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Associate Finger Engagement During Manual Assembly in Automotive Production for Smart Wearable Systems

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Abstract

Electrical connection defects represent a significant source of overall defects during automotive assembly. Human detection of these defects during the assembly process has proved insufficient. To rework electrical connection defects, much time is spent uninstalling and reinstalling components such as the instrument panel, carpeting, and cover panels, which can be time-consuming and costly, as some parts are easily damaged, for a rework that may be as simple as fully seating a connector. This work aims to provide an understanding of which fingers and finger locations associates use to interact with objects during manual automotive assembly processes to better guide development of future wearable associate assembly assistance systems that will detect and inform the associate of potential defects at the point of assembly thereby reducing the complexity of rework. In this work, two types of flexible force sensors were used to measure finger activation and area of force application for automotive electrical connections. The flexible force sensors were layered into a standard work glove with sensors at each of the five fingertips, and for each connection type, a digital fingerprint of output signals was created for novice assembly users.

Keywords: Cyber-Human Systems, Manual Assembly, Assembly Assistance, Wearable System

1. Introduction

Electronic assembly components contribute to control of much functionality within a vehicle, from the powertrain and engine to safety critical seatbelts and airbags, electronic components make up an increasingly significant portion of a vehicle's components. With the increasing amount of electronic content, the correct assembly and connection of these components is becoming increasingly important, and why detecting and correcting issues with vehicle assemblies prior to them leaving the plant continues to be a major focal point within the automotive industry. Automotive assembly is a highly complex assembly process that requires significant manual assembly content as current automation is not yet capable of handling the complexity and number or parts and variation of a modern vehicle. Work by Vineyard and Meredith [1] shows that up to 40% of all total defects in a manufacturing plant are caused by humans. With the understanding of the required high levels of manual assembly content and highly complex products, it can be seen how important quality inspection and subsequent rework are to the vehicle assembly process. With large, highly complex assemblies, rework can involve a significant portion of the overall production time as previously assembly components must be removed to reach a defect as simple as a missed electrical connection. The rework process may involve removing seats, carpeting, mounting assemblies, and interior panels. All of which may be damaged by the rework

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process adding additional cost to the vehicle manufacturing process. From this understanding of the assembly and rework process, a better understanding of the interaction and feedback process between the automotive assembly associate and process is needed to allow improved design for future vehicle components, processes, and tools.

It can be seen that a real time measurement and detection system receiving data from the hand of an associate could provide feedback and notification to alert an associate to either a defective or unsuccessful electrical connection prior to the assembly leaving the workstation could reduce the impact of assembly defects. The work herein involves the measurement of finger contact location and engagement to provide an understanding of the human-process interaction for automotive assembly electrical connection processes. It can be shown that the engagement area of a worker's fingers for an electrical connection differ from those used to install vehicle seating. This work is a part of an overall larger work building upon human activity recognition by evaluating human-process interaction recognition using wearable sensors and feedback systems. As with human activity recognition, multiple sensors are being used to provide higher confidence in the predicted assembly activity.

To measure the specific engagement area, a pressure sensitive film was cut and affixed to the bare hand of a novice worker prior to completing an electrical connection process. The knowledge of specific areas used will enable future efforts in sensing of human-process assembly interaction to target key areas of the hand.

To measure the finger engagement of manual assembly tasks, a nitrile dipped standard work glove was affixed with flexible fingertip force sensors made from layered conductive fabric and piezoresistive material. The fingertip was chosen for this initial work as the sensor material and adhesive was selected. A focus on not hindering the worker's tactile feel or causing discomfort was prioritized to allow for dexterous tasks to be carried out with small electrical connectors. The layers were joined together by a heat-activated adhesive, and a signal conditioning and amplification circuit was used for each individual sensor to measure the resistance change of the piezoresistive material. As this work was interested in contact force location and overall finger engagement, the specific calibration and repeatability of the sensors were able to be wider than comparable past literature where the target was ergonomic evaluation. For testing, novice associates wearing the gloves carried out electrical connection over a range of connection sizes

