Qualification Challenges of Footwear and Flooring Systems

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Abstract – Measurement of body voltage alone can result in erroneous conclusions in qualification of footwear and flooring systems in combination with a person. Measurement uncertainties should be taken into account. We have studied the time dependency and charge generation of some footwear and flooring systems. The most significant inconsistencies of the voltage measurement are discussed in this technical paper.

I. Introduction

Charging of the human body is one of the main concerns in establishing electrostatic discharge (ESD) control in electronics and the automotive industry. It is also important in healthcare due to the prevention of shock to personnel, electromagnetic interference (EMI) to equipment, contamination control and ignition of flammable agents [1, 2, 3].

A peak voltage measurement is widely established in the qualification of footwear and flooring systems [4, 5]. As shown by Smallwood and Swenson [6], simple probability analyses may give more useful means of evaluating the performance of personnel in combination with footwear and flooring for some applications.

Measurement methods are well described in the standards, but uncertainty estimation is ignored. A fast dynamic phenomenon cannot be measured correctly without considering the time and voltage dependency including the response time of the measurement system. From the metrology point of view, the result is complete only when accompanied by a quantitative statement of its uncertainty [7].

In risk evaluation, "risk" is defined as a combination of the probability of occurrence of harm and the severity of the harm [8]. Voltage is generally thought as a simplified indication of electrostatic risk. However, without the charge assessment, an electrostatic source remains unknown. In practice, evaluation of real risks may need understanding of parameters such as stored charge and energy as well as the body voltage.

Smallwood [1] gave a circuit model that explained body voltage generation related to body, footwear and flooring resistance, capacitance and charge generation parameters.

In this study, we have concentrated on electric charges and potentials as functions of time. The purpose of the work was the assessment of the suitability of the qualification method in environments where criteria may be different from the electronics and automotive industries, and combinations of insulating and dissipative or conductive footwear and floor materials may be in use. The terms "insulating", "dissipative" and "conductive" are themselves often defined differently for different products and industries [1]. In this paper, we have for convenience defined insulating, dissipative and conductive footwear as giving resistance from the wearer's body to a test footplate according to Annex A of IEC 61340-5-1 [9] or ANSI/ESD STM 9.1 [10] of $> 10^9\ \Omega$, between $10^9\ \Omega$ and $10^6\ \Omega$ and $< 10^6\ \Omega$ respectively. Similarly, we have defined insulating, dissipative and conductive flooring as giving resistance from the surface to a groundable point according to IEC 61340-4-1 [11] or ESD S7.1 [12] of $> 10^9\ \Omega$, between $10^9\ \Omega$ and $10^6\ \Omega$ and $< 10^6\ \Omega$ respectively.

Time dependency and initial charge states are probably the most common error sources in voltage body measurements. Current standards specify that the time constant of the measurement should be 0.2 s or the response of the measurement should be faster than 250 ms [4, 5]. Our study examines how instrument response can influence the peak body voltage measured in experiments. Electrostatic induction and charge transfer between footwear and flooring and the human body are discussed in detail.

II. Footwear and Flooring System

Body voltage does not always result from contact electrification or triboelectrification between footwear and flooring. Contact electrification refers to the charging process in which two materials are connected and then separated from each other. It is a consequence of electron transfer, which is influenced by the work functions of the materials. Charging depends on the density of surface states, contact area between the objects and other factors. Electrons flow from the material with a lower work function to material having a higher work function, terminating when the Fermi levels are equalized [13]. Body voltage can stay close to zero even with the high charge levels, or may be surprisingly high with the weak contact electrification depending on the changing magnitudes of capacitances and resistances of the flooring and footwear system.

Conductive or static dissipative surfaces can charge insulating surfaces more highly than insulating surfaces [14]. Electrostatic dissipative or conductive footwear used on insulating flooring transfers electrons to the human body more efficiently than the insulating footwear. If the footwear is insulating, an electrostatic field of the sole affects the body voltage by induction. Humidity affects the contact electrification and surface resistivities of the materials as shown by Talebzadeh et al. [15, 16].

Walking is not always the worst-case charging mechanism. For example, standing up from a chair or taking off a garment may result in very high body voltages [15, 16].

Electric potential is limited to the breakdown field strength. A thick insulating sole may enable higher body voltages than the conductive or dissipative footwear. We measured 27 kV at 35 mJ energy from a person after standing up from armchairs in 12 % relative humidity (RH) and 23 °C.

III. Test Methods

Measurements were performed in accordance with the reference standards in a laboratory environment after 48 h conditioning at (23 ± 2) °C, (12 ± 3) % RH. Real world experiments were carried out in prevailing conditions in healthcare facilities and in electronics manufacturing.

A. Response Time Experiments

High impedance voltmeters and electrostatic field meters were evaluated with an oscilloscope and a high voltage amplifier controlled by a function generator.

A source capacitance of the reference pulse at the test plate was 18 pF and the source resistance was 1 MΩ. The time constant was then 18 µs.

