ONLINE SUPPLEMENTARY FILE

Static Advanced Headform (StAH) Casting Process

The Static Advanced Headform (StAH) was created in several stages. First, an acrylonitrile–butadiene–styrene (ABS) plastic model was made from a digital headform (d-HF) file of the NIOSH medium-size headform (Figure 1a) described by Zhuang et al. [(1)]. To achieve the design task of generating a skin with locally defined thicknesses, first, a clay HF (Figure 1b) was fabricated, then a negative mold was created from the clay HF which permitted the execution of a mechanical design, and finally the Frubber ™ covered StAH was fabricated. It was first necessary to add properties and details of the human face, such as skin texture, mouth form, lip physiology, nose detail, and neck anatomy that were absent from the ABS plastic model. A mold (a negative tool) of the ABS plastic model was created first, in which a replica was cast in clay. The clay HF with additional sculpted details is shown in Figure 1b. These changes did not affect critical fitting dimensions, but did require creation of a new mold of the refined clay HF (Figure 1c-d). The completed StAH was mounted on a base (Figure 1e).

Hanson Robotics created a digital three-dimensional (3-D) representation of this map as a design study (Figure 2), from which a strategy for physical implementation was derived, wherein satisfactory anatomical accuracy was achieved by physically sculpting the skull form within the mold.

As it was necessary to “mark” the thickness of soft tissue within the casting tool to generate an anatomically accurate skull form, precisely measured spacers/jigs were pinned to the inner face of the mold cavity, approximately normal to the surface, as shown in Figure 3a-b. This process is analogous to forensic facial reconstruction; but applied in reverse, constructing a skull from a facial form rather than a face form from a skull. Clay was then applied into the mold around the spacers, with repeated measurements and sculpting to attain anatomical accuracy. Clays of differing colors were used to fill (and identify) differing regimes of facial tissue thickness (Figure 3c).

The negative skull form so defined was validated against anatomical models of the human skull, and the tissue thicknesses were tested using depth gauges throughout the clay form. Next, urethane plastic (Smooth-On Corporation, Easton, PA) was poured into the negative skull form of the clay and set to produce a rigid, positive core of the tool. The positive core of the tool included registration tabs that connect it to the negative core of the tool in such a way that the two precisely register during the Frubber™ casting process. This plastic skull form was then checked for accuracy, and features were added for registering the cast skin on the skull form. The skull form was then laser scanned to provide a 3-D model for digital design verification (Figure 4). Subsequently, a reproduction of the skull was made in rigid urethane plastic (Smooth-On), with an integrated breathing tube (PVC pipe with 2.5 cm inside diameter) cast directly into the skull, leading from the center of the mouth to the base of the neck.

To reproduce the properties of the human face for respirator fit experiments, a custom variation on the surfactant was used to optimize the Frubber™ formula. By balancing ratios of oil, water, surfactant, dextrose, sodium chloride, and polydimethylsiloxane (PDMS), a chaotic condition was created that gave rise to self-assembling, complex, porous structures, which were controlled to adjust the hardness, Young's modulus, and Poisson's ratio to simulate those of human skin. Hanson Robotics evaluated the Frubber™ material properties using ASTM methods for strength, compression and shear, Poisson's ratio, and hardness [2-5]. The progression in Figure 5 shows the increased complexity from a conventionally prepared sample (left and center) to the custom-tuned formulation of the rightmost sample, which exhibits hierarchical porosity down to nanoscale. These scanning electron micrographs (courtesy of NSF funding and Richland College, Dallas, TX) illustrate the basis for some of the exotic properties of Frubber™ that result in more-lifelike facial deformations or expressions.

The Frubber™ used in the StAH was made from PDMS, using a platinum catalyst to improve stability and longevity. It was made porous by two major techniques: first, macropores were generated by introducing a sacrificial matrix of soluble material, which was removed after the silicone set, to leave a porous network. Next, a surfactant–oil–water mixture was used to facilitate the formation of 4–40 nm vesicles in the silicone elastomer [(6)]. This surfactant emulsion allowed the sacrificial matrix to migrate through the silicone material and form a contiguous matrix, achieving a pore geometry tuned to the desirable mechanical properties of strength and elongation. Additionally, the resulting reverse micelles serve as molecular-scale ripstops, deflecting stress concentration when a tear happens due to molecular defects in the silicone material [(7)]. This results in a stronger yet more supple silicone material that exhibits greater elongation [(7)].

