The Human Body Impedance Model for Assessing the Performance of Capacitance-Sensing Based Active Injury Mitigation Systems for Table Saws

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TABLE OF CONTENTS

INTRODUCTION

Over the past few years, UL has been conducting a multi-phased research program focused on developing performance requirements and a practical testing methodology for table saw safety standards to help address finger injuries due to contact with the blade. The first phase of the research concentrated on understanding the potential scenarios that might lead to a hazardous condition for table saw users and to suggest key parameters that could help define performance requirements. This research lead to a recommendation for performance requirements consisting of a defined relationship between approach velocity (speed of finger at a specified angle relative to table/blade) and depth of finger cut[1].

The next phase moved onto the practicalities of drafting a new test method to assess table saws equipped with active injury mitigation (AIM) technology. The goal of this phase was to identify the key attributes of a test probe that would attempt to mimic a human finger and help trigger any AIM technologies on table saws. Since the design of an AIM system could be based on a variety of technologies, from thermal to mechanical to electromagnetics, it was necessary to develop a comprehensive listing of attributes of the human finger. The outcome of this phase was a research report[2] that discussed some of the general characteristics that an AIM-focused test probe would need to possess such as triggering sensitivity, measurement of depth of cut and minimum level of rigidity when subjected to the bending forces applied during contact. Since it is very challenging to recreate a human finger with all its possible attributes, it is likely that a practical AIM test probe would be designed to demonstrate the attributes necessary to trigger the characteristic specific to the AIM technology installed on a table saw being tested. For example, in (UL, 2015) report, one possible design of a test probe for impedance-sensing based AIM technologies for table saws was proposed.

In this report, the technical basis for the design of an AIM test probe for impedance-sensing (or more specifically, capacitance-sensing) AIM is discussed in more depth. One of the challenges from the previous phase was the scarcity of experimental measurements on human body impedance relevant in designing the test probe that could trigger the capacitance-sensing AIM technologies. So in this

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[1] (UL, 2013) Table Saw Hazard Study on Finger Injuries Due to Blade Contact, UL Research Report, 2013.

[2] (UL, 2015) General Characteristics of a Surrogate Finger for Table Saw Safety Testing, UL Research Report, 2015.

report, new measurements taken by UL on a sample of adults is presented along with a more streamlined design proposal for the AIM test probe for capacitance-sensing AIM technologies on table saws. The reason for the focus on the capacitance-sensing based AIM technologies is that, to our knowledge, this is the only technology that is commercially available.[3,4]

Capacitive Sensing AIM Technologies

The main mechanism by which the table saws studied in this report detect the presence of a human body part (mainly finger) contacting the blade is a capacitance coupling. For such systems, the blade is part of a capacitor that is, in turn, a component of a circuit within the AIM system. Figure 1 shows a simple schematic of this capacitor. One conductor is the blade while the other conductor, separated by a very small distance and a dielectric, is considerably larger (through grounding) creating what is called a self-capacitor. This means that disturbances to the smaller conductor, the blade, will result in a change in the effective capacitance value, and it is this change that an AIM system is tracking[5]. The circuitry of an operational AIM system sends a continuous signal and when a human finger comes in contact with the blade, depending upon the electrical impedance of the human (and other conditions), there will be a change in the signal. Knowing the possible range of human body electrical impedance is a prerequisite to designing a test probe that can properly trigger and assess these capacitance-sensing based AIM systems.

There are several challenges to determining the human electrical impedance for capacitance-sensing AIM technologies. First, the electrical impedance for the human body is a function of frequency as shown in Figure 2[6]. This is important since each manufacturer may have a capacitive-sensing AIM circuitry that generates a signal at a single, different frequency. The second challenge is that as the finger contacts the blade and the blade begins to cut through the skin, the human body electrical

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[3] www.sawstop.com

[4] https://www.boschtools.com/us/en/boschtools-ocs/table-saws-gts1041a-09-113798-p/

[5] This assumes that small disturbances applied to the larger conductor would be negligible in changing the effective capacitance.

[6] (De Santis, 2011) De Santis, V., & et al., Assessment of human body impedance for safety requirements against contact currents for frequencies up to 110 MHz, IEEE Transactions on Biomedical Engineering, Vol. 58, No. 2, 2011.

impedance is likely changing. This change will be a function not only of the substructure within the local area of the cut, but also the approach speed of the finger and possibly the approach angle of the finger to the cutting surface of the blade. However, to gather data on the electrical impedance of the human body, due to the safety issues, the only measurements possible were those of people touching a stationary blade. Finally, the algorithm used by such systems could rely on several characteristics of the system impedance to make a decision on when to activate a safety mechanism. These characteristics could include monitoring the change in the magnitude of impedance, the rate of impedance magnitude change, the impedance phase or some combination thereof.

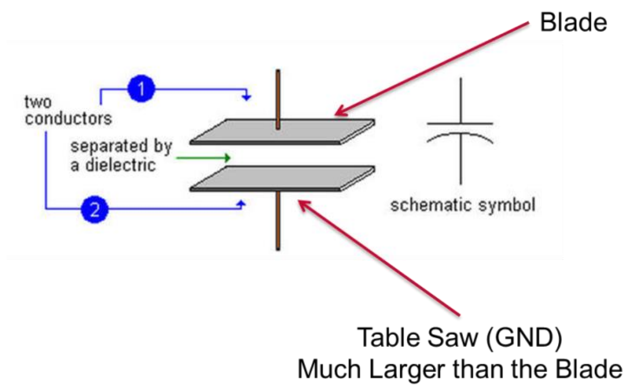

Figure 1 Simplified Schematic of Role of Blade in Capacitive Sensing AIM

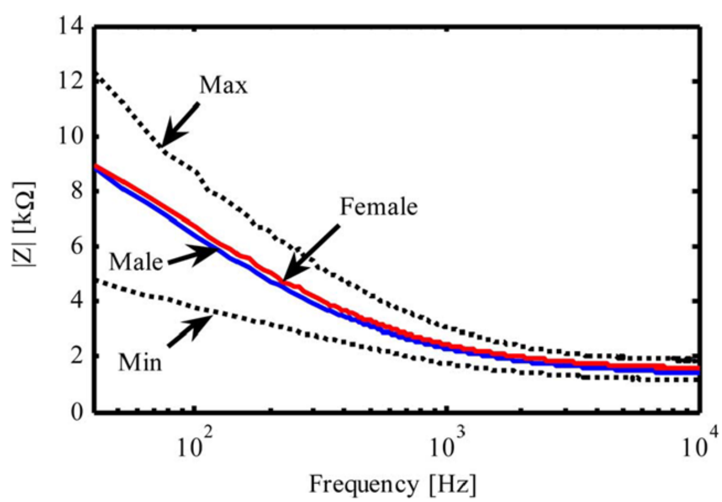

Figure 2 Magnitude of Human Body Electrical Impedance versus Signal Frequency (De Santis, 2011)

Human Body Electrical Impedance

One of the main works that was the basis of the 2nd phase of UL research was human body electrical impedance measurements conducted on 55 adults, 30 males and 25 females by De Santis (De Santis, 2011). The impedance as a function of frequency (Figure 2) of each person was measured under the following conditions: grasping contact of electrode with wet hand, bare feet standing on metal conductor and one hand to feet pathway. The purpose of the De Santis research was to assess the worst case condition for electric shock. The worst case condition for electrical shock is when the opposition to current afforded by the human body touching a live circuit is the lowest. In other words, the impedance is the lowest. Obviously, standing with bare feet and having wet hands will lead to relatively very low impedance. However, for capacitance-sensing AIM technologies, the worst case is when the impedance presented by the table saw user touching the blade is the highest possible. For example, De Santis goes on to demonstrate that by adding shoes, impedance could increase by an order of magnitude; that finger contact as opposed to grasping contact could increase impedance magnitude by 2; and, of course, dry skin will lead to increased impedance. Any insulation between the human and ground or the human and the blade will lead to higher impedance. Clearly, certain conditions (person wearing shoes, dry finger contact) are likely to better characterize table saw users which may be very different than the worst case for electric shock. So it was necessary to generate measurements that tended to be more representative of the impedance of table saw users.

More recently, the Consumer Product Safety Commission (CPSC) published a report[7] on the topic of the appropriate electrical model of a table saw user for capacitance sensing AIM technologies. They reviewed research and safety standards on human body electrical impedance from studies on electric shock and electrostatic discharge. The CPSC proposed a hybrid human electrical impedance model (or human body network - HBN) combining the circuit developed for electric shock (De Santis, 2011) in series with a capacitor whose initial value was set to 50 pF representing the self-capacitance of the human body to space. They recommended increasing the value of this capacitor up to short circuit to represent the additional effect that surrounding conductive surfaces such as walls, floors and nearby electrical equipment might have on increasing the capacitance of the human body. For this approach, the worst case condition is the initial condition of 50 pF capacitor. Any increases in the capacitance only serve to further lower the impedance of the human body model.

