(REFEREED RESEARCH)

ELECTROSTATIC DISCHARGE PROTECTIVE GARMENT: RESULTS OBTAINED FOR KNITTED FABRICS WITH HYBRID YARNS

ELEKTROSTATİK BOŞALIM KORUYUCU GİYSİ: HİBRİT İPLİKLE ÖRÜLMÜŞ KUMAŞ İÇİN ELDE EDİLMİŞ OLAN SONUÇLAR

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ABSTRACT

Abstract: This paper presents a study, which is conducted to analyze the performance of electrostatic discharge (ESD) garments. The reasons of ESD, the possible scenarios that may occur in manufacturing hall and the requirements of the ESD garments are mentioned. A knitted structure consists of a double layer hybrid yarn, which consists of a dielectric layer at the outer layer and a conductor at the inner layer, is presented. The performance of the proposed structure is evaluated in terms of various criteria such as the cost, efficiency and weight.

Keywords: electrostatic discharge (ESD), ESD precautions, ESD protective garments, ESD protective textile

ÖZET

Bu makalede, elektrostatik yük boşalımı koruyucu giysilerin performans analizine yönelik bir çalışma sunulmaktadır. Elektrostatik yük boşalımının sebepleri, bir üretim holünde gerçekleşebilecek olası senaryolar ve elektrostatik yük boşalımı koruyucu giysilere ait gereksinimlerden söz edilmektedir. Bu gereksinimleri sağlayan, dış katman yalıtkan ve iç katman iletken olan iki katmanlı iplik ile tasarlanmış bir örgü topolojisi önerilmektedir. Söz konusu yapının performansı maliyet, performans etkinliği ve ağırlık gibi farklı ölçütler ele alınarak değerlendirilmektedir.

Anahtar Kelimeleri: elektrostatik boşalım (ESD), ESD önlemleri, ESD koruyucu giysiler, ESD koruyucu tekstil

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1. INTRODUCTION

Mankind wears garments for various purposes since the ancient times until now. Once it was for protection from the cold, once it was for veiling, once it was only for fashion. Since the textile industry has reached to a sophisticated level, the expectations have also evolved in several manners. Due to technological developments, the garments required to have extra features such as being dirt-repellent, waterproof and ESD-free. Due to these particular demands, multidisciplinary collaborations are needed to design and manufacture such products. Garments for ESD protection are one of those examples, since ESD has high and direct impacts on the losses in electronics industry. ESD can be defined as the sudden and out-of-control flow of charge between two objects, which is caused by proximity, direct connection, electrical shortcut, or dielectric breakdown. This sudden energy transfer may directly damage the structures in the environment. In the worst case, where explosive material exists, this sudden energy transfer might be quite catastrophic 1.

The damaging effects of ESD forced the researchers to take precaution 2. Several experiments conducted for avoiding this situation and determining the standards of ESD between 1950 and 2000s. Technical report of Billon stated the charging characteristics of different objects and then ESD effects resulting from different action and motion types are studied by Gonzalez et al. 3, 4.

Supervene upon the standards and the experiment about determining the ESD characteristics reached a level of maturity, alternatives of protection solutions have been started to be investigated. The solutions were mostly based on using a conductor device such as handcuffs, which restrain workers from comfortable movements during the working. In order to avoid such disrupter designs researchers started to look for designs that are more comfortable and can be used as casual wear. For this purpose, the conductors used as core of a yarn and surrounded by a dielectric layer, which is based on a textile material and can protect the conductor part from corrosion 5,6.

In this research paper, a low weight core conductor hybrid yarn knitted topology has been proposed for ESD protection. The structure parameters have been evaluated for different core and outer shell materials. Performance analysis of this conformal, electrically isolated structure has been conducted in material, weight, ESD properties and price viewpoint. To our belief, this study proposes a cheap, conformal, low weight and a practical structure. In the following sections of the paper, ESD will be described, and the reasons causing ESD will be discussed via different scenarios. The protection methods will be summarized, and the advantages of the ESD garments will be mentioned. In the next section, the requirements of the ESD protective garments will be presented. The topology of the proposed ESD protective garment will be presented, and the structure will be explained. At the results and at the last section, the performance criteria of the ESD garments will be presented, and the proposed garment topology will be discussed as regards not only the electrical criteria, which consists of consists of static, time-domain and frequency-domain analysis, but also the textile criteria. Textile parameters will also been presented in terms of loop length, wales per inch (WPI) and course per inch (CPI) information, stitch density, weight and yarn count.

