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Virtual zooarchaeology: building a web-based reference collection of northern vertebrates for archaeofaunal research and education

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ABSTRACT

Osteological reference collections are a crucial tool in archaeofaunal analysis, but few are comprehensive; most lack a broad range of taxa or multiple individuals per taxon. This problem is especially prominent in arctic zooarchaeology, where difficulty in obtaining, transporting, and processing northern taxa has led to a dearth of appropriate reference collections. The Virtual Zooarchaeology of the Arctic Project, or VZAP, seeks to develop a comprehensive virtual comparative assemblage for the skeletons of northern vertebrates. VZAP (http://vzap.iri.isu.edu) is designed to assist with identifications in the lab or field and provides significant educational value, for both classroom demonstration and personal consultation. The VZAP website presents high-resolution digital photographs and 3D models of skeletal elements via an intuitive graphical user interface, designed to mimic the visual experience of working with a real comparative collection. This custom-built interface, the Dynamic Image Engine, represents a new way to present heritage media in an interactive and engaging format. VZAP also implements unique 3D scanning protocols to increase the realism of 3D models, and delivers them on a platform that allows for point to point measurements, cross-sections, morphological labels, and anatomical orientations.

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1. Introduction and background

Reference collections are a crucial tool in the natural and social sciences, but especially in archaeology where the identification of artifacts, animal remains, pollen, and other physical materials is a basal component of analysis (Banning, 2000: 52–57; see discussion in Driver, 1992: 36–37 for differences between biological- and artifact-based classificatory systems). With the recent reduction in the cost of high-resolution digital photography, three dimensional (3D) scanning, digital storage, and broadband Internet, archaeologists and physical anthropologists are beginning to develop virtual reference collections made available online. This may be viewed as part of a growing movement in the social and natural sciences to build comprehensive digital reference collections made available through media-rich websites. These digital collections typically employ two dimensional photographs, movies, or QuickTime VR™, a technique that allows for virtual rotation of objects along one or two axes (e.g. Digimorph; Kappelman et al., 2000, 2001). More recently, real-time 3D models have been incorporated into these reference collections, through the use of 3D PDF (Niven et al., 2009; Smith and Strait, 2008; Strait and Smith, 2006), WireFusion™ (Aves 3D), and Pointstream™ (Brown et al., 2008; Hess et al., 2009) software. These projects dramatically demonstrate the possibilities of digital, and especially 3D, reference collections. Nevertheless, the development of such virtual comparative collections is not widespread, and can still be considered a nascent tradition among archaeologists and anthropologists.

In this paper we describe the construction of a virtual reference collection for arctic vertebrate skeletons. The Virtual Zooarchaeology of the Arctic Project, or VZAP (http://vzap.iri.isu.edu), is intended to provide a comprehensive aid to the analysis of osteological remains from northern archaeological (and palaeontological) sites. The goal of the project is to replicate the characteristics of a traditional osteological reference collection, while providing functionality only possible in a digitally-based environment. In the following pages we examine the structure of

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traditional osteological reference collections and outline the technologies and methods we apply to recreating this structure in a virtual, web-based, environment. In so doing, we introduce a new graphical user interface, the *Dynamic Image Engine*, designed to provoke intuitive visual exploration of the digital collection. We discuss the technical challenges associated with constructing such an interface and the new research opportunities that may result from its use.

1.1. Background to the project

Osteological assemblages (archaeofaunas) derived from archaeological sites can provide a critical record of ancient human behaviors, paleoclimate, and former ecosystems. To analyze archaeofaunas efficiently and accurately, zooarchaeologists require access to a comprehensive reference collection consisting of taxa representative of the environment from which the archaeofaunal sample was derived (Chaplin, 1971; Davis, 1987; O'Connor, 2000; Reitz and Wing, 1999). Creating and accessing these regionally-focused collections remains the most fundamental barrier to the study of osteological remains from archaeological sites.

The creation of a comparative collection is often a painstaking and unglamorous undertaking. While carcasses of domesticated species are relatively easily obtained from local farmers and butchers, acquiring those of wild animals require special arrangements with wildlife officials, zoos, and biological research facilities. Once the carcass is obtained, transporting and processing it often requires specialized vehicles, facilities, chemicals, and subsequent waste disposal protocols. Storing, organizing, and maintaining a reference collection requires a large laboratory space with storage and layout areas, and trained staff to maintain and organize the collection. Despite these difficulties, developing and maintaining an osteological collection is a necessary and ultimately rewarding experience, which should form a fundamental component of any zooarchaeologist's training and career. Dedication to collections development not only builds capacity for osteological research, but also provides an ongoing teaching opportunity (for example, many zooarchaeology courses incorporate collections development into their curriculum as a means of teaching skeletal anatomy and vertebrate taxonomy).

For zooarchaeologists who study animal remains from arctic archaeological sites, the problems with developing a reference collection are compounded by a series of additional constraints. These range from the comparatively late penetration of biological scientists into northern regions (resulting in few collections), and the remote distribution and low densities of northern taxa, to logistical constraints in collecting, preserving, and transporting fresh specimens from uninhabited areas. The size of many northern vertebrates is also an issue; large sea mammals are difficult to prepare, transport, and store. Moreover, international and national laws, such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which restricts the use and transportation of endangered or marine taxa, have significantly restricted the ability to create or gain access to northern vertebrate collections. As a result, only four vertebrate collections exist in North America with relatively comprehensive arctic components: the Smithsonian Institution (Washington, DC, USA), the Burke Museum (Washington, USA), the Canadian Museum of Nature (Quebec, Canada), and the University of Toronto (Ontario, Canada). Many other smaller reference collections exist; though all have well-known deficiencies, either lacking a diverse suite of taxa and/or multiple ages and sexes of individuals.

