Rawr! Study in Sonic Skulls: Embodied Natural History

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Figure 1. The instrument being played at Arizona State University's Emerge 2013 Festival

ABSTRACT

Lambeosaurine hadrosaurs are duck-billed dinosaurs known for their large head crests, which researchers hypothesize were resonators for vocal calls. This paper describes the motivation and process of iteratively designing a musical instrument and interactive sound installation based on imagining the sounds of this extinct dinosaur. We used scientific research as a starting point to create a means of sound production and resonator, using a 3D model obtained from Computed Topology (CT) scans of a Corythosaurus skull and an endocast of its crest and nasal passages. Users give voice to the dinosaur by blowing into a mouthpiece, exciting a larynx mechanism and resonating the sound through the hadrosaur's full-scale nasal cavities and skull. This action allows an embodied glimpse into an ancient past. Users know the dinosaur through the controlled exhalation of their breath, how the compression of their lungs leads to a whisper or a roar.

Author Keywords

NIME, dinosaur, sound installation, digital fabrication

ACM Classification

H.5.1 [Information Interfaces and Presentation] Multimedia Information Systems– Audio I/O

1. INTRODUCTION

Music has often drawn inspiration from nature and in recent years, composers such as David Dunn, have investigated natural phenomena through the medium of sound [1]. *Rawr! A Study in Sonic Skulls* seeks to explore natural history through the use of embodied musical interface, enabling users to create sound inspired by an extinct dinosaur. In this paper, we present 1) our motivations and approach, 2) previous work and precedent of artist as researcher, 3) the design and construction 4) results and user reaction 5) future directions and conclusion.

The stimulus for this project was the simulated call of another hadrosaur, a Parasaurolophus, at the Mesalands Dinosaur Museum, New Mexico. The researchers generated this recorded sound by resonating a low horn-like input sound through a computer simulation of the skull and crest, modeled from CT scans of the fossils [2,3]. The recent advances in 3D printing and machining provide an opportunity to experiment using a physical reconstruction of such a skull.

Creating this enormous intricate resonating object was a complex process. The first prototype took two years to complete, and the assistance of multiple experts in 3D modeling, machining, and printing. Thus, we expect our presentation of the design and construction process to be a valuable aid to those in the NIME community interested in using this technology for large body resonation. This work is preceded by Amit Zoran's groundbreaking work digitally fabricating smaller acoustic instruments, such as flutes [4].

Although we have fossils of the Corythosaurus skull, an early conversation with Lawrence Witmer revealed that hadrosaur larynx remains have yet to be discovered because soft tissue, like the larynx, is not amendable to fossilization [Witmer, private conversation]. Thus, one of the challenges is creating a voice for a creature that has left no known traces of a sound-producing organ! Yet, room for invention exists within 1) the limitations imposed by the known fossils, and 2) the demands of musical interface. Hence, while this project uses scientific research as a starting point to determine the design specifications for hadrosaur sounds, imagination also plays an integral role in the sound design.

2. APPROACH

Our intention is to lift dinosaur sound from disembodied simulation into physical being. Gallery visitors and performers complete this process by blowing into the installation, momentarily becoming the dinosaur. Uniquely, this instrument offers an embodied, experiential window into the distant past. For example, the skull requires effort to roar. It is not easy. Our lungs are human-sized, a fraction of the Corythosaurus'. Through this effort, we can feel the enormity. We no longer need to see it to understand it. We know it in our gasping for breath. It exists in the relation between our diaphragm, the roar and the sputter.

Accordingly, our design requires users to give their own breath. This action activates the larynx mechanism, resonating through the Corythosaurus' nasal cavities and crest. The roar is not synthesized. This roar is the consequence of physical processes produced by the breath, mediated by the construction and materials of the skull and larynx. Vibrations flow back into the lungs and become part of the experience. This instrument provides an interaction rich in complexity because of the physicality of its design.