A single footstep in the footwear and flooring system was measured directly with a 200 MHz oscilloscope using 1 MΩ, 10 MΩ and 100 MΩ input impedances.

B. Electronic Model of Footwear and Flooring System

A simplified equivalent circuit of the footwear and flooring system is shown in Figure 1, where C_1 and C_4 are capacitances between the floor surface and footwear sole. C_1 and C_4 are highly variable capacitances that go from a very high value when the footwear is in contact with the floor, to a low value when the foot is lifted. R_1 and R_4 are resistances of the footwear-floor contact. This contact is only present when the footwear is on the floor, and the switches S_1 and S_2 represent loss of contact when lifting the foot. Similarly, the charging current I can only occur when the footwear is in contact with the floor. C_2, C_5, R_2 and R_5 are between the soles of footwear and the feet of a test person. C_3, C_6, R_3 and R_6 are between the flooring surface and ground. These vary, for example if the floor covering is on an insulating substrate, grounded or ungrounded conducting substrate. C_7 is a stray capacitance of the test person's body to earth including an input capacitance of the instrumentation. R_7 is a leakage resistance from the body to earth via the measurement setup and surroundings. R_7 will usually be a very high resistance unless the person touches a grounded conductor. R_8 is a resistance of the flooring surface between the footwear soles.

If the flooring and the footwear are conductive, then C_1, C_2, C_3, C_4, C_5, and C_6 are discharged by the resistances R_1, R_2, R_3, R_4, R_5 and R_6. Charges equalize in a short time after contact electrification, governed by the time constants given by R_1, R_2, R_3, R_4, R_5 and R_6 with C_1, C_2, C_3, C_4, C_5, and C_6. This is a desired function of the footwear and flooring system in ESD-control.

If the flooring is insulating and the footwear is conductive, then C_2 and C_5 are discharged by R_2 and R_5 providing the time constants $C_2 R_2$ and $C_5 R_5$ are sufficiently short. Charge transfers from the sole to the person's body are represented by the charging current I. The same quantity of charge with an opposite polarity will stay on the flooring surface in a quasi-static situation. A theoretical capacitance of the person is then:

$$C_{\text{Person}} = \frac{1}{1/C_1 + 1/C_3} + \frac{1}{1/C_4 + 1/C_6} + C_7 \quad (1)$$

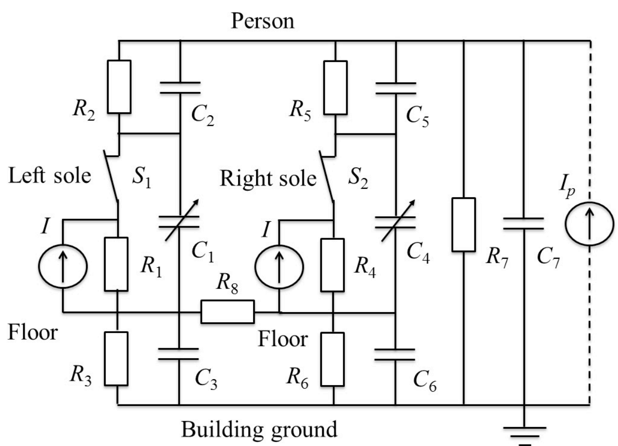

Figure 1: Simplified equivalent circuit of footwear and flooring system

The capacitances C_1 and C_4 depend on the surface states and work functions and they cannot be determined in practical measurements.

If the flooring is conductive and the footwear is insulating, then C_3 and C_6 are discharged through R_3 and R_6 providing the time constants $C_3 R_3$ and $C_6 R_6$ are sufficiently short. In that case, the charge transfers quickly from the flooring to the ground. The same quantity of charge with an opposite polarity will stay on the sole of footwear and test person, thus influencing the body voltage. The capacitor C_1 or C_4 is charged but has high capacitance when the foot is on the floor. When the foot is raised, the capacitance is dramatically reduced and, given that the charge has no path to move away, the voltage at the junction of C_1 and C_2 or C_4 and C_5 can be significantly increased. The body voltage is increased in response. Subsequent steps can increase the charge stored on the shoe sole and contribute to increasing overall body voltage, with peaks and valleys governed by capacitance changes as well as charge leakage. The rates of rise and fall of body voltage can be highly influenced by the rate of change of C_1 and C_4 and hence rate of movement of the feet.

Direct charging of the person's body is also possible, for example by rising from a chair or charge transfer from another object. This possibility is represented in Figure 1 by the charging current I_p.

C. Footwear and Flooring Experiments

Footwear was qualified in accordance with IEC 61340-4-3 [17] or ANSI/ESD STM 9.1 [10]. Flooring was characterized in accordance with IEC 61340-4-1 [11] and ESD S7.1 [12]. Resistance of the person, footwear and flooring system was measured in accordance with IEC 61340-4-5 [4] and ANSI/ESD STM 97.1 [18].

1. Body Voltage Measurements

The body voltage was measured in accordance with IEC 61340-4-5 [4] and ANSI/ESD STM 97.2 [5]. A six-step walking pattern was used for laboratory evaluations.