The lack of northern reference material causes several related problems for arctic zooarchaeologists. First, at the few institutions where adequate material exists, it causes wear and tear on irreplaceable collections and burdens collections staff with research and loan requests. Second, it stretches budgets and schedules as researchers are forced to deal with the lack of local comparative material. Third, and most importantly, it too often results in an inadequate analysis. For these reasons, the majority of northern-derived faunal assemblages remain unanalyzed or under-analyzed. This is an ironic analytical bottleneck; while most archaeological excavations in the north result in very large and well-preserved faunal samples, there are few locations where they can be adequately analyzed. These issues generally confound archaeological, palaeontological, and palaeoecological research in arctic regions.

It is important to note that these issues are not limited to the Arctic, and elsewhere researchers have lamented the lack of regionally or topically focused reference collections. In fact, most zooarchaeological reference collections are far from comprehensive and are generally "inadequate for their intended purpose" (Driver, 1992: 39). Zooarchaeologists deal with the deficiencies in their comparative collections in various ways. Where adequate collections are not available, researchers are forced to transport their samples to those few institutions where they can be analyzed. When "face-time" with real reference specimens is not possible, researchers are forced to consult anatomical drawings, photographs, and published morphological keys.

While it is clear that virtual media can never wholly replace a real reference collection (Driver, 1992: 40; Reitz and Wing, 1999: 362), most zooarchaeologists have assembled large collections of such reference material to be used as anatomical references (critical for proper description of animal remains), aids to identification, and to fill in the "holes" in the physical reference collections they consult. In a practical assessment of zooarchaeological methods, Driver (1992: 40) outlines the importance of illustrated references: "Most zooarchaeological identifications are made through a combination of comparative collections and illustrated guides, generally used in complimentary fashion". It is for this reason that numerous manuals and keys have been written specifically to assist zooarchaeological analysis (Brown and Gustafson, 1979; France, 2009; Cannon, 1987; Gilbert, 1990; Gilbert et al., 1985; Hilson, 1986; Howard, 1929; Olsen, 1960, 1964, 1968, 1972; Pales and Garcia, 1981; Pales and Lambert, 1971; Schmid, 1972; Smith, 1979). Recently, zooarchaeologists have resorted to posting pictures of bone fragments on websites such as Bone Commons (http://www.alexandriaarchive.org/bonecommons/), and the Zooarchaeology Social Network (http://zooarchaeology.ning.com/) where experts with access to appropriate reference collections can provide opinions and insight.

The use of two dimensional media such as line drawings and photographs has its drawbacks; line drawings often only depict outlines and major morphological features (e.g. Cannon, 1987; Gilbert, 1990; Gilbert et al., 1985; Olsen, 1964; Smith, 1979), while photographs, particularly those in printed formats, are typically of a resolution too low to see minute morphological details (e.g. Olsen, 1964, 1972; France, 2009). Furthermore, drawing and photographic-based manuals reproduce only limited angles of elements, and simply cannot convey their complex 3D morphology. A recent solution to this problem has been to utilize surface scanning technology to make interactive 3D models of bones. For example, Niven et al. (2009) have developed a 3D reference collection of the bones of multiple Pleistocene fauna, and Strait and Smith (2006, see also Smith and Strait, 2008) have created a 3D interactive database of mammal dentition from the Paleocene/Eocene boundary using surface scanners. When presented in a real-time format, these models can be rotated and magnified into any position and view, which offers the means to interactively scrutinize the three dimensional detail so necessary for proper identification and study.

Despite its critical advantages, 3D modeling is not yet a panacea. Current scanning technology limits the amount of detail that can be effectively reproduced (see discussion below). However, by combining this technology with ultra-high resolution digital photographs, which can be magnified to display minute surface details such as nutrient foramina, sutures, and even haversian canals, a comprehensive suite of resources that overcome the limitations of conventional paper-based identification aids can be created. With the advent of broadband Internet connections, these high-bandwidth media can be effectively delivered to anyone with access to high-speed Internet.

We believe high resolution 2D photographs and 3D models, delivered over a web-platform, provide four critical benefits over traditional paper-based illustrated guides: 1) in resolution and detail, they are superior to traditional paper-based photographs and drawings; 2) they are easily updated and corrected; 3) they are easily accessed via the Internet (and for free); and 4) they provide obvious teaching possibilities both for personal study and in digitally equipped classrooms. Properly designed, a virtual collection can both enhance an existing collection, by filling in taxonomic deficiencies and providing additional individuals, and can provide researchers with a comprehensive resource to be used in the field or other locations where no comparative collection exists.

1.2. *Components of an osteological reference collection*

Osteological reference collections are complex, multi-component entities which imbed hierarchical information at several levels. Each individual specimen typically contains data on its taxon, age, and sex, as well as known life history traits and information on the circumstances of its collection and method of preparation. Each specimen can be further subdivided by its skeletal anatomy, which includes the elements present and data on their symmetry, size, and condition. Most labs organize their specimens taxonomically, while in some labs subsets of the collections are arranged synoptically (i.e. by anatomical element) to increase identification efficiency.

As described by Reitz and Wing (1999: 362–368; Driver, 1992: 38–43; Chaplin, 1971: 41–54; Gilbert, 1990: 31–32), a comprehensive osteological reference collection should consist of four elements: 1) a diverse range of taxa representing a specific region or regions, with multiple individuals per taxon representing size, age, environmental, and sexual differences; 2) complete skeletons, properly prepared and labelled; 3) a hierarchically arranged collection which is ordered either taxonomically and/or synoptically; and 4) comprehensive aids to identification, in the form of biological and taxonomic information, osteological reference manuals, photographs, and other materials.