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[7] (CPSC, 2017) Proposed Rule: Safety Standard Addressing Blade-Contact Injuries on Table, U.S. Consumer Product Safety Commission, 2017.

HUMAN BODY IMPEDANCE EXPERIMENTS

As mentioned earlier, one of the main challenges has been access to human body electrical impedance data over the frequency range of interest that best represents the relevant conditions of a table saw user that might come into contact with a blade. So in this section, measurements, taken on 40 adult volunteers, all of whom were UL employees, are presented. For these tests, the methodology for measuring human body impedance followed that of De Santis (De Santis, 2011) with some modifications. One modification was that the data was taken under a wide range of conditions, some of which were considered to be more representative of the users of a table saw. The other modification was that the saw blade (removed from the table saw) was used as one of the electrodes, and the contact area was set up to be human fingertip contact with a single blade tooth. This is understood as "a small contact area" according to IEC 60479-1[8]. All these factors from contact area to contact pressure to skin conditions at the point of contact to footwear to weight of the person and several others will affect the values for human body impedance of an individual and were tracked and controlled where practical.

Test Equipment

The Keysight impedance analyzer model E4294A (Figure 3) was the piece of equipment used for the impedance measurements. In addition, the Keysight impedance probe 42941A (Figure 4) was used with the E4294A to perform the impedance measurements to help ensure accuracy and sufficiently wide frequency coverage (40 Hz to 110 MHz). The specifications for the analyzer are shown in Table 1.

[8] (IEC 60479-1, 2015) IEC 60479-1; Effects of Current on Human Beings and Livestock – Part I: General, 2015.

Figure 3 Keysight Impedance Analyzer Model E4294A

Figure 4 Keysight Impedance Probe Kits 42941A, 40Hz to 110MHz

Table 1 Key Specifications for the Impedance Analyzer

Agilent 4294A key specifications

Operating frequency	40 Hz to 110 MHz, 1 mHz resolution
Basic impedance accuracy	±0.08%
Q accuracy	±3% (typical) @ Q = 100, f ≤ 10 MHz
Impedance range	3 mΩ to 500 MΩ*1
Measurement time	3 msec/point @ f ≥ 500 kHz, BW = 1 (fast)
Number of points per sweep	2 to 801 points
Measurement type	Four-terminal-pair measurement (standard) 7-mm one port measurement (with the 42942A) measurable grounded devices Impedance probe measurement (with the 42941A) measurable grounded devices
Impedance parameters	IZI, IYI, θ, R, X, G, B, L, C, D, Q
DC bias	0 to ±40 V/100 mA, 1 mV/40 µA resolution Constant voltage/constant current mode, DC bias V/I monitor function
OSC level	5 mV to 1 Vrms/200 µA to 20 mArms OSC level V/I monitor function
Sweep parameter	Frequency, OSC level (V/I), DC bias (V/I)
Sweep type	Linear, log, list: manual sweep mode: up/down sweep
Other function	Equivalent circuit analysis function, Limit line function Trace accumulate mode
Marker	Eight markers (one main marker and seven sub markers) Delta marker function, marker search function (Max, Min, Peak, Next peak, etc.) Marker analysis function

(*1) 30% typical accuracy range: 3 mΩ (100 Hz to 110 MHz), 500 MΩ (100 Hz to 200 kHz)

Test Setup and Data

Figure 5 shows a simple schematic of the test setup. All impedance measurements were taken between a point on the saw blade and ground plane. For this setup, subjects stood on a metal plate that was raised off the floor using wood planks to provide insulation from the floor and then each subject contacted the blade with a finger (Figure 6). In addition, the materials supporting the blade were composed of electrically non conducting materials. Finally, to ensure safety of the test subjects, the current was set to 200 uA. Figure 7 shows a picture of a test subject contacting the blade.

A frequency sweep was conducted for each test subject from 40 Hz to 110 MHz. The following parameters were recorded during each test run: Impedance Magnitude $|Z|$, Impedance Phase θ, Parallel Capacitance.

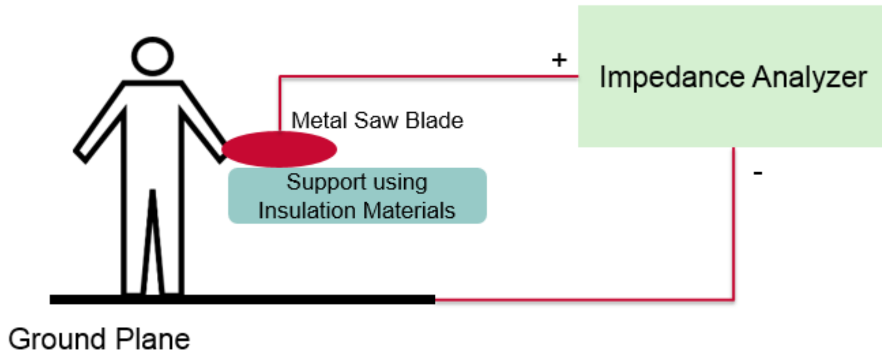

Figure 5 Test Configuration for Human Body Impedance Measurement

Figure 6 Measurement Setup with Test Subject

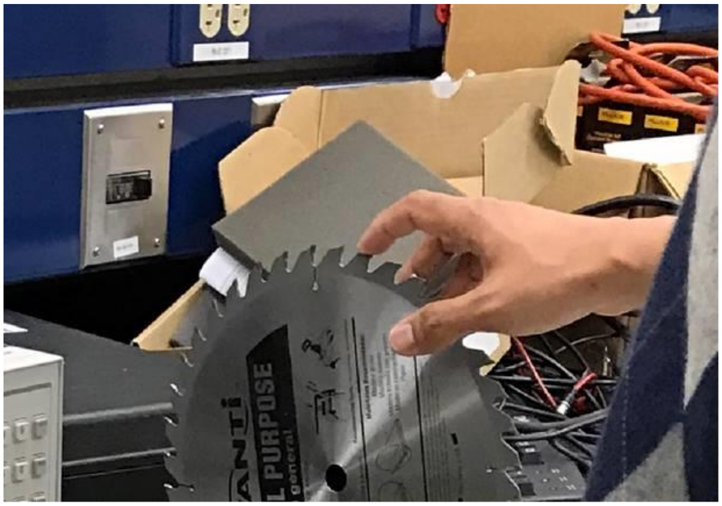

Figure 7 Index Finger contact with Blade

Test Parameters

For this study, 40 adult volunteers[9] were subjected to impedance measurement testing. The group included 10 women and 30 men with ages ranging from 25 to 60 years old. In addition to age and gender, weight and height were also measured and the individual anonymized data are shown in Appendix A.

According to the CPSC (CPSC, 2017) 75% of estimated table saw injuries occur in adults with ages ranging from 41 to 80 years old. Almost all of these incidents involve men. The bulk of the injuries within the 41 to 80 years old range occur for adults of ages 61 to 80 years old. Figure 8 shows a histogram of the age distribution for the sample of adults tested in this study. The distribution shows a good balance across the adult age range.

[9] All test subjects were employees of UL.

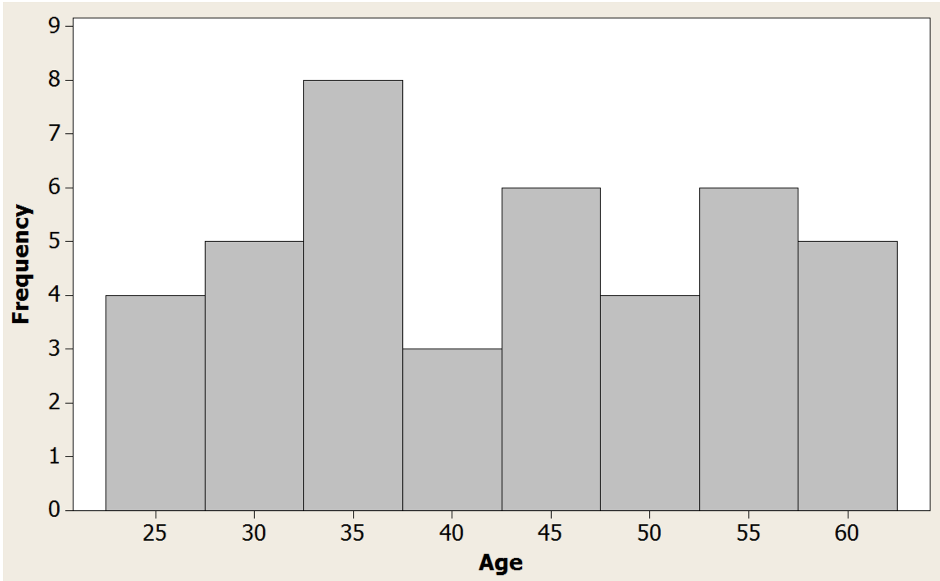

Figure 8 Histogram of Age

In addition to parameters associated with the physiology of an adult, there are other parameters that could affect the measured human body electrical impedance measurements. Of these parameters the following were deemed to be most pertinent to the users of table saws:

