The Integration of 3D Printed Conductive Composite Materials in Textile-Based Wearable Technology

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ABSTRACT

In the current field of wearable technology, silver yarns are used to provide electrical conductivity to non-conductive textiles required for monitoring and measurement. However, these yarns are also an irreparable failure point in textile-based wearables. This research aims to provide an alternative to silver yarn by exploring innovative methods to integrate 3D printed circuitry onto textiles. Different conductive composite filaments (CCFs) were investigated for improved electrical conductivity and drapability. Specimens were fabricated by 3D printing electrically conductive material on a textile between two disconnected silver yarn squares. Electrical performance and drapability were two objectives considered in this work. 3D printed samples were made from off-the-shelf CCFs: two carbon black/polylactic acid (PLA) filaments and one copper/PLA filament. All samples were manufactured using a Material Extrusion (MEX) 3D printer. The impact of trace patterns, width, and thickness on electrical conductivity on a hard surface and a textile was evaluated along with drapability. The copper/PLA trace integrated onto the textile through 3D printing was found to have electrical and draping performance similar, or better, to the reference textile made with silver yarn. The best performing copper/PLA trace geometry integrated onto a textile consisted of an S-pattern (SP) with a 2.5mm turn radius, 4mm width and 1.5mm thickness. This trace displayed a resistance of 3.58 Ω/cm and draping coefficients (DCs) of 36.36% across the trace and 54.55% along the trace.

1 Introduction

The field of additive manufacturing conductive composite filaments (CCFs) is novel; however, it has advanced greatly over the last 17 years. Some of the first experiments on this topic involved the additive manufacturing of silver conductive inks [1, 2]. These experiments quickly advanced over the next decade to 3D printing CCFs made from various polymers. Polylactic acid (PLA) is a commonly used polymer due to its biocompatibility and has been investigated for electrical performance when combined with different conductive fillers [3, 4]. For industrial applications, 3D printing commercially available filament is much more efficient than developing a new filament. For this reason, many researchers focus on characterizing the electrical performance of commercially available CCFs [5, 6, 7, 8]. 3D printing CCFs on textiles has allowed for many novel approaches to manufacturing flexible electronic components, such as sensors, circuits, and interconnects [7, 9]. Commercially available PLA based CCFs were commonly chosen when 3D printing on textile and demonstrated good adhesion [10]. On the other hand, thermoplastic polyurethane (TPU) based CCFs showed some difficulty printing on textiles along with inconsistent electrical performance [9, 11]. For this reason, PLA based conductive composites were chosen for investigation. The CCFs selected for this experiment were 3DKonductive, Protopasta Conductive PLA and Electrifi. Previous research has investigated Protopasta Conductive PLA printed on conductive textile. However, this research had a very limited scope and did not compare different CCFs [12]. Previous research has also been conducted attempting to integrate Electrifi filament with textiles, such as heat transferring 3D printed Electrifi structures onto textile via thermocompression [7]. However, there is a gap in the literature which could be filled by directly 3D printing Electrifi onto a textile.

Although many papers have investigated the electrical performance and adhesion of CCFs integrated onto textiles, none of these papers investigated the drapability of the resulting structure. When integrating 3D printed structures with textiles, drapability is an important characteristic for textile performance. Drapability is crucial for the aesthetics and functionality of 3D printed textile structures [13]. If a material has limited drapability, it may not be appropriate for specific wearable technology applications which require high flexibility from the textile. Drapability can be measured in different ways and the method of measurement has changed over time. In current research, comparing the draped and undraped areas of a structure, through a parameter called draping coefficient (DC), has been accepted as an appropriate methodology [13, 14]. The drapability of 3D printed structures have been investigated, but no textiles with 3D printed structures integrated onto their surface have been investigated for this property [13, 14]. This is crucial to identifying the best CCFs to integrate with textiles for wearable technology applications. Materials with better draping performance are more suitable for integration into textiles and investigating drapability aimed to determine the difference between PLA composites integrated with textiles.