3. RELATED WORK

A rich body of work exists exploring natural sounds and sonic history. This project extends this inquiry into musical interface. Dinosaurs are a popular subject of science exhibitions and animatronic shows. These exhibits occupy a space between the imagined and the real, where dry facts are displayed next to fantastic realizations of long dead creatures. Similar tensions are found in dinosaur movies, from National Geographic documentaries such as *Dino Autopsy* to *Jurassic Park* [5,6]. *Jurassic Park III* even features a tiny hadrosaur skull whistle [7]. This project also plays with these tensions, while aiming for a rigorous investigation of embodied dinosaurian sounds.

Of particular relevance to this project is Marguerite Humeau's work, *The Opera of Prehistoric Creatures* (2012), imagining sounds of extinct mammals, such as the woolly mammoth[8]. She collaborated with paleontologists, veterinarians, sound designers, and 3D modeling experts in an impressive effort to reconstruct vocal chords. Her sculptures look futuristic, looking forward to the possibility of cloning, as well as gazing into the past. Sounds are created via the use of pressurized air tubes, and can be programmed to create musical works [8,9]. In contrast, the focus of this project is on musical interaction in which the experience of blowing into the instrument conveys information about ancient natural history.

Another related research area is musical interface creation engaging with bioacoustic models, for instance, de Silva, Smyth, and Lyons' mouth controller for an avian syrinx physical model [10]. A further example is the tymbalimba, a musical interface designed to mimic the cicada's sound producing organ [11]. Other work engages with the human vocal tract [12,13,14]. These interfaces use physically-based computer-generated synthesis, rather than pure physical mechanism.

This work also has precedent in the fields of music archeology and acoustic ecology. One notable case is the research into the Divjab Babe flute, made of the remains of a juvenile bear femur [15]. The controversy over whether this object is the earliest known musical artifact or the result of chance animal tooth-marks has led several researchers to recreate this artifact [16,17]. This project enriches this area of research into even more ancient, non-human sounds. Further, not just researchers but the general public, as gallery visitors, are be able to give voice to the dinosaur.

An acoustic ecologist, Dunn, mentioned previously, is an inspiration in the role of artist as researcher. His work on bark beetle populations has led to insights about the beetles beyond what scientists had previously found [18]. The acoustic ecological approach of natural soundscape investigation is another way that artists have engaged with the natural world. An example is David Monacchi's work exploring soundscapes of endangered rainforests [19].

4. DESIGN PROCESS

This exhibit and instrument consists of two major components, the larynx, generating the sound, and the skull, which consists of the resonating inner nasal passages and the outer skull.

We used an iterative process to design this piece: we made many successive prototypes, evaluating them by playing, performance, and exhibition, then revising. Overall, eleven iterations exist. Various have been publically exhibited and performed. This paper is the only written publication of it.

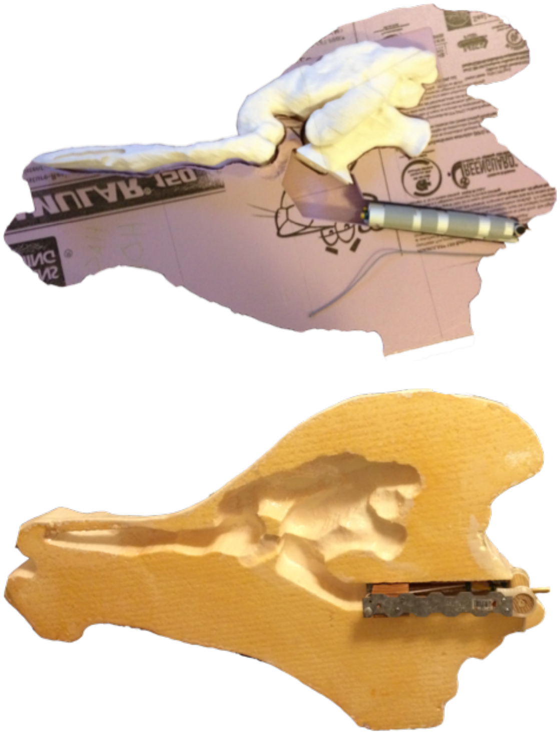

Figure 2. Cross-sections of two versions of the hadrosaur instrument, showing nasal passages, outer skull, and larynx.

