Progress Report: *VoltaFeet*

Presented by: Logan Groneck, Matt Heiken and Ashton Naumann

Date: 11/30/2018
Class: Senior Capstone Design- Group 2

Project Updates

Our goal in delivering a prototype that addresses the need for a simple, effective, and long-lasting treatment for reliably eliminating toe/foot fungus as well as foot and shoe odor in a diverse population remains unaltered from the preliminary report. Likewise, the project scope, design schedule, and team responsibilities are without change. However, we recently discovered a double benefit for a portion of our target population. Per interviews with Dr. Weiss, a podiatrist within the WUSM physician group, a heightened consideration for the diabetic subset of our “diverse population” is motivated due to a clinical need for ulcer and infection protection in these patients. Our optimal prototype is the union of a preventative measure for the infection of diabetic foot ulcers with the active treatment of odorous feet for the general population. Notably, the ailments both rise from the same cause of uncontrolled microorganisms on the feet (Cleveland Clinic). Therefore, the design considerations are congruent in requiring the key antibacterial and antifungal design features previously emphasized. An exhaustive list of new design specifications is provided in Table 1.

Table 1: New Specifications of Prototype

Device Weight	Not significantly heavier than a normal pair of sock (60-120 grams). Our maximum threshold will be 180 grams.
Long Functional Duration	Antimicrobial effects remain functional for at least 1 month and withstand at least 50 washing and drying cycles on high heat (135°F).
User Safety	● DC current only if electrical means are used. ● A negative allergic skin test results from the contact of the product material with the user in 95% of sampled population ● If metals or their ions are delivered to the dermis, the respective federal dermal exposure limits are 100% compliant even in product failure
Comfortability	Rated on a Likert scale as not significantly worse (ideally better) than an ordinary wearable of the same material.

Design Alternatives and Analysis

Because the design choices for this prototype are dependent on any preceding choices, a progression of four Pugh charts is used to arrive at our chosen solution. The design alternatives emerge from decisions regarding general modality of odor elimination (e.g., inserts, wearables or washes), anti-microbial agent, circuit design, and power source. The following sections introduce each design concept by discussing important features of each option and then analyzing them through a Pugh chart to arrive at a conclusion. Collectively, the Pugh chart results, found in Appendices A, B, C and D, amount to our chosen solution.

Modality of Odor Elimination

Among existing odor eliminating strategies, the viable solution space for a novel intervention for bromodosis is incredibly broad with regard to delivery modality. Moisture wicking inserts, deodorants/antiperspirants, antimicrobial lotions, foot washes, passive wearables, and circuit controlled wearables offer room for innovation to varying degrees based on our patent searches. A gold standard for alleviating foot odor has proven elusive to the marketplace due to accepted trade-offs between curative and preventative properties as well as other trade-offs involving simplicity to the user, effectiveness, and longevity.

Moisture Wicking Inserts

Inserts that may be applied above or in lieu of the shoe sole add negligible burden to the user since wearing shoes are already well-integrated into everyday life. Additionally, sweating that promotes microorganism growth increases in times of high activity--a period when the user is already accustomed to wearing shoes. Moisture wicking facilitates water evaporation during this critical window. However, an insert approach does not account for users who experience baseline sweating; the bottom of the feet have the highest concentration of sweat glands of anywhere on the body, which make this fairly common (IPFH). The inserts are ill-equipped to target bacteria or fungi directly because they lack antimicrobial properties; they only cover the bottom of the foot when foul odor producing bacteria can proliferate between the user's toes and on the tops of their feet.

Deodorizing, Antiperspirant, and Antimicrobial Lotions

A lotion that is comprised of deodorizing, antiperspirant and anti-microbial elements can cover all foot surfaces, including between the toes, with relative ease. The lotion mirrors the preventative measures present in the inserts by reducing available water to the microorganisms via antiperspirant with the addition of a symptomatic treatment of foul odor via deodorant and a curative measure of directly killing microbes with antimicrobial chemicals. However, applying lotion by hand to a region of fungal or bacterial excess brings the risk of spreading these malign organisms across oneself and to other individuals directly or indirectly. Even when specifying dose amounts, the lotion is subject to non-homogenous application across the skin that creates lapses in coverage. The efficacy of a lotion also depends heavily on it having adequate time to soak into the dermis prior to contact with clothing capable of rubbing it away.