- **The type of shoes being worn**: For this test, subjects were measured with the shoes that they were already wearing (denoted as shoe), a pair of work boots provided to them (denoted work boots) and finally with one foot bare (denoted as barefoot). This last condition was added just to demonstrate the sensitivity of human body electrical impedance measurements to this parameter and also it would be closer to conditions typically used for electric shock related research.
- **Wetness of hand** (or more specifically, the finger/thumb that would come into contact with the blade): There were two conditions, wet and dry. Wet describes a process where the finger was wetted using a sponge soaked with tap water. For the Dry condition, the hand was exposed to a hair dryer for a set amount of time.
- **Finger**: Index finger and thumb
- **Contact conditions**: Light touch, point contact between finger and single against designated tooth.

Given these parameters, each volunteer was subjected to 12 different tests for measurement of human body electrical impedance. Table 2 shows the different combinations of variables used for each test where a green box indicates the presence of that parameter. For example, in Test 1, the subject contacted the blade with a dry index finger while wearing their own shoes. In Test 5, the subject contacted the blade with a wet index finger while wearing the work boot.

	Index Finger	Thumb	Shoe	Work Boot	Barefeet	Dry hand	Wet hand
Test 1							
Test 2							
Test 3							
Test 4							
Test 5							
Test 6							
Test 9							
Test 10							
Test 11							
Test 12							
Test 13							
Test 14							

Table 2 Testing Conditions for Human Subjects

RESULTS

For each test subject, impedance (magnitude and phase) was measured over 12 different testing conditions with a frequency sweep from 40 Hz to 110 MHz. This impedance can also be broken down into a resistive component and a capacitive component. Since the intent is to duplicate actual humans with circuits that present the same impedance to a capacitive-based AIM system, the full impedance (magnitude and phase) was necessary. The reason for selecting a wide range of frequencies is that the operating frequency of potential AIM systems could be different. According to several patents issued for capacitance-based AIM systems[10,11,12], the operating frequency could range from 20 kHz to 2 MHz. For this reason, the results of impedance versus frequency are presented.

Figure 9 to Figure 12 show log plots for impedance magnitude versus frequency for four different groupings: the median impedance magnitude versus frequency for the entire sample, the mean impedance versus frequency for the entire sample, the 5th percentile of impedance magnitude versus frequency and the 95th percentile for the entire sample, respectively.

The first observation is the human body electrical impedance decreases monotonically as the frequency increases. After 10 MHz, the impedance magnitude displays some undulations; this is likely due to high frequency effects such as radiation from surrounding objects that begin to impact the measurements. Clearly, the impedance measurements are not accurate for frequencies above the range of 10 MHz and possibly even 5 MHz[13]. Overall, these results are qualitatively similar to those seen in De Santis (De Santis, 2011).

From these figures, it can be seen that the conditions where the subject was standing with bare feet and wet hand (Test 6 and Test 14) resulted in the lowest magnitude of impedance, as expected. As discussed previously, for electric shock this would be a worst case condition. However, for the purposes of testing an AIM system which detects changes in impedance, this would be the least

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[10] Gass, S. F. (2009) US Patent No. US 7,536,238 B2

[11] Gass, S., & et al. (2012) US Patent No. 8,291,797 B2

[12] Butler, J. D. (2012) US Patent No. US 8,336,432 B1

[13] See (CPSC, 2017)

severe case. Next highest impedance magnitude levels occur for bare foot but with dry hands (Test 3 and Test 11). The remaining test cases have higher magnitudes of impedance but are generally very similar, where the users all are wearing shoes. Finally, it can be seen that once the frequency reaches a value beyond 1 MHz, all the curves basically fall on top of each other.

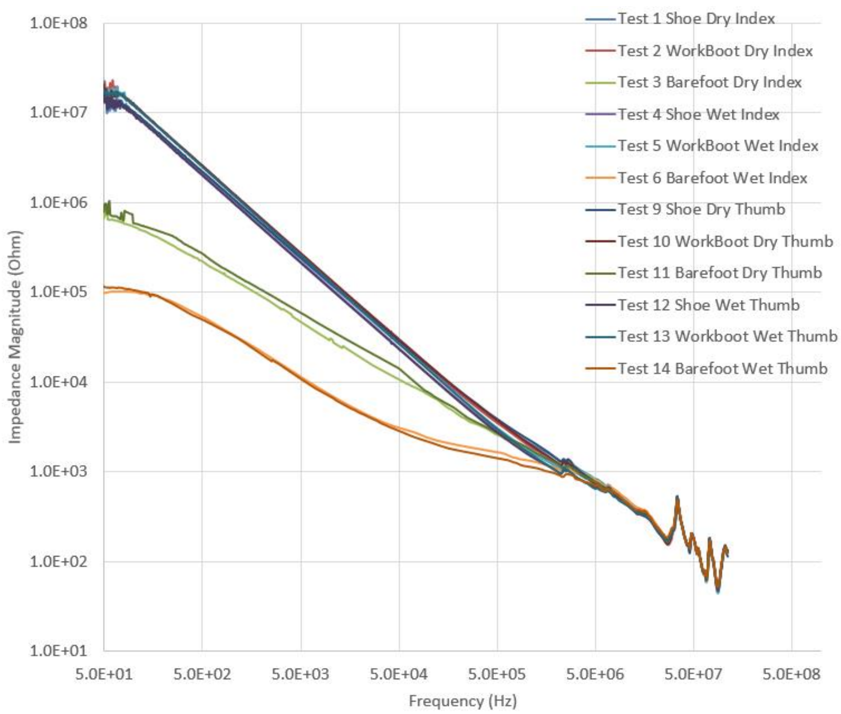

Figure 9 Median Values of Human Body Impedance versus Frequency

However, looking at the data more closely, if a single condition had to be selected as the worst case, it would be the condition of the dry thumb contacting the blade with the user wearing shoe wear (Figure 13) which is Test 9.

As noted previously, the CPSC reported that most injuries occur in age bracket from 41 to 80 with the 61 to 80 age bracket experiencing a fair share of the injuries. Looking at the data and parsing it per age, the data does not show any significant difference in the human body electrical impedance as a function of frequency with this sample of adults.