2. ESD: Reasons and Possible Scenarios in a Manufacturing Hall

As mentioned before, ESD can be defined as the sudden and out-of-control charge flow between two objects. Close proximity, direct contact, electrical shortcut, or dielectric breakdown may cause ESD. The sudden energy transfer during the ESD might damage the structures in the environment. In case of the electronics manufacturing halls, such events directly yield permanent malfunctions in the electronic devices under production. Technological developments and eventual miniaturization of the systems have increased the necessity and importance of ESD protection, since the miniaturization of the systems have increased the sensitivity of the components which may get damaged due to the charge flow during the production stage in the manufacturing halls 1-13. ESD events cause 30-50% of the losses in electronic industry as reported in the studies in literature 1.

If a manufacturing hall is considered, electrostatic charging might result due to the foot friction of the personnel while walking. The body–chair and elbow–table frictions might also cause electrostatic charging while sitting at the desk. These cases are quite typical movements in a manufacturing hall. Both are mimicked via the illustrations seen in Figure 1a and Figure 1b, and the charge distributions are presented.

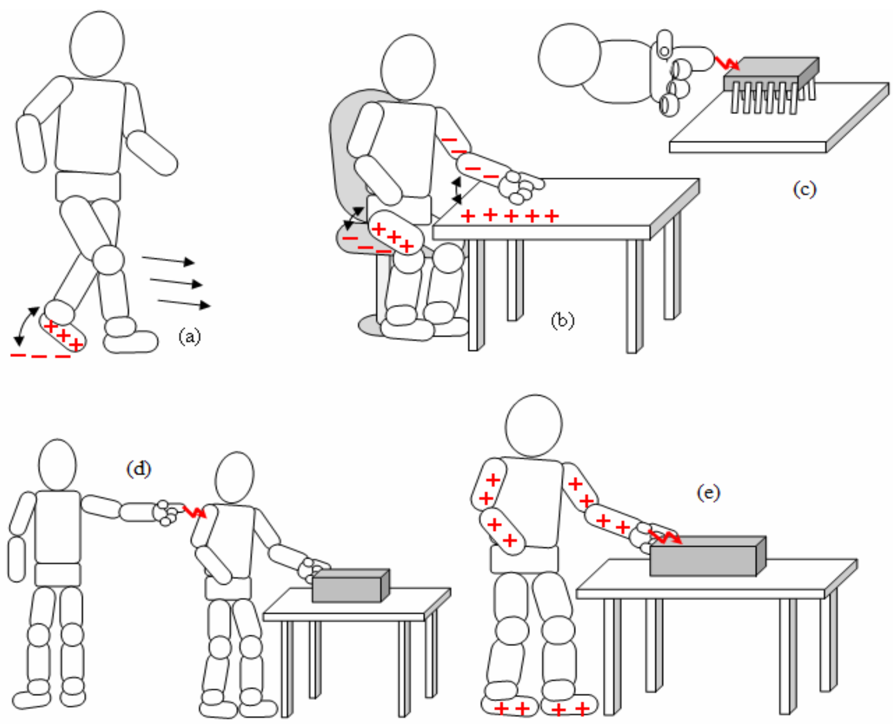


Figure 1. Typical examples of a human body charging electrostatically a) Resulting from walking and motions of the feet b) Movement of hips and elbows while sitting at the desk) c) A typical electrostatic discharge accident in a manufacturing hall: discharge due to proximity or direct contact of two people d) The first scenario that may be observed in a manufacturing hall (Scenario 1) e) The second scenario that may be observed in a manufacturing hall (Scenario 2)

If two people in the personnel are considered, the charge flow may occur via proximity or direct contact as presented in Figure 1b, and it may indirectly damage the electronic device as presented in Figure 1c. Via these mentioned cases, two reliable scenarios can be defined regarding the losses in manufacturing halls. The first scenario corresponds to a person whose movements cause the electrostatic charging; and in the resulting ESD event, the charge flows through the electronic device from the person's hand as seen in Figure 1d. The second scenario presented in Figure 1e corresponds to charge flow from one person to another. The electronic device will be the indirect victim due to the charge flow through the people's bodies. The requirements obtained from studies and the standards in the literature and the scenarios lead the designers to categorize the ESD models, which are discussed in the following section.

3. ESD models

ESD models consist of three main categories. One of them is the machine model (MM(, which studies the electrostatic discharge from a machine to another device. The second one is the charge device model (CDM), which studies the electrostatic discharge from a charged device to the electronic device. The last one is the human body model (HBM). Human body model considers the electrostatic discharge from a human body to the electronic device. The scenarios explained above all consider the human body model in which charge analyses should be performed. The voltage is a function of the total charge and the capacitance defined as, where *C* is the capacitance of the human body, *Q* is the charge induced on the body and *V* is the corresponding voltage value.