Measurements were performed with contacting and non-contacting voltmeters with a walking test adapter. The response time of the contacting voltmeter was 500 µs from 10 % to 90 % step. The non-contacting voltmeter had a 50 µs response, respectively.

2. Charge Measurement Methods

The body voltage of the test person was continuously measured with a contacting or non-contacting voltmeter. When the potential was steady with the person stationary and both feet on the floor, the charge stored on the body was captured with an electrometer or with a current transformer and oscilloscope. The total capacitance of the person C_{person} including the combined effect of C_1, C_2, C_3, C_4, C_5, C_6 and C_7 was calculated from the body voltage V and charge transfer Q of the discharge:

$$C_{\text{Person}} = \frac{Q}{V} \quad (2)$$

A potential energy W stored by the voltage on the person was then calculated with the formula:

$$W = \frac{Q \times V}{2} \quad (3)$$

Slow charge accumulations of walking patterns were measured with a high accuracy standard capacitor and ultra-high impedance contacting voltmeter.

Fast charge transfer was measured by integrating the current from the discharge path. A charge of the single footstep was calculated by integrating the voltage divided by the sum of input impedances of the oscilloscope and voltage probe.

3. Samples under Test

Resistances of the dissipative footwear were between 10 MΩ and 80 MΩ. Person and footwear system on the test plate was between 10 MΩ and 30 MΩ. Insulating footwear with different thicknesses of soles were used for the experiments.

Flooring samples: Resistance to groundable point of the dissipative samples were between 1 MΩ and 100 MΩ. Polyvinyl chloride (PVC) floor mats, screed and self levelling epoxy floorings were studied. Insulating floorings were measured on the insulating and conductive substrate.

IV. Test Results

Many experiments were performed for the study. This paper presents some examples that demonstrate the main conclusions of the work.

A. The Effect of the Measurement System Response Time

Three body voltage measurement instruments with different response times 50 µs, 40 ms and 100 ms were evaluated with the square pulses of 1 Hz, 10 Hz and 100 Hz as shown in Figures 2, 3 and 4.

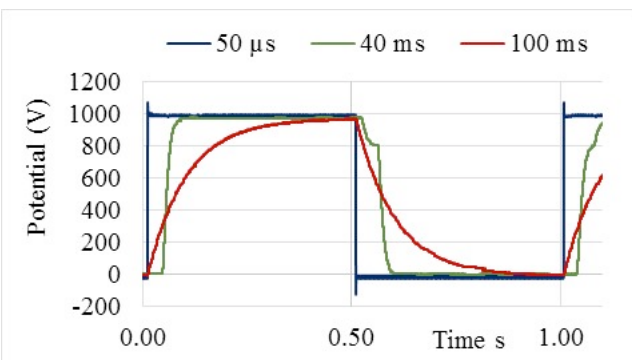

Figure 2: The effect of response time on square pulse 1 Hz

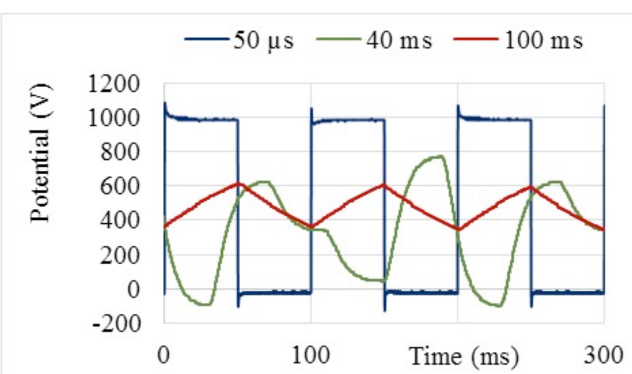

Figure 3: The effect of response time on square pulse 10 Hz

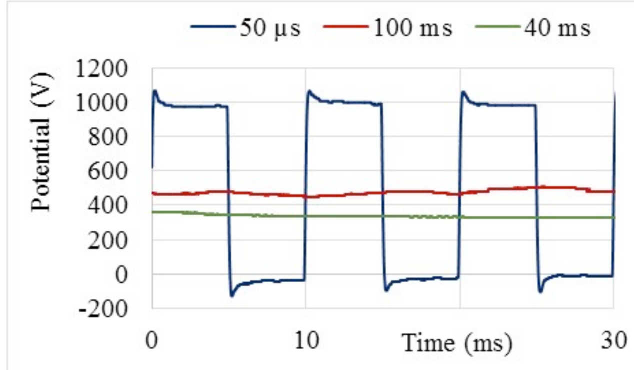

Figure 4: The effect of response time on square pulse 100 Hz

The standard instrumentation response time constant specification of 0.2 s is adequate for longer than one second pulse widths. Faster pulses cannot be measured correctly with the standard specifications. The pulse width and rise time of body voltage obtained for the footwear and flooring system depend on the system time constants. Slow instrumentation response causes errors in the peak values with low system resistances and low capacitances.

