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Three dimensional printing as an effective method of producing anatomically accurate models for studies in thermal ecology

Charles M. Watson*, Gamal R. Francis

Midwestern State University, Department of Biology, 3410 Taft Blvd. Wichita Falls, TX 76308, United States

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ABSTRACT

Hollow copper models painted to match the reflectance of the animal subject are standard in thermal ecology research. While the copper electroplating process results in accurate models, it is relatively time consuming, uses caustic chemicals, and the models are often anatomically imprecise. Although the decreasing cost of 3D printing can potentially allow the reproduction of highly accurate models, the thermal performance of 3D printed models has not been evaluated. We compared the cost, accuracy, and performance of both copper and 3D printed lizard models and found that the performance of the models were statistically identical in both open and closed habitats. We also find that 3D models are more standard, lighter, durable, and inexpensive, than the copper electroformed models.

1. Introduction

Electroformed copper models fitted with temperature data loggers are standard tools used to establish operative temperatures (T_e) for comparison to field-active temperatures of free-ranging animals (Dzialowski, 2005). First described and implemented in Porter et al. (1973), such biophysical models theoretically combine the conductive, convective, and radiative characteristics of an animal in thermodynamic equilibrium, without regard to metabolism or evaporation (Bakken, 1976; Bakken and Gates, 1975; Porter et al., 1973). This methodology assumes that the animal is without body mass and, therefore, without thermal inertia (Christian et al., 2006). The distribution of environmental temperatures gathered from an array of these models then serves as the null hypothesis of an organism exhibiting no physiological thermoregulation (Bakken, 1976; Hertz et al., 1993). This method (with slight variations) is particularly prevalent in studies of squamate ecology (e.g. Grant and Dunham, 1988; Hertz, 1992; Peterson, 1987) but has also been used for birds and mammals (e.g. Sears et al., 2006; Weathers and Sullivan, 1993).

These models are typically made by electroforming copper onto a paraffin mold of a particular animal, melting and draining the paraffin, and painting the model to approximately match the animal's natural reflectance (Bakken and Gates, 1975). This process is time consuming and involves the use of potentially hazardous chemicals (acids) and low-intensity electrical currents. Although morphologically accurate copper models are superior to non-realistic models, many studies in thermal ecology resort to simpler models, such as copper tubing, presumably because of the time and effort required to produce better models (Bakken and Angilletta, 2014). This approach, while common practice, is known to introduce significant error into operative temperature data (Walsberg and Wolf, 1996). Here we show that models created by three dimensional (3D) scanning and printing in an Acrylonitrile Butadiene Styrene (ABS) medium are potentially more anatomically accurate, cheaper, and more easily produced.

We evaluated 3D printing as an alternative to the electroformed copper model standard for studies in thermal ecology. In this study, we compared the cost and effort associated with production degree of standardization (variation among models). We then used field studies to compare operative temperature distributions of both ABS and copper models.

2. Materials and methods

We printed 10 ABS models of a frozen specimen of *Phrynosoma cornutum* (SVL=71 mm) from the Midwestern State University Vertebrate teaching collection. These 3D-printed ABS models were manufactured using a Makerbot Replicator 2× 3D printer and Makerbot Digitizer 3D Scanner (Makerbot® Industries LLC, Brooklyn NY, USA). The lizard was frozen in a position that this lizard typically assumes in the field and scanned for printing. We then used the open source computer aided design (CAD) software FreeCAD (http://freecadweb.org/) to program a well into the

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* Corresponding author.
E-mail address: charles.watson@mwsu.edu (C.M. Watson).

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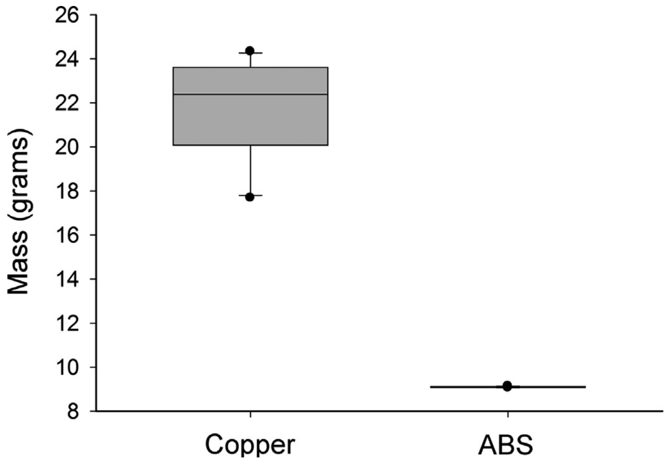

Fig. 1. Median and quartiles for electroformed copper models and three-dimensionally printed acrylonitrile butadiene styrene (ABS) models of *Phrynosoma cornutum* (SVL=71 mm).