4.1 Larynx

Three factors weighed heavily in the design of the larynx: scientific research concerning Corythosaurus hearing and sound production, artistic considerations, and user experience as an interactive exhibit and as a musical instrument.

4.1.1 Larynx Design

The most widely accepted hypothesis regarding hadrosaurid head crests is the acoustic resonance model, suggesting their purpose is to amplify vocal calls [20]. Evidence includes the length of the hadrosaur cochlea, used to predict both the best frequency of hearing and the high frequency hearing limit [20]. This research was based on an earlier finding showing that for many birds, including living archosaurs, the most sensitive frequency in a species is inversely related to both body mass and length of the basilar papilla, a section of hair-like cells in the inner ear [21]. The frequency of best hearing can be used to predict the high-frequency limit of hearing [21]. In addition, the length of the cochlea is related to the length of the basilar papilla, and is used to estimate those properties [21]. The cochlear measurements of the specimen were 12.3mm averaged, which according to the Gleich equations imply that the best range of hearing for this dinosaur was 267Hz, and the high frequency limit was ~1534Hz [20]. These frequencies are our goal posts for the design of the larynx.

In addition to having a specific pitch range, the larynx needs to produce plausible animal-like sounds. Since crocodiles are the closest, albeit still distant, living relatives to hadrosaurs, we investigated their larynx mechanism and sounds [22]. However, crocodiles most likely originated their version of a producing larynx [22]. Other related reptiles do not have sounding larynges and therefore, the sound-producing aspect of crocodilian larynges is not inherited from archosaurian ancestors [22]. Thus, we did not adhere closely to the crocodilian model, and merely used it for inspiration. We did not emulate the syrinx of birds since they are not descendants of hadrosaurs, and their relation is even more distant than that of crocodiles.

The composer Trevor Wishart's work on both human and non-human utterance also provided some guiding principles. He describes gestural sound indicators found in many animals such as tremulous breathing indicating fear, and some trans-species characteristics of the timbral morphology of scream sounds, such as the initial rise in pitch, sustain, then the gradual drop in pitch when it ends. He further asserts, "most sounds of higher animals are of complex spectrum and dynamic morphology" [23]. Dynamic morphology describes a sound-object with most or all of its properties in a state of change. Thus, in order to be plausible as a natural animal sound, the larynx must afford a dynamic and rich gestural sound palette.

A versatile sound palette is also important in terms of developing the larynx for expert musical users, as well as a large repertoire of potential sounds. However, the larynx must be also able produce low, loud pitches at levels of air pressure that humans can produce with reasonable effort. Our challenge was to strike a balance between a realistic representation of the enormity of the dinosaur and the accessibility of the interactive exhibit. Further, it is important that the interface respond in predictable ways according to our gestural experience with voice and breath. For example, as one blows into the instrument, sound increases in volume, brightness, and eventually, pitch in response to the variation of force in the breath.

Another design concern is robustness, e.g., as an installation, the dinosaur skull must endure hundreds of users, who may treat it roughly.

4.1.2 Larynx Construction and Prototypes

Our early larynx prototypes approximated sound producing biological mechanisms via use of balloons. The first design of the mechanical larynx was constructed from a large, stretched, open balloon, with the end cut off, so that the air could pass through. Two ends of the balloon were attached to a boxed metal frame with hinges all on four sides. The user blew through one end of the balloon and caused the stretched balloon to vibrate against itself, producing sound. High sounds were easy to produce, but it was very hard to produce low pitches. Further, the constant tension of the balloons made this design vulnerable to tears and rips in the balloon.

A second prototype used a balloon stretched over a long length of PVC pipe. Blowing across the stretched membrane created a fairly loud, very low sound. The inspiration for this design was the popular children's instrument, the balloon bassoon [24]. The size of the PVC pipe determined the lowest pitch of the sound, and pressing down on the balloon raised the pitch, but only as much as three semitones. Again, the balloon was always in danger of breaking. Thus, though this design produced a beautiful low pitch, it lacked both robustness and a large repertoire of pitch and timbres. A further refinement of this model used different lengths of tube to increase the number of available pitches, but this required tubes that were too long and large to fit in in the skull. Additionally, changing pitch via tube length was not at all analogous to known biological mechanisms.

