Reproducible Prosthetic Skin Color

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Date: December 12, 2007

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Abstract

Currently, artists color prosthetic skin by hand to match each patient's natural skin color and texture. However, this is an expensive and time-consuming process. Therefore, the goal of this project is to design a faster, systematic method to produce reproducible prosthetic skin color in such a manner that the color can be quantified. After analysis of some proposed solutions, it was determined that the inkjet printer design is the most feasible and therefore became part of the final prototype. Silicone is currently used as the substrate for prosthetic skin, but its hydrophobicity requires a surface treatment method to make water-based ink adhere to it. The final process involves plasma treating partially cured silicone, printing on it, and sealing the color with a second layer of silicone. Testing results indicate that coloring done via this process allows the color to remain intact through frequent cleaning.

Background

Current Method

Currently, medical artists, such as the client, Greg Gion from Medical Art Prosthetics, must use his or her eyesight and intuition to match the prosthetic skin color to the patient's natural complexion. The first step of coloring prosthetic skin is to apply as much color and detail as possible into the inside of the mold of the prosthetic by using a paintbrush. The pigment that is currently used to color these prosthetic skins is a mixture of a catalyst and un-catalyzed silicone-based ink. After the artist finishes coloring the inside of the mold, it is filled with room temperature vulcanizing (RTV) silicone. This mold-silicone complex is then cured in the oven, at which point the ink from the inside of the mold is transferred to the prosthetic limb itself. The second stage of prosthetic skin coloration takes place during installation. At this point, Mr. Gion paints additional detail onto the prosthetic to ensure that it blends perfectly to the surrounding natural skin.

The biggest challenge of this coloration method is the reliance on eyesight and intuition. The lack of systematic methodology contributes greatly to excessive need for time, effort, and money. For example, a prosthetic nose takes 3 to 4 hours for only coloring and curing and it costs approximately $750 to $1000. As a result, natural-looking prosthetic skin becomes expensive and inaccessible to many patients, especially those who live in countries where medical artists are not available.

Problem Statement

Currently, the procedure for prosthetic skin coloration is done manually, which requires a lot of time, money, and energy. Although there are many different skin tones and color, resemblances exist among individuals from similar regions of the world. The client proposes a systematic method to mass-produce skin colors to create realistic prostheses. He would like to create a process that can color prosthetic skin with consistent characteristics and qualities.

Design Requirements

As stated in the Problem Statement, the client is looking for a systematic method to reproduce skin colors for prosthetic skins. As a starting point, he suggested a printing process that can mass-produce a certain pattern, such as wood grain. Several criteria were considered while researching different methods:

1) Pigment: adheres well to the substrate and consists of the primary colors – red, yellow, blue. Specifically, pigment must adhere more strongly to the substrate than to human skin for the process to pas the first stage of testing (refer to ***Preliminary Testing***).

2) Substrate: silicone. Silicone is widely used in the prosthetic industry. The focus of this project is to print on the existing substrate rather than finding a new one.
3) Materials: must be non-toxic and hypoallergenic. The materials cannot cause any allergic reaction to the patient who uses the completed prosthetic, since it will be fixed to his or her skin.
4) Process: operable by one person
5) Cost: less than $500

Problem Motivation

The final design would reduce the time, labor, and cost, from the current manual method. An automatic printing process would allow a rapid and accurate prosthetic skin production. Each customer's skin color and texture will be mimicked, quantified, and recorded by computer software such as Adobe Photoshop. Increasing printing efficiency will help reduce the time and cost of producing prosthetic skin. Moreover, skin quantification records allow production for replacement prosthetic skin without the presence of patients (since reproduction generally happens every 5 years for adults and 6 months for children – data given by client)

Competition

In industry, most skin prosthetics are colored manually. A possibility that was recently proposed is to modify a rapid prototyping machine to facilitate three-dimensional printing of prosthetic limbs. Rapid prototyping, or stereo-lithography, starts with a three-dimensional Computer-Aided Design (CAD) generated image, which is then sliced into layers of 0.1 mm thickness. Next, the computer instructs the rapid prototyping machine to discharge liquid photopolymer to form these thin layers one by one. Once all layers are formed, the prototype is then cured inside an ultraviolet oven (www.howstuffworks.com).

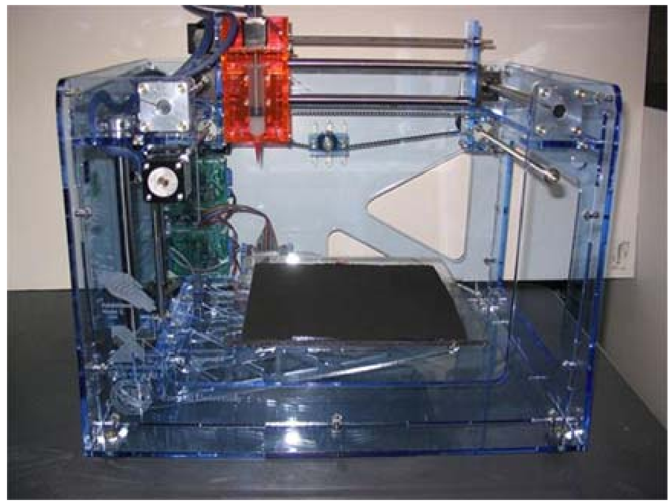


Figure 1: *Rapid prototyping machine.* The Rapid prototyping machine used for testing at UK National Center for Product Design and Development Research. Source: www.newscientist.com

Domenic Eggbeer and the United Kingdom National Center for Product Design and Development Research are currently performing a laboratory study on modified 3D printer as depicted in Figure 1. As of January 16, 2006, trials on reproducing skin texture are currently being conducted on wax. These prototypes cannot yet match skin texture accurately, and the methodology for prosthetic skin coloration has not been explored (Copying wrinkles, 2007).