Foot Washes

Foot washes provide the most thorough and uniform coverage to the submerged feet that can even reach under the toenails--a refuge for festering microbes. Optimally, the intervention briefly enacts inhospitable conditions that precipitate microbial reduction. However, the washes would require a shower-like setting and compliance to standardized wash times and frequencies. Because the washes necessarily derive from salts and acids, sensitive skin can dry out and crack; this results in an environment more conducive to deeper microbe penetration into the dermis leading to increased infection risk.

Passive Wearables and Circuit Controlled Wearables

Compared to other modalities, wearable technology opens the door for more intricate design features. The customizability permits a finer approach to user needs. Yet, including complex features inherently adds expense for the consumer. The return of investment on this larger upfront cost hinges on the longevity of the product combined with its effectiveness. Notably, a wearable would implicitly have greater longevity due to its reusability compared to one time use approaches such as a lotion or wash. A wearable has the benefit of contact with the affected foot for extended periods of time without requiring the attention of the user to be effective.

A passive wearable would rely solely upon contact diffusion as the delivery method. An advantage of a less involved strategy is a low failure risk due to progressive wear or incidental stresses and strains, such as when the device is dropped. Because of the minimal components, this method would be lightweight compared to the control circuit; furthermore, it would not likely require creation of a comfortable interface with the foot since the material properties necessary could be woven into a fabric similar to clothing.

The critical distinction between these passive concepts and those that are circuit controlled lies in dose regulation. In this spirit, a control circuit can be used in conjunction with Ohm’s Law, electrochemical relationships, or other well established circuit properties to ensure the therapeutic threshold is always sustained to best combat bromodosis. Passive methods not only lack the ability to modulate and assess dosage, but also risk a fading effect overtime due to a lack of a true driving force to facilitate diffusion. A potential drawback of the control circuit is bulkiness that can be a source of discomfort.

Modality Selection

To elucidate the optimal modality for our prototype, a Pugh chart analysis shown in Appendix A was conducted with the criteria of safety, efficacy, convenience, comfort, cost and longevity (in descending order of importance to our design). The foot wash underperformed across all measures relative to the other alternatives. The washes are time intensive and can exacerbate the bromodosis severity due to the cracking of a dry dermal layer that permits microbes to burrow deeper. A strategy employing lotion has an inherent exposure hazard to the consumer and those around them due to the requirement of hand application to the affected areas. With safety as the primary concern, this possibility is unacceptable. Despite high scores for other measures, the moisture wicking inserts only cover the soles of the feet and do not possess any direct antimicrobial properties. This greatly reduces efficacy because fungi and bacteria aggregate between the toes where they can persevere the moisture wicking. On the surface, the decision to use a circuit controlled wearable over a passive one is close with a total score difference of two points from the 46 possible. Considering safety and efficacy are our principle concerns here, the circuit controlled wearable outscoring the passive model by four points makes for a clearer decision. Ultimately, the ability to predict, monitor and modulate a therapeutic dose across the affected foot region is an invaluable asset of a control circuit.

Antimicrobial Agent

From the previous section, the ideal strategy for antimicrobial delivery is a circuit controlled wearable device with antimicrobial ingredient(s). Many wearable devices exist in the market; however, they all rely on uncontrolled mechanisms that deplete rapidly over time, mainly due to washing cycles where the anti-microbial particles are washed out (Benn & Westerhoff). It is now necessary to determine what antimicrobial compound(s) can be used in this wearable product that maximize antimicrobial efficiency, cost-effectiveness, and longevity. The safety of the compound is paramount in this endeavor. Since the exact amount of agent required in the wearable is unknown at this point, cost comparisons will be done relative to a gram of the agent.

Silver

Silver functions as an antimicrobial by oxidizing membrane proteins of bacteria, damaging nucleic acids, and interfering with cellular respiration (Mijnendonckx, K, et al.). Silver neutralizes a diverse range of bacteria (including gram-positive, gram-negative bacteria, and Methicillin-Resistant Staphylococci), which is a vital feature due to the diversity of bacterial colonies that may form on feet (Sotiriou, Morrill et al). Silver is antimicrobial at concentrations as low as 5 ug/ml (Spadaro et al.). Notably, resistance has been noted in several bacterial strains that can be transferred via mobile genetic elements, which is a potential drawback for long-term silver usage as an antimicrobial agent (Mijnendonckx, K, et al.). No safety concerns have been seen using silver as an external topical agent in low dosages; however, if ingested, silver can lead to bluish-grey cosmetic skin discoloration called argyria (NIH). The only documented cases of argyria are in subjects who intentionally ingest large amounts of silver (Hobman & Crossman). As a result, no ingested forms of silver have FDA approval, but many external forms are approved, such as wound dressings and washing machine drums (Hobman & Crossman). Silver anodes have potent antimicrobial properties under DC currents as low as 4 uA and voltages as low as .38V (Spadaro et. Al.). A gram of silver is currently valued at $0.46 USD.