Finally, we found that skinny balloons connected to tubes could produce low tones. The pitch increased both with greater air velocity and with greater tension, obtained by pulling them. The material of the tubes impacted the volume of the resulting sound. PVC tubes were serviceable, but brass tubes were the loudest. Twisting the balloons and folding them against each other created more timbre variations. Further, inspired by birds, which can produce two-voice melodies, we tried using multiple balloons simultaneously [25]. Using two balloons was the most feasible option, given the air required to make sound. They are tuned differently, by cutting one balloon slightly shorter than the other, creating chorusing effect like an accordion musette reed setting.

Figure 3. The final version of the larynx, showing one of the two balloons (yellow), with a quarter for scale. The mouthpiece is on the right. The strings pull on the balloons.

After these discoveries, the process of refining and creating mechanisms for usability began. In order to control the pulling action, we attached a string to each tube with a balloon attached. Pulleys at the end of the outer tube mitigated the friction of the string against the tube, and enabled the direction of the pulling action to be changed. One advantage of using the action of pulling strings to change pitch was that the strings could be unobtrusive, unlike handles or levers, which could destroy the context of breathing life into an a dinosaur.

4.1.3 Larynx Deployment and Iteration

For the first installation with the skull, we did not include strings to modify pitch in order to protect the exhibit. Gallery visitors could only change pitch and timbre by the acceleration of their breath. The exhibit was popular despite the lack of pitch control.

A second version of the larynx was created for a performance, a duet with a tuba. This larynx added a rotating mouthpiece, allowing the performer to fold the balloon and create timbre variation. This added complexity for the user, since there were mouthpiece positions in which it was very difficult to sound. Further, the strings were included in this version, and the skull proved robust in this setting. Initially, we substituted copper tubes in place of brass tubes because of the availability of the materials. However, the copper tubes had a significant dampening effect on the sound, and we switched back to brass. Further, we experimented with extending the larynx by blowing through tuba mouthpiece and, then a bassoon reed in order to create more variation in the sounds. For the second full installation, at NIME 2014, we kept the performance-style larynx because it allowed users more control and sound variety. While this control sometimes made it harder to make sound, visitors spent a great deal more time playing the dinosaur, came back for repeat visits, and even brought their friends to hear them play. Additionally, instead of disposable straw mouthpieces, we provided the option of disinfectant wipes so that they could use the larynx directly. We were skeptical that users would use a communally shared mouthpiece, but in fact, this encouraged participation since the sound was easier to produce.

4.2 Skull

Like the larynx, the skull had to be designed to enable fabrication, transport, and performance. The starting point was CT scans of a subadult Corythosaurus fossil, provided by Witmer. In the eleven iterations of the entire instrument, there were three major iterations of the skull.

4.2.1 Prototype II

The most challenging aspect of the skull and nasal construction was their size. 3D printing a life-sized hadrosaur skull was expensive and complicated. Therefore, we constructed Prototype II in two parts, using different processes. The inside of the skull, i.e., the nasal passages under the crest, were constructed separately from the outside skull. Thus, since the outer skull was not resonating, it was cost-effective to use insulation foam, allowing the nasal passages fabrication a different process with more precise construction and design promoting resonation. We recreated the Corythosaurus skull fossil instead of crafting an artistic rendering of the skin and face because we felt that the bones were visually attractive.

4.2.1.1 Nasal Passages

Because of accuracy and availability, we used a FDM (fused deposition modeling) process to print the nasal passages. Unlike older processes like CNC machining, the FDM process allows undercuts, of which the nasal passages have many. At ~0.76m long, the nasal passages were too large to print in one piece, so we printed them in sections and then assembled. Additionally, one side of the fossil skull was very crushed, making it impossible to fit together outer skull and nasal passages. We resolved this by mirroring the less-crushed half. Further, a support rims were added to the edges of the sections to reduce warping, a common 3d printing problem. They were removed after assembly so as not to interfere with resonation.