VZAP is designed replicate to all four of these traits, by combining high resolution visual media, a robust and complex database structure, and a unique graphical user interface (GUI). Because of its digital nature, VZAP also achieves some functionality not possible with traditional collections. Below, we describe how VZAP implements these characteristics in a virtual environment; in so doing we will outline the methods, technologies, and rationale behind the features of our virtual collection.

2. Materials and methods

Perhaps the most challenging aspect of the project has been populating VZAP with a diverse array of taxa and individuals. The specimens used in this project are derived from three separate collections, including the Idaho Museum of Natural History (birds and terrestrial carnivores), the Burke Museum (sea mammals and terrestrial ungulates), and the Canadian Museum of Civilization (terrestrial ungulates and fish). The latter two collections were transported for scanning at the Idaho Virtualization Laboratory, located on the Idaho State University campus. Table 1 lists the taxa we intend to include in VZAP (those currently in the database are highlighted), derived from a careful review of zooarchaeological reports and publications from Alaska, the Northwest and Yukon Territories, Nunavut, and Labrador. We intend to include multiple individuals for many of the species in the collection (see Table 1); in general, we will include male and female individuals for those mammals with pronounced sexual dimorphism, as well as juvenile individuals for the most common mammals found in northern archaeological contexts, such as caribou (*Rangifer tarandus*) and seals (Phocidae and Otariidae families). We are also attempting to include multiple individuals for bird taxa, especially those in the family Anatidae (waterfowl), which are often morphologically similar and difficult to identify to species (and even genus) without multiple individuals for comparison.

The specimen's, age, sex, and life history traits, as well as catalogue data, are recorded in 29 separate fields drawn from discussion in Reitz and Wing (1999: 363) and cataloguing protocols developed at the Canadian Museum of Civilization. In a standard reference collection, these data would be stored in a separate laboratory catalogue and sometimes written on each specimen box. In VZAP, all of these fields are entered into a custom relational database which directly links the specimen data to every piece of media generated for every skeletal element (see discussion below). VZAP functions only with the original catalogue numbers in use by the loaning institution, and does not supply unique identifiers, reducing the possibility of miss-assignment of media to the wrong specimen.

To reduce the workload required for the project, we do not scan and photograph all skeletal elements from each specimen. Only one of each of the bilaterally symmetrical elements are included in the virtual collection, and only a representative selection of elements in each class of vertebrae, ribs, and phalanges are included (see website for details). This reduces the number of elements scanned for each specimen to a maximum 78 for mammals, 58 for birds, and 79 for fish.

2.1. *Virtual media*

VZAP relies on two complimentary forms of media to document each skeletal element: 1) high resolution digital photography, and 2) surface laser 3D scanning. Both media have deficits, and therefore we believe the use of both is critical for building a comprehensive virtual reference collection. Two dimensional photographs cannot convey the unique morphological attributes of a three dimensional structure, and while micron-level resolution is possible with most commercially available 3D scanners, most cannot replicate minute morphological and color detail, such as sutures and foramina, which are often needed for accurate identification. For those scanners capable of capturing such minute detail, the resulting models are often too processor intensive for standard computer equipment to effectively manipulate. Thus, while three-dimensional models are the only means to convey accurate shape data, high resolution digital images are the only means to provide accurate color and minute morphological detail (ca. 10 microns and less). Each form of media is presented separately in VZAP, and then combined using a technique developed by videogame and special effects professionals. Known as "texture mapping", this technique merges 2D and 3D images to dramatically increase the realism of 3D models (see description below).

We have developed a programmatic sequence (an imaging pipeline) to produce a virtual record of each skeletal element in our collection. First, each specimen is catalogued to record its

Table 1
List of taxa to be included in the VZAP reference collection. Those taxa and individuals already completed are in bold.