Isopropanol

Isopropanol is a non-residue producing antimicrobial, which means that it quickly disappears leaving no material behind (Tufts). In a pure form, isopropanol is toxic to humans as it is quickly absorbed into the bloodstream. Additionally, it is a highly flammable alcohol. Even though it has very potent antimicrobial effects, except against bacterial spores, the combination of the safety issues and its non-residue producing nature make it an impractical solution to be used in a wearable device that must demonstrate antimicrobial properties for a long periods. However, periodic dispensing of a small dosage of isopropanol to the wearable device would diminish this issue. Since isopropanol cannot be stored in wire form, a reservoir full of the substance would need to be present with a pump or motor to enact periodic dispensing to the wearable. This additional bulky hardware could be uncomfortable for users. Despite this, isopropanol is very cheap; it usually costs around $0.00055 USD per pound.

Chloroxylenol

Commonly used in antibacterial lotions, chloroxylenol is a skin disinfectant used in surgeries. According to NIH’s PubChem, “chloroxylenol is on the World Health Organization's List of Essential Medicines, the most effective and safe medicines needed in a health system.” Chloroxylenol is shown to be safe for topical use on humans; however, it too is flammable as an alcohol. It is also highly effective against gram-positive bacteria, but is less effective against gram-negative bacteria and strains of Staphylococci (NIH). Staphylococci infections are common and potentially life-threatening if it is a methicillin-resistant strain. Therefore, chloroxylenol’s subdued strength against it is noteworthy. Like isopropanol, chloroxylenol cannot be stored in a wire. Therefore, a reservoir of it would have to be present on the wearable, which could make it bulky and uncomfortable. Unlike isopropanol, chloroxylenol is residue producing, meaning that it persists for a prolonged period of time, so dispensing chloroxylenol onto the wearable would not need to be as frequent. Chloroxylenol is more expensive than isopropanol at around $0.03 USD a gram, but it is still very cheap compared to the alternatives.

Copper

The antimicrobial effects and safety of copper are not well-researched compared to silver. Yet, initial research shows that copper exhibits antimicrobial properties similar to silver (Kruk et. al). Copper electrodes demonstrate mild antimicrobial properties against several bacterial strains under DC currents of 40 uA and 1.3V. Higher current and voltage requirements make copper a less safe and effective alternative to silver for electrochemical applications. A byproduct of copper's antimicrobial process is hydrogen peroxide, and while toxic to bacteria, it is also toxic to human cells; however, most cells have the machinery to eliminate peroxides. Regardless, copper is considered marginally less safe than silver for skin contact (Pecci et. al). Vitally, the amounts of these metals that would be used in our product are on a small scale where adverse health consequences are expected to be negligible, but must still be considered nonetheless. A gram of copper is valued around $0.01 USD.

Gold

Both silver and gold were found to be the second most useful metal against E.coli (behind mercury which was withheld due to drastic safety concerns) in a study of 17 metals (Nies). Antimicrobial efficiency similar to silver was also seen across other tested bacteria species. Notably, the body absorption of gold into the skin is greater than that of silver (Wang). Since this product will only be used to treat the external skin of a subject, minimizing absorption is desirable (Wang et. al). Gold electrodes exhibit antimicrobial properties with DC currents of 40uA and 3V (Spadaro et al.). The higher voltage from a more polarizable electrode relative to silver and copper makes gold less safe for electrochemical applications. Additionally, gold is prohibitively expensive in contrast to silver and copper. Currently, a gram of gold is valued around $39.44 USD.