This study investigated the electrical performance and drapability of commercially available CCFs to determine if they could be an appropriate substitute for conductive silver yarn commonly used in wearable technology applications. Electrical performance was characterized by comparing the resistance per unit length of different CCF traces printed on a rigid surface. The two CCFs with the lowest resistance per unit length were then integrated with textiles to observe how their electrical performance and drapability compared to conductive silver yarn.

2 Methodology

2.1 Materials and Specimen Manufacturing

Three commercially available PLA based CCFs were selected for testing. These filaments were chosen based on their specific volume resistance reported from the manufacturer. Two conductive filaments used a carbon black filler to achieve conductivity. These two carbon black/PLA filaments were 3DKonductive (3DK) (3DK.Berlin, Berlin, Germany) which had a reported resistivity of 24 Ω.cm for a 3D printed structure and Protopasta Conductive PLA (Protoplant Inc., Vancouver, USA) which had a reported resistivity of 30 Ω.cm in the x/y direction and 115 Ω.cm in the z-direction [15, 16]. The last commercially available CCF used was Electrifi (Multi3D, Middlesex, USA), which utilized copper as its filler. This copper/PLA CCF had a reported resistivity of 0.006 Ω.cm [17]. All filaments were 1.75mm diameter and could be 3D printed with a 0.8mm nozzle diameter.

A Creator Pro 2 (Flashforge, Jinhua, China) 3D printer was used to manufacture the 3D printed conductive composite traces. Two categories of traces with different geometries were designed: straight-line (SL) traces and S-pattern (SP) traces. The cross-sectional area (CSA) for the SL trace with the lowest resistance per unit length was selected for the SP trace design in order to maximize electrical performance. The SL traces were designed with different CSAs with widths of 2,3 and 4 mm, thicknesses of 1 and 2 mm and fillets of 0, 1 and 2 mm (Figure 1). Two variations of the SP traces were designed from the most conductive geometry of the SL trace. One geometry of the SP trace had a 2.5 mm turn radius with eight 180^o turns and 2 90^o turns, while the other SP trace had a 5 mm turn radius four 180^o turns and 2 90^o turns (Figure 1). Samples were named based on their distinct geometries. For example, an Electrifi SL trace of 4mm width, 2mm thickness and 1 mm fillet would be denoted as E-SL-W4T2F1. These samples were 3D printed once with each filament using the 3D printer. These samples were printed on painter's tape with no pre-extrusion and no raft in order to closely resemble the settings that would be used when printing on the textile. Since the traces were so thin, there was no room for an infill between the rectangular ends of the trace. However, the rectangular ends of each trace were wide enough to be printed with an infill. Therefore, 100% infill was used to minimize gaps which would inhibit electrical performance. The 3D printing settings for each material are presented in Table 1.

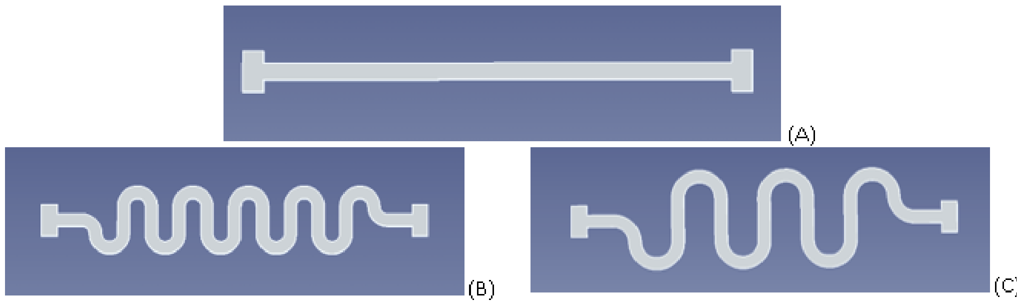

Figure 1. (A) SL trace Geometry, (B) SP-TR2.5 trace geometry, (C) SP-TR5 trace geometry

Table 1. 3D printing settings used for each CCF.