Although this method presents the exciting possibility of producing prosthetic limbs and coloring prosthetic skins in one step, the technology is still at its infancy. A typical printing of a medium sized object ranges anywhere between six to twelve hours. Larger objects have been known to take days to produce. Since the study of three-dimensional printing has only been started recently, a less innovative but highly productive method of coloring skin prosthetic would probably be more beneficial to the field of prosthetic skin.

Design Proposals

The following will describe the proposed alternate printing processes: pad printing, offset lithographic printing, laser printing, and inkjet printing.

Pad Printing

Pad printing is a printing process that utilizes three main components, excluding the substrate: a cliché, ink, and a silicone pad. A cliché is a plate made of either steel or plastic with an etched design on the top where the ink is applied. The process usually uses a solvent-based ink; however, there are some companies that use a silicone-based ink. The silicone pad is used to transfer the ink from the cliché to the substrate, and is the most important part of the process.

The silicone pad has some important factors to take into consideration for use: the hardness of the pad, the shape of the pad, and the surface energy of the pad. The hardness determines how much deformation occurs with the pad. Deformation of the silicone pad will affect ink transfer between the pad and the substrate. The shape of the pad is usually one of three types: conical, rectangular, or roof-shaped. Each shape works best with different substrates. Lastly, the surface energy of the silicone pad has to be lower than that of the substrate in order for ink to transfer (Pad Print Process).

Applying this process to printing colors on prosthetic skin is highly feasible. The basic materials needed – ink, silicone pad, substrate (silicone or polyurethane), and cliché – are available at many different companies. The challenge is to make sure that the ink will transfer from silicone to silicone, if that is chosen as the substrate. In order to make this process work, the substrate will need to be surface-treated to alter its surface energy, by using plasma treatment for example to achieve this.

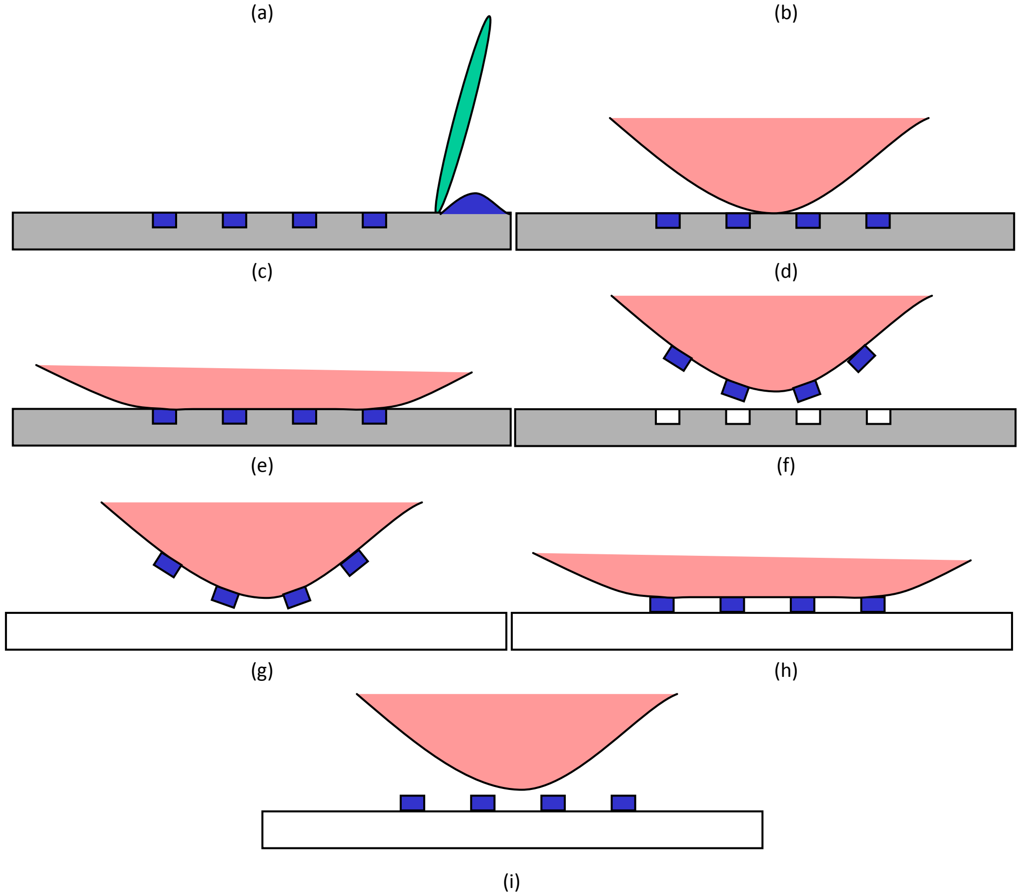


Figure 2: *Basic process of pad printing.* Chronological order of steps involved in pad printing. (a) Basic cliché ready for use. (b) Ink flooded onto cliché. (c) Top layer of ink scraped off cliché. (d) Silicone pad lowered to cliché. (e) Pad applied with force onto cliché; deformation of pad contacting cliché. (f) Pad lifted off cliché; returned to normal shape. (g) Pad lowered over substrate. (h) Pad applied with force onto substrate; deformation of pad. (i) Pad lifted off substrate; ink transferred.