Antimicrobial Agent Selection

As seen in Appendix B, a pugh chart was used to determine that silver is the best option for delivering antimicrobial functionality to a wearable device while still providing user safety, ease of implementation, and cost-effectiveness. Copper was the second choice; a more limited pool of research, coupled with copper's ability to create dangerous peroxides made it a less attractive option. Although silver will solely be used in initial prototypes, there is a possibility of using multiple antimicrobial agents to maximize the range of microbes that are eliminated and prevent silver resistance from nullifying device functionality. Further research into alloys will be performed to examine this idea.

Circuit Design

Thus far it has been determined that a wearable device that can electrochemically deposit silver ions onto the foot is the optimal antimicrobial strategy for meeting user needs. Therefore it is next necessary to evaluate various circuit designs that could be utilized to achieve a continuous active dose of antimicrobial silver ions. Across all designs, there are several necessary features for electrochemical deposition. First, these circuits must have an anode in contact with or in close proximity to the user’s skin to facilitate contact killing of microbes by leached ions (Spadaro et al). Contact, therefore, must be made with the entire foot to ensure sterilization, which necessitates a sock-like design that conforms tightly to the user's foot. Second, these circuits must include wiring capable of stretching. This feature accounts for repeated loading and deformation during walking, as well as accommodating variations in foot size. Traditional elastic clothing fibers, such as cotton, must be intermixed with conducting silver wires to ensure these material properties. These wires will be crimped in a wave-like pattern to allow for longitudinal deformation (IEEE, Brosteaux). Even with these design constraints, there are several circuit variations to consider.

User Integrated Voltage Controlled Circuit (UIVCC)

The first circuit concept to consider would be a “User Integrated” two-electrode circuit that conducts through the user. The antimicrobial anode would be a series of silver wires incorporated into the weave of the

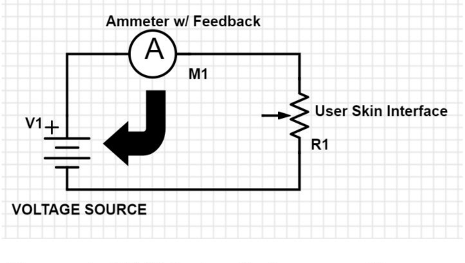


Figure 1: UIVCC circuit diagram with current regulating ammeter safety feature.

sock's foot. The ground electrode would be a thin flat electrode lining the interior of the sock's ankle. A voltage source would be wired at the ankle, away from load-bearing regions of the foot. This design ensures uniform electrical potential throughout the antimicrobial anode around the foot. This is beneficial for establishing an electrical potential field of a consistent direction that will drive antimicrobial silver ions toward the skin. A potential drawback of this design is great variability in resistance at the user skin interface that results in fluctuating current magnitude. This variability comes from the natural impedance of the skin. As the user sweats, impedance will decrease, potentially varying between approximately 100,000 and 1,000 ohms (Eplasty, Fish). For user safety and comfort, a current regulating microchip would have to be integrated into the circuit to shut off current exceeding 1 mA, the threshold of feeling (Eplasty, Fish).

User Integrated Current Controlled Circuit (UICCC)

An alternate circuit model to achieve electrochemical deposition of silver would maintain the simple silver wiring configuration throughout the foot of the sock, however it would utilize a constant current source rather than a voltage source. This feature would ensure that current is driven at a set value within the therapeutic range and that voltage would be capped at a safe compliance voltage determined by the power input. Using commercially available constant current chips or Op Amps, the circuit could be built for minimal cost. This circuit configuration stably drives silver ions toward the foot with minimal hardware. The constant current power supply would be located at the ankle in a non-load-bearing region.

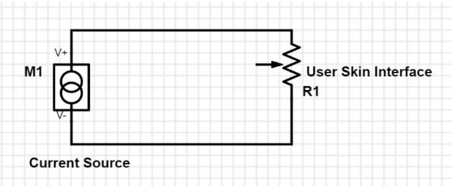


Figure 2: UICCC circuit diagram.

Parallel Circuit Mesh

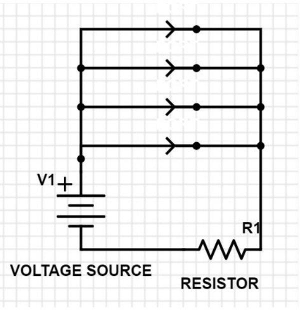


Figure 3: Parallel Circuit Mesh circuit diagram.