Filament	3DKonductive	Protopasta Conductive PLA	Electrifi
Bed Temp [°C]	60	60	20
Infill percentage [%]	100	100	100
Print Speed [mm/s]	60	35	30
Nozzle Temp [°C]	215	215	142
Extrusion Ratio [%]	100	100	102
Layer Height [mm]	0.2	0.2	0.24

Experimental textile samples were prepared from the two filaments with the best electrical performance. These samples were fabricated by printing the best performing CSA of each sample in SL and SP geometries. Three SL traces and two of each SP trace were printed onto the experimental textile samples.

2.2 Resistance and Drapability Measurement

The reference and experimental textile samples were measured using the same procedure. Resistance measurements were taken using a the 2-point method with two multimeters, a Neoteck™ (Taiwan, China) XL830L and Mastercraft (Tennessee, USA) 052-0060-2. The 2-point method of measuring resistance was chosen due to the negligible contact resistance of silver yarn. Length was measured with Vernier calipers (Accusize, Ontario, Canada) between the inner edges of the silver pads and resistance was divided by this value to get the unit of Ω/cm. Conductive traces 3D printed on painter's tape required the application of silver conductive epoxy 8330S (MG Chemicals, Ontario) to the rectangular ends in order to negate the effects of contact resistance. This was a common practice in the literature measuring the electrical performance of 3D printed filaments [6]. These samples were cured at 65°C for 2 hours in a dehydrator (Noztek, Shoreham-By-Sea, Engalnd), then cooled to room temperature before the resistance was measured.

Drapability of the experimental and reference samples were measured by calculating the *DC* of each sample. The DC was calculated according to the Equation 1:

$$\frac{draped\ area}{undraped\ area} \times 100 = DC \tag{1}$$

To find the *draped area* and *undraped area* for each sample, 3D scans were taken using the Creaform Handyscan (Ametek, Pennsylvania, US). Based on this measurement, a lower DC signified better draping performance.

3 Results & Discussion

3.1 Electrical Performance

When 3D printing a trace of equal length and decreasing CSA, the resistance was expected to decrease according to Equation 2 where ρ is resistivity, R is the trace resistance, A is CSA and l is length of the trace.

$$R = \frac{\rho l}{A} \tag{2}$$

The effects of trace geometry on electrical performance of each 3D printed CCF can be observed in Figure 2. The Protopasta filament was found to perform as expected and as the CSA decreased, the resistance of the trace increased. The Protopasta trace with a CSA area of 8 mm^2 resulted in the best performance with a resistance of 185.3 Ω/cm. The worst performing Protopasta trace had a CSA of 1.57 mm^2 and resistance of 946.9 Ω/cm. Electrifi followed this trend quite closely but demonstrated some anomalies. The Electrifi CCF had the best electrical performance overall. The trace with the worst electrical performance was also found at an area of 1.57 mm^2 and a resistance of 13.56 Ω/cm, an order of magnitude lower than Protopasta. However, the best performing Electrifi traces were found at areas lower than the largest. The best performing Electrifi trace was the SL-W4T1.5 geometry. This sample had a CSA of 6 mm^2 and resistance of 0.791 Ω/cm which was 48.5% lower than the resistance of the 8 mm^2 structure. The electrical performance of Electrifi filament was found to be sensitive to the ratio between width and thickness of the trace geometry, while the Protopasta filament was largely unaffected by this ratio. The 3DK CCF demonstrated extremely inconsistent electrical performance across different trace geometries and the worst electrical performance. An example of the 3DK CCF's inconsistency can be seen comparing the 3rd best performing geometry which had a CSA of 3 mm^2 and the worst performing geometry with a CSA of 4 mm^2.