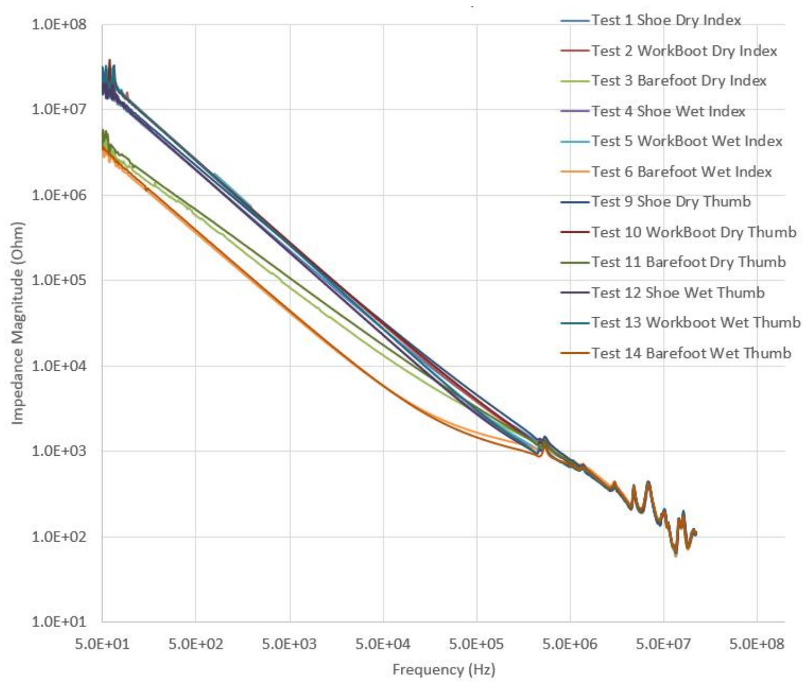

Figure 10 Mean Values of Human Body Impedance over Frequency

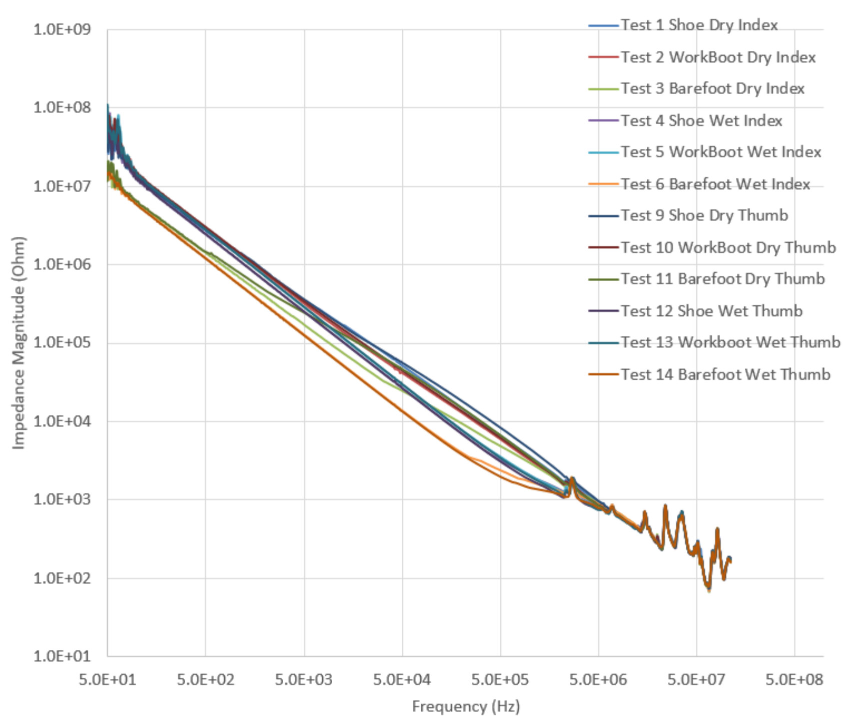

Figure 11 95th percentile of Human Body Impedance over Frequency

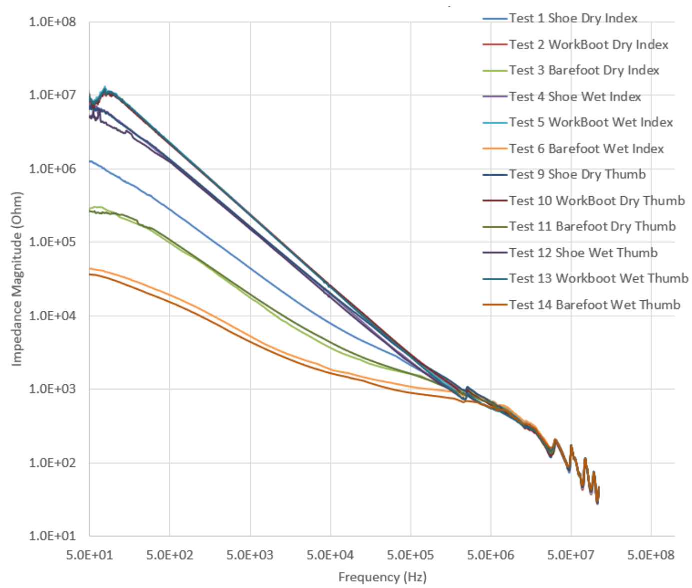

Figure 12 5th percentile of Human Body Impedance over Frequency

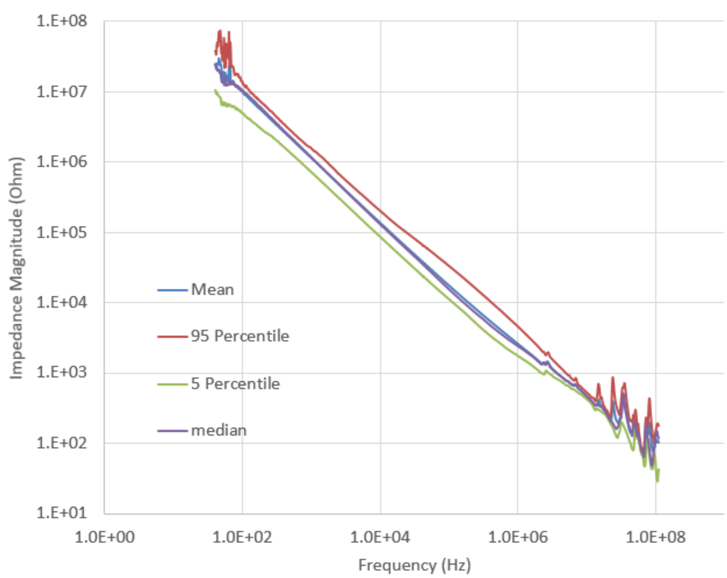

Figure 13 Human Body Impedance Frequency Curve for Shoe-Dry-Thumb

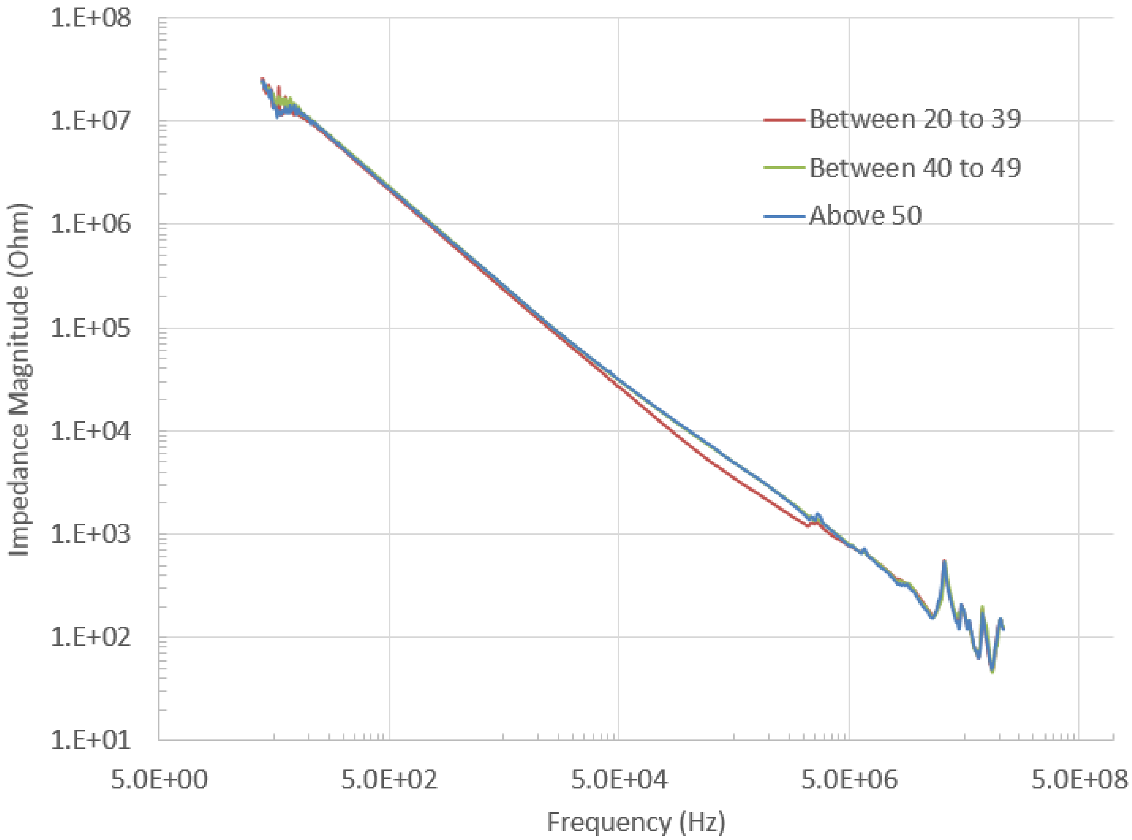

Figure 14 Median Impedance versus Frequency for Different Age Brackets

HUMAN BODY IMPEDANCE MODEL

To replace a human table saw user with a test surrogate that can effectively generate the same impedance to help trigger and assess the performance of an AIM equipped table saw, it is likely that the test probe would need to have a component that can cleanly register a depth of cut by contacting the blade at a specified speed and angle. If an impedance of Z_1 is assigned to this (grounded) component, it is still necessary[14] to add some (grounded) circuitry, with its own impedance (denoted Z_2) so that the overall impedance of the typical human, denoted Z, would still be reached (Figure 15). The best approach is that the Z_1 impedance would be set to a value that is as low as possible, while the Z_2 circuit would mimic the impedance taken from measurements on humans such as those presented in this report. Even here, there are two possibilities: design a simple circuit for human electrical impedance at a select frequency or design a more complex circuit that captures the impedance over a range of frequencies. For the single frequency circuit, Z_2 could be the impedance of a single capacitor in parallel with a single resistor.