Mammalia (32 taxa):	Type	Aves (66 taxa):	Type		Type	Actinopterygii (34 taxa):	Type
Lepus americanus	**A**	***Gavia arctica***	**A**X	*Somateria spectabilis*	AX	*Lamna ditropis*	A
Spermophilus richardsonii	**A**	*Gavia pacifica*	AX	*Somateria mollissima*	AX	*Bathyraja parmifera*	A
Castor canadensis	**A**X	***Gavia immer***	**A**X	*Melanitta fusca*	AX	*Clupea pallasii*	A
Ondatra zibethicus	**A**	***Podiceps auritus***	**A**X	*Melanitta nigra*	AX	***Esox lucius***	**A**
Erethizon dorsatum	**A**	*Podiceps grisegena*	AX	***Clangula hyemalis***	**A**X	*Hypomesus pretiosus*	A
Delphinapterus leucas	A	*Diomedea immutabilis*	A	***Bucephala clangula***	**A**X	*Thaleichthys pacificus*	A
Delphinus delphis	A	*Diomedea nigripes*	A	*Mergus merganser*	AX	***Coregonus clupeaformis***	**A**
Phocoena phocoena	A	*Diomedea albatrus*	A	***Mergus serrator***	**A**X	*Coregonus sardinella*	**A**
Canis latrans	**AX**	***Fulmarus glacialis***	**A**	*Pandion haliaetus*	A	***Oncorhynchus gorbuscha***	A
Canis lupus	**A**X	***Puffinus pacificus***	**A**	*Haliaeetus leucocephalus*	A	***Oncorhynchus keta***	**A**
Canis familiaris	A	*Sula bassanus*	A	***Buteo lagopus***	**A**	*Oncorhynchus kisutch*	A
Alopex lagopus	**AX**	***Phalacrocorax auritus***	**A**X	***Dendragapus canadensis***	**A**	***Oncorhynchus nerka***	**A**
Vulpes vulpes	**A**X	*Phalacrocorax urile*	AX	***Logopus lagopus***	**A**X	***Oncorhynchus tshawytscha***	**A**
Ursus americanus	**A**X	*Phalacrocorax pelagicus*	AX	***Lagopus mutus***	**A**X	***Salvelinus alpinus***	**A**
Ursus arctos	**A**X	*Anser albifrons*	AX	*Tympanuchus phasianellus*	A	***Salvelinus namaycush***	**A**
Ursus maritimus	**A**	*Chen canagica*	AX	*Phalaropus lobatus*	A	***Stenodus leucichthys***	**A**
Martes americana	A	***Chen caerulescens***	**A**X	*Stercorarius pomarinus*	A	***Gadus macrocephalus***	**AJ**
Mustela vison	**A**	***Branta canadensis***	**A**X	*Stercorarius parasiticus*	A	***Gadus morhua***	**AJ**
Gulo gulo	**A**	*Branta bernicla*	AX	***Larus argentatus***	**A**	*Theragara chalcogramma*	AJ
Lontra canadensis pacifica	**A**X	*Cygnus buccinator*	AX	*Larus hyperboreus*	A	*Lota lota*	A
Enhydra lutris	**A**J**X**	***Cygnus columbianus***	**A**X	***Sterna hirundo***	**A**	*Gasterosteus aculeatus*	A
Callorhinus ursinus	**M**FJX	*Aix sponsa*	AX	*Sterna paradisaea*	A	*Sebastes* sp	A
Eumetopias jubatus	**MFJ**X	*Anas americana*	AX	***Rissa tridactyla***	**A**	*Hexagrammos lagocephalus*	A
Odobenus rosmarus	**MFJX**	*Anas rubripes*	AX	*Alle alle*	AX	*Pleurogrammus monopterygius*	A
Phoca vitulina	**A**JX	***Anas platyrhynchos***	**A**X	***Uria aalge***	**AX**	*Myoxocephalus quadricornis*	A
Pusa hispida	**M**FJ**X**	*Anas discors*	AX	*Uria lomvia*	AX	*Hemilepidotus hemilepidotus*	A
Pagophilus groenlandicus	AJX	***Anas clypeata***	**A**X	***Cepphus columba***	**A**X	*Myoxocephalus polyacanthocephalus*	A
Erignathus barbatus	**MF**J**X**	***Anas acuta***	**A**X	*Pinguinus impennis*	AX	***Sander vitreus***	**A**
Alces alces	**A**	*Anas crecca*	AX	*Ptychoramphus aleuticus*	AX	*Trichodon trichodon*	A
Rangifer tarandus	**AX**	***Aythya valisineria***	**A**X	*Fratercula corniculata*	AX	*Pholis* sp	A
Ovibos moschatus	**A**	***Aythya marila***	**A**X	*Fratercula cirrhata*	AX	*Scomber japonicus*	A
Ovis dalli	A	***Aythya affinis***	**A**X	*Bubo virginianus*	A	*Hippoglossus stenolepis*	**A**
Homo sapiens	**A**			*Nyctea scandiaca*	A	*Lepidopsetta bilineata*	A
				Corvus corax	**A**	*Platicthys stellatus*	A

Abbreviations: A = Adult; J = Juvenile; M = Male; F = Female, X = Additional Individuals.

disposition and life history data. Next, each element is identified, weighed, and then photographed using a high resolution (3072 × 2048 pixels) digital camera with a macro lens attachment. We utilize a "digital gray" background specifically suited to digital cameras, allowing us to color correct to a digital standard with image processing software (if necessary). A minimum of six angles representing standardized anatomical views are taken. Each individual photo is uploaded to a database created for each specimen and is then coded with information related to symmetry, anatomical orientation, and any available metric data.

The next step in the pipeline is to produce a 3D model of each element. Many different techniques exist for creating 3D models of osseous materials. Recently, Niven et al. (2009) have described a technique for scanning faunal remains using a structured light scanner. Similar to laser scanners, this technology captures both 3D and color data simultaneously, outputting full-color models with ca. 50–10 micron resolution (measured as the space between each vertex, or point on the object, captured in x, y, and z dimensions). Similarly, Strait and Smith (2006) describe the use of a laser scanner capable of reproducing models with a resolution of ca. 25 microns. An ongoing project at the University of Austin Texas, Digimorph (http://digimorph.org/), has utilized medical and Micro CT (computer-aided tomography) scanners to build a virtual collection, primarily of skulls of vertebrate taxa. CT scanners are capable of resolutions less than 10 microns, revealing small foramina and even sutures, but no color data is captured with this technology, so the model must be assigned an artificial color. Debating the effectiveness of these different techniques is beyond the scope of this paper; instead we simply describe the technique utilized for VZAP, which we believe effectively balances accuracy, resolution, realism, time, and cost.

The cost of commercial laser scanning equipment has reduced dramatically in recent years, and excellent scanners can now be purchased for a few thousand dollars. VZAP utilizes three different laser scanners (depending on the size of the element) to capture three dimensional data from each element. The resolution of our scanners ranges from ca. 500 microns (Cyberware models) to ca. 64 microns (NextEngine models), with a ca. ±1 micron accuracy. While all of our scanners come with proprietary software, we also utilize a suite of commercially available software to post-process the raw image data.