2. Background

Sensing human grip strength and object interaction has previously been investigated by Koiva et al. [2], who designed and tested a machine to measure forces generated by fingers. Their work demonstrated a typical range of 13-16 newton (N) for average finger force exertion and 20 N for average thumb force exertion. A variety of activities, including assembling, painting, labeling, fastening, and welding, were investigated by Lee and Jung [3], [4] by filming hand postures and object properties. Their work described a preference for grasping postures where the palm is in contact with the object for cylindrical objects and a picking posture where the palm is not in contact with the object for rectangular or sheet type objects. Lee and Jung continued to define different types of grasping actions based on the fingers used and palm contact and described that the grasping posture used is related to the shape, size, and orientation of the object to be grasped. In much existing work, the primary goals were to either measure hand forces or hand postures for ergonomic analysis.

2.1. Non-commercial Sensors

Sensors used in existing literature primarily use two types of force sensors for in-situ measurement, Micro-Electro-Mechanical Systems (MEMS) force sensor or piezoresistive fabric/elastomers. Tognetti *et al.* [5] described an application for tracking hand movements with a conductive elastomer layered sensor glove. The piezoresistive properties of the conductive elastomer located on the back of the hand were used in a manner similar to strain sensors with the goal to track hand movement and posture and not force exerted. Sato *et al.* [6] measured handgrip forces using a glove made from sewn electrode wire into pressure-sensitive conductive rubber and leather to determine the distribution of grip force and hand position. Wang *et al.* [7] utilized carbon nanotube filled silicon-rubber composite as the piezoresistive material with a fringe electrode up to 8 mm away from the actual sensing area, enabling the sensing area to remain uncovered thereby reducing the overall thickness required. Flexible printed circuit boards were used by Sagisaka *et al.* [8] to sense hand forces through thin, branched modules to create tactile sensors. Their work aimed to incorporate flexibility around joints and skin wrinkles during sensing and ensure hand mobility was not impacted. This was achieved by spraying the inner layer of a glove with silicone elastomer and polyurethane to create approximately 1000 taxels, individual sensor points in the overall sensor matrix, per hand.

Work by Nikonovas *et al.* [9] used Force Sensing Resistors (FSRs) affixed to a glove to sense hand forces and examined the swinging of a golf club and validated against the traditional method of instrumenting the object, in this case, the golf club handle, rather than the hand. FSR's were used by Lee *et al*. [10] to measure grip forces exerted on cylindrical handles varying from 50-75 mm in diameter. They observed that for the same weight of object, the grip force exerted to hold the object for smaller diameter objects was the same as that of larger objects.

MEMS force sensors were used in work by Kalra *et al.* [11] and mounted on the objects to be gripped, and the work targeted to understand the hand to handle interface forces exerted during operation of power tools. Kalra *et al.* examined the feasibility of using low-cost MEMS sensors in the measurement of grip forces on a vibrating power tool and concluded that sensors which were applied symmetrically around the central axis of the tool provided a good estimate of the grip force and that the vibration of the tool had a negligible impact sensitivity of the sensor.

Piezoresistive fabric, similar to FSR, was used by Harris [12], who described the use of two layers of piezoresistive fabric sewn together using a cross pattern of conductive thread to create a grid on the two layers with the intersection points. Atalay *et al.* [13] measured hand interaction forces using capacitive force sensors composed of fabric electrodes with silicone elastomer as the dielectric. The sensors were manufactured as a sheet before being cut into the required shape so as to provide a more consistent baseline capacitance value and improve the manufacturability of individual sensors. Day *et al.* [14] described a tactile sensor grid from piezoresistive fabric material and fabric electrodes. The array design was accomplished by using two pieces of spandex along with conductive fabric strips glued with iron-on adhesive. The two conductive fabric strips orientation was perpendicular to one another, and the piezoresistive fabric was inserted between the two strips. The aim of the work was to create tactile sensing skin for soft robots. Eeonyx fabric, a piezoresistive fabric, was used by Büscher *et al.* [15] to develop a force-sensing glove with conductive fabric as electrodes and a spacer mesh to increase the idle resistance. The conductive fabric had the conductive material removed through etching at a specific location to create a pattern of 54 taxels or tactile pixels that spanned the fingers and palm. The matrix of taxels was sewn onto a glove, and a thin 1.5mm rubber coating was applied to protect the sensors and provide a better tactile feel. The resulting glove was used to examine grasping and manipulation tasks performed by humans to enable a future skin layer for robotics.