The basic process is detailed as follows, also shown in Figure 2. First, the cliché is flooded with ink. Then the top of the cliché is scraped clean until the only ink that remains is that which resides in the etched design. Next, the silicone pad is pressed with force onto the cliché, with slight deformation of the pad, ensuring that all the ink is picked up. The pad is then lifted off the cliché, pad returning to its original shape. Then the pad is pressed with force onto the substrate, slightly deforming the pad again. The ink transfers completely from the silicone pad to the substrate. Lastly, the pad is lifted from the substrate, and the process can be repeated.

The benefits of this process are that it is easily operable by one person, the components used are versatile, a variety of ink colors can be used, and the process is easy to modify. There are not many components needed to operate this process, so each operator should not have difficulty with learning the steps to pad printing. Also, pad printing allows the user to print colors on many different substrates, including metal, plastic, wood, and fabric (TNT Distributors). Pad printing is currently used commercially to print labels on products such as shampoo bottles, t-shirts, and mugs. The variety of ink colors available for pad printing includes the primary colors is an advantage for creating natural skin color. The limitations, however, are that the process mainly uses solvent-based ink, the substrate needs a higher surface energy than the silicone pad, as mentioned before, and the ink is thin (Pad Print Process). Also the resolution of 300 dots per inch (DPI) is low compared to the other proposed designs.

Offset Lithographic Printing

The offset lithographic printing design applies the technique that is widely used to print newspapers and magazines. It works based on the principle that water and oil-based ink do not mix. The ink will adhere to the image areas, while the water will adhere to the non-image area. First of all, the desired image is created on a negative film, and then transferred to a plate or cylinder using the same technique used in photography to develop photographs. A certain amount of light is allowed to pass through the negative film to expose the plate. The light will activate the ink-receptor on the plate, which will then pick up ink released from the ink rollers (Printing Process Descriptions). Ink will be washed off from the non-image area by water since the oil based ink does not mix with water. Then, the image from the plate will be "offset", or transferred, to a rubber "blanket", and the image will be printed onto the substrate. We would like to modify this system so that we will be able to use silicone-based ink instead of oil-based ink, as well as use the silicone substrate instead of paper.

This design has two separate inputs of ink and water. This can be applied when using silicone-based ink because it is necessary to keep the ink and its catalyst separated. Areas where silicone ink and catalyst interact will form images, which will be transferred to the offset drum. The drum must be made of materials that can hold silicone ink, and the image will be printed on silicone substrate. This technique is very useful for mass production (web-fed printing). Moreover, it allows precise reproduction once the image is created. However, it is very expensive and extremely difficult to re-modify. The image shown in Figure 3 illustrates a one-color ink unit lithographic printer. The typical cost to build a lithography system (including color units, computer control, and capital investment) is approximately $ 1 million. Moreover, similar to pad printing, lithographic printing is limited by a resolution of 300 DPI. In order to create natural skin colors, multiple units must be installed to accommodate three primary colors. This will increase the cost and difficulty of building the prototype.

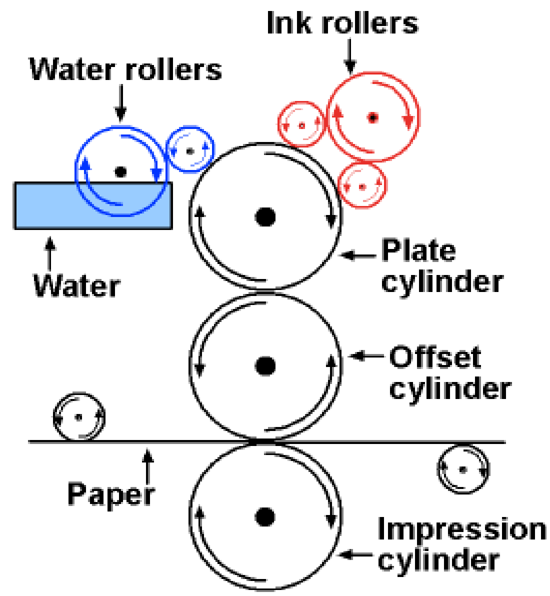


Figure 3: *Lithographic printing.* Diagram shows one color unit in offset printing. Ink rollers release ink to plate cylinder for ink-receptors to pick up and form image. Water rollers dampen water to plate cylinder to wash off ink from non-image area. Image on plate will be transferred to offset cylinder, and printed on substrate.

Source: www.howstuffworks.com

Laser Printing

Static electricity is the basic principle behind laser printing. There are five main components of laser printers: corona wire, laser scanning unit, photoreceptor drum assembly, toner, and fuser. Figure 4 depicts the basic components of the laser printer. As soon as the printer receives the command to print, the corona wire gives the photoreceptor assembly a positive charge. The laser inside the printer then draws the document to be printed according to the electrostatic image on the photoreceptor drum assembly.