A further challenge is that the FDM process does not create dense, resonate material. Thus, after sections were printed, we infiltrated them with epoxy to add density, ensuring that the nasal passages would be resonant and responsive to sound. Finally, we was attached the mechanical larynx and enlarged the nostril orifices, which had to be a large enough size for sound amplification.

Figure 4. Nasal passages. Divided into smaller pieces for printing (above), assembled and epoxy infiltrated (below)

4.2.1.2 Outer Skull

As can be expected from fossilized remains, the skull was crushed. Furthermore, the polygonal data was extracted from a noisy CT image, resulting in model surfaces having countless gaps, cracks, and self-intersections. In contrast, physical models for 3D printing require surfaces with "water-tight" skin. As mentioned earlier, we mirrored the relatively uncrushed side of the fossil. We carved the first outer skull prototype (Prototype I, Figure 5) via band saw from XPS foam layers, using templates produced by sectioning the 3D skull using Rhinoceros CAD software. This was unusable as the nasal passages were too large for the skull due to a flawed 3D model.

For Prototype II, we used the same software to fill the large holes in the 3D model, draped a continuous surface over the original noisy polygonal data, and then added offsets to account for nasal passage location and size, creating an inner cavity in the foam fitting over the nasal passages. The skull was then divided into 5cm thick foam sections, and CNC machined from both sides. We layered the sections to create the skull. However, the sections did not fit due to warping and foam collapsed around the nostril openings and crest (Figure 5). Thus, we spent a great deal of effort rebuilding these sections manually. The resulting shape is partly a sculptor's interpretation of the skull.

4.2.2 Prototype III

The experience fabricating, exhibiting and performing with the first prototype lead us to our second design. The goals were to 1) decrease the damping caused by XPS foam, 2) reduce air leakage 3) increase ease of transport and reassembly, and 4) make the outer shape more faithful to the original CT model. The key innovation was to carve the nasal cavity into the solid skull pieces – the air passages formed by negative space (Figure 5). The skull and nasal passage were machined out of EPS foam, like foam cups, and coated in 2-part urea epoxy. This coating cured into lightweight and resonant structure

Figure 5. A progression of outer skull prototypes. Top: Prototype I assembled from 5cm thick foam sections. Middle: Prototype II assembled from 5cm thick section of CNC machine foam. Bottom: Prototype III from a block of EPS foam, coated in epoxy, forming the resonant body.

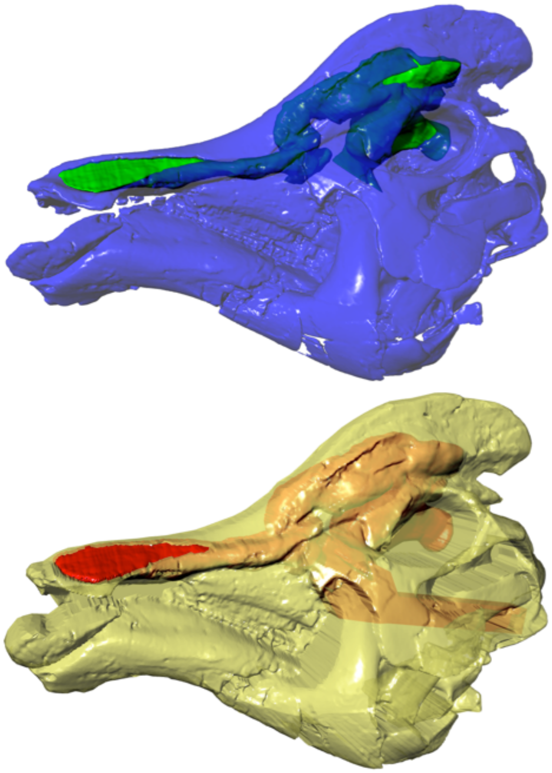

Figure 6. Top: original skull (blue) from the CT scan showing fractures. The nasal passages (green) extend beyond the skull's outer surface near the eye socket. Bottom: the final skull model (yellow), showing the recess forming the nasal cavity and airway containing the larynx.

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5. RESULTS

In early discussions regarding the work, it was an open question as to how many gallery visitors would be bold enough to make the dinosaur sing. Due to the nature of the installation, each user becomes a performer creating an enormous sound heard by many. However, most curious visitors decided to play the instrument, although there were a few that were clearly too shy.