One of the performance criteria of the ESD garments is quick charge dissipation; hence, analyzing the voltage may be one approach to measure the efficiency of the garment. It can be claimed that an efficient ESD protective garment shall yield a significant amount of voltage drop per knit-stitch, so that imposing high values of charges (as in Scenarios 1 and 2) will not cause harmful voltage levels on the electronic equipment. The amount of the induced charge and the corresponding voltage value are highly dependent on the movements of the people, their clothes and the material used as the floor coating. Typical values of such variety are evaluated experimentally by several studies and reported in relevant standards 15-19. In such scenarios, the corresponding capacitance is the human body capacitance; and there are various studies in the literature regarding the calculation of the human body capacitance 8-11. Those models are based on surface charge density approach, polyhedral approach and spherical approaches 8,9,10. Throughout this study, we have picked the model given in 8, which considers the effects of mass, age and length for calculating the human body capacitance. Three different adult models are chosen to be 30, 35 and 60-year old males. The capacitance values of 30, 35 and 60-year old models are calculated as 47.1723 pF, 50.9582pF and 47.8323pF, respectively. As seen from these values, the capacitance of the human body varies about $\pm$20% as regards the affecting parameters. Throughout this study, we evaluated the performances of the ESD garment under the assumption of human body model, and considered a 30-year old male model with a weight of 63kg, a height of 170cm and with a surface area of 1.70×10^4 cm^2. The surface charge density of the 30-year old model is shown in Figure 2. The charge distribution is quite dense on the fingers, toes and around the elbows.

4. Analysis Approaches

The scenarios mentioned in the previous sections cause malfunctions and financial losses in the electronics industry. Three relevant analysis methods exist: static analysis, time domain analysis and frequency domain analysis.

In the static analysis, an electrostatic charge (the form of a surface charge density of ρ_s) is assumed to be imposed at some particular point on the ESD garment. The electric potential or the voltage (due to the imposed charge) at each point on the garment is calculated via the Poisson's Equation as demonstrated in Figure 3a. In the time domain analysis, the surface current seen in Figure 3b (due to the imposed charge) at each point on the garment is calculated via the Equation of Continuity.