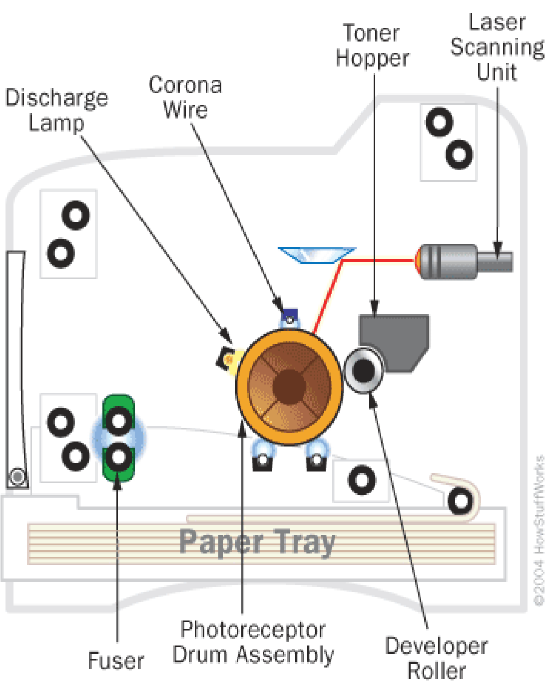


Figure 4: *Basic laser printer components.* This figure shows the main components of laser printer and their relative positioning inside a typical laser printer.
Source: www.howstuffworks.com

At this point, the corona wire gives the paper a negative charge. As the paper passes under the photoreceptor drum assembly, the positively charged toner (a powder containing pigment and plastic particles) becomes attracted to the negatively charged paper. Gravity is the only force keeping the toner on the paper until the electrostatic image is fully drawn, at which point the positively charged toner is discharged from the toner hopper.

The toner-covered paper then passes through the fuser, which functions as a heater that melts the toner powder. The melted toner powder binds into the fibers of the paper; hence, laser printer images have high tolerance to smudging. As the paper continues to travel to outside tray, the electrostatic image on the drum assembly is erased by a discharge lamp. This completes the process of laser printing (www.howstuffworks.com).

Advantages to this design come from speed, precision, and accuracy. A typical color laser printer can print up to 6000 pages per hour. This rate of printing would be useful when scaling up for mass production. The maximum resolution of laser printers is 2400 x 1200 DPI, which is extremely high compared to pad printing, lithography, and the ink-jet printer. The incorporation of the laser in the formation of the electrostatic image gives rise to this design's precision and accuracy. Compared to other designs that we have explored so far, the laser printer should have the longest lasting prosthetic skin color. This comes from the fact that the toner actually binds into the substrate instead of adhering only to the substrate's surface.

Laser printers, however, have several great disadvantages. The biggest disadvantage to a laser printer is the extremely high fuser temperature, usually above 200^{o}C. The high temperature of the fuser is required for the toner powder to melt and bind into the substrate. Currently, many companies are still trying to develop an effective fuser temperature control apparatus. The melting point of silicone is between 200 to 260^{o}C (How a laser printer operates, 2001; Butts, et al., 2000). Unless there is a toner that melts at a lower temperature and a corresponding fuser, this design is very likely to cause the silicone substrate to melt inside the laser printer, a problem that would cost the client time, money, and possibly the printer itself.

Another disadvantage to this design is the current high cost of a laser printer. One of the reasons that laser printers are commonly used only in professional settings is due to their current unaffordable price. The price of a laser printer and its modification is very likely to exceed the given budget of $500.

Inkjet Printing

In an inkjet printer, a nozzle holds ink and contains either a resistor (in thermal printers) or a piezoelectric heater. In the thermal printer design, the resistor warms the ink, causing it to expand until the surface tension can no longer counteract gravitational force. The piezoelectric design utilizes a vibrating piezoelectric heater that pushes the ink out of the nozzle. For the purpose of this project, a plate-feed inkjet printer is ideal in that it can print a variety of surfaces rather than only sheets.

There are several advantages to modifying a regular inkjet printer. First, it is inexpensive. On amazon.com, for example, a new Epson Stylus Photo 260 Inkjet Printer costs $79.99, and a new Epson Stylus Photo R380 Inkjet Printer costs $99.99. Both are less than 20% of the $500 budget the client suggested. Second, the materials are easy to obtain in that most retail stores that carry printers sell inkjet printers. Third, this is a simple design, since it merely requires tweaking an existing inkjet printer. Finally, the design should be easy to operate by one person in the same way that most people can easily print a document on paper without assistance. These attributes make this design a feasible prototype.

Unfortunately, there are a couple of problems with this design. The ink may adhere only to the surface of the substrate, therefore decreasing the durability of the color. However, a toner (such as in the laser printer design) may be applied to the ink to counteract this potential problem. In addition, the resolution of an ink-jet printer is limited to 720 x 720 DPI, which has lower resolution than the laser printer design.

Design Evaluation

In order to select a final design, a matrix with eight features weighted based on their importance to the design constraints was created. For example, one of the largest goals is to build a prototype and test it within the allotted time, so feasibility is weighed most heavily. Accuracy and durability of the process are also rated heavily since high resolution is required to precisely produce skin color and texture. Moreover, the process must be durable and last up to 5 years for it to be cost effective. Usability refers to the ease of use and level of maintenance needed for each process. The laser printing process receives the lowest score in usability since there is a great chance that the substrate will melt and damage the printer.