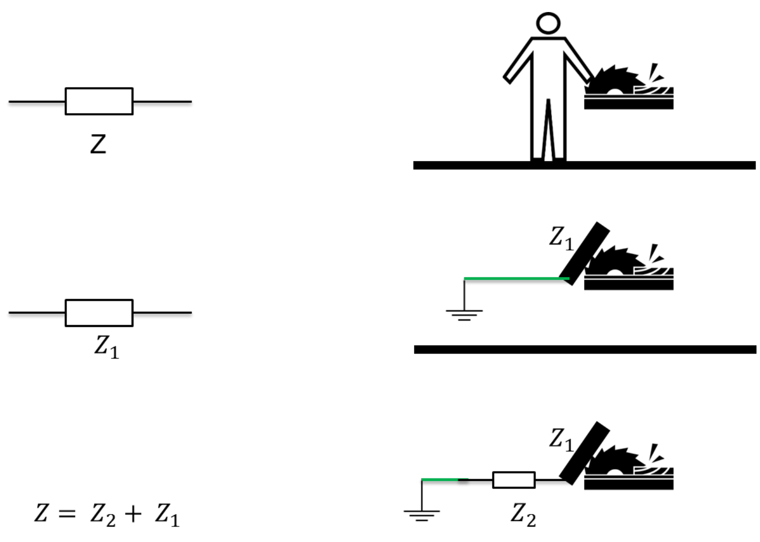

Figure 15 Human touching blade (top) Test probe that registers depth of cut (middle) and Test probe with circuit (bottom)

[14] It would be very challenging to find a simple material that would have the necessary impedance versus frequency characteristics while being able to be cut.

CPSC Human Body Impedance Model

CPSC (CPSC, 2017) proposed a model to simulate the human electrical impedance (HBN) over a range of frequencies with the circuit shown in Figure 16. The lone capacitor, designated C_s, is connected to the test probe that would contact the blade while the other end of the circuit would be grounded.

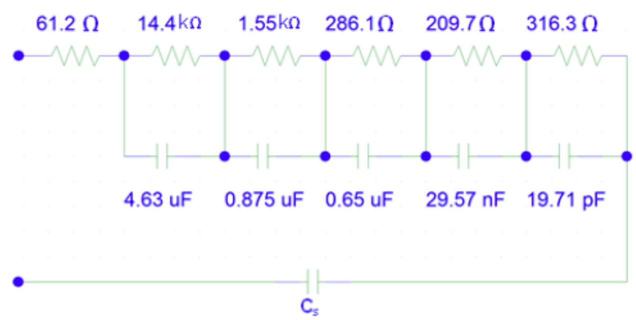

Figure 16 CPSC Hybrid Human Body Impedance Network

This circuit combines the electrical human impedance over a frequency range taken from De Santis and adds a capacitor in series. They recommend changing the capacitance value for this single capacitor, denoted Cs, to 50 pF, 66 pF, 100 pF, 150 pF, and 200 pF. The initial value of 50 pF represents the self-capacitance to space. Figure 17 shows impedance magnitude versus frequency for the CPSC proposed human impedance model. All the curves begin to converge towards a similar form after 500 kHz.

As noted previously, the circuit for the De Santis model was derived based on a worst case condition for electric shock, which means a very low value of impedance. If the impedance value is too low, then it is likely that the AIM system can be too easily triggered, not providing a good assessment of the detection system. Instead, it would only be measuring the mitigation response that is activated once the algorithm determines that a dangerous contact condition exists. A comparative plot of the DeSantis model by itself, the CPSC model at two different values for Cs and two test cases (from the measurements presented in this study) is shown in Figure 17. Clearly the De Santis model and Test 14 (5^{th} percentile) are the lowest, as expected, based on the conditions of the test subject. Test 9 (95^{th} percentile) of humans who contacted the blade with a dry thumb while wearing shoes resides in between the two CPSC cases until approximately 100 kHz where it becomes slightly higher.

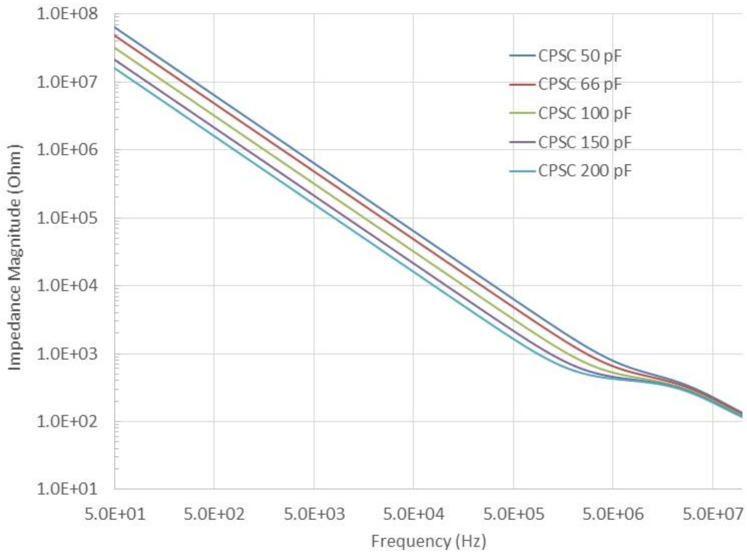

Figure 17 CPSC Hybrid Human Body Network at proposed values for C_s

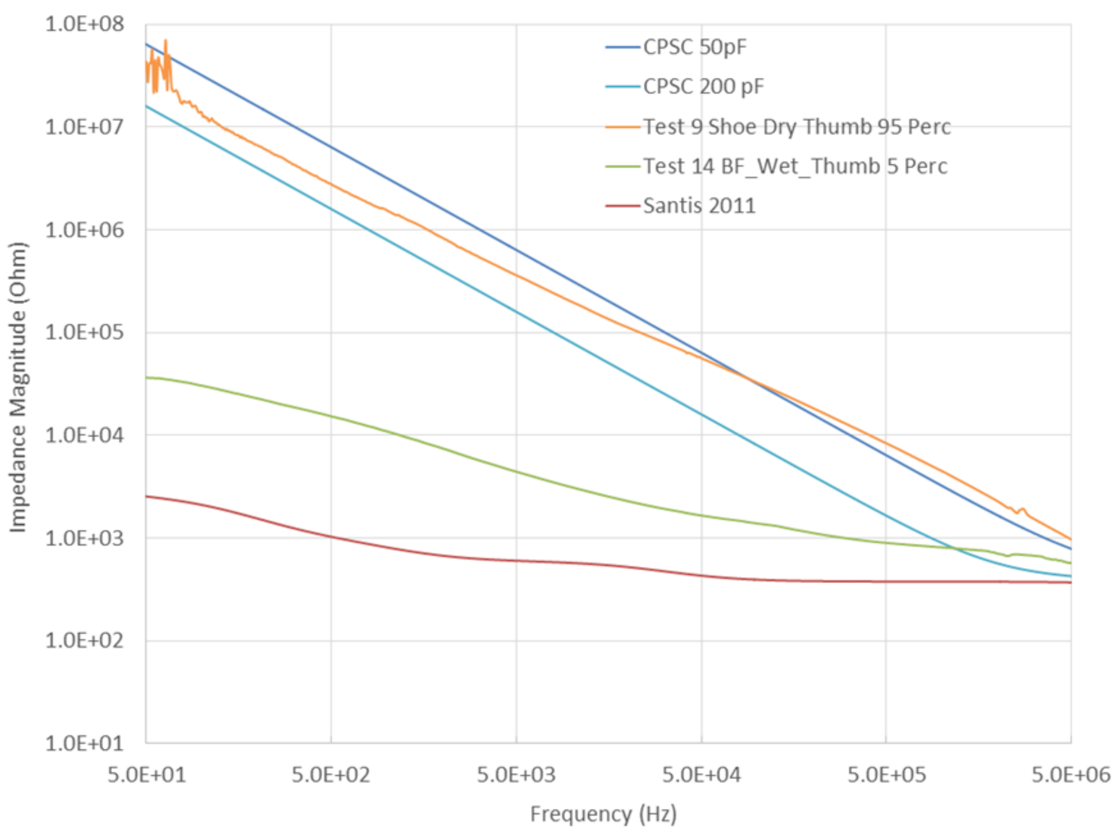

Figure 18 Comparison of Different Human Body Impedance Models

Capacitance Results at 500 kHz

At the time of this research, there were two commercially available table saws equipped with AIM technology, from SawStop and Bosch. Both saws operate using the principle of sensing impedance changes, however, the operating frequency of the AIM system for SawStop is set to 500 kHz while for Bosch, it is set to 1.22 MHz. In this section, the results for human body electrical impedance are studied at a specific frequency followed by an example of one possible test probe circuit specially designed to assess the performance of an AIM technology operating at 500 kHz.