The 3D models provided in VZAP are a form of graphical information language; a new way to visualize osteological information. Unlike lithic illustration, conventions for osteological documentation and illustration are not universal. Most illustrations in manuals only convey surface outlines and major features, without conveying internal structure and cross-sections. Some of the best provide special notations and shading for articular surfaces, or specific structures (e.g. Brown and Gustafson, 1979; Olsen, 1964; Pales and Lambert, 1971; Pales and Garcia, 1981). Our goal with the 3D models in VZAP is realism; that is, accurately and precisely conveying shape and color data in three dimensions. Our scanning protocols are designed to effectively balance the need for realism and accuracy (documentation) with the need to efficiently communicate 3D information. The latter aspect involves two subcomponents 1) optimizing usability of the files by managing their size, and 2) slightly modifying realistic models to increase the conveyance of the 3D data.

The first step in creating a 3D model is scanning its surface; a single element can require up to a dozen individual scans from various angles to produce a complete image. These files (.ply format for the Cyberware scanners, and. scn format for the NextEngine scanner) are manually edited to remove any aberrations that resulted from the scanning and merging process, such as structures used to support the object while it was being scanned. These individual scans are then consolidated, or merged, into a single solid model with special consideration given to any errors which may result from overlapping scans. A final edit of the model is conducted inside of Geomagic Studios™ (.obj file format), to remove any intersecting polygons, fill any remaining holes, and clear any vertex color data saved by our scanners (the NextEngine scanners encode color data as they scan).

From this model, we create a "manifold surface", which defines the model's dimension and topology in terms of a measurable, or Euclidean, space. We create two different models of the manifold surface, one at full resolution (several hundred thousand to several hundred million polygons), and one at roughly 1000 polygons, to facilitate the creation of multiple resolution files. The full resolution model produced at this stage are far too large for average computers to process efficiently, but the details they encode are critical for accurate and realistic models. We reduce the size of these models by a unique method of removing inconsistent areas of polygon mesh density (often created by overlapping scan surfaces or other scanning errors). This is a two step process; first we subdivide the 1000 polygon models several times until we achieve the same polygon count as the original model. This creates a model with consistent polygon mesh densities that is the same general shape and size as the original bone, but with far less surface detail. We then superimpose the original full resolution model onto the smooth surface of the subdivided low density model, which reintroduces the detail and proper dimensions of the original model (this process is analogous to the mechanical process of vacuum forming). The resultant model has a consistent topology at every level of subdivision, and is now more manageable in terms of its file size and usability.

To increase the realism of the model, we introduce two dimensional color data in the form of a texture map, derived from the multiple high resolution photos taken of each element. Each photograph is cut from its background and then carefully positioned and "wrapped" onto the surface of the model at the same orientation. Generally, six photographs are sufficient to create a texture map that fills the model's surface; however, in elements with a high degree of surface morphology, such as crania, more photos are taken to fill in gaps. The result of the texture mapping process is a dimensionally accurate virtual object with photographically accurate color data.

The texture-mapping process can unfortunately cause issues with the ability to see three dimensional relief, because the color data (especially light and dark colors) can interact with light and shadow rendered by many model viewers. To increase the transmission of this information, we add a glossy surface texture to the models, which dynamically reacts with the rendered light source in the model viewer, increasing the ability to scrutinize 3D surface topography.

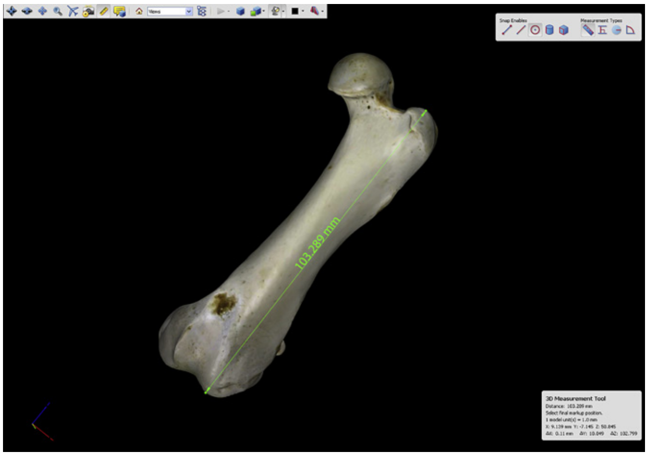
The final stage in our modeling pipeline is translating and rendering the completed models into a distributable file format. For this, we use the Adobe™ 3D Toolkit which allows us to set a default material (which affects the way light reflects on the surface of the model), the angle and intensity of the virtual light source, and the orientation of the model. This model (.u3d file format) is then converted into a PDF (portable document format)[1] for final distribution.

3D PDF format offers a number of advantages over browser-based viewers; the files are optimized for distribution and can be viewed by any modest computer with the current Adobe Acrobat reader installed. The 3D PDF format also provides a range of functionality not possible in many browser-based model viewers (see discussion below). Furthermore, the 3D PDF format can be incorporated into digital versions of journal articles (Goodman et al., 2009). Fig. 1 represents the first 3D model to be embedded in a PDF article in the *Journal of Archaeological Science*, and provides an example of the functionality we have implemented in VZAP 3D models.

As discussed above, full resolution 3D files can be very large and most users will have difficulty downloading and manipulating them efficiently with standard equipment. Thus, to produce a broadly accessible archive, we must trade-off realism and accuracy for smaller file sizes and usability. An interesting outcome of this struggle for balance has been the realization that one model cannot meet both of these needs; therefore VZAP offers three different resolutions of 3D models, each with specific usages. These include: 1) *Low Resolution*: Ca. 8000 + polygons with a high resolution (1024 × 1024, 72 dpi) texture map. These models are appropriate for cursory inspection of the element to gauge overall morphology, comparing multiple elements simultaneously, or use with low-bandwidth Internet connections; 2) *Medium resolution*: Ca. 140,000 + polygons with a high resolution (1024 × 1024, 72 dpi) texture map. These are intended as a realistic 3D representation of an element, with resolution adequate for detailed anatomical comparisons, analysis, and teaching purposes; 3) *Full Resolution*: Several hundred thousand to several million polygons (depending on the surface area of the object and the scanner used in the modeling process), with no texture map. Full resolution models provide the maximum three dimensional data captured by the laser scanner. These models are suitable for detailed analysis involving measurements and high-resolution morphometric comparison, and can also be used for rapid prototyping. These models are processor intensive, and are best viewed on computers with advanced graphics processing capabilities.