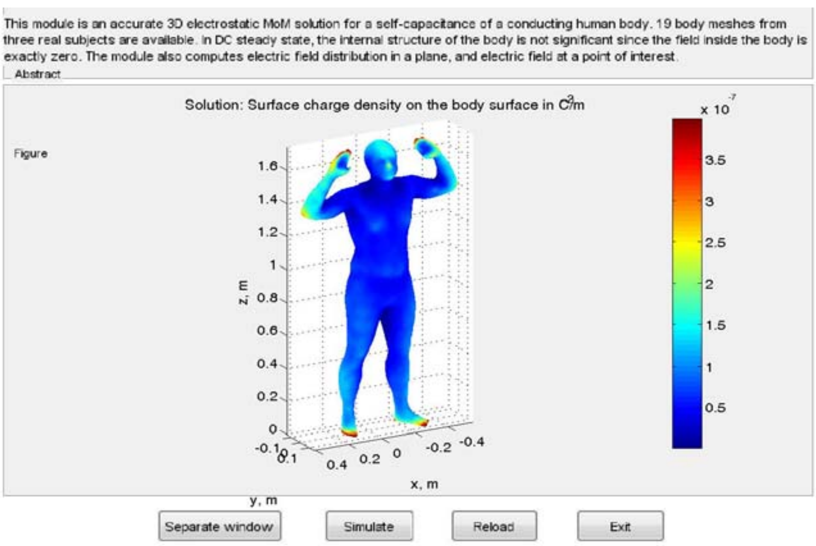


Figure 2. Charge distribution of the 30-year old model

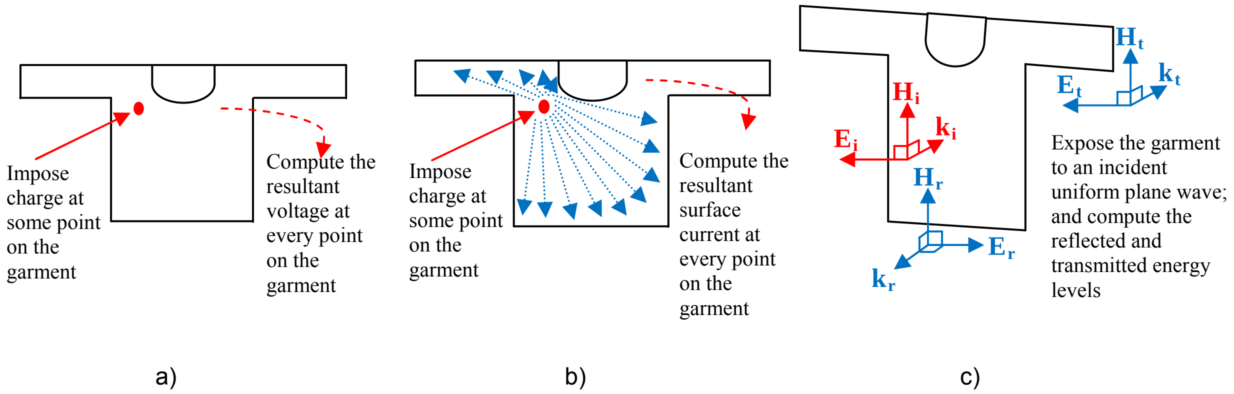


Figure 3. a) Static analysis approach b) Time domain analysis approach c) Frequency domain analysis approach for Scenarios 1 and 2.

The last analysis is the frequency domain analysis, which is based on the solution of the Helmholtz wave equation. In this analysis, unlike the other ones, a charge density is not imposed to the garment, but the garment is exposed to a plane wave at a certain frequency propagating perpendicularly to the garment. Incident electric field ($\mathbf{E}_i$), incident magnetic field ($\mathbf{H}_i$) and propagation vector ($\mathbf{k}_i$) are perpendicular to each other. This relation is also valid for reflected wave ($\mathbf{E}_r$,$\mathbf{H}_r$,$\mathbf{K}_r$) and transmitted wave ($\mathbf{E}_t$,$\mathbf{H}_t$,$\mathbf{k}_t$). In this analysis, via the Helmholtz wave equations, the reflection and transmission characteristics of the ESD garment is evaluated by calculating the amount of reflected and transmitted power ratios. Details of this analysis and the calculated/measured parameters can be found in 14.

5. ESD Protection Methods and Requirements of the ESD Protective Garments

Increasing demands of the electronics industries about ESD protection have forced the studies regarding the development of ESD protective devices and other means. Studies in the literature presented not only grounding bracelets, gloves and shoes but also ESD protective garments in order to provide acceptable levels of ESD protection. The efficiency of ESD garments have increased dramatically throughout the last decades. This level of efficiency owns its reputation to the standardization of garments via several standard systems, which are presented in 8-12.

The tests conducted in order to form standards for ESD garments yielded de-facto requirements for ESD garments. According to these, an ESD protective garment shall satisfy the following:

i. High surface resistivity (and eventual outward electrical insulation) in order to prevent charge transfer with external structures.

ii. High conductivity for quick charge dissipation in order to achieve protection of the other structures in the vicinity.

iii. Sufficient shielding in order not to be effected by the electromagnetic waves propagating in the environment.

In order to ensure the first two requirements, the half-decay time of the electric field must be under 4 seconds, and the surface resistivity of the garment shall be less than $2.5\times10^{9}\Omega$. For satisfaction of the third requirement, the shielding factor must greater than 0.2 12,13.

Even though the first two requirements seem to be contradicting to each other, both can be satisfied in case of multi-layer structures are used. Those multilayer structures can be either knit structure that is multilayer or the yarn itself, which has a core and outer shell of different materials; however, in the proposed study the yarn is multilayer which has a core and outer shell of different materials. The new knit model is created by using that multilayer yarn. The main idea beneath the multi-layer structures is to choose the outer layer to be an insulator in order to satisfy the first requirement, and the inner layer as a conductor to satisfy the second. Presence of the sufficient amount of conducting material will eventually satisfy the third requirement. For better charge dissipation and eventual ESD protection, the conductors in the textile shall constitute continuous paths. If possible, these paths shall also be connected to the ground. Thus, sewed parts usually constitute bottlenecks, since they cause discontinuities. One practical approach for avoiding sewing and overcoming this issue is to prefer a knitted topology rather than a woven topology.

In light of the information proposed above, we propose the double-layer (conductor core and textile outer shell) yarn based-knitted structure as shown in Figure 4 in this study.

As seen in Figure 4, r_{out} and r_{in} represent the outer and the inner radius of the knit stitch, respectively. A piece of the relevant textile product of 6×6 knit stitches can also be seen the same figure. The outer layer of the structure is made up of a dielectric (insulating) layer, which may be chosen any textile product at any permittivity value. The outer layer additionally provides physical isolation and protection of the conductor inside against external effects such as oxidation and corrosion.

In this proposed study, we analyzed and compared the ESD protection performances of different inner and outer materials. For the outer layer silk (with relative permittivity ε_r=4.5), polyimide (ε_r=3.5), and cotton having two different permittivity values (ε_r=3.7 and ε_r=7.9) are considered as the four alternatives. For the inner part, five conducting alternatives, aluminum, steel, nickel, silver and copper are considered. While choosing the materials, some requirements of textile products, such as the toxicity shall be taken into account. For example, despite of its good properties such as high level of conductivity, low weight and low price, beryllium is not considered since it is reported as a toxic material and banned in the textile industry.