First, the capacitive component of the impedance is examined. Figure 19 displays boxplots of capacitance at 500 kHz showing how, in general, females tend to have a lower capacitance than males.

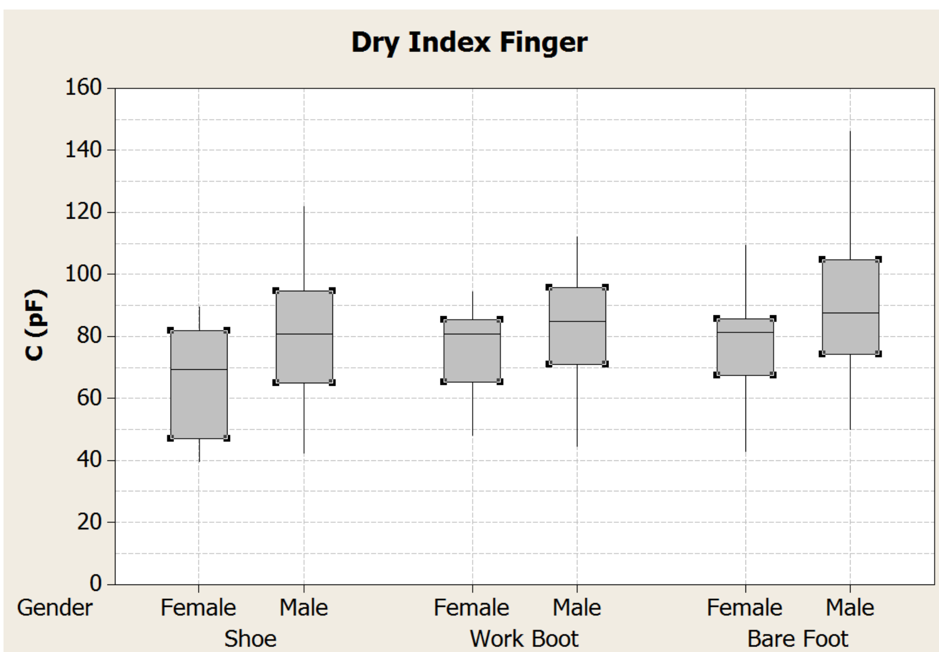

Figure 19 Capacitance Values for Dry Index Finger Tests

Next, the 12 different test cases are ranked based on different characteristics of the capacitance distribution: median, mean, 5th percentile and 95th percentile at 500 kHz. Each table starts with the smallest value of capacitance at the top, as this would be equivalent to the largest impedance, and therefore, would impact the least the AIM technology being studied in this report. As the impedance drops, or the capacitance increases, the system signal being tracked is disturbed more and the expectation is that it is more likely to trigger a response to blade contact.

Table 3 through Table 6 shows the difference in relative placement of the test runs. For example, Test 9 leads to the lowest capacitance value, based on the median, mean and 95th percentile criteria. Test 10 leads to the lowest capacitance value based on a 5th percentile criterion.

No	Index Finger	Thumb	Shoe	Work Boot	Barefeet	Dry hand	Wet hand	Median C (pF)	Mean C (pF)	5% Percentile (pF)	95% Percentile (pF)
Test 9								73.7	72	37.6	106.4
Test 10								79	77.8	50.5	105.12
Test 1								79.8	77.5	44.4	110.6
Test 2								83.8	81.9	55.3	108.47
Test 3								84.7	86.9	51	123
Test 11								90.3	87.1	46.2	128.1
Test 6								93.8	102.4	55.4	149.3
Test 5								98.9	98	84.5	111.64
Test 13								102.1	101.9	87.7	116
Test 4								106.1	106.3	88.6	123.93
Test 12								111	112	93.6	130.71
Test 14								112.7	119.8	67.6	172

Table 3 Test results ranking based on Median Capacitance value at 500 kHz

No	Index Finger	Thumb	Shoe	Work Boot	Barefeet	Dry hand	Wet hand	Median C (pF)	Mean C (pF)	5% Percentile (pF)	95% Percentile (pF)
Test 9		■	■			■		73.7	72	37.6	106.4
Test 1	■		■			■		79.8	77.5	44.4	110.6
Test 10		■		■		■		79	77.8	50.5	105.12
Test 2	■			■		■		83.8	81.9	55.3	108.47
Test 3	■				■	■		84.7	86.9	51	123
Test 11		■			■	■		90.3	87.1	46.2	128.1
Test 5	■			■			■	98.9	98	84.5	111.64
Test 13		■		■			■	102.1	101.9	87.7	116
Test 6	■				■		■	93.8	102.4	55.4	149.3
Test 4	■		■				■	106.1	106.3	88.6	123.93
Test 12		■	■				■	111	112	93.6	130.71
Test 14		■			■		■	112.7	119.8	67.6	172

Table 4 Test results ranking based on Mean Capacitance value at 500 kHz

No	Index Finger	Thumb	Shoe	Work Boot	Barefeet	Dry hand	Wet hand	Median C (pF)	Mean C (pF)	5% Percentile (pF)	95% Percentile (pF)
Test 9		■	■			■		73.7	72	37.6	106.4
Test 1	■		■			■		79.8	77.5	44.4	110.6
Test 11		■			■	■		90.3	87.1	46.2	128.1
Test 10		■		■		■		79	77.8	50.5	105.12
Test 3	■				■	■		84.7	86.9	51	123
Test 2	■			■		■		83.8	81.9	55.3	108.47
Test 6	■				■		■	93.8	102.4	55.4	149.3
Test 14		■			■		■	112.7	119.8	67.6	172
Test 5	■			■			■	98.9	98	84.5	111.64
Test 13		■		■			■	102.1	101.9	87.7	116
Test 4	■		■				■	106.1	106.3	88.6	123.93
Test 12		■	■				■	111	112	93.6	130.71

Table 5 Test results ranking based on 95th percentile Capacitance value at 500 kHz

No	Index Finger	Thumb	Shoe	Work Boot	Barefeet	Dry hand	Wet hand	Median C (pF)	Mean C (pF)	5% Percentile (pF)	95% Percentile (pF)
Test 10								79	77.8	50.5	105.12
Test 9								73.7	72	37.6	106.4
Test 2								83.8	81.9	55.3	108.47
Test 1								79.8	77.5	44.4	110.6
Test 5								98.9	98	84.5	111.64
Test 13								102.1	101.9	87.7	116
Test 3								84.7	86.9	51	123
Test 4								106.1	106.3	88.6	123.93
Test 11								90.3	87.1	46.2	128.1
Test 12								111	112	93.6	130.71
Test 6								93.8	102.4	55.4	149.3
Test 14								112.7	119.8	67.6	172

Table 6 Test results ranking based on 5th percentile Capacitance value at 500 kHz

Equivalent RC Circuit

If a test probe including a circuit were to be specially designed to assess the performance of an AIM technology operating at specific frequency (such as 500 kHz) the circuit could consist simply of a capacitor and resistor in parallel (Figure 20). One end of the circuit would be grounded and the other end would connect to the test probe that would contact the blade. The values for resistance and capacitance could be extracted from the data presented in this report.

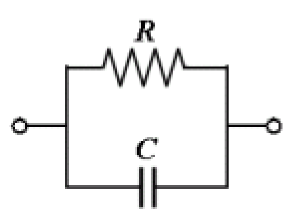

Figure 20 Simple Design of Test Circuit

In human body impedance experiments, the impedance and the capacitance are both recorded. From the two values, the resistance value can be calculated at the frequency of interest according to the following relationship, where Z is impedance and C is capacitance:

$$R = \frac{1}{\frac{1}{Z} - j\omega C}$$

For example, for Test 9, the 5th percentile capacitance C at 500 kHz is 37.6 pF. The corresponding impedance found in the experimental database is $Z = 8.342 \times 10^3 e^{-78.4°} = 1677 - j \cdot 817$. Using the above formula, R can be calculated as 41.5 kOhm. Therefore, a test circuit, simulating the human impedance (under the conditions of the 5th percentile of Test 9) for an AIM technology operating at 500 kHz, would be as follows[15]:

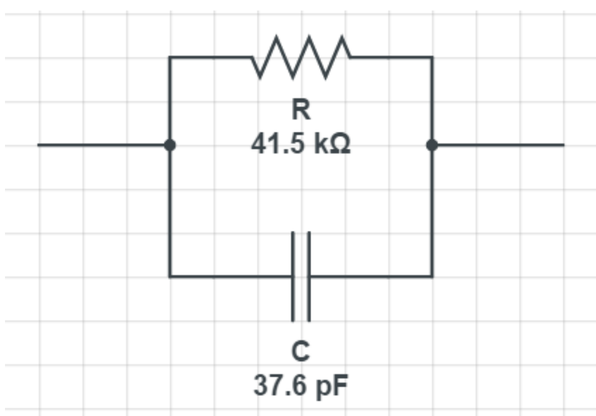

Figure 21 Equivalent Circuit human body impedance model at 500 kHz for Shoe-Dry-Thumb Condition (5th Percentile)

[15] Actually, this circuit may need to be slightly modified depending upon the impedance value of the test probe that records the depth of cut (Figure 15) as discussed previously.