Each alternative design was evaluated on a scale out of 10 for each criterion, with a grand total of 80 possible points. Each team member evaluated these criteria individually, and then the team discussed and averaged the points. Finally, the average points were multiplied by the weight percent assigned as shown in Table 1.

Table 1: Summary of criteria used to evaluate the four designs.

Criteria	Weight	Laser	Pad Print	Litho	Inkjet
Feasability	0.35	5.3	9.0	8.3	10.0
Accuracy	0.15	9.5	7.5	7.5	9.0
Durability of Process	0.15	3.8	7.3	7.8	10.0
Efficiency (Mass Production)	0.1	7.0	5.8	9.3	7.0
Usability	0.1	6.0	8.5	8.5	9.0
Cost	0.05	3.5	8.3	4.0	7.0
Safety	0.05	6.5	8.8	8.5	8.0
Durability of Color	0.05	9.0	7.0	7.0	7.0
Total	1	50.5	62.0	60.8	67.0
Total with Weight		6.1	8.0	7.9	9.1

After rating all of the designs, it was found that the inkjet design scored the highest based on its high feasibility and durability. Therefore, it was pursued as the final design.

During the first half of the semester, the focus was solely on printing on silicone hydrophobic surfaces. As the semester continued, it was apparent that printing on silicone substrate was possible, but the color layer can often easily fade. Therefore, the second half of the semester was dedicated to finding a process that would print on silicone and protect the color.

Materials

The final design requires a plate feed inkjet printer and the substrate, silicone. The design also required pigments to color the substrate. The pigments could be the same paint currently used by the client or some other type of ink, so the ink within the inkjet printer was used. Lastly, a surface treatment set-up is necessary to attach hydroxy groups to the silicone, which is naturally hydrophobic, so that the pigment would adhere to it.

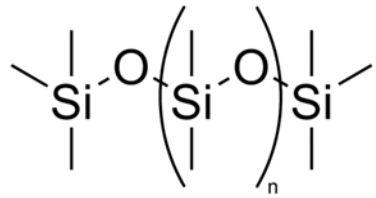


Figure 5: Basic chemical structure of PDMS.

For developing the final design, polydimethyl siloxane (PDMS) was used. PDMS is the silicone with the lowest molecular weight. It consists of a siloxane backbone (alternating silicon and oxygen atoms) shielded by R-groups such as, in the case of PDMS, methyl groups. Figure 5 shows the structure of PDMS. PDMS, as are other silicones, is biocompatible and widely used in personal care products and have numerous medical applications (Ratner, *et al.*). PDMS costs $46.90 per 500 grams, making it an affordable substrate to test upon (Ellsworth Adhesives).

Preliminary Testing

There were two testing stages in this design process. The first stage of testing was done to eliminate several surface treatment options and develop an optimal process, and the second stage of testing was done to test the color quality produced by the final process. For the first stage, three different surface treatment methods were explored: hydrochloric acid (HCl) treatment, plasma oxidation, and partially curing PDMS. Hydrochloric acid treatment was done by immersing the PDMS sample in 1 N HCl for one hour and letting the sample to air dry before printing color on it.

Next, PDMS was plasma-treated using a cattle prod. Plasma oxidation electrically heats the air and creates radicals on the surface of the PDMS. These radicals are hydroxy groups, which make PDMS much more hydrophilic. A sample of PDMS was oxidized for 5 minutes with the cattle prod, then immediately printed on; plasma oxidation only lasts a maximum of 30 minutes before the PDMS returns to its hydrophobic state.

The last idea was to print on a partially cured PDMS surface. This method exploited the fact that uncured PDMS is hydrophilic to some extent. In a silicone such as PDMS, hydrophilic portions may be exposed to the surface while uncured. The initial procedure was to print on a thin PDMS surface (approximately 200 μm) that has only been cured for four minutes at 90^{o}C (compared to 15 minutes needed to fully cure a PDMS sheet).

Each treatment method was tested, by touching the surface with a finger, once it was printed, to see how well the ink adhered. The purpose of this basic test is that the prosthetic skin will likely be touched by skin, so a process that fails to preserve color through touch by fingertips should not be pursued. The HCl treatment had minimal ink adherence; the ink smeared immediately after printing. The plasma oxidation treatment improved the hydrophilicity of the PDMS surface. However, the ink still did not adhere well. The finger-touch test showed that the partial curing treatment had more improved hydrophilicity. The partially curing and plasma oxidation methods were combined to see how hydrophilicity would improve. Printing on this last sample dramatically increased the area that ink adhered to the substrate. Results of the preliminary testing are summarized in Table 2 below.