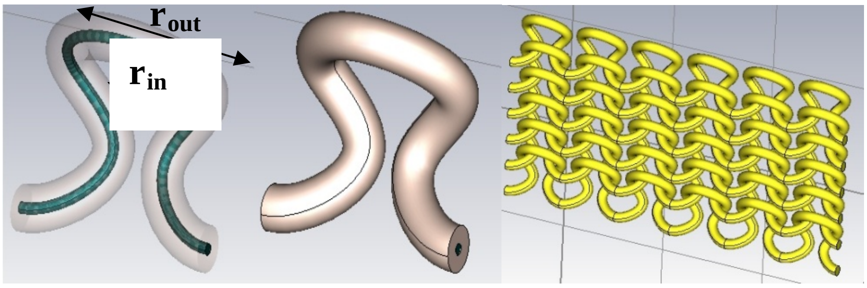


Figure 4. Unit element of the proposed knitted topology; and the fabric structure - a piece having 6 wales and 6 courses

In another viewpoint the proposed structure is evaluated for different outer shells such as loop length, wales per inch (WPI) and course per inch (CPI) information, stitch density, weight and yarn count. In order to evaluate the weight and yarn count the single loop is considered as a cylinder shown in Figure 5 with a length of *h*=31.69mm. Internal and external radius values are denoted as r_{int} and r_{ext}.

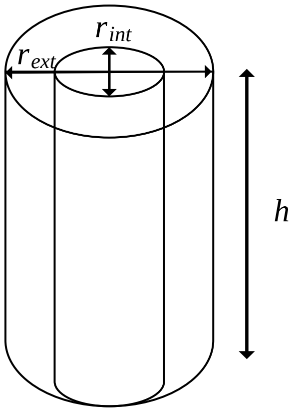


Figure 5. Cylindrical form of a single loop of the yarn

For a single loop, the inner part of the cylinder is a conductor layer and the corresponding volume is calculated as in equation (1) and denoted as V_{in};

As stated before the outer layer is the dielectric layer and the volume of the outer layer of the cylinder is denoted as V_{out} and corresponding volume is denoted as in equation (2);

In order to calculate the yarn counts, the material density values (Aluminum=2.7g/cm^3, Steel=7.75 g/cm^3, Nickel= 8.908 g/cm^3, Cotton=1.56 g/cm^3, Silk=1.33 g/cm^3, Polyamide=1.14 g/cm^3) are considered and weight of a single loop calculated by using the inner volume (V_{in}) and outer volume (V_{out}) determined above.

The results obtained from the calculations presented in Table 1 for different material combinations consists of Aluminum & Silk, Steel & Silk, Nickel & Polyamide, Aluminum & Cotton, Steel & Cotton and Aluminum & Polyamide. For each combination, single loop weight is calculated as well as the weight of a 1-meter sample. As seen in Table 1, Aluminum & Polyamide combination yields the smallest weight for a single loop.

Yarn counts are proposed in Table 1 in terms of metric units' gram/meter, Tex and Dtex. Aluminum is again the preferable material in terms of weight as the conductor layer. The results of yarn counts also show that cotton is also preferable as a dielectric layer after polyamide.

$$V_{in} = \pi {r_{in}}^2 h = \pi(0.49)^2 31.69 = 23.9\mathrm{mm}^3 = 2.39 \times 10^{-8}\ m^3 \quad (1)$$

$$V_{out} = \pi(r_{ext} - r_{int})^2 h = \pi(0.7 - 0.49)^2 31.69 = 24.87\mathrm{mm}^3 = 2.487 \times 10^{-8}\ \mathrm{m}^3 \quad (2)$$

Table 1. Weight and yarn count data for each material combination

		Aluminum & Silk	Steel & Silk	Nickel & Polyamide	Aluminum & Cotton	Steel & Cotton	Aluminum & Polyamide
$W_{single\ loop}$ (g)		0.10	0.22	0.24	0.10	0.22	0.09
Weight of a 1 meter yarn (gr)		3.12	6.99	7.72	3.31	7.17	2.97
Yarn Counts	Yarn count (gram/meter)	3.12	6.99	7.72	3.31	7.17	2.97
	Tex (gram/1000meter)	3124.14	6986.97	7721.48	3307.25	7170.08	2972.87
	Dtex (gram/10000)	31241.38	69869.68	77214.75	33072.50	71700.80	29728.72

The sample model consists of 6 wales and 6 courses. The wales are located 5mm away from each other as shown in Figure 6.