Rather than conducting through the user, an alternate design could be implemented with a single internal resistor connected to the silver mesh of the foot. The resistor would be located in the ankle of the sock, between the power source and the anode circuit. This design would not establish a driving potential toward the surface of the foot, however, this circuit would have a constant resistance. A potential drawback of this design is the potential loss of conductivity through all or part of the silver mesh if the connection to the internal resistor is broken. All anode wires would need to originate at the power source and then return to a single connection, which requires closed loops of wiring with two points where failure would shut down the entire circuit. Wear on the device could therefore result in the failure of part or all of the silver foot mesh.

Series Circuit Mesh

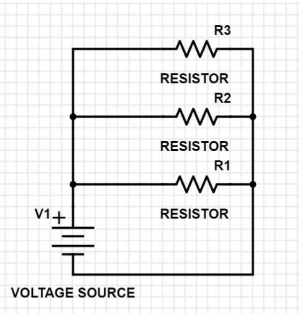


Figure 4: Series Circuit Mesh circuit diagram

Another alternate circuit design would be using individual circuit loops each with their own resistor. This design would have greater redundancy than the parallel circuit mesh in the case of a mechanical failure at one of the resistor connections. With this design, one failure at a resistor connection would eliminate only one loop of silver wiring rather than risking the complete loss of conductivity to the whole circuit. Conversely, this design would be bulky at the power source due to the increased number of connections at the cathode. The additional resistors could interfere with user comfort through added weight and thickness at the ankle. Additional resistors would also increase hardware expenses. This design, similar to the parallel circuit mesh and unlike the user integrated circuit, requires connected loops of wiring that constrain potential deformation.

Circuit Design Selection

As seen in Appendix C, Pugh chart analysis comparing circuit designs indicates that the User Integrated Controlled Current Circuit is the best solution for meeting user needs for comfort, efficacy, safety, longevity, and cost minimization. The UICCC excels in comfort relative to both circuit mesh designs, which necessitate the use of one or more embedded resistors in the sock and bulky wiring that separates from and returns to a single connection. The UICCC is well suited for this device due to greater effectiveness in driving the release of ions relative to the other designs. By controlling current output, variable skin impedance does not result in large output current swings, which is a major disadvantage of the UIVCC. Research indicates that ion leaching is proportional to current output, and therefore the UICCC strategy allows for controlled therapeutic release of antimicrobial ions (Spadaro et al.). Previous studies with antimicrobial silver anodes suggest that the size of the sterilized area is proportional to the size of the anode, so that the UICCC has the potential to sterilize the entire foot at the skin interface (Young et al.).

<u>Power Source</u>

Across all of these circuit designs, there will be some universal features. To provide feedback to the user, an LED indicator would be implemented that shines green if sufficient current is flowing and red if the maximum voltage is reached without the set point current being maintained. To create a functioning circuit, a power source is necessary. It is important that the chosen power source protect user safety, is able to function for more than a month, costs under $1.00 when bought in bulk, is practical in a broad range of user activities, and can be implemented into the product without effect on comfortability. A variety of power supply options will be examined to find the best fits to product needs.

Battery

A common way to power a small-scale circuit is with a battery, i.e., children toys, watches. Since this product's desired circuit only needs about 10 mA output, a small 3-volt 220mAh button cell battery would theoretically power the circuit for around 916 days which is well over the desired 1-month of longevity. Additionally, a 3-volt battery could not produce enough of a DC current to produce physiological harm, so it would be a safe supply of power. A 12-pack of 3-volt 220mAh batteries sells for $7.99 USD, so each individual battery costs less than $0.67 especially if bought in bulk. The battery is similar in size to a nickel, so it could be discreetly placed in the wearable with minimal effect on comfort.

Piezoelectric Generator

A piezoelectric generator converts mechanical energy into electrical energy. Since the desired product is a foot-wearable, the cyclic loading nature of walking could provide the mechanical energy necessary to power the circuit and release ionic silver to the foot periodically. This option could theoretically power the circuit indefinitely, with variable current, as long as the user is walking, or until the generator broke. Unlike the battery, the generator would be positioned under the foot of the user. This compromises comfort, as the user would feel a hard electronic device under their foot when walking. This power source would necessitate an inconvenient electrical connection between the piezoelectric insole and the sock itself. Additionally, they cost around $1.50 USD which slightly exceeds the desired cost.