Several special characteristics make Frubber™ a good simulated skin for the application of simulating human faces in respirator fit testing. First, the softness of the material compares well to that of human facial soft tissues, as does the force required to elongate the material [(6, 7)]. Second, because it is a porous material, it is able to compress locally, in the manner of the fluid-filled cellular material of the human face, to reproduce natural creases and folds. Third, the material is exceptionally strong due to the molecular ripstop effect mentioned above. The first 500 μm of the surface of this Frubber™ is non-porous (or effectively so), and therefore has a Poisson's (compressibility) ratio near the maximum value, 0.5. The next 1 mm of depth (from 0.5 mm to 1.5 mm) has very little porosity, and Poisson's ratio is estimated to be 0.48. Thence, porosity increases with depth from the surface. The fluid-filled nanopores (ripstops) are distributed throughout the Frubber^{TM} and reinforce the base material. Finally, the Frubber^{TM} skin was cast into the mold, between the face mold and the skull form, thus reproducing the defined anatomical skin thicknesses. During this process, a patch of reinforcing cloth was added to the bridge of the nose—the region of the procerus muscle, at the top of the nose. This skin was then glued to the surface of the cast skull form using Platsil Gel-10 silicone adhesive (Polytek, Easton, PA). The resulting skin was rigorously measured with a lance to validate the accuracy of the tissue thicknesses. The resulting punctures in the skin were sealed with more Platsil Gel-10 to achieve a watertight seal of the skin for respirator testing.

The StAH was mounted on a portable acrylic base. A length of PVC pipe was installed in the base which connected to the breathing tube from the headform on one end, and on the other end, terminated in a threaded female connector at the bottom of the base. Watertight sealant was applied to these connections. A 5" length of PVC pipe with a male threaded connector was attached to the bottom of the base (protruding straight down). This projecting PVC pipe accommodated the attachment of a hose which connected to a breathing machine.