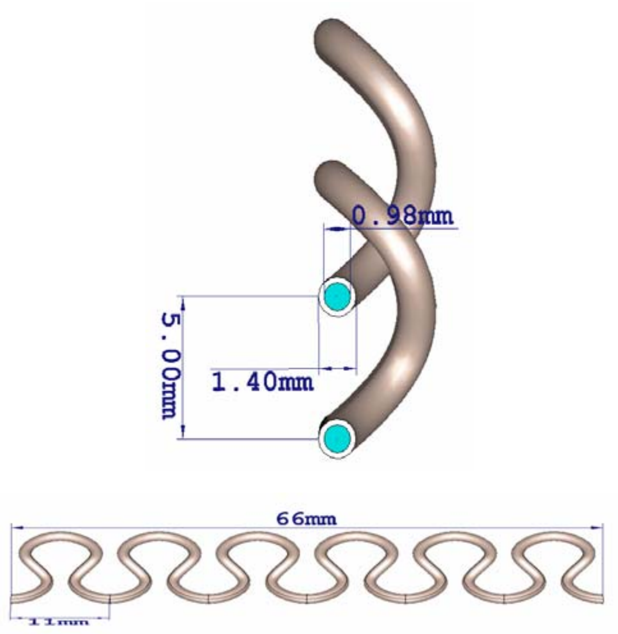


Figure 6. Wale and course sizes of the proposed structure

The width of a single loop is 11mm and the course width is 66mm. The loop length of the structure is 31.69mm, and fabric density values are calculated as 6 wales per inch (WPI) and 3 courses per inch (CPI). Since the stitch density determined as *S*=WPI×CPI, the structure has a stitch density of 18.

The most significant study regarding the development of ESD protective textiles so far has been the ETATS-Garments project, which was a multinational project executed in between 2002 and 2005 20. This project yielded the pioneering publications regarding the test and measurement methods regarding the ESD protective textiles as well as identification of the potential threats (most of which have led the scenarios given in Figure 1 and the analysis approaches given in Figure 3 of this paper); but there has been no specific novel ESD protective garment structure as an outcome of the ETATS-Garments project. With this point of view, the structure proposed by us in this paper can be considered as a design satisfying whole criteria pointed and imposed throughout the ESTATS-Garments project.

6. Results

According to the presented human models the surface current density values are 3.9×10^{-7}, $4\times10^{-7,}$ 4.3×10^{-7} for 30, 35 and 60-year-old human respectively. The 30-year-old model considered for the evaluations and static, time domain and frequency domain analysis are conducted for the capacitance value of the aforementioned model.

Static Analysis: In static analysis part of the study, several structures evaluated in order to analyze material of the yarn, geometric impacts of the structure. Continuity is also determined as a parameter for evaluating the performance and it is evaluated for different topologies. As a performance criterion of the satisfactory charge dissipation, maximum voltage in 2D plane of the knitted topology is analyzed. The studies were extended to 35-year-old and 60-year-old human body while analyzing the conductor impact and the corresponding results are presented in Table 2. Not only according to the data presented in this table but also according to the additional analyses it is shown that the conductors having the same conductivity value such as Aluminum, silver and copper achieved quick charge dissipation and have the same performance.

Table 2. Impact of conductor layers to 2D maximum voltage value for 5 courses, R_{ext}=0.7 mm, p=0.7 structures

	2D results maximum voltage value		
Conductor material	5 courses Polyamide (ε_r=3.5)		
	30-year-old	35-year-old	60-year-old
Aluminum	44167.6	45300.1	48697.6
Nickel	44265.7	45400.7	48805.8

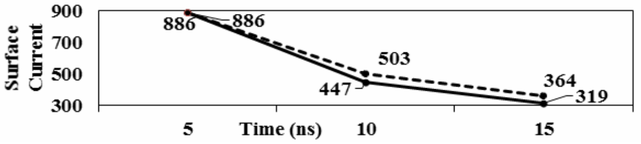
Table 3. Data obtained for different materials for outer layers and inner layers of a structure having R_{ext}=0.7mm, p=0.7

		2D results maximum voltage value	
	Material	ε_r=4.5	ε_r=7.9
5 courses	Aluminum	42680.8	39599.0
	Steel	42758.5	39652.7
10 courses	Aluminum	42806.8	39770.1
	Steel	42834.5	39811.7

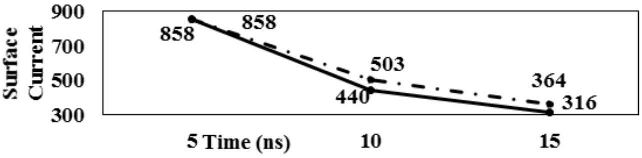
The number of the courses and the dielectric layer properties are also evaluated and the results presented in Table 3. As shown in table the higher permittivity values cause quicker charge dissipation. The results showed that the number of the courses has not a significant effect on performance as much as the permittivity value. It can be concluded the more course number, the better dissipation achieved. However, after a threshold number such as 15 courses, the impact of the courses number can be denoted as negligible.