Updated Human Electrical Impedance Model

A simple parallel RC circuit can only match the impedance at one single frequency. A more complicated circuit is required if the test probe circuitry is designed to match the impedance curve over a wider frequency range and be available for general testing of such AIM equipped table saws.

To demonstrate the process, one example is developed using the 95th percentile impedance measurements taken from Test 9 with shoe, dry and thumb finger. The fitted impedance circuit model can be derived by different methods, and for this example, the parameters and form of the fitted impedance circuit model were found using the Powell algorithm[16]. The final fitted circuit model is shown in Figure 22 with the values of C1=132.33pF, C2=281.32 pF, C3=104.92 pF, C4=105.04 pF, R1=106.39 Ohm, R2=391 kOhm, R3=41.6 kOhm, and R4=3.57 kOhm.

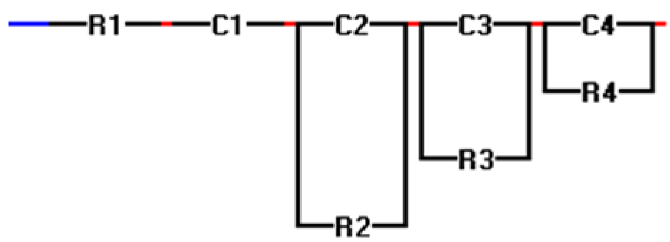

Figure 22 Form of Human Electrical Impedance Circuit Fitted to Test 9 (95th percentile)

Figure 23 shows the fitted results compared with the experimental data. The red dotted line represents the experimental data and the green solid line is the impedance obtained from the fitted circuit model. It is observed that an excellent fitted impedance curve is achieved for impedance magnitude. For the real and imaginary parts, the fitting results are also good. It is noted that this circuit model has an extra capacitance in-series and one fewer parallel RC circuit as compared to the

[16] (Powell, 1964) M. J. D. Powell, An efficient method of finding the minimum of a function of several variables without calculating derivatives, Computer Journal, Vol 7, PP 155-162, July 1964.

De Santis model. The De Santis model has five parallel RC circuits, but for this example with a three RC circuit model, the impedance magnitude was already showing good agreement. More parallel RC circuits could be added to improve the fitting, but with marginal improvements in results.

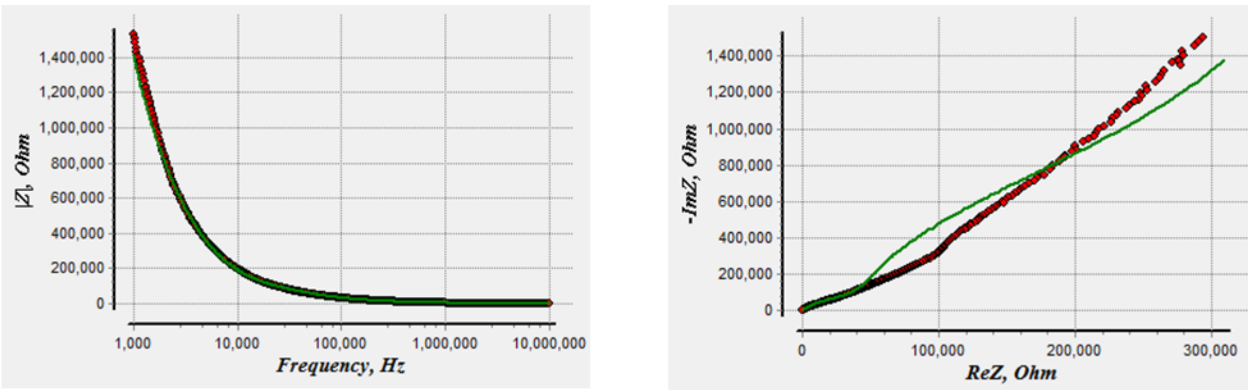

Figure 23 Comparison of Fitted Circuit vs Measured Results for Magnitude (left) and Components (right) of Impedance for Test 9

One other condition that would be worth testing is the 5th percentile of Test 14, which is a barefoot operator with a wet hand contacting the blade. The values for the circuit components (Figure 22) are C1=84 nF, C2=13.8 nF, C3=151.7 pF, C4=5.85 nF, R1=393.2 Ohm, R2=8987 Ohm, R3=755.6 Ohm, and R4=1647.6 Ohm. Figure 24 shows the fitted results compared with the experimental data. The red dotted line represents the experimental data and the green solid line is the impedance obtained from the fitted circuit model.

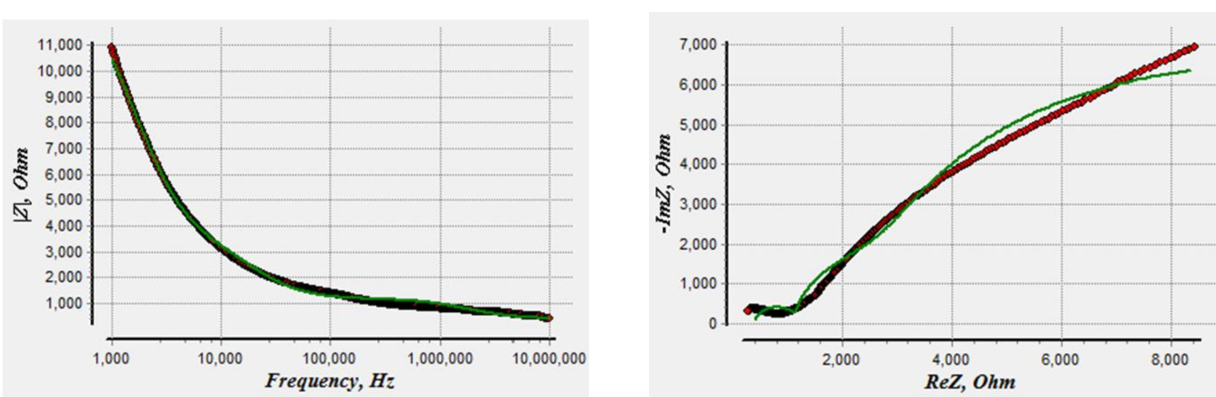

Figure 24 Comparison of Fitted Circuit vs Measured Results for Magnitude (left) and Components (right) of Impedance for Test 14

Figure 25 shows a comparison between the two cases from this study with two cases from CPSC model. There is a question on what is the expected frequency range for such systems. Based on review of the literature[17], it appears that for a capacitive-sensing system, the typical operating frequency is between 1 kHz and 3.5 MHz. For the AIM systems, this frequency range may be in the range of 100 kHz to 5 MHz.