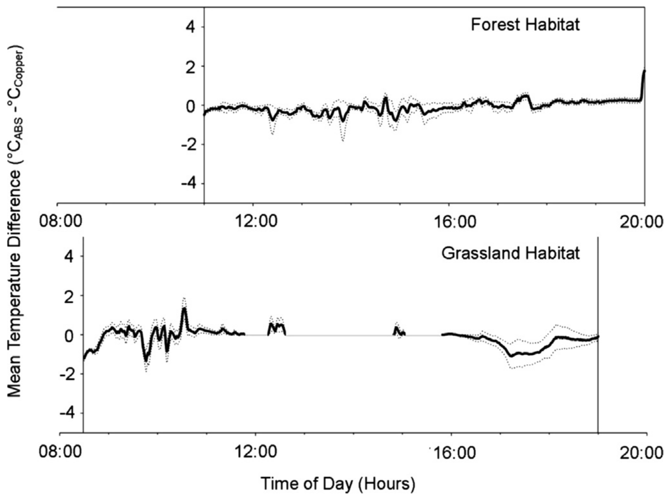

Fig. 2. Mean difference (dotted lines ± SE) between paired models throughout the sample period for the closed canopy habitat and the open canopy habitat. Those values that equal zero in the middle of the day for the open canopy habitat represent times when the temperature of the model exceeded the maximum temperature recordable by the data logger.

underside of the model for a DS1921H Thermocron iButton Temperature Data Logger (Maxim Integrated, San Jose CA, USA). The DS1921H iButton measures 17.35 mm in diameter and is 5.89 mm thick. It logs temperatures between 15 °C and 46 °C in 0.125 °C increments and ±1 °C accuracy with a published thermal response time constant of 130 s (Maxim Integrated Datasheet: DS1921H–DS1921Z). We printed this file using Makerbot's "True Gray" ABS filament to make a morphologically accurate model of the lizard. Printing averaged 54 min per model at standard resolution.

We also created 10 copper models of the same specimen of *P. cornutum* using methods derived from (Bakken and Gates, 1975). We delivered an electrical current from a 5 A Constant Current Rectifier (Model NSP-2060, Caswell Inc. Lyons NY, USA) for 24 h to electroplate a thin copper layer over a conductive paint-coated paraffin model. The paraffin was melted and drained through a hole in the underside of the model left for insertion of the temperature data logger. The entire model was then dipped in a matte finished latex paint mixed by a commercial paint provider to match the reflectance of the ABS material used in the previous process of model production.

2.1. Comparison of production costs

We compared initial monetary cost ($ USD) of setup for model production using online retail price lists from Makerbot Industries, LLC (ABS models) and Caswell Incorporated (Copper models). Shipping costs were not included. Per-unit materials costs were estimated using the average number of models produced from a single roll of ABS filament or single copper anode sheet divided by the unit cost of the respective resource. To determine the number of models produced, we divided the mass of one unit of the raw material by the average mass of the models produced assuming 100% efficiency in the production process. We did not consider the cost of ancillary materials, such as paraffin and conductive paint for the copper models because the paraffin can be recycled and paint is not applied in a consistently measurable manner. Effort, measured in time (*h*), was calculated for comparison by timing each step of production of a single model and summing them to evaluate effort per unit model produced. This comparison was made assuming that one model is electroplated at a time. Because these are simple cost comparisons that are typically judged by practical evaluation, no statistical analyzes were used.

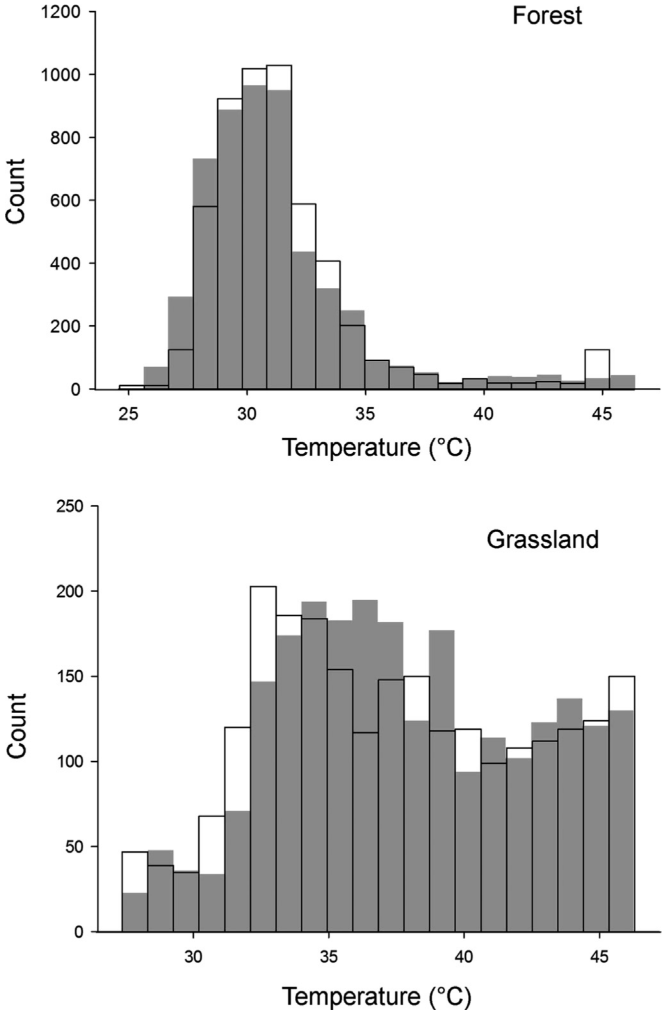

Fig. 3. Distribution of all temperatures over the course of the sampling period for (A) closed canopy habitat and (B) open canopy habitat. Copper model histograms are filled with the acrylonitrile butadiene styrene (ABS) model distributions overlaid upon them. Values that equaled or exceeded the maximum temperature recordable by the data loggers were removed from the data set.