Time Domain Analysis: The performance of the knitted topology is evaluated by considering a sample consisting of 6 wales and 6 courses. An ESD gun is used to mimic the flow of the charges. The surface currents and the magnetic fields are evaluated for different materials. The charge flow is assumed to start via the connection of ESD guns' port (which has a voltage magnitude of 4000V) to the knitted topology. The structure is evaluated for 20ns duration at where the surface current reduced to zero. For each 5ns step, the surface current is evaluated and presented.

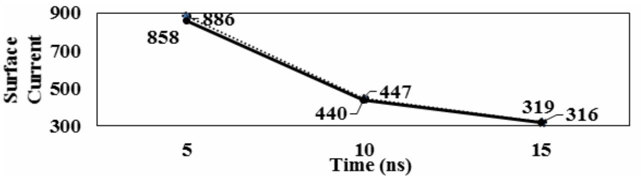
For a structure made from a yarn contains silk as the outer material and copper as the inner material, the surface current was 886 at 5ns and reduced to 503 and 364 for the 10ns and 15ns, respectively. Than in order to evaluate the uniformity, one of the outer shell of a single course in the knitted structure is determined as copper instate of polyamide, for creating a nonuniform structure. Since the metal ratio in the structure increased, the discharge occurred faster than the homogenous structure. Although the surface currents was the same at 5ns, it reduces to 447 and 319 for the 10ns and 15ns as seen in Figure 7a.



a) Silk & copper uniform vs nonuniform



b) Polyamide & steel uniform vs nonuniform



c) Polyamide & steel nonuniform vs Silk & copper nonuniform

Figure 7. Surface currents of the 6x6 knitted topology for different materials

The same procedure is followed for the structure consists of yarn with polyamide and steel. The surface current, which was 858 at 5ns reduced to 503 and 364, at 10ns and 15 ns, respectively for homogenous topology. It reduces to 440 and 316 for the nonuniform topology as presented in Figure 7b. The nonuniform topologies with different materials are considered and a significant difference cannot be observed as shown in Figure 7c.

The comparison of Silk & copper homogeneous and nonuniform for H-field intensities at t=5s, t=10s and t=15s and the comparison of Polyamide & steel uniform and nonuniform for H-field intensities at t=5s, t=10s and t=15s is presented in Figure 8 and in Figure 9, respectively. Lower magnetic field intensity values obtained for nonuniform topologies in both.

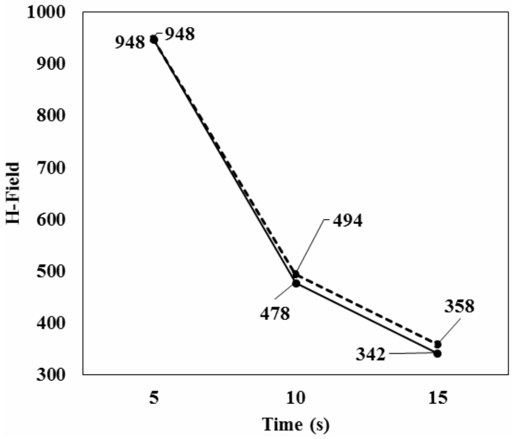


Figure 8. Silk &copper uniform vs nonuniform topology comparison of H-field intensities at t=5s, t=10s and t=15s

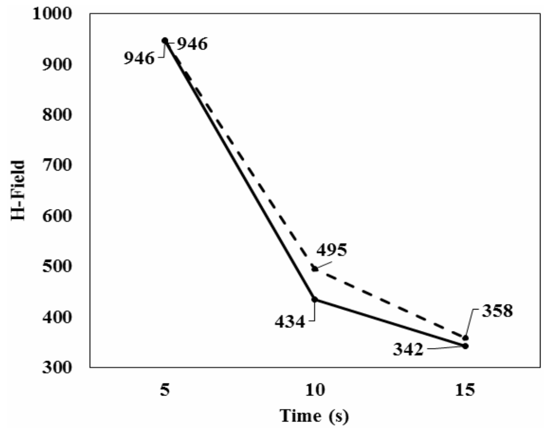


Figure 9. Polyamide & steel uniform vs nonuniform topology comparison of H-field intensities at t=5s, t=10s and t=15s.