2.2. Database structure and web-interface

VZAP implements a complex hierarchical and relational database system that combines multiple files (Banning, 2000: 63), consisting of a specific array of fields, attributes, and associated media. The VZAP database is designed primarily to be a media



Distance: 103.289 mm
Select final markup position.
1 model unit(s) = 1.0 mm

Fig. 1. Low resolution 3D model of a left sea otter femur (*Enhydra lutris*, UWBM 38690, Burke Museum, adult female) with measurement feature enabled. This model is interactive in the digital PDF of the article.

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[1] Adobe software currently compresses the texture maps applied to models, resulting in apparent loss of image resolution (images are reduced to 1024 × 1024 pixels). If this feature of the software is upgraded to allow better texture resolution, our models can easily be adapted to increase the quality of the texture maps.

content delivery device; therefore every attribute in each file is linked to a specific array of media (2D and 3D).

Zooarchaeologists work by visual comparisons of shape, size, and texture, informed by knowledge of taxonomy and comparative skeletal anatomy (and sometimes biometric traits). During a typical analysis, a researcher is confronted with an array of visual information as they search through specimen boxes containing complete skeletons or trays containing synoptically ordered elements. We designed VZAP to replicate this visual experience. VZAP implements a custom-built visual interface known as the *Dynamic Image Engine* (DIE), that can simultaneously stream hundreds of high resolution digital images to an interactive "element wall" (Fig. 2), which can be magnified and repositioned using a "deep-zoom" technology. This element wall is designed to mimic the boxes or trays of skeletal elements encountered by a zooarchaeologist during their analyses.

To facilitate the rapid streaming of so many high-resolution images, we utilize a custom compression technology that reduces the file size of our raw image data without compromising image quality or dimension. When a full-resolution image is uploaded to the database, the software automatically re-renders each image into a low resolution and medium resolution file. When many images are displayed on the element wall simultaneously, our servers only stream the low resolution content to the user; progressively higher resolution images are streamed as the user increases magnification to scrutinize a particular image.

The DIE is essentially a graphical user interface (GUI) which works as both a media display tool and a database query tool. All of the images displayed on the element wall are interactive in the sense that the engine will retrieve any linked metadata, additional images, and 3D files when an image is selected from the element wall. The user simply clicks on the image and information regarding the taxon, element, symmetry, and sex of the element is displayed, along with links that launch 2D images or 3D models of the element. The user may also choose to view additional media related to the specimen it belongs to, or recall detailed information on the specimen and its precise taxonomy (Fig. 2). The DIE can also dynamically recall images related to any combination of attributes in the taxon, element, side, age, and sex fields of the database allowing for significant synoptic functionality (Fig. 3).

Thus, the Dynamic Image Engine represents a new way to interact with a visual media collection and a new way to think about documenting and building a virtual reference collection. By utilizing 2D media as the primary graphical interface for the collection, it negates the need to use tedious text-based lists or tables with links to media. It offers a more familiar and natural way to interact with a virtual collection because it mimics the visual experience encountered by researchers as they interact with a real comparative collection. The focus on 2D imagery also provides a low-bandwidth solution in regions or areas where downloading large 3D files is difficult.

2.3. Aids to identification

VZAP incorporates several features that are designed to aid the faunal analyst. The image engine responds to database queries by reorganizing the images on the element wall or by calling up and arranging new images. By sorting the chosen taxa by a specific element, age, or sex (or any combination thereof), the user is easily able to produce a synoptic collection, which can greatly increase the efficiency of the identification process (Fig. 3). Synoptic comparison is also possible with the 3D models, though the researcher must download each individually, and only the most robust computer systems can handle more than a few 3D files simultaneously. Given that many osteological collections are not arranged synoptically, this should be a substantial aid to many zooarchaeologists.

Comparative metrics are often used in species, age, and sex determinations (Driver, 1992: 40). Basic data on maximum length and width are included with all specimens in the VZAP database (the data are automatically generated during the 3D scanning

Fig. 2. Screen capture of the Dynamic Image Engine graphical user interface for a Steller sea lion (*Eumetopias jubatus*, UWBM 39483, Burke Museum, sub adult male), with menu system for one element activated.