2.2. Commercially Available Sensors

In previous studies involving skin contact pressure, commercial sensing methods include Fujifilm Prescale and Tekscan pressure mapping sensors. Fujifilm Prescale has been widely used in bioengineering research studies involving contact forces, areas, and pressures [16]–[20]. Fujifilm Prescale is a pressure-sensitive film consisting, at the lower pressure range, of two sheets of the polyester base material. One coated in micro-encapsulated color-forming material and the other with a layer of color-developing material [21]. As pressure is applied to the material, the bubbles of color-forming material burst and the color-developing material is stained, which becomes darker and denser as more of the material is burst. The mechanism of the color change is not reversible; therefore, the film will only illustrate peak force values, and the film cannot be reused. Fujifilm Prescale has historically shown 10-25% measurement error [16], [17], [22].

To acquire real-time hand pressure data, Tekscan pressure mapping systems have been used in place of Fujifilm material. Unlike the Fujifilm material, which permanently bursts under load, the Tekscan sensor consists of rows and columns of piezoresistive material and a connected hardware data logger, which measures a change in electrical resistance at each row-column intersection (sensel) and can typically be reused. Previous studies have shown that the Tekscan system has a lower measurement error depending on the contact interface materials, 4-20% [22]–[24].

The surveyed works primarily were aimed at ergonomic or robotics research for measuring grip strength or posture of the hand. The work herein builds upon previous research by extending wearable force sensors to human process-interaction recognition by first understanding the finger engagement and contact forces of manual assembly tasks such as the example in this work of automotive electrical connections with the future goal to facilitate future development of hand wearable devices and sensing systems.

3. Methodology

3.1. Finger engagement

Piezoresistive fabrics and MEMS force sensors were investigated for this work due to their prevalence in past literature and inclusion in research and commercial systems. After early investigation, the MEMS sensors were not continued primarily due to their increased thickness being an impediment to the tactile feel and dexterity of the worker during manual assembly processes, which can include small parts. The hardness and limited flexibility of commercially available MEMS sensors were additionally found to negatively impact the tactile feel and dexterity of the worker and were found to be better suited to mounting on the physical object to be grasped which can also be seen in previous literature. A loss in dexterity by the wearer was undesirable as small and complex assembly components require touch sensitivity, including during low visibility or occluded assembly operations where the worker must use touch alone to locate assembly features that enable the completion of the assembly task.

The thin and flexible piezoresistive fabric was used to measure hand interaction forces in this work with the research by Büscher *et al.* [15] providing an influencing reference for the sensor makeup and construction as they had similar goals for the sensor usage while their objective and scope of resulting sensor varied.

Two thin and flexible piezoresistive materials were investigated in this work based on previous literature and being commercially available at the time. These included Eeontex piezoresistive fabric by Eeonyx and Velostat, manufactured by Desco Industries. Velostat, a carbon black impregnated polyolefin material has a surface resistivity of approximately 31 kohm/sq. cm. Eeontex has a conductive coating applied to a nylon-spandex blend material (72%-28%, respectively). Through testing, it was found that the Eeontex fabric had a better resistance range and durability.

Design and layering from previous literature and new design were evaluated and tested in a simulated production environment at the Clemson Vehicle Assembly Center to examine the shape and use of spacing materials, non-conductive vs. conductive thread, conductive fabrics, and the number and shape of layers. Future work is planned to present the design and evaluation of examined sensors and shapes is in progress. A three-layer design was chosen that included a layer of piezoresistive material sandwiched between the conductive material and was found to be both durable and simple to manufacture while providing a good output signal.

The electrodes to carry the signal were chosen between the conductive thread, knitted conductive fabric, and woven conductive fabric. The stainless-steel conductive thread was not selected as it tended to have noticeably varying contact with the piezoresistive fabric as the sensor was stretched and flexed and a noticeable physical seam that resulted in discomfort by the wearer. The knitted conductive fabric had an increased thickness when compared to a similar woven fabric but was functionally similar otherwise. The woven conductive fabric was selected as the electrode as it minimized the thickness of the conductive layers while not creating noticeable seams to the wearer by creating a smoother transition from sensed to non-sensed area, which improved the tactile feel of the resulting sensor.