Table 2: Summary of different surface treatment methods and their corresponding ink adherence. T = temperature; t = time

Trial	Procedure	Results
1	• Soak cured PDMS in 1 N HCl for 1.5 hours • Air dry for 5 minutes • Dry with N2 (g) for 15 seconds • Print	ink did not adhere to PDMS
2	• Soak cured PDMS in 1 N HCl for 1.5 hours • Air dry for 10 minutes • Dry with N2 (g) for 15 seconds • Print	Ink did not adhere to PDMS
3	• Plasma treated cured transparency with cattle prod for 1 minute • Print	Ink smeared easily
4	• Plasma treated cured transparency with cattle prod for 2 minutes • Print	Ink smeared easily
5	• Plasma treated cured transparency with cattle prod for 3 minutes • Print	Some smearing, moderate adherence.
6	• Spun uncured PDMS at 2000 rpm for 35 seconds • Cured T=90^{o}C; t= 4 minutes • Print • Spun 2nd layer of PDMS at 2000 rpm for 35 seconds • Cured T=90^{o}C; t=10 minutes	Ink flew off the PDMS surface during 2nd spinning.
7	• Spun uncured PDMS at 2000 rpm for 70 seconds • Cured T=90^{o}C; t= 4 minutes • Print • Cured T=90^{o}C; t= 5 minutes • Spun 2nd layer of PDMS at 2000 rpm for 70 seconds • Cured T=90^{o}C; t=10 minutes	Some of ink flew off PDMS during second spinning. Adherence is better than trial 6.
8	• Spun uncured PDMS at 2000 rpm for 70 seconds • Cured T=90^{o}C; t= 4 minutes • Plasma treated for 5 minutes with cattle prod • Print • Cured T=90^{o}C; t= 5 minutes • Spun 2nd layer of PDMS at 2000 rpm for 70 seconds • Cured T=90^{o}C; t=20 minutes	Ink did not print evenly (appearance of stripes). Ink adhered.
9	• Spun uncured PDMS at 2000 rpm for 70 seconds • Cured T=90^{o}C; t= 4 minutes • Plasma treated for 5 minutes with cattle prod • Print • Cured T=90^{o}C; t= 5 minutes • Spun 2nd layer of PDMS at 2000 rpm for 70 seconds • Cured T=90^{o}C; t=20 minutes	Ink did not print evenly (appearance of stripes). Ink adhered.

After reviewing results from the preliminary testing, a combination of the partial curing and plasma oxidation were chosen for the final design. The rationale is that the moderate hydrophilicity of a partially cured silicone surface is increased using plasma oxidation. The goal was to make sure that the silicone surface was cured just enough to reach a solidity level that prevents jamming inside the printer while still remaining hydrophilic enough to ensure adherence of the ink. With the combined process, further experimentation was done to find the optimal time and conditions to obtain the maximum hydrophilicity of the silicone surface. This was done by varying the time and temperature to partially cure the PDMS surface, as well as the duration of the plasma oxidation.

Table 3 summarizes variations done during this experiment. The ink adherence was judged by comparing the percentage of colored area after printing and after the final curing.

Table 3: Summary of different variations made during testing to partially cure PDMS.

Trial	Temperature of 1st curing (^{o}C)	Time of 1st curing (min)	Color after print	Temperature of 2nd curing (^{o}C)	Time of 2nd curing (min)	Color area after 2nd spin	Color after final curing (T=90^{o}C; t = 20 minutes)
1	65	5	95%	90	5	60%	30%
2	65	5:30	40%	90	5	10%	discontinued - error at 2nd spinning
3	70	4	95%	90	5	70%	70%
4	70	5	95%	90	5	85%	85%
5	90	5	95%	90	5	95%	95%

During testing, the ink often got scraped off of the PDMS surface during printing thus creating stripes with no color. This was caused by the printer's rollers that guide the media inside the printer as it is being printed. The roller is a spring-loaded bar that consists of a hard plastic wrapped inside a rubber casing. After consulting with Professor Justin Williams, the rubber part of the roller was removed. This resulted in a decrease in the lines created upon the PDMS; however, the plastic parts of the rollers still exert force on the PDMS sample and continue to cause some scraping. Though an attempt was made to print with the plastic portion and the spring removed, the printer was unable to exert any force on the media being printed. As a result this modification prevented any printing from being done.

Final Design Process

The final printing process uses a modified inkjet printer to color silicone. An advantage of the inkjet printer design is that a software program, such as Adobe Photoshop, can be employed to digitally record quantified skin color. The challenge of using this design, however, lays in the fact that the printer uses water-based ink. Completely cured silicone is highly hydrophobic and water-based ink only adheres to hydrophilic surfaces. It would be very difficult and expensive to modify the nozzles of ink cartridges to accommodate silicone-based ink due to its viscosity. In addition, the inkjet cartridge contains a circuit board that, when the cartridge is emptied, sends signals to the printer to indicate that it can no longer be used.

In order to overcome this problem, the surface of the PDMS was treated to make it hydrophilic enough for printing. In order to achieve this purpose, PDMS was partially cured so that some hydrophilicity was maintained and then plasma treated using a cattle prod to increase its ability to adhere ink.. The color layer was also protected by sealing it with secondlayer of PDMS. Overall, the process proved to be effective in printing color gradients of a variety of colors on the PDMS surface.

Materials and Methods

- Epson R200 Inkjet Printer
- Print on CD/DVD Epson Software

- Polydimethyl siloxane (PDMS) – Sylgard 184
- PDMS curing agent
- Vacuum Pressure System – Barnant Company
- Sonication – Haier ultrasonic cleaner
- Spin Coater – Cookson Electronics, Specialty Coating Systems
- Hot Plate – Electro-Technic Products, Inc.
- Transparency sheets