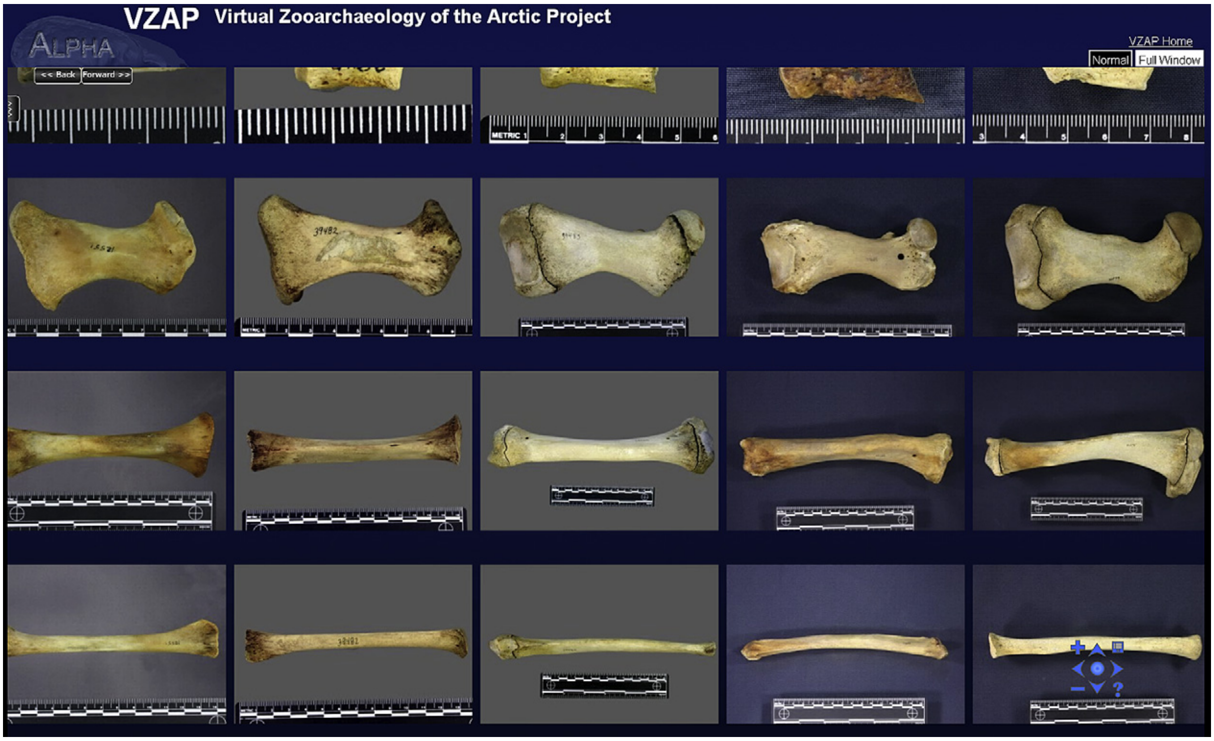

Fig. 3. Screen capture of the Dynamic Image Engine graphical user interface. In this instance, multiple sea mammal skeletons (family Otariidae) are being compared.

process), but these data do not replicate the specific measurement standards often used by zooarchaeologists, which tend to be based on the landmarks available on specific fragments. The Adobe 3D platform includes a robust measurement tool for measuring point to point, allowing the user to reconstruct any required measurement from any element in the database. We have tested this tool by comparing measurement made in the virtual PDF environment to those made with digital callipers on the real elements and determined that the full resolution PDF is accurate to within ±10 microns (0.01 mm). We note that for VZAP two significant digits past the decimal should also be taken as the limit of accuracy of the PDF measurement tool, which retrieves data to three decimal places (0.001 mm).

Beyond measurement, 3D PDF incorporates a host of other applications which will allow the user to create cross-sections and profiles (useful for comparing bone fragments or cut bone), change rendering and lighting modes (for examining the structure of the model), and make annotations (for later consultation). In essence, by adopting the 3D PDF format, VZAP provides a large array of graphical information which can be defined by the user.

Zooarchaeologists must constantly check taxonomic information to identify closely related species in an area of study, for reporting results, and for organizing data prior to quantification and analysis. VZAP links every piece of media in the database to an associated entry in ITIS, the Integrated Taxonomic Information System (http://www.itis.gov/). When accessed, these links provide detailed taxonomic information on each species in the database, as well as useful links to classic and recent scholarship on the taxonomic classification.

Finally, we note that archaeologists must often consult anatomical manuals and materials to refer to anatomical features and orientations, which are crucial for describing bone fragments, cut marks, pathologies, and age and sex characteristics. We have created a suite of didactic 3D models for each element in the mammalian skeleton. Each model provides preset “views” which can be accessed from a menu to display morphological labels and correct anatomical orientations (the downloadable version of Fig. 1 incorporates this functionality). We believe these instructional aids will be of great utility to students as study guides, and to zooarchaeologists who may require a quick anatomical reference during their analysis. Lastly, we have included a page on VZAP with links to other useful digital osteological aids on the web.

3. Conclusions

The use of keys and illustrated materials to make identifications is a systemic component of the zooarchaeological endeavour, given that nearly all collections are deficient in some manner or another (e.g. Driver, 1992). VZAP is designed to replicate, as closely as possible, the characteristics of a real osteological reference collection. Similar to the authors of more recent osteological manuals and online aids (e.g. Cannon, 1987: 1; Gilbert, 1990: 31; Gilbert et al., 1985:i; France, 2009:xi; Niven et al., 2009), we envision it as an aid to identification, a virtual enhancement for the many limited physical collections that exist, and a comprehensive alternative in situations (field or lab) when access to a real comparative collection is impossible.

Our rationale for building VZAP is primarily to provide comprehensive access to osteological collections (and the data they contain) which are not easily accessed by the general archaeofaunal researcher. VZAP is not designed as a replacement, but as another piece of the *conscientious* zooarchaeologist’s toolkit – an instrument to aid more accurate, efficient, and detailed analyses of arctic faunal samples. We propose that the creation of a virtual comparative collection such as VZAP, which provides numerous advantages over the paper-based reference media so frequently used by zooarchaeologists, can only serve to enhance the accuracy, precision, and efficiency of zooarchaeological research on arctic sites.