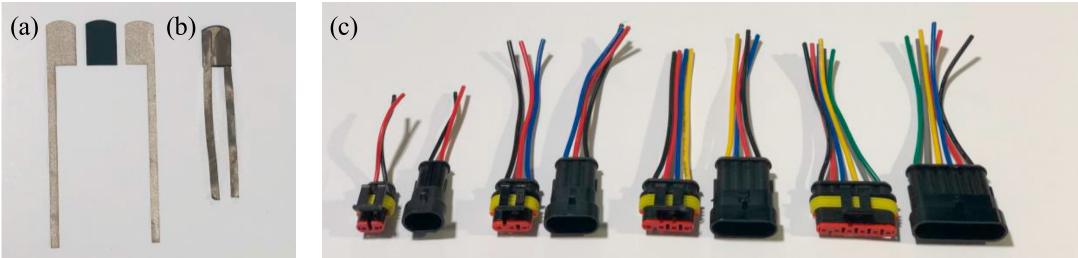

Fig. 1. (a) Unassembled layers; (b) assembled layers; (c) electrical connectors used for testing

Similar to previous works, the sensor layers were joined together with a non-conductive heat-activated adhesive applied along the edges of the sensor outline, which added limited stiffness and thickness to the resulting sensor. Future work continues to investigate alternative adhesives that provide additional peel resistance as this was found to be a cause or failure after prolonged usage but was found to have the required strength and had a limited effect on the piezoresistive properties of the sensor fabric during stretching and flexing of the fingers from a fist to open hand posture. Silver conductive epoxy was used to adhere to the leads from the individual sensors to the measurement circuit.

A nitrile dipped glove was used as a template for the outline sizes of the sensors to enable the sensors to be affixed to the exterior of the glove for hygiene purposes. The electrode layers of conductive fabric were cut marginally smaller than the piezoresistive layer to minimize the chance of the two conductive layers touching and shorting the sensor and 5mm wide fabric leads were included to allow for the electrodes to connect to the measurement circuit away from the fingers and can be seen in Figure 1.

All layers were cut using a CNC laser and allowed for precise, repeatable sensor outlines to be attained. This was required due to the flexible nature of the piezoresistive fabric being difficult to cut without producing a dedicated cutter in the desired pattern or variation in hand cutting resulting in a non-uniform sensor outline.

Characteristic simulant samples of electrical connections used in automotive assembly were used for testing the resulting sensor glove. These included commercially available 2-pin, 3-pin, 4-pin, and 6-pin connectors representing an increasing size of a connector with single rows of pins and a single locking latch mechanism. The connectors included pins, wires, and weather-resistant layers. Each wearer wore a pair of sensor gloves and was presented the required connections while sitting at a table. Future efforts will move the assembly process to a production vehicle and include more ergonomically challenging and occluded view assembly scenarios.

Five replications per size of connector per wearer were completed to characterize the resulting finger engagement output from the sensor glove. The connectors chosen can be seen in Figure 1 and had no connection to additional cabling past a short lead. The sensors were connected to an amplification circuit and output data was measured at a frequency of 250 Hz by a connected microcontroller. Video recording of the testing process was used to verify the finger engagement during testing as the sensor did not cover the entire length of the finger, which had the possibility to not record an engagement that did not take place in a sensed area.

(a)
(b)

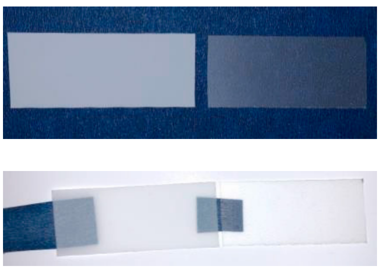

Fig. 2. (a) Cut Fujifilm Prescale material; (b) material ready to be applied to finger

3.2. Force location

The Fujifilm Prescale Ultra Low (0.19-0.58 MPa) material was selected to measure the contact force location during manual assembly tasks primarily due to lower cost of sensing material, speed of application of the sensing material, and lack of requiring the assembly associate to wear a data collection system on each arm potentially interfering with the assembly process during future planned lineside trials. It should be noted that the reduced application time of the sensors was partially negated by the Prescale material only lasting approximately three replications before needing to be replaced in addition to only the peak force being measurable. For the purpose of the experiment in measuring the contact area during assembly processes, it was determined that the peak force in the Prescale material would be sufficient to determine the area and level of force that was applied to the associate's hand.