Transparency sheets were cut to match the size of a CD (15 cm in diameter) in order to fit into the plate feeder and they served as the frame for pouring PDMS on. PDMS was mixed with its curing agent in a 10:1 ratio to make the substrate. During the mixing process, a lot of bubbles appeared and were removed by using a vacuum chamber for 5 minutes and a sonication machine for 3 minutes (Step 1, 2, 3 in Figure 6). Approximately 6g of PDMS were poured onto the transparency to create a thin layer 250μm in thickness. The PDMS was spun at 2000 rpm for 70 seconds using a spin coater to distribute it evenly on the surface of the transparency (Step 4). The PDMS was partially cured on a hot plate at 90^{o}C for 4 minutes (Step 5). The surface of PDMS was plasma treated using a cattle prod for 5 minutes (Step 6). After the sample was printed using the modified inkjet printer, the first layer of PDMS was then completely cured at 90^{o}C for 5 minutes (Step 7 and 8). A second layer of PDMS was poured on top of the colored layer to protect the color from fading. The final steps were spinning 6g of PDMS at 2000 rpm for 70 seconds using the spin coater and completely curing the sample at 120^{o}C for 20 minutes. The following (Figure 6) depicts our entire process from making PDMS to the complete product:

1) Made 10:1 ratio of PDMS.

2) Vacuum chamber: drew bubbles to surface.

3) Sonication: removed bubbles.

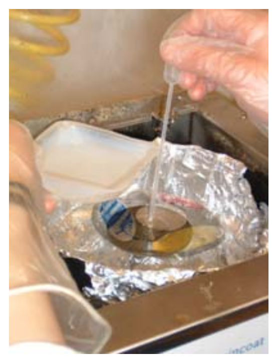
4) Spun 6g PDMS on transparency for 70 sec at 2000 rpm.

5) Partially cured PDMS for 4 min at 90°C.

6) Plasma treated PDMS for 5 min.

7) Printed on sample.

8) Cured printed sample for 5 min at 90°C.



9) Added second layer of PDMS; spun for 70 sec at 2000 rpm. Cured finished sample for 20 min at 120°C.

Figure 6: Process of making and coloring PDMS using an Epson Inkjet printer

Results and Testing

The second stage of testing was done once the design process procedure was finalized as outlined above. First, five samples were printed using a set pattern as shown in Figure 7. The designated pattern includes gradient of primary colors. Printing this fundamental pattern successfully would show that any color or pattern could be printed to color the prosthetic skin.

Figure 7: Template used for samples in further testing stage: the primary colors displayed in gradients arranged around the disc.

Four of the samples were then subjected to different tests that simulated daily conditions:

- Cleaning with isopropyl alcohol (IPA): The first sample was soaked in IPA then wiped clean with a paper towel. This is an important test because prosthetics are cleaned daily with IPA.
- Washing with soap and water: The second sample was lathered with soap rinsed off with regular tap water.
- Exposing it to a cold environment: The third sample was placed in a refrigerator (thermostat set at maximum) for half an hour.
- Abrasion resistance using sandpaper: The last sample was rubbed with sandpaper using different degrees of pressure. The remaining sample that was not tested was used as a control.

All five samples were then shown to twelve independent observers. A ballot was given to them to rate the appearance of the sample on how well the ink adhered on a scale of 1 to 10. The control sample was given the rating 10, and the observers compared the tested samples to the control. The results were then averaged for each sample (Table 4) and plotted on the following graph (Figure 8).

Table 4: Results of independent observer analysis – averaged scores of 12 ratings for each sample.

Sample	Averaged Score
Control	10
IPA	9.167
Soap and H_2O	7.083
Low Temperature	8.833
Sandpaper	7

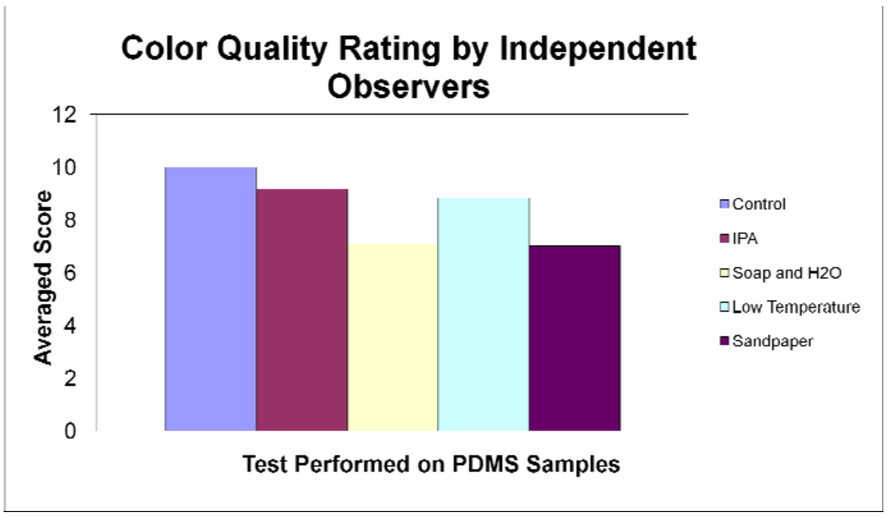


Figure 8: Summary of color quality as rated by 12 independent observers.

The observers judged the sample cleaned with IPA to be most similar in appearance to the control sample. Also, the sample exposed to a cold environment was fairly close in color appearance to the control. However, the sample that was rubbed with sandpaper was destroyed in the process of testing, thus the rating being the lowest of the group. This is a consequence of creating samples that were less than a millimeter in thickness.

