 002 2A: A) digital micrograph, B) RTI image rendered with Diffuse Gain. Both images demonstrate the easy visibility of both exit chipping (dashed arrows) and breakaway spurs (solid arrows). The RTI image demonstrates two instances of tooth hop that are not visualised with the microscopic image (white ovals).*