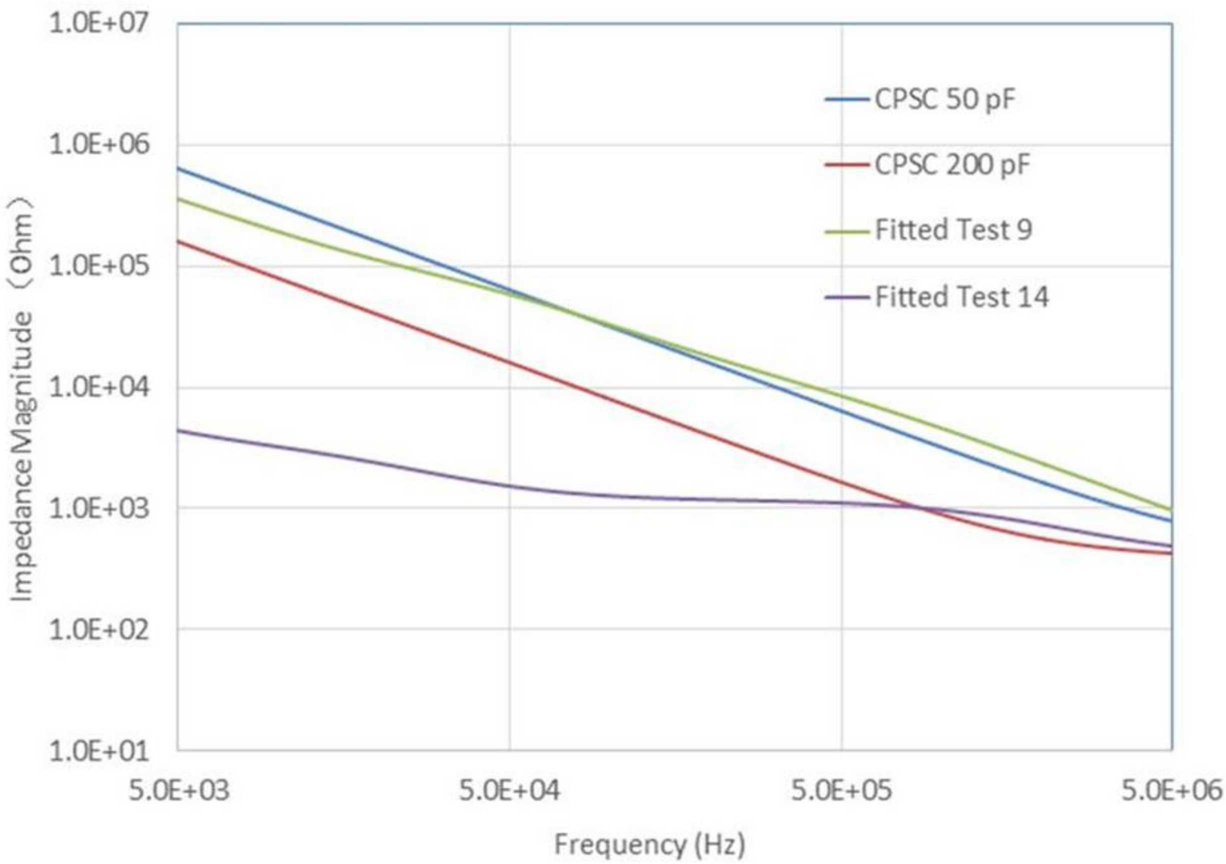

Figure 25 Comparison of Fitted Model for UL Test 9 (95th percentile), Test 14 (5th percentile) and the CPSC Human Body Network at two Self-Capacitance Values

[17] (Colin, 2014) Colin H., et al., "Techniques in Swept Frequency Capacitive Sensing: An Open Source Approach", Proceedings of the International Conference on New Interfaces for Musical Expression, 2014.

COMMENTS AND CONCLUSIONS

This research focused on the development of a database of human body electrical impedance measurements that could be the basis for the design of circuit-based test probes that would assess the performance of AIM equipped table saws. The AIM systems are basically active systems that would attempt to mitigate the hazards associated with finger and blade contact. Specifically, the type of AIM technology being assessed in this report would be one that relies upon the electrical impedance of a human user of the table saw to make a decision on a mitigating action when a finger comes into contact with the blade.

In previous research by UL (UL 2015), the human electrical impedance model being recommended included a circuit taken from research related to electric shock. For electric shock, the worst case condition is one where impedance, or opposition to current flow, is the lowest. In this case, a person touching a live wire would be exposed to maximum current possible and experience greater risk. For AIM technologies that sense impedance to take a corrective action, the opposite is true. A person with the highest impedance will present the greatest risk. This is because the smaller the disturbance to the signal, that is monitored by the AIM systems, the longer it is likely to take the decision algorithm to initiate an action to stop the blade rotating and/or remove the blade from its position to mitigate or eliminate the hazard.

In this research, some new measurements on human electrical impedance have been presented that might be more suitable for assessing the performance of AIM technologies that rely on impedance changes to initiate a safety mitigation action. These measurements were conducted under conditions that might be closer to those of actual table saw users, such as wearing shoes, dry hands and small contact area, versus what is typically carried out for electric shock, which is bare feet, wet hands and large contact area.

Figure 26 shows the generic components of a tester for such systems that was proposed in previous UL research (UL, 2015) with some revision[18]. This work provides data that can help build the

[18] In (UL, 2015) an additional high impedance outer layer was part of the finger, called finger skin, to compensate for the low impedance of the human body circuit. Now with the new human body impedance data which includes dry skin effects, this layer is no longer needed.

internal human body electrical impedance circuit model either to test a AIM technology operating at a specific frequency (single parallel RC circuit) or one that generalizes across a wide operating frequency (multiple parallel RC circuits along with some resistances and capacitances in series). The choice of which scenario and what characteristic of the population (median, mean, certain percentile) is now available in determining the circuit parameters for the human body impedance model that would be suitable to testing AIM systems equipped to sense impedance changes due to human contact with a blade. The finger body simply needs to be material that can cleanly and robustly register a depth of cut when coming into contact with the blade and to have a very low impedance relative to the human body circuit so that the AIM system is immediately impacted by the impedance of the human body circuit.

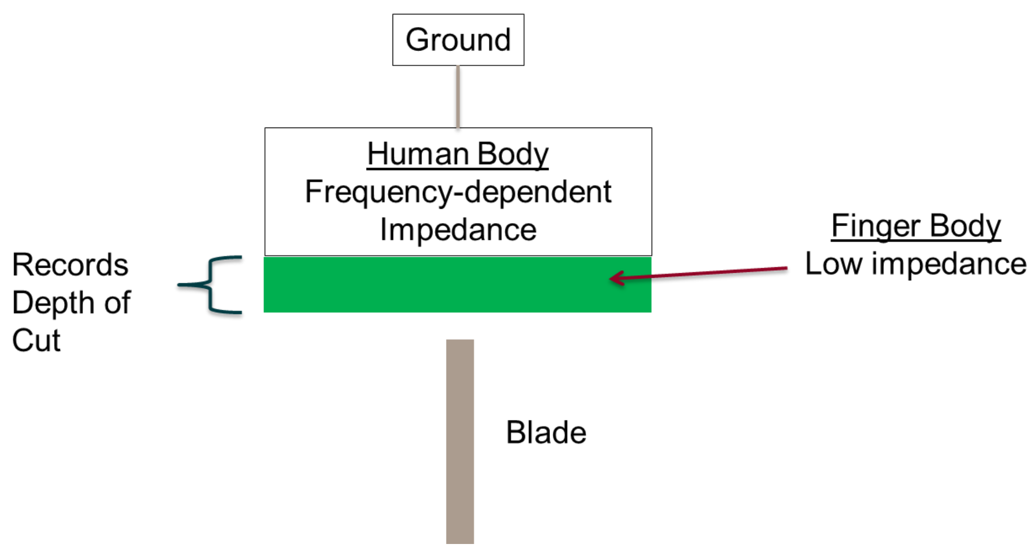

Figure 26 Recommended Test Probe and Circuit Design

Based on the data gathered in this study, we would propose two scenarios for representing the impedances of operators coming into contact with a blade: one scenario where the operator is wearing shoes and is contacting the blade with a dry finger (Test 9) and a second scenario where a barefoot operator is contacting the blade with a wet finger (Test 14). These scenarios are expected to represent two reasonable extremes, in terms of human body impedance seen by the AIM technology of interest in this study. Circuit parameters for the human body circuit over a wide frequency range were presented for the 95th percentile of Test 9 and the 5th percentile of Test 14.

Appendix A

Key information on the test subjects measured in this study

Candidate No	Gender	Weight	Height	Age
1	Male	155	5'11''	36
2	Male	170	5'10''	33
3	Male	200	5'7''	30
4	Male	180	6'0''	59
5	Female	125	5’3’’	43
6	Male	155	5'10''	43
7	Male	164	5'7''	41
8	Male	143	5'3''	45
9	Male	195	5'11''	40
10	Male	132	5'8''	51
11	Female	160	5'5''	25
12	Male	225	5'11''	55
13	Male	155	5'2''	31
14	Female	112	5'3''	35
15	Female	175	5'6''	45
16	Male	156	5'7''	61
17	Female	232	5'9''	53
18	Male	275	6'4''	38
19	Male	215	5'10''	35
20	Male	210	6'2''	49
21	Male	225	5'8''	53
22	Male	260	5'11''	59
23	Maler	150	5'7''	34
24	Female	121	5'6''	27
25	Male	192	5'9"	28
26	Male	190	5'11"	37
27	Female	118	5'3"	25
28	Female	169	5'3"	48
29	Male	145	5'7"	26
30	Male	180	6'2"	53
31	Male	185	5'10"	34
32	Female	150	5'	56
33	Male	240	6"4"	31
34	Male	160	5'6"	62

Candidate No	Gender	Weight	Height	Age
35	Male	186	5'11"	32
36	Male	160	5'6"	59
37	Male	210	6'	51
38	Male	180	5'2"	37
39	Male	150	5'5"	44
40	Female	210	5'8''	54