Younger children, unfortunately, had a harder time producing the air required to make the dinosaur sound loudly, much the way that they have trouble playing the tuba. A few adults also had some trouble. Some have suggested alternative input mechanisms such as bellows or air pressure sensors, but we feel that these interfaces distance the user from becoming dinosaur. More than one user remarked upon how the instrument caused them to reflect upon the size disparity between their own lungs and the hadrosaur's. One possible alternative could be the recreation of a smaller, juvenile dinosaur skull, which would require less air and could be displayed alongside the subadult hadrosaur skull.

The process of creating the tuba and hadrosaur duet allowed us to more fully explore its sonic capabilities. *Rawr!* easily lends itself to playing gestural shapes rather than specific pitches, yet pitches are possible with practice. Folding the balloons via rotating mouthpiece yielded the lowest pitches. This process also varies the pitch unpredictably at times, which is exciting. Additionally, via the two balloons, it is possible with practice to create multi-phonic sounds, with separate pitch/timbre envelopes. Moreover, we discovered that using mouthpieces from a tuba and a bassoon created sounds modulated by the larynx in interesting ways.

More than an interactive exhibit and musical instrument, this project is also an investigation into dinosaurian sound. In order to explore the resonant properties of the skull, we recorded the larynx playing by itself, as well as through the new prototype. We kept the mouthpiece and string position constant for both recordings, with the resulting pitch approximately Eb4 or ~315Hz.

The resonation drops the perception of this pitch a bit lower. The spectral analysis of these two recordings (Figure 7) shows that the skull begins to strongly resonate the sound around the range of best hearing for the Corythosaurus, 267Hz. Then, at ~1000Hz, the skull begins to attenuate the sound.

However, it is interesting that there is a peak of resonation right at the limit of the proposed hearing range, perhaps indicating the resonant frequency of the skull. After this spike of resonation, the skull attenuates higher frequencies. Thus, these results are

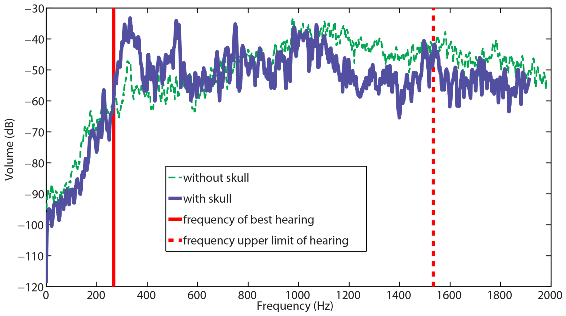

Figure 7. Power spectrum of the sound made by the larynx alone (dashed green line), and when the larynx is interacting with the nasal passages and skull (purple line). The skull and nasal passages amplify the sound near the predicted peak frequency of the hadrosaur's predicted hearing (solid red line).

consistent with existing research of proposed hadrosaur hearing ranges and skull resonation properties.

6. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented *Rawr! A Study in Study in Sonic Skulls*, demonstrating the potential for investigating natural history via the use of musical interface and digital fabrication. We have addressed both the challenges and opportunities that paucity of the fossil record presented as well as the challenges and techniques of large resonant body fabrication. Our latest skull version improves upon the previous by producing louder, richer tones while maximizing portability up the possibility of creating duets for dinosaurian sounds, and we also look forward to deepening our performance practice of this instrument. An additional avenue for exploration is reconstructing the larynx for more homology to known biological sound-producing mechanisms. We are also exploring the idea of having a museum installation, in which the life-size skeleton is carved into a wall, showing how paleontologists found this individual. The instrument would be connected to the head, and the visitor would climb up onto a platform to reach the skull and play it. Our goal is instill, in the user, an even greater sense of *being* the hadrosaur.

A main motivating factor in this work is the expansion of the existing knowledge of ancient hadrosaurine sounds, using an acoustic ecological model of artist as researcher. We hope to open a space for future new musical interfaces bringing visceral experiences of natural and historical phenomena in pursuit of sonic embodied knowledge.

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