Frequency Domain Analysis: Two-course knitted garment is considered during the frequency domain analysis and is evaluated under open boundary conditions. The materials of the yarn for the knitted topology are determined as polyamide at the outer layer and aluminum at the inner layer. The shielding is evaluated under the assumption of a normal incidence electromagnetic wave penetrating in the knitted structure. Reflection and transmission parameters are evaluated in terms of dB, for a structure having R_{ext}=1 and p=0.7 (inner to outer radius ratio).

7. CONCLUSIONS

Static, time domain and frequency domain analyses are performed for the proposed topology by altering the dielectric and the conducting materials as well as the inner/outer radii and course number. Throughout the static and the time domain analyses, typical total charge values are estimated and imposed by considering the human body capacitance values (mentioned in the previous sections). Major outcomes of the numerous analyses can be outlined as follows:

- Static analyses show that, regardless of the material used, the proposed structure decreases the voltage from the level of 10000V (at the point where the charge is imposed) to the level of 5V (at a point 10-20 knit stitches away). This means that in case of typical ESD accidents described in Scenarios 1 and 2, the relevant electronic equipment will be safe since the voltage in its vicinity will be much smaller than 50V, which is the critical level for most electronic devices and components.
- Time domain analyses show that, regardless of the material used, the proposed structure achieves charge quick dissipation due to the conductor inside, and limits the instant energy transfer due to the dielectric outside.
- Regardless of the material used, the proposed structure demonstrates high surface resistance as desired.
- Frequency domain analyses show that, regardless of the material used, the proposed structure provides high shielding efficiency especially at low frequencies as desired, as previously reported in 13.

- Static analyses show that dielectric materials with higher permittivity values demonstrate higher performance. Among all alternative dielectric materials, cotton with a permittivity value of 7.9 yields the best performance.
- Static analyses show that higher inner/outer radius ratio increases the performance. On the other hand, higher inner/outer radius ratio increases the weight and the cost of the garment. Moreover, this makes the outer dielectric coating layer thinner; which means that the garment will be less resistant to external effects.
- Time domain analyses show that, loss tangent (a measure of how much electrical energy is absorbed and converted to heat inside the relevant material) value of the dielectric layer is a quite significant factor in quick charge dissipation. As a design guideline, dielectric materials having high loss tangent values at low frequencies shall be preferred, as previously reported in 13.
- Both the static and the time domain analyses show that, regardless of the material used, deformities in the garment has an impact on the performance. Two types of deformities are considered separately: discontinuation of the inner conductor layer, discontinuation of the outer dielectric layer. These deformities can be caused by external effects throughout the daily use as well as laundry. Discontinuities of the inner conductor layers are tolerable since there are numerous alternative conducting paths in the proposed structure. Static analyses show that, unless the imposed charge is quite close (less than 5 courses knit) to the point of deformity, discontinuity in the conductor layer does not have much impact. On the other hand, discontinuities of the outer dielectric layer are much risky. At those points, since the physical protection of the conductor layer is no more valid, the garment gets less resistant to external impacts. At this point, it should be noted that the scope of our analyses in this study is quite limited as regards observing the practical impacts of deformities. This topic is rather complicated but very important due to the following facts: garments are much more prone to deformities at the tips of the body, such as the elbows. Ironically, as seen in Figure 3, these regions of the human body have also high tendency to be charged. Further research shall be performed in order to:
    - Model the impacts of the size and the position of the deformity,
    - Simulate/measure how catastrophic if the charge is imposed exactly at the point of deformity
    - Asses the short and mid-term direct and indirect impacts of the deformities.
- Static analyses show that, copper, silver and aluminum outperform to nickel and steel. There is no significant performance difference among copper, silver and aluminum as regards the static analyses. Nevertheless, according to the time domain analyses, copper outperform to the others.
- Considering the weight of the proposed structure, the density of the conducting material is the dominating factor. By comparing the densities of five conductors considered, aluminum has the lowest density (2.7 g/cm^3), and the silver is the heaviest (with a density value of 10.49 g/cm^3).
- Considering the economic figures of merit, aluminum outperforms to copper and silver (since aluminum, copper, and silver have the prices 1814 USD/Tone, 7239 USD/Tone and 733000 USD/Tone, respectively according to the data obtained from London Metal Exchange).
- Considering oxidation and corrosion-resistance, steel might be the best choice among the 5 alternatives, but it demonstrates bad performance in other aspects. At this point, again it should be noted that the scope of our analyses in this study is quite limited as regards observing the impacts of oxidation and corrosion. Further research shall be performed in order to model, simulate/measure the short and mid-term impacts of these factors.

In light of the information given above, among all the considered alternatives, aluminum and high permittivity cotton seem to constitute the ideal configuration for our proposed topology considering multiple criteria. Other criteria such as elasticity, performance dependence to temperature and pressure etc. shall further be considered and studied in future studies.

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