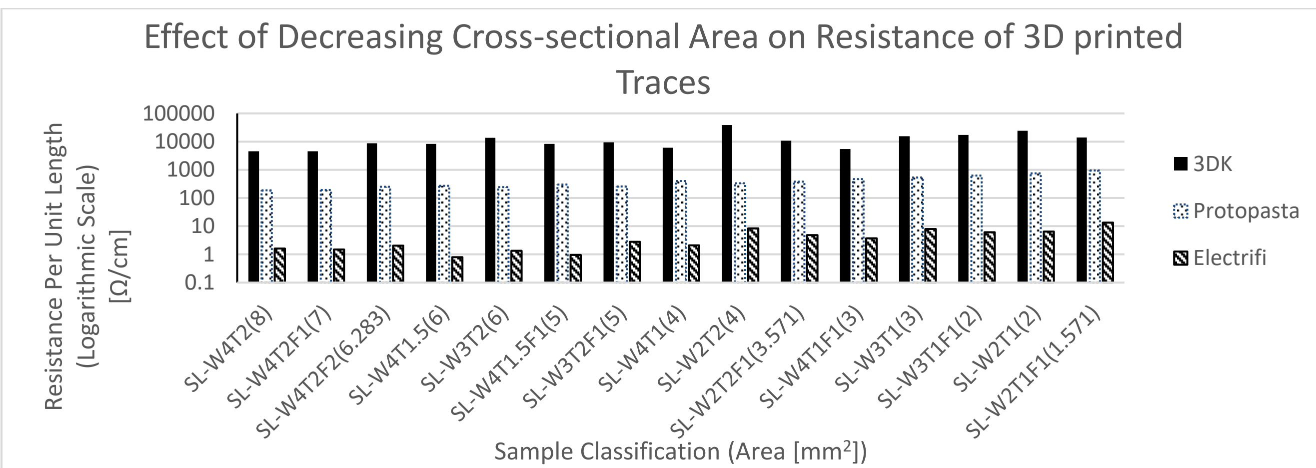

Figure 2. The effect of cross-sectional area and trace geometry on the resistance of 3D printed 3DK, Protopasta and Electrifi traces. Resistance measurements were normalized to a 1 cm length.

The two best performing 3D printed CCFs in terms of electrical performance were Electrifi and Protopasta. As a result, these CCFs were integrated onto textiles. Here, the results for Electrifi are presented in detail (Figure 3).The Electrifi filament followed the expected trend that was found in previous literature and demonstrated an increased resistance when printing on textile compared to the painter's tape, which was more rigid [9]. An unexpected trend was observed in Figure 3 when comparing SP and SL traces of the 3D printed Electrifi filament. These traces behaved as expected, when 3D printed on painter's tape, and the Electrifi traces with a longer path length had a proportionally higher resistance. This trend did not hold true for Electrifi traces 3D printed onto the textile. In this case, there was a decrease in resistance of the SP traces compared to SL traces, despite the longer path length of the SP traces. This could be explained due to the Electrifi's sensitivity to print settings and the SP trace forcing the 3D printer to move more slowly. Therefore, 3D printing on a soft surface was observed to make the Electrifi trace more sensitive to the print speed. Comparing Electrifi to the reference revealed that SP-TR2.5 and SP-TR5 geometries 3D printed onto textile had resistances of 3.58 and 4.76 Ω/cm, respectively, while the reference textile had a resistance of 3.85 Ω/cm. This demonstrated that an Electrifi trace can achieve similar electrical performance to silver yarn when integrated with a textile.