A contact electrification of the single footstep of dissipative footwear was measured on different insulating flooring surfaces. In this experiment, time constants $C_2 R_2$ and $C_5 R_5$ are sufficiently short to rapidly equalize the voltages across these components. The highest voltages found were below 400 V @ 10 MΩ resistance from body to ground, but significantly higher than in previous experiments found in literature [19, 20]. If the flooring or footwear is conductive or dissipative, the electric potential changes rapidly at contact electrification when the footwear touches the flooring. Separation affects potential more slowly. Examples of the single footstep charging curves of the dissipative footwear on PVC floorings are shown in the Figures 5 and 6. The figures represents a contact phase of the step.

Examples of the footstep charging curves of dissipative footwear on self-leveling dielectric epoxy flooring are shown in Figure 7, measured with 10 MΩ input impedance of the oscilloscope. The maximum recorded charge generation of the single footstep with dissipative footwear was approximately 500 nC. Insulating footwear resulted in less than 300 nC.

Despite the low impedance, the peak potential can be surprisingly high, depending on the charging current, when measured with the fast instruments. As shown in Figure 7 the contact electrification resulted in 360 V with 10 MΩ. This test models the behavior of a wrist strap system while walking on insulating flooring. The resistance to ground is lower than the standard required upper limit for resistance to ground of wrist strap systems of 35 MΩ [9, 21]. Dissipative footwear and flooring systems did not result in such high peak potentials.

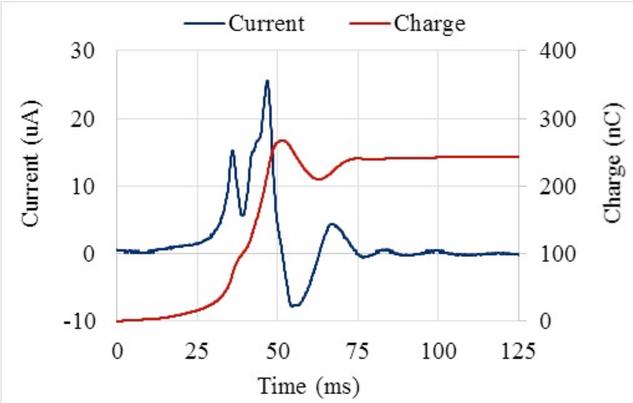

Figure 5: Example of current and charge response of footstep on PVC flooring, Resistance R_7 from body to ground was 1 MΩ

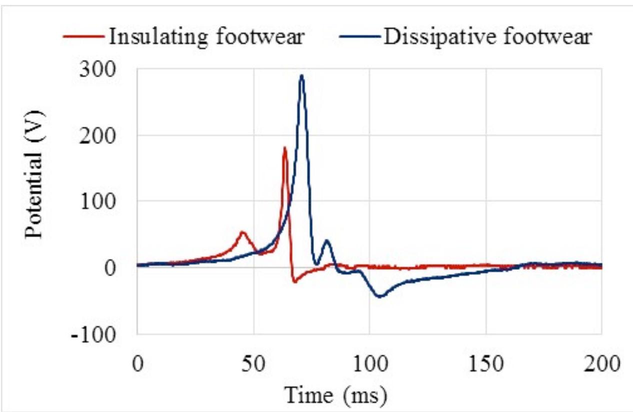

Figure 6: Example of voltage response of footstep on PVC flooring, Resistance R_7 from body to ground was 10 MΩ

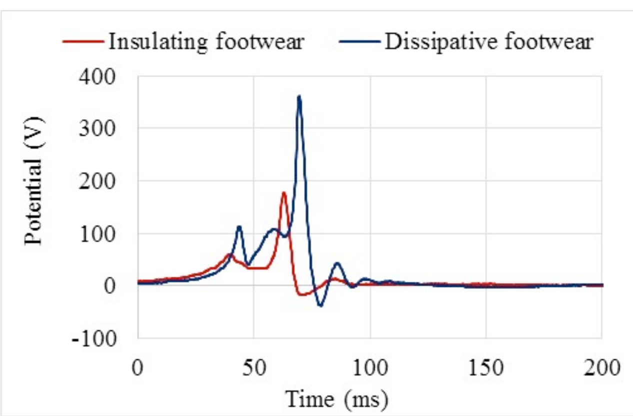

Figure 7: Example of voltage response of footstep on self-leveling epoxy flooring, Resistance R_7 from body to ground was 10 MΩ

The single footstep charging was also measured on the ESD control epoxy flooring with 100 MΩ oscilloscope input impedance. If the footwear is insulating, the charge flows only through the R_7 to ground. When the footwear is not insulating, charge transfers through the footwear and flooring in parallel with R_7. Examples of charging curves of person's body are shown in Figure 8. In this case, the dissipative footwear and dissipative screed epoxy flooring met the resistance to ground requirements of 1 GΩ given in current electronics industry ESD control standards. The peak potentials exceeded 200 V when measured with using fast response. When measured with instruments having a time constant of 0.2 s, the peaks were below 100 V.