Inductive-Battery

The circuit could be powered inductively by an insert placed within the user's shoe. A battery would be needed to power an oscillator in the insert, that would wirelessly power a rectifier in the wearable. The inductor and transistor necessary are cheap with a cost around $0.08 per wearable; however, producing another component is costly and can lead to a less practical solution that could only be powered when wearing shoes. This powering system (assuming that the insert would be as comfortable as the ones commonly used for comfort) would lead a to final product more comfortable than the battery and piezoelectric solutions as no power source would need to be placed into the wearable itself.

Inductive-Piezoelectric

Similar to the inductive-battery solution, this solution uses a piezoelectric generator in place of a battery. This makes the final product even more expensive because a generator costs more than a battery, but also provides greater longevity to the outcome.

Power Source Selection

A Pugh Chart analysis (shown in Appendix D) of the power source options demonstrates that a simple battery is the solution that best provides adequate longevity, cheap cost, and a wide range of use without compromising comfortability or safety.

Overview of Chosen Solution

In summary, a progression of Pugh chart analysis was conducted to establish the best features for the prototype. First, it was determined that a wearable device with some form of replenishment circuitry worked best in completing the goal of creating a simple and long-lasting product to treat and prevent bacterial and fungal foot infections. Second, multiple antimicrobial agents were examined to see which provided the most safety, effectiveness, and antimicrobial efficacy, while also keeping costs down. It was deduced that silver was the best solution to move forward with, due to its potent antimicrobial activity at low concentrations and wide clinical acceptance. To ensure antimicrobial quantities of silver ions are electrochemically released with microamperage DC currents, the UICCC circuit was chosen because of its simplicity (leading to greater comfort in the end product) and its ability to safely and effectively cover a large portion of the foot. Finally, a battery was chosen to power the circuit because of its relatively good longevity, lack of bulkiness, cost-effectiveness, and reliability. Thus, the plan is to create a sock-like prototype that leeches silver ions to the foot using a battery-powered circuit that conducts through the user themselves. More information on part requirements is in Table 2.

Budget Proposition

The estimated cost of our prototype, including testing equipment, is $183.50. Table 2 provides an itemized list of essential prototype parts and vital experimental equipment along with the sources of our cost estimates. We plan to request $183.50 (the full cost) from the BME department with the plan of funding unmet needs through personal funds, negotiated funds from our client Professor Moran, and any other undergraduate funding, such as stipends, available to us that we may come across at a later date. We will be supplementing our budgeted materials with manufacturing equipment and circuit components borrowed from the Moran Lab.

Table 2: Itemized Project Budget

Budget Item (Quantity)	Cost
Arduino Uno (x1)	$14.99 (Amazon)
Microamp Ammeter, 0-100 uA w/ 2 uA resolution (x1)	$21.39 (Amazon)
Constant Current Control Chip; PSSI2021SAY (x10)	$5.74 (Chip1stop)
3V Lithium Coin Batteries, 6 pack (x1)	$4.78 (Amazon)
99.9% Silver Wire, .1mm diameter, 2.5m length (x1)	$52.50 (Sigma Aldrich)
100 mm Cell Culture Dishes 20/pk (x2)	$28.00 (Ebay)
Agar 100g (x1)	$56.10 (Sigma Aldrich)
	Total Cost = $183.50

References

"Chloroxylenol." *National Center for Biotechnology Information. PubChem Compound Database*, U.S. National Library of Medicine, pubchem.ncbi.nlm.nih.gov/compound/4-Chloro-3_5-dimethylphenol#section=Top.

"Diabetic Feet & Skin Care Information." *Cleveland Clinic*, Cleveland Clinic, 5 Apr. 2015, my.clevelandclinic.org/health/diseases/9492-diabetes-foot--skin-related-complications.

Fish, Raymond M., and Leslie A. Geddes. "Conduction of Electrical Current to and Through the Human Body: A Review." *U.S. National Library of Medicine: National Institutes of Health*, EPlasty, 12 Oct. 2009, www.ncbi.nlm.nih.gov/pmc/articles/PMC2763825/.

"General Background: Antibiotic Agents." Index of /, emerald.tufts.edu/med/apua/about_issue/agents.shtml.