Conclusion

Future Work

Over the course of developing the final design and testing, several areas of possible improvement were identified. First, the printer rollers should be modified so that they do not create lines as shown in Figure 9. Though some modification of the printer was made, further alterations are necessary to completely eliminate these lines.

Figure 9: Picture of the final product. It has lines without color due to scraping by the printer.

During testing, rubbing sandpaper- applying frictional force- on the PDMS caused the sample to tear and color to wear off. It is possible that increasing the thickness of PDMS will reduce this problem. Currently, two layers comprised of 6 grams of PDMS form the final product. If the thickness of the layers were increased to the final product would better withstand abrasion.

In addition, it may be favorable to explore other surface treatment methods methods in addition to those tested during the semester. The cattle prod utilized in the final design may not be precise and safe enough from the client's perspective. One possible option is to use a plasma chamber, which is a safer and more precise method of plasma treatment than using a cattle prod.

Once the process of making and coloring PDMS has been perfected to the client's liking, several enhancements can be implemented to the printing process. For example, a program such as Adobe Photoshop could be used to quantify the patients' skin color and archive images for future use, such as touch-ups or replacements. Furthermore, this process can be scaled up for mass production. This may involve increasing the size of the plate feed of the printer to accommodate prostheses with larger surface areas.

Ethical Considerations

The final design should be beneficial to the patients. The primary material used in this design is PDMS, though other silicones are used in industry. Due to the extensive use and testing of silicones done in industry, it is expected that PDMS should not cause any harm to the patient.

If any breaches to safety occur, it will probably involve the technician. Though most of the processes included in the final design are safe and done often, such as handling PDMS, one may want to determine the safety of frequent exposure to the cattle prod. Thus, it is advisable to test other surface treatment methods, as mentioned previously.

References

Brain, M. How stereolithography works. Retrieved October 17, 2007, from http://computer.howstuffworks.com/stereolith.htm

Butts, M., Cella, J., Wood, C. D., Gillette, G, Kerboua, R., Leman, J. et al. (December, 2000). Silicones. *Kirk –Othmer Encyclopedia of Chemica Technology*.

Copying wrinkles for better prosthetics. Retrieved October 17, 2007, from http://www.newscientist.com/blog/technology/2007/01/copying-wrinkles-for-better.html

Ellsworth Adhesives: Specialty Chemical Distribution. Retrieved December 11, 2007 from http://www.ellsworth.com/display/productdetail.html?productid=216&Tab=Vendors

Harris, T. How laser printers work. Retrieved October 04, 2007, from http://home.howstuffworks.com/laser-printer.htm

How a laser printer operates. (October, 2001). Retrieved October 10, 2007, from http://www.bbc.co.uk/dna/h2g2/A613090

Offset Lithography. Retrieved October 05, 2007. Serif Printing Resource. http://www.serif.com

Pad Print Process: Overview. Retrieved October 01, 2007 from http://www.padprinting.net/proc1.htm

Printing Process Descriptions: Printing Industry Overview: Lithography. Retrieved October 04, 2007. *Printers' National Environmental Assistance Center*. http://www.pneac.org/printprocesses/lithography/

Ratner, B., Hoffman, A., Schoen, F., Lemons, J. *Biomaterials Science: An Introduction to Materials in Medicine, 2nd Edition*.

TNT Distributors, Inc. Retrieved October 4, 2007 from http://tntdistributors.com/inks.html

Project Design Specification

December 12, 2007

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Problem Statement:
Currently, artists perform the procedure for skin coloration of facial prosthetics manually, which requires a lot of time, energy, and money. However, there are numerous similarities among individuals from similar regions of the world. Therefore, our client proposes a systematic method to mass-produce the different layers of skin for skin prostheses.

Client Requirements:
- Design a systematic procedure to color prosthetic skin
- Find a suitable substrate for production
- Devise a method to quantify skin color

Design Requirements:
1. Physical and Operational Characteristics
a. Performance Requirements- The design must be low-cost, safe to use and produce natural looking skin tones.

b. Safety- Materials must be non-toxic and hypoallergenic. Process must not cause harm to the operator and may require FDA approval.

c. Accuracy and Reliability- Produce prosthetic skin that precisely matches the natural skin color of the patient.

d. Shelf Life- The prototype of the process must last at least 5 years and withstand frequent use. The color applied by the process must last so that it will not need touch-ups for 6 months.

e. Operating Environment- The prototype of the process will operate at room temperature.

f. Ergonomics- The prototype of the process will be operated on a table for presentation purposes. It must also be easy to operate by one person.

g. Size and Shape- The prototype of the process will be no more than 3 cubic feet.

h. Weight- Not applicable to design.

i. Materials- Prefer materials to be silicone-based, but any substrate will work.

j. Aesthetics - It should be streamlined in appearance.

2. Product Characteristics:
a. Quantity- Only one final design process is needed.

b. Target Product Cost- The device should stay within the client budget, ideally under $500.

3. Miscellaneous:
a. Standards and Specifications- Not applicable since silicone is widely used in prosthetics and other medical products.

b. Customer- The substrate that will be used should preferably be silicone, but polyurethane and thermoplastic elastomer (TPE) are also options. Silicone-based paint will be used.

c. Patient-related concerns- The color must match the natural skin color of the patient.

d. Competition- Similar prosthetic devices exist which are mainly created manually. Currently mass-produced prosthetic skins are unnatural looking. This team will combine merits of the two processes, therefore creating mass-produced natural looking skin.