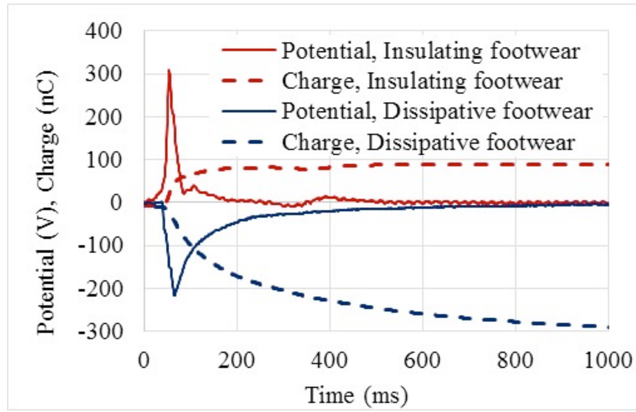

Figure 8: Example of voltage response of footstep on ESD control flooring, Resistance R_7 from body to ground was 100 MΩ

Another example of the qualification dilemma is shown in Figure 9. Absolute values of the highest peaks were below 100 V using 100 ms response, but these were exceeded when using 50 µs response equipment. This floor can be accepted or rejected depending on the response time of the instrumentation used.

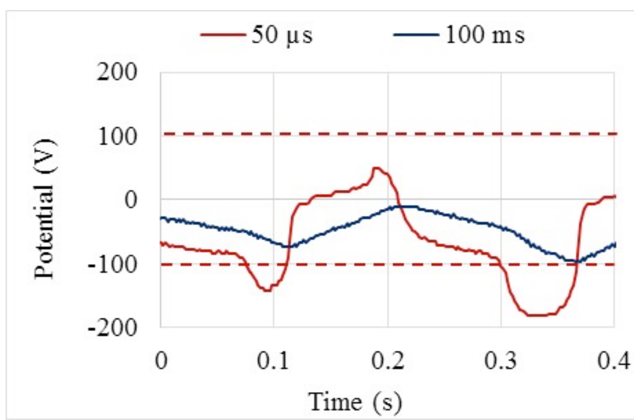

Figure 9: Example of peak potentials of ESD control flooring

B. Footwear and Flooring System

1. Evaluation of Variations in Body Capacitance

Electrostatic parameters of ten different insulating footwear and flooring systems were assessed using a test person standing stationary on two feet on the test floor, pre-charged to 100 V. The body voltage was measured with the high impedance voltmeter and charge was then captured by discharge into an electrometer. Both voltage and charge transfer were recorded. The summary of results is shown in Table 1.

A thin dielectric mat on a conductive plate resulted in high capacitances of C_1 and C_6 causing significantly higher charge and potential energy than a raised floor.

Table 1: Summary of ten footwear and flooring systems

	V (V)	Q (nC)	C (pF)	W (nJ)
Minimum	100	8	80	400
Maximum	100	60	600	3000
Median	100	24	240	1200

Capacitances of the dissipative and conductive systems cannot be evaluated with the quasi static measures. As an example, dissipative footwear on different flooring structures were measured with a multi-frequency inductance, capacitance, resistance (LCR) meter. Resistance to ground of the conductive screed epoxy sample was below 1 MΩ. Resistance to ground of the dissipative PVC mat was between 200 MΩ and 300 MΩ. System resistance on the metal plate was approximately 10 MΩ. The result depends on the frequency as shown in Figure 10.

In the dissipative system, capacitances between the footwear and flooring (C_1 and C_4) dominate the body capacitance in low frequencies below 1 kHz. In the insulating system, a total capacitance is reduced due to the series effect of C_1, C_2, C_3 and C_4, C_5, C_6.

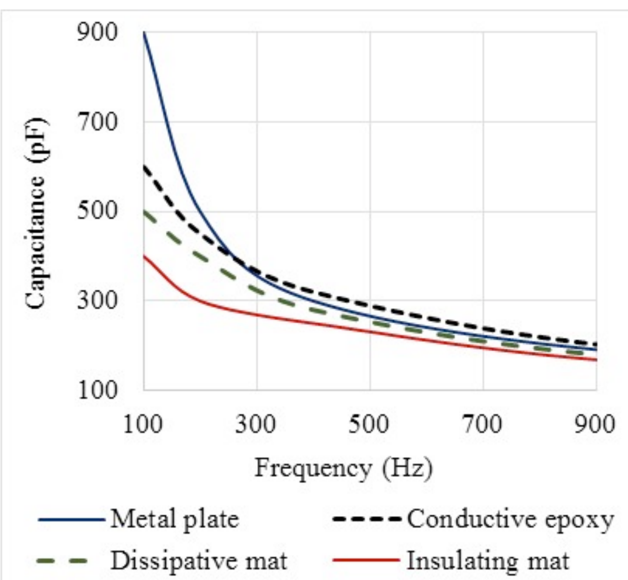

Figure 10: Variation of capacitance with frequency on various floor surfaces

2. Contact Electrification

The body voltage of the walking test may indicate charge generation only if the leakage resistance R_7 and serial resistances R_1 to R_3 and R_4 to R_6 are high enough to prevent significant charge flow away from the body over the duration of the test.