REFERENCES

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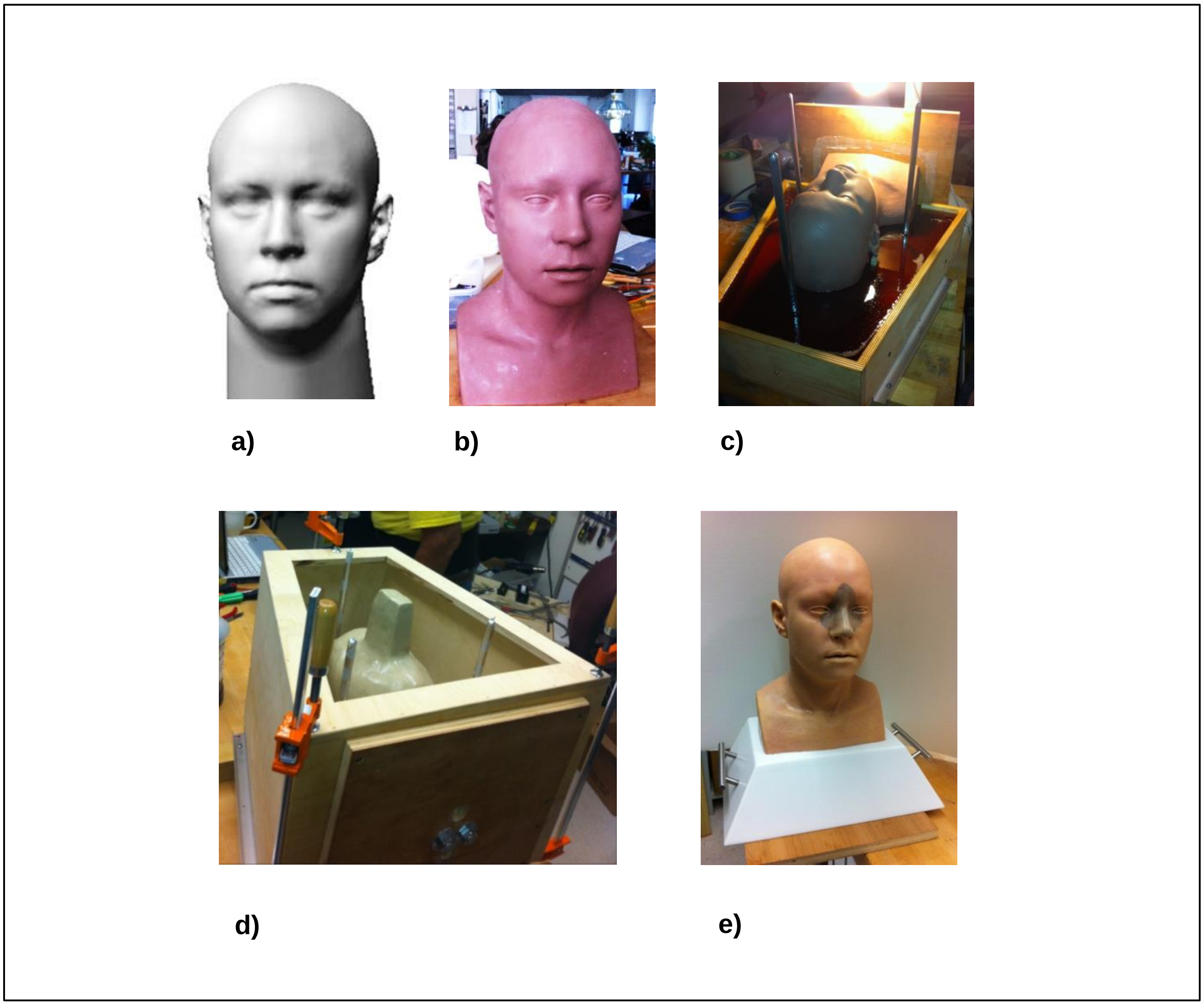

Figure 1. a) NIOSH Medium headform (digital image); b) NIOSH Medium headform with additional details (clay model); c and d) Mold of the clay NIOSH Medium headform showing alignment jigs; e) completed NIOSH Medium Static Advanced Headform (StAH).

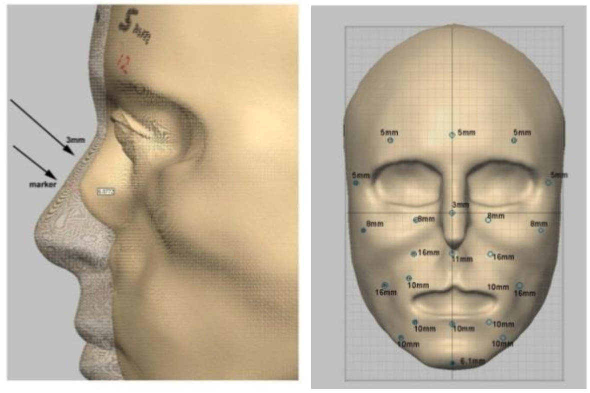

Figure 2. Three-dimensional design study of facial landmark thickness.