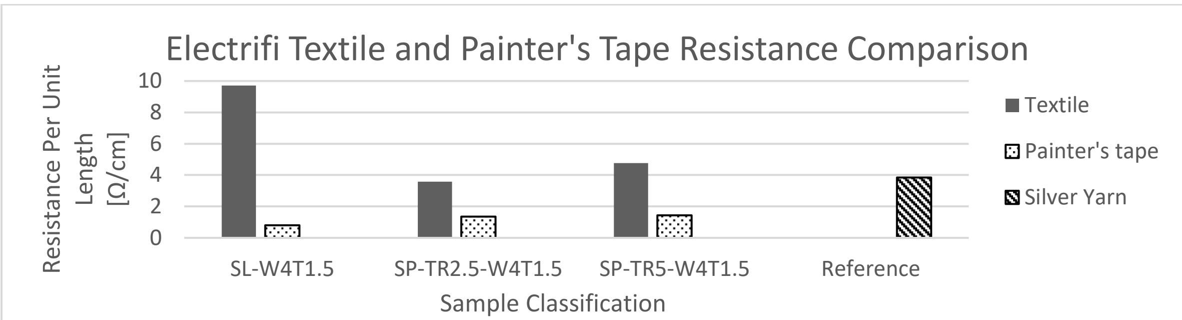

Figure 3. Resistance of different Electrifi trace geometries 3D printed on textile and painter's tape compared to the resistance of the reference sample.

3.2 Drapability Results

The comparison of DCs in Figure 4 revealed some interesting information about the drapability of the 3D printed samples compared to the reference. The reference demonstrated DCs of 49% and 58% in the x and y-direction, respectively. The best performing Electrifi textile integration, in terms of drapability, was found to be the SP-TR5 trace geometry. This geometry had DCs of 30.54% and 54.55% in x and y-directions. All Electrifi SP traces were able to achieve lower DCs than the reference sample with assisted draping in the y-direction. The SP traces also displayed a lower DC across the trace, in the x-direction, compared to the reference. This was caused by the 3D printed trace adding stiffness to the textile, allowing the textile to fold under itself when elevated on the draping pole. As a result, less was draped along the surface of the 3D scanning platform resulting in a lower DC. Overall, both SP trace geometries were found to increase drapability in the y-direction, compared to SL geometries. Although the DCs of Electrifi textile integrations are lower for both x and y-directions of the SP trace, it does not necessarily have better draping performance than the reference. It can be concluded that SP Electrifi textile integrations are able to achieve comparable draping performance to the reference, textile-only, samples across the trace and along the trace.

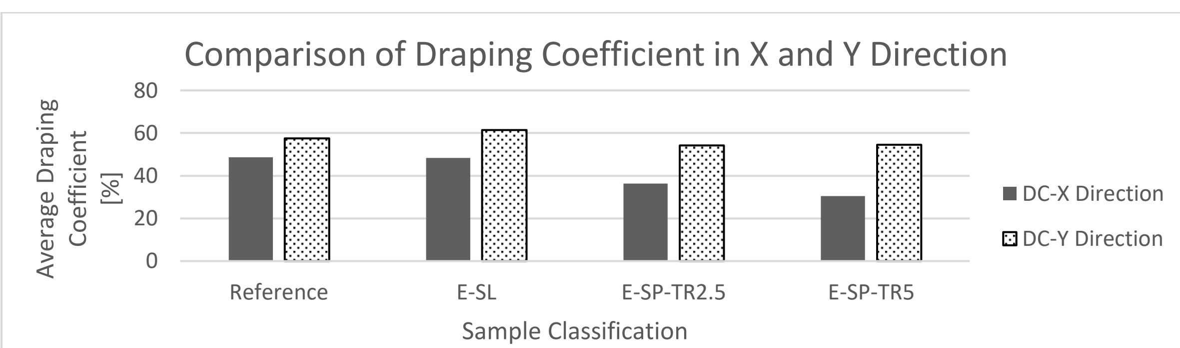

Figure 4. Comparison of drapability across the trace (x-direction) and along the trace (y-direction) between the reference sample and different Electrifi (E) trace geometries.

4 Conclusion

Overall, the Electrifi traces 3D printed directly onto textiles were able to achieve similar performance to the textile-only reference utilizing silver yarn connections. The Electrifi sample E-SP-TR2.5-W4T1.5 with a recorded resistance of 3.58 Ω/cm and DCs of 36.36% and 54.55% in the x and y-direction performed most similarly to the reference.

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