The result depends on the uncertainties and repeatability of the contact electrification as well as changes in foot-floor-ground and body-ground capacitances. In practice, triboelectrification is a variable and unpredictable phenomenon as shown in Figure 11. The same test person with the same footwear and flooring system caused different charge accumulations after three different measurements of the six step walking pattern.

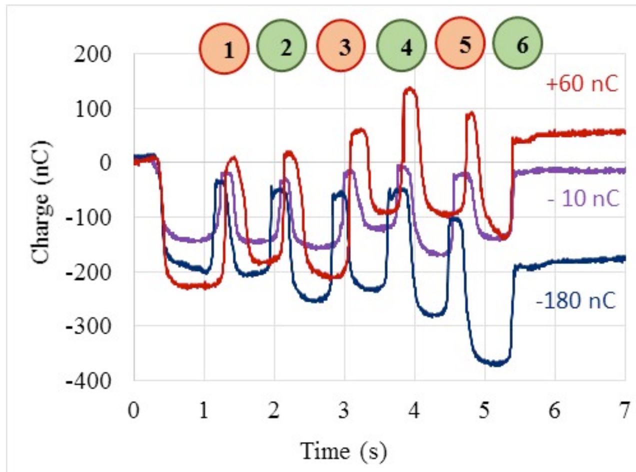

Figure 11: Variation in charge measurements

As shown in Figures 6 to 8, the dissipative footwear resulted in higher contact electrification than the insulating footwear. If the flooring is highly resistive, dissipative footwear can also result in higher electrostatic potentials in the walking test compared to insulating footwear as shown in Figure 12, depending on the footwear-flooring charge generation characteristics.

The body voltage can also remain low even if the flooring footwear system resistance to ground is high, if the footwear-flooring charge generation levels are low. High body-ground capacitance can also lead to reduced body voltage. The contact electrification cannot always be seen due to the electrochemical effects or other unknown reasons of the charging process, even if the resistances R_1 to R_7 are very high.

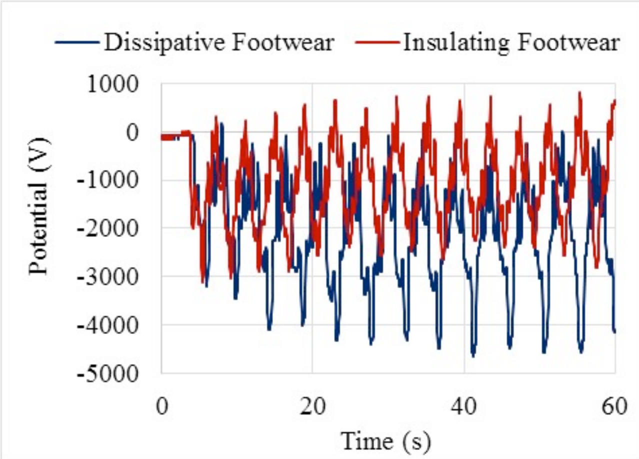

Figure 12: Body voltage developed while walking on an insulative floor with dissipative or insulating footwear

A walking test can result in an erroneous conclusion for a footwear and flooring system if other stronger charge generation processes can be present, as shown in Figure 13. In this example, the body voltage stayed below 100 V during a continuous six-step walking pattern until a test person removed their jacket. The person had dissipative footwear on insulating PVC flooring. This is a classic example of how a footwear and flooring system may give low body voltage in a standard walking test, leading to acceptance, but can fail to give good body voltage control in general usage. The body voltage produced decays with a long time constant due to the high footwear-floor-ground resistance and can cause an ESD event tens of seconds after the activity that generated the voltage.

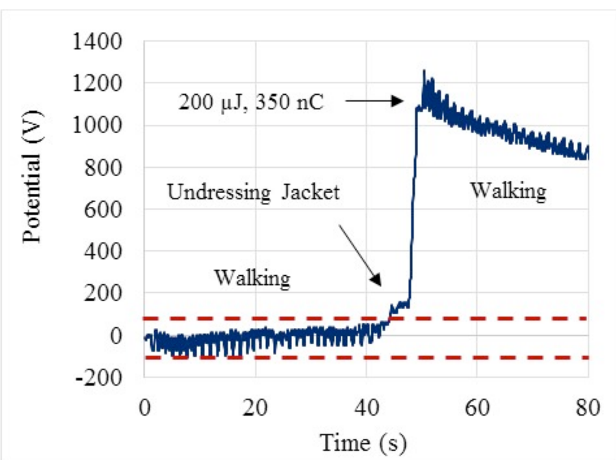

Figure 13: Undressing jacket during walking test

A similar example of the body voltage caused by a charging source other than the footwear and flooring system is shown in Figure 14. Standing up from an armchair resulted in 35 mJ energy at 27000 V. After 70 s of walking, potential energy was decreased to 22 mJ resulting in unpleasant shock when the person discharged. According to the standard procedures, a walking test is performed after discharge [4, 5]. The body voltage did not increase anymore above 3000 V in 60 s walking.