The characteristic electrical connector chosen for evaluation was the 6-pin connector and presented in the same manner as in the prior finger engagement testing. The larger connector was chosen in this initial investigation as a proof of concept for the determination of the contact area as it was found to have a noticeable force on the associate's fingers. The Prescale material is delivered in sheet roll form and was carefully cut into 15mm wide and 38mm long rectangles to best cover the test associate's fingers and thumb while still allowing the wearer to move freely, as seen in Fig. 2 above. In this initial exploration of using the material for force location determination, only the top 2/3 of the associate's fingers and the top half of the thumb was covered in Prescale material and affixed using blue tape that was able to be applied and removed without bursting the material. Care had to be taken during application and after testing was complete to avoid bursting the material.

4. Results

4.1. Finger engagement

The output from the sensor glove was normalized from 0 to 100, with zero being no resistance change and 100 being the maximum output resistance change as measured per participant. An output plot can be found in Figure 3 and illustrates the output per finger for a single participant. It can be seen from the plot that the thumb and index finger were primarily used during the connection process of five subsequent 2-pin connections. This agrees with the hypothesis of finger engagement varying based on the physical characteristics of the connector, in this case, size.

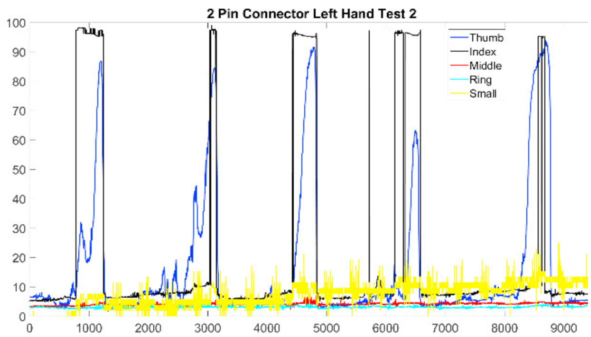

Fig. 3. Left hand raw sensor output

A finger was determined to be engaged when the force signal achieved 20% or higher of the maximum value during the connection. The engagement was further verified by using the video recording of non-occluded finger interaction. In limited instances, the non-sensed side of the finger was used by participants rather than the sensed area and was found through the video recording when sensor output did not match with the other participants. This demonstrates the importance of the video recording but also the importance of an understanding of hand contact location during manual assembly processes for future sensor design. Future work will include varying the size and shape of the sensed area to cover the active areas of the hand during manual assembly.

Average finger engagement was plotted in Figure 4 and illustrates the predicted trend of increasing finger engagement with an increase in the size of the connector with the thumb and index finger used in all size connections.

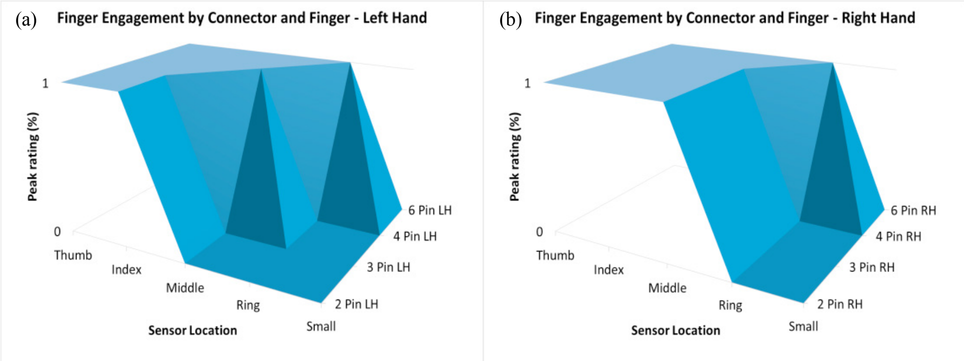

Fig. 4. (a) Left hand finger engagement by connector; (b) Right hand finger engagement by connector

It was also seen that the user's dominant hand fingers became involved prior to the same fingers on the non-dominant hand and is seen in Figure 4, with all included wearers being right hand dominant. Future work will need to consider and evaluate hand dominance to better account for natural variation in a learning model with the overall goal of human-process interaction recognition. The ring and small finger prior to the larger connections.