No less important is VZAP’s educational potential. The website provides a useful means to teach basic skeletal anatomy (now standard in many archaeological laboratory courses), and can be used as a demonstration aid in more advanced zooarchaeological courses. Even in those locations with access to abundant reference materials, the bones used as teaching aids are often too small or fragile for students to view during a large lecture. VZAP makes the teaching of comparative skeletal anatomy possible in any classroom equipped with a digital projector and Internet connection. It also provides a powerful study-aid for students, who can access it at their leisure to study comparative vertebrate anatomy.

Ultimately, VZAP represents an experiment in informatics. The project utilizes innovative protocols for documenting and providing access to complex physical collections in an engaging digital environment. These protocols could be easily transferred to any type material assemblage; as such, we hope that VZAP will vividly demonstrate the utility of interactive digital collections to the academic, museum, and educational communities. We feel that VZAP and similar projects participate in a movement to democratize science and education, by permitting virtual access to publicly-funded collections normally available only to advanced researchers and scholars. From a collections management and museums perspective, the project highlights the potential for making collections accessible in an engaging manner to the research community and general public.

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Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jas.2010.06.021.

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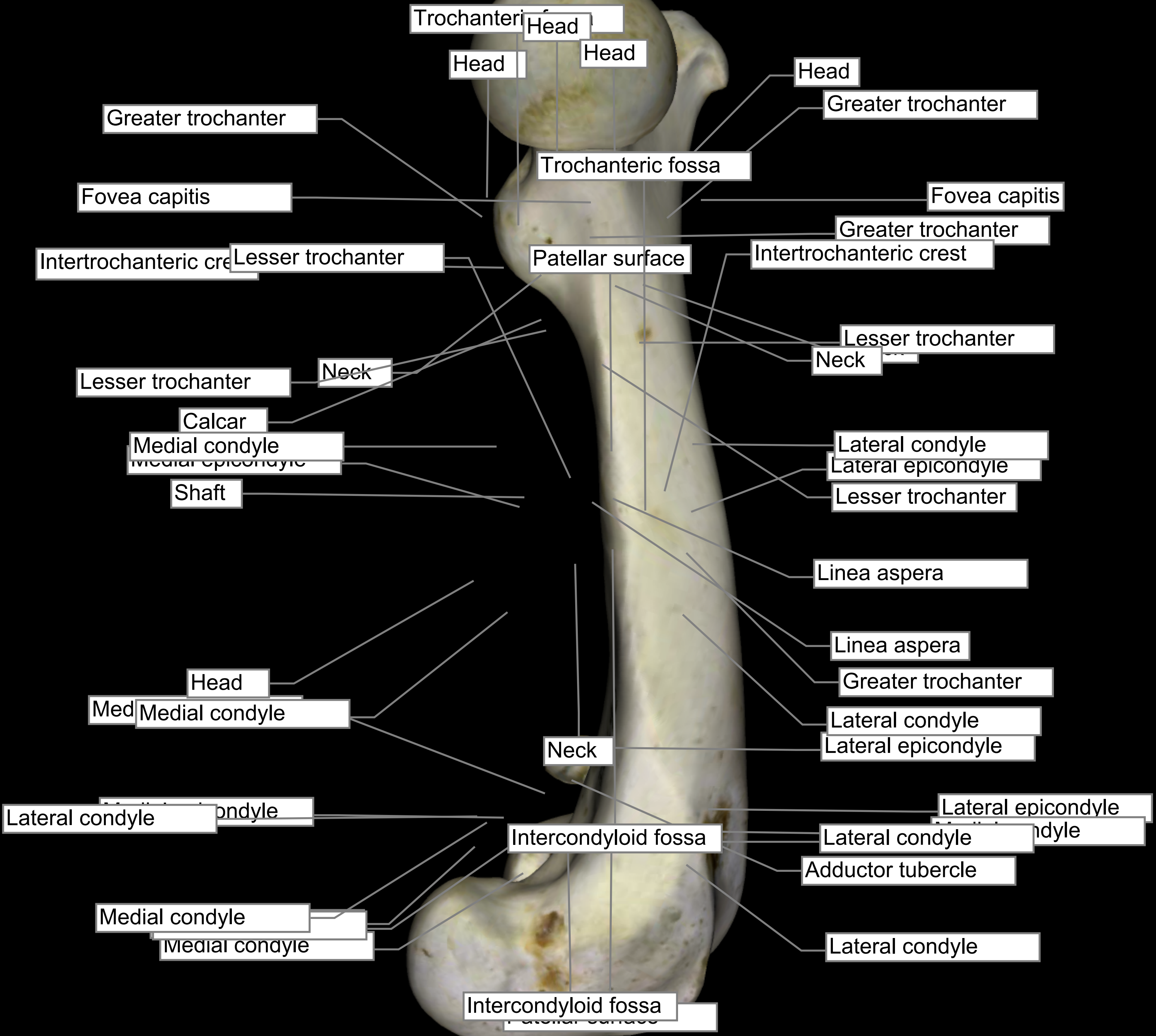
Trochanteri
Head
Head
Head
Head
Greater trochanter
Greater trochanter
Trochanteric fossa
Fovea capitis
Fovea capitis
Greater trochanter
Intertrochanteric cre
Lesser trochanter
Patellar surface
Intertrochanteric crest
Lesser trochanter
Neck
Neck
Lesser trochanter
Calcar
Medial condyle
Medial epicondyle
Lateral condyle
Lateral epicondyle
Shaft
Lesser trochanter
Linea aspera
Linea aspera
Greater trochanter
Head
Med
Medial condyle
Lateral condyle
Lateral epicondyle
Neck
Lateral condyle
ondyle
Lateral epicondyle
dyle
Intercondyloid fossa
Lateral condyle
Adductor tubercle
Medial condyle
Medial condyle
Lateral condyle
Intercondyloid fossa