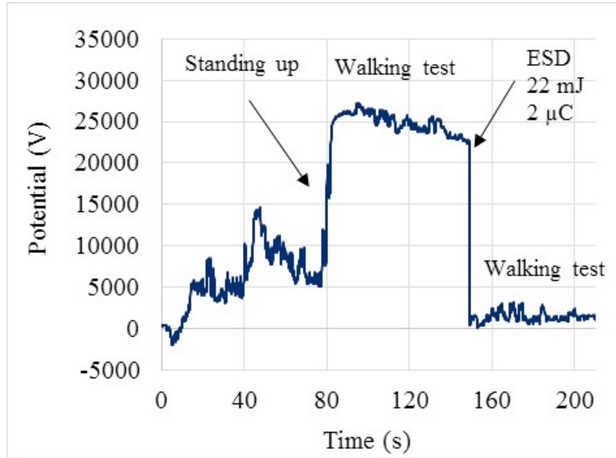

Figure 14: Standing up from armchair on insulating flooring

3. Initial Charge States

The results of walking tests also depend on the initial charge states of the flooring surface and soles of footwear as shown in Figure 15. The sequential walking patterns were measured with insulating footwear on conductive flooring. The soles of footwear were neutralized with an ionizer before the test. An average surface potential of the soles, measured with the footwear worn before neutralization, was approximately -5 kV. The body voltage was shifted after each ground connection depending on the voltage level at the moment of the discharge. An average surface potential of the soles after the walking test sequences was again approximately -5 kV despite the low potential of a standing person.

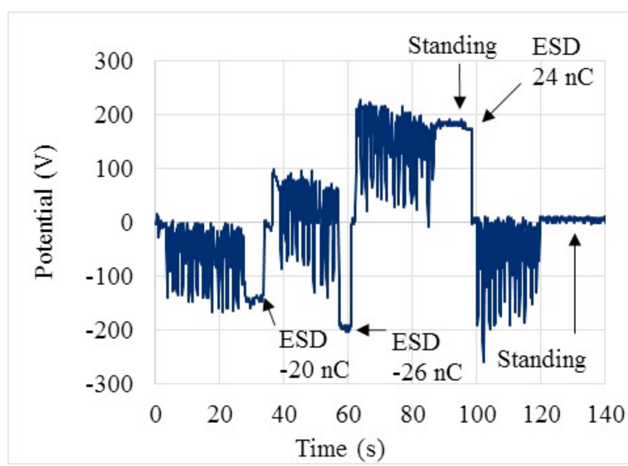

Figure 15: Sequential walking patterns

4. The Effect of System Capacitance on ESD Risk

An example of sequential walking patterns with dissipative footwear and two insulating flooring structures are shown in Figure 16. The measurements were made with the same insulating floor mat, footwear and test person. The measured body capacitance range is given for each case. Higher body voltage and greater voltage fluctuations can be seen in the case of lower body capacitance. The higher capacitance case gave a higher charge transfer at the discharge (320 nC compared to 250 nC) even though the body voltage was considerably lower at the time of discharge (1000 V compared to 2700 V).

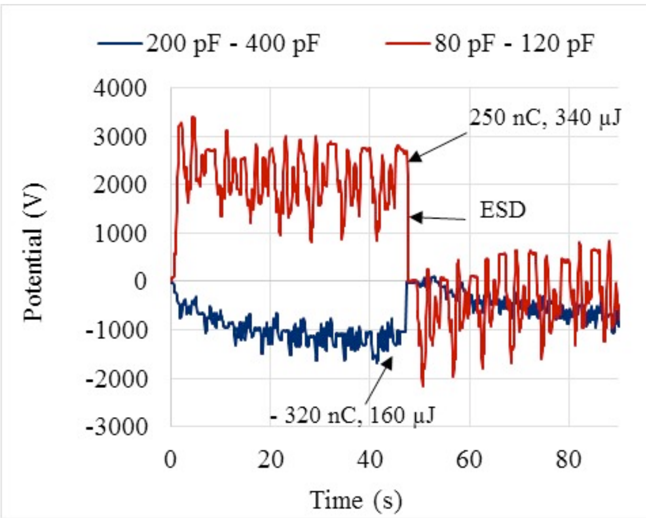

Figure 16: Sequential walking patterns

If the energy is calculated for each case, it is found to be 160 µJ and 340 µJ for the high and low capacitance floor installations, respectively. So, for the same materials and subjects, the risk in terms of voltage and energy is raised by factors of 2.7 and 2.1 for the low capacitance installation despite the charge on the body being a factor of 0.8 reduced in the low capacitance test.

5. Charge Transfer Mechanisms

Generally, the outcome of the measurement is a combination of the charge transfer and induction as shown in Figure 17. In this case, a stationary person standing with both feet on the floor increases in body potential. This is presumed to be due to the low leakage current between isolated structures of the thick flooring substrate while the charge of the soles of insulating footwear was constant.