Hobman, John L, and Lisa C Crossman. "Bacterial Antimicrobial Metal Ion Resistance." *Microbiology Society Journals*, Journal of Medical Microbiology, 1 May 2015, www.microbiologyresearch.org/docserver/fulltext/jmm/64/5/471_jmm023036.pdf?expires=1543455902&id=id&accname=guest&checksum=90F1277DCC4FF0F7C0D988737EE6FFD8.

Kruk et al. "Synthesis and Antimicrobial Activity of Monodisperse Copper Nanoparticles." *Science Direct*, Academic Press, 13 Feb. 2015, www.sciencedirect.com/science/article/pii/S0927776515000855.

Mijnendonckx, K, et al. "Antimicrobial Silver: Uses, Toxicity and Potential for Resistance." U.S. National Library of Medicine, Aug. 2013, www.ncbi.nlm.nih.gov/pubmed/23771576.

Morrill, K, et al. "Spectrum of Antimicrobial Activity Associated with Ionic Colloidal Silver." U.S. National Library of Medicine, Mar. 2013, www.ncbi.nlm.nih.gov/pubmed/23017226.

"National Foot Health Assessment 2012." *Foot Odor | Institute for Preventive Foothealth (IPFH)*, Institute for Preventive Foot Health, June 2012, www.ipfh.org/resources/surveys/national-foot-health-assessment-2012.

Nies, D. H. "Microbial Heavy-Metal Resistance." *SpringerLink*, Applied Microbiology and Biotechnology, June 1999, link.springer.com/article/10.1007/s002530051457.

Sotiriou, G A, and S E Pratsinis. "Antibacterial Activity of Nanosilver Ions and Particles." U.S. National Library of Medicine, 15 July 2010, www.ncbi.nlm.nih.gov/pubmed/20583805.

Spadaro et al. - Spadaro, J A et al. "Antibacterial effects of silver electrodes with weak direct current" Antimicrobial agents and chemotherapy vol. 6,5 (1974): 637-42.

"Table of Antibacterials*." Index of Antimicrobials, emerald.tufts.edu/med/apua/about_issue/antibactTable.shtml.

Wang, M., and C. Xu. "Inorganic Nanoparticles for Transdermal Drug Delivery and Topical Application." *Science Direct*, Academic Press, 19 Aug. 2016, www.sciencedirect.com/science/article/pii/B9780128029268000057.

Young, Por Chye, et al. "Antibacterial Effects of a Silver Electrode Carrying Microamperage Direct Current in vitro." *e-Publications@Marquette: Physical Therapy Faculty Research and Publications*, Marquette University, 1 June 1994, epublications.marquette.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1110&context=phys_therapy_fac.

Zyga, Lisa. "Elastic Circuit Connectors Designed for Rubber-Band-like Circuits." *Phys.org - News and Articles on Science and Technology*, Phys.org, 10 July 2007, phys.org/news/2007-07-elastic-circuit-connectors-rubber-band-like-circuits.html.

Appendices

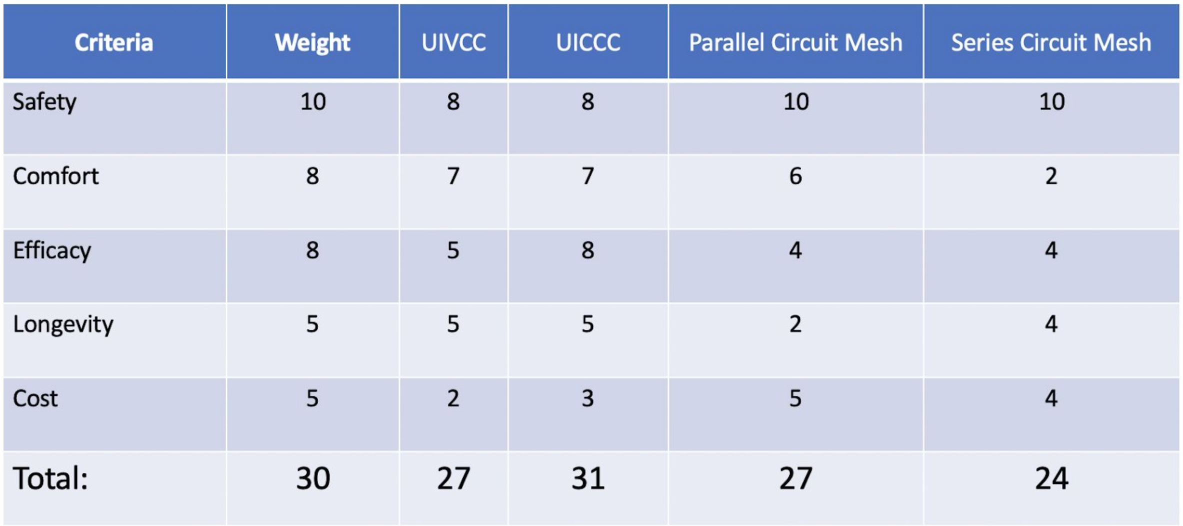
Appendix A: Delivery Modality Pugh Chart