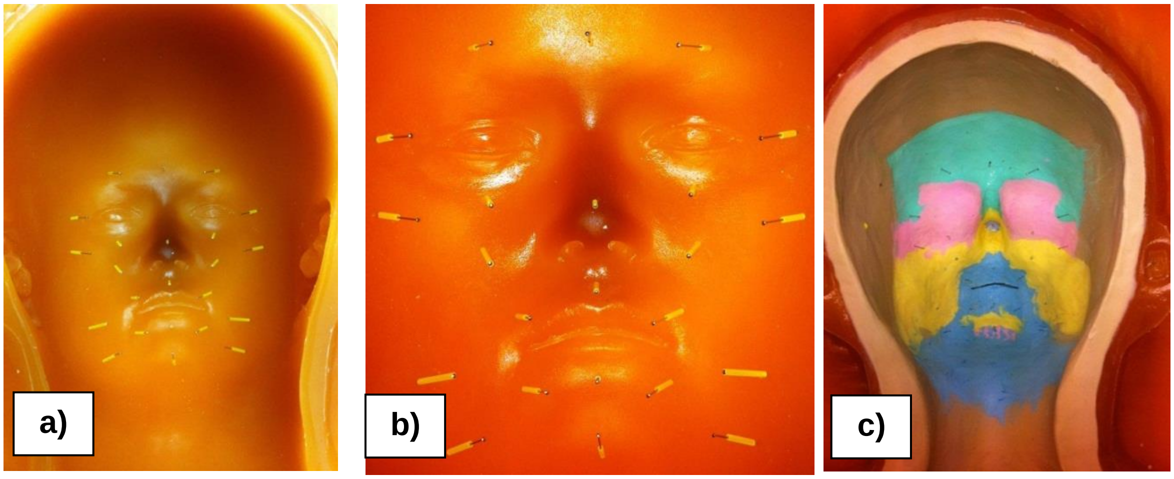

Figure 3. a–b) Face mold negative form with tissue thickness markers applied; c) Reverse forensic facial reconstruction used to generate an anatomically accurate skull form.

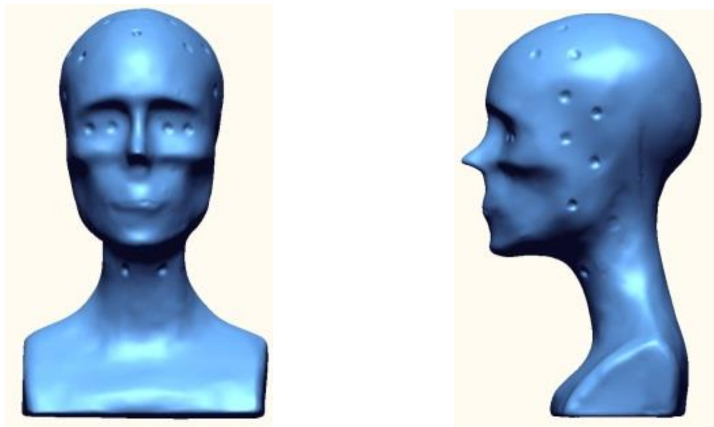

Figure 4. Laser scan of the skull form.

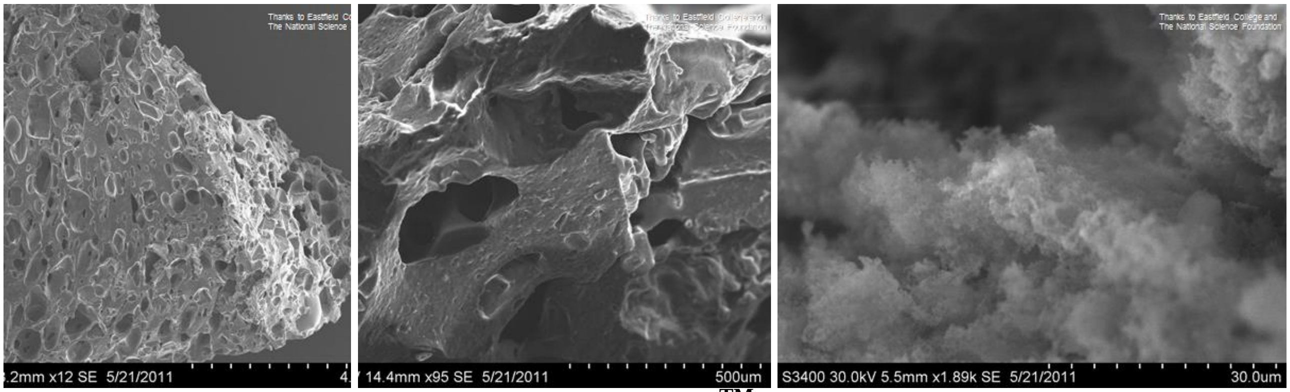

Figure 5. Scanning electron micrographs of Frubber™ formulations, showing enhanced hierarchical porosity from the left and center sample (original preparation) to the rightmost material, prepared using a lower concentration of surfactant. (Courtesy of NSF funding and Richland College, Dallas, TX).