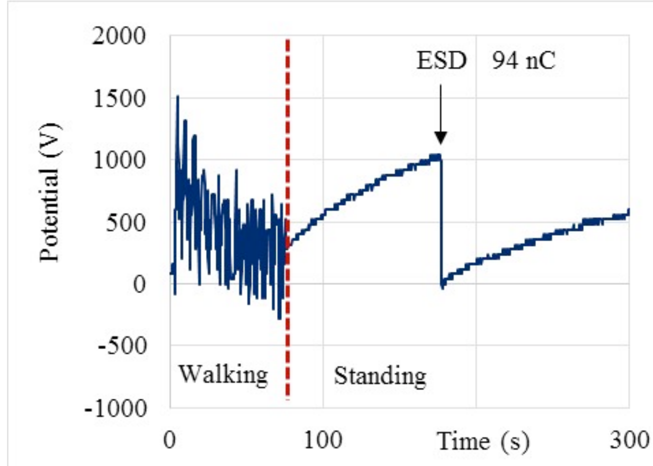

Figure 17: Footwear and insulating flooring with the leakage current charging the person

V. Conclusions

Measurement of the walking test peak body voltage has significant inconsistencies for footwear-flooring system performance qualification. The peak voltage result may depend on the response time of the instrumentation. A single footstep may cause short but relatively high peaks that cannot be recorded with the slow instrument response specified in the standards [4, 5]. If the short pulses exist, measurements made using instruments in accordance with these standards ignore these peaks due to this inadequate response time. The footwear and flooring system maybe mistakenly rejected or accepted by selecting instrumentation that has slow enough response to give a pass result.

Secondly, a voltage alone does not necessarily fully indicate the risk of ESD. In some applications, the stored energy and charge transferred in a discharge may be important risk factors. The stored charge and energy of an electrostatic source depends highly on the source capacitance. The body voltage result only represents the balance of charging and charge dissipation for the footwear flooring system in combination with the system capacitance. The body voltage may remain low if the charge generation in walking is low, regardless of poor charge dissipation properties. So, the walk test does not necessarily represent the ability of the footwear-flooring system to dissipate charge from other activities such as rising from a chair.

For insulating floor structures, body voltage is also lowered for an installed floor that gives high body-ground capacitance compared to a low body ground capacitance installation. The risk in terms of voltage and energy is greater, even for a lower body charge level. This means that material evaluated in a high capacitance test arrangement can underestimate the risk occurring in a low capacitance installation.

Thirdly, repeatability of the contact electrification is very low due to the unpredictable uncertainties. The results of repeated measurements may show remarkable variation.

Fourthly, ESD control programs in electronics factories are usually based the Human Body Model component ESD susceptibility test that assumes that the capacitance of the human body is fixed at 100 pF. According to the results above, capacitances were often much higher than used in the device testing of human body model. For example, the dissipative footwear used on the dissipative epoxy flooring resulted in over 600 pF body capacitance.

Discussion

In the electronics industry, the scopes of the ESD control programs are based on the assumption of the safe handling of parts susceptible to damage by electrostatic discharges greater than or equal to 100 V human body model (HBM) [9, 21]. A potential energy of the human body at the certain voltage level varies in the real world. The real energy can be lower than in device testing, or in worst-case several times higher. As shown in the results of the study, the capacitances of dissipative footwear and flooring systems were significantly higher than in device testing.

The low repeatability of the triboelectrification produces the situation that the peak voltages are not necessarily seen at the moment of qualification. A relatively low limit of a person's body voltage in electronics and automotive industries is often sensitive enough to detect contact electrification in case that the flooring or footwear are insulating. If the limit is higher, for example in healthcare, the outcome depends more on uncertainties related to triboelectrification. Incorrect acceptance is more likely to result than wrong rejection. One aspect that has not yet been studied is the influence of surface contamination or common cleaning practices on body voltage results. Surface conditions can make a big difference to triboelectric charging.

Electrostatic dissipative footwear caused higher charge accumulation than insulating footwear on insulating flooring. However, the higher capacitance of the person with the dissipative footwear reduces the body voltage for a given body charge level. A thick insulating sole also enables higher electrostatic potentials than the conductive or dissipative footwear, for example when charging is resulted in other reason than walking. As a summary, dissipative footwear may reduce the risk of ESD due to the lower potential and higher capacitance of the person even if the flooring is insulating. Uncontrolled floorings may also have some leakage. Therefore, as a final conclusion, electrostatic dissipative or conductive footwear may reduce human body voltage and high-energy ESD events even if the flooring is uncontrolled. ESD control flooring may also reduce the risk of ESD to some extent even if the footwear is uncontrolled.

We recommend that the bandwidth of the measuring system specified by the standards should be reviewed. Standard test methods should allow the results to be reported in a form that is most relevant to risk evaluation in the particular application. However, it does not make sense to characterize flooring with the fast-dynamic phenomenon if the ESD risk is related to the quasi-static phenomenon. If the peaks are considered risks, then fast instrumentation is needed and grounding requirements shall be reviewed.

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