Criteria	Weight	Insert	Lotion	Wash	Passive Wearable	Circuit Controlled Wearable
Safety	10	10	7	7	9	9
Comfort	8	7	7	6	8	7
Cost	5	4	3	3	4	3
Longevity	5	4	2	2	5	5
Convenience	8	7	5	4	8	8
Efficacy	10	3	6	4	6	10
Total:	46	35	30	26	40	42

Appendix B: Antimicrobial Agent Pugh Chart

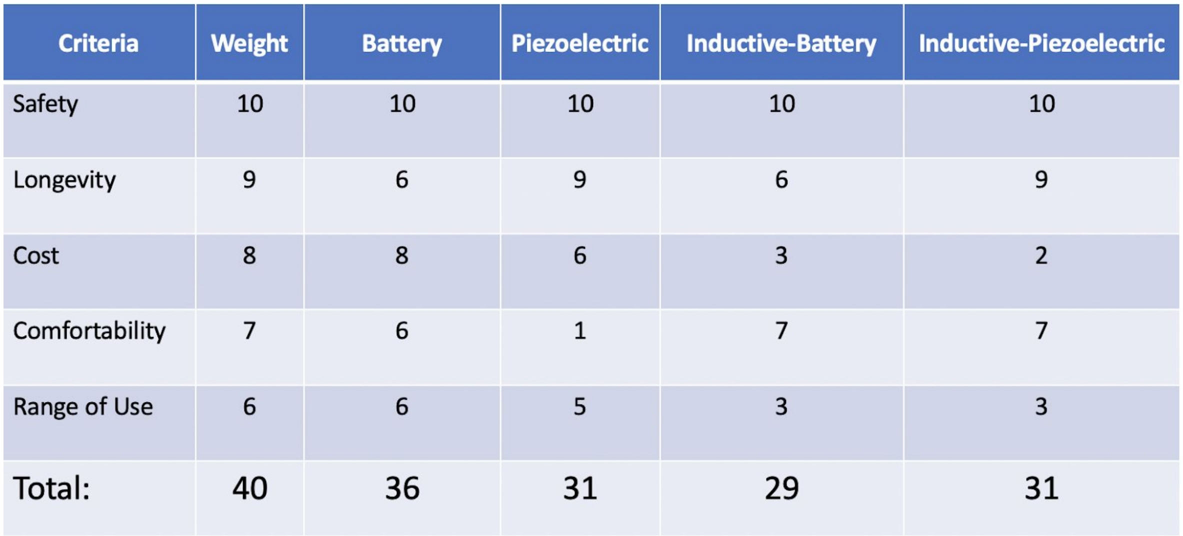
Criteria	Weight	Silver	Isopropanol	Chloroxylenol	Copper	Gold
Safety	10	10	3	4	8	10
Anti-Microbial Efficacy	9	7	5	4	7	7
Ease of Implementation	8	7	2	2	6	5
Cost	7	3	5	5	4	0
Total:	30	27	15	15	25	22

Appendix C: Circuit Design Pugh Chart



Criteria	Weight	UIVCC	UICCC	Parallel Circuit Mesh	Series Circuit Mesh
Safety	10	8	8	10	10
Comfort	8	7	7	6	2
Efficacy	8	5	8	4	4
Longevity	5	5	5	2	4
Cost	5	2	3	5	4
Total:	30	27	31	27	24

Appendix D: Power Source Pugh Chart



Criteria	Weight	Battery	Piezoelectric	Inductive-Battery	Inductive-Piezoelectric
Safety	10	10	10	10	10
Longevity	9	6	9	6	9
Cost	8	8	6	3	2
Comfortability	7	6	1	7	7
Range of Use	6	6	5	3	3
Total:	40	36	31	29	31