4.2. Force location

The Prescale material after one connection can be seen in Figure 5 on the associate's hand and laid out in Figure 6. After one connection, the material was removed from the associate's hand, the remaining encapsulated sheet was discarded, and the remaining sheet was mounted on poster board to complete developing for 30 minutes. From

Fig. 5. Left hand post-test contact area

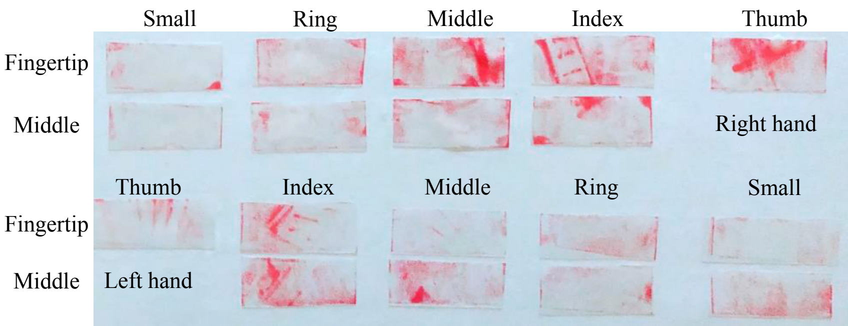

Fig. 6. Left hand mounted post-test contact area, one connection completed

Figure 6, the outline of the major features of the electrical connector are clearly visible. By analyzing the total colored area of each finger, it can be seen that the right hand appeared to have a firmer grasp on the connector than the left hand, which corresponds to the results from the previous finger activation results. It should be noted that all of the participants in this work identified as right-hand dominant, hence favoring the right-hand during tasks was expected. Each finger segment was broken down into three sub-segments, left, center, and right, to correspond to the fingertip and the two sides of each finger. An example of the same is shown in Figure 7, which shows the sub-segments of the right fingertip area of the index.

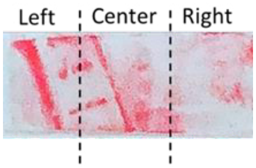

Fig. 7. Subsegments for a given region of interest

From each finger segment on the right hand, the central fingertip area of the thumb, the left fingertip area of the index, and the right fingertip area of the middle were favored during this testing. On the left hand, it appears that the index finger was primarily favored. However, during a review of the test on video, it can be seen that the associate did not use the sensed area of the thumb to apply pressure. Future improvements to increase the sensed area are planned and include altering the shape of the cut material to better accommodate the more complex curves of the thumb and fingertip.

In Figure 8, the same 6-pin connector was used and connected three times by the associate after having the Prescale material replaced. From this figure, it can be seen that the sensed area of the left hand was used more heavily but was lighter in color than the right hand, indicating a lower force was applied at the left-hand contact areas. On the right hand, the thumb center and left, the index fingertip center and left, and the middle fingertip center and right areas were indicated. This can be seen as similar to the indication in Figure 6 but with the additional variation of the associate grasping the connector with some variation in each of the three runs. On the left hand, the thumb center, index fingertip center and middle center, and middle fingertip left and center was indicated. In both hands, the amount of lightly indicated area was increased over the single connection indicators. This was due to the additional flexing that occurred during the longer three trial run than in the single trial. Similarly, the edges of the three trial run were more heavily indicated, but this was seen as an effect of the affixing/removal process and increased flexing of the material during the trials. Overall, the preliminary results in using Fujifilm Prescale material for measuring contact area were promising and corresponded well with the finger engagement tests and video review of finger engagement and enabled the recording of visually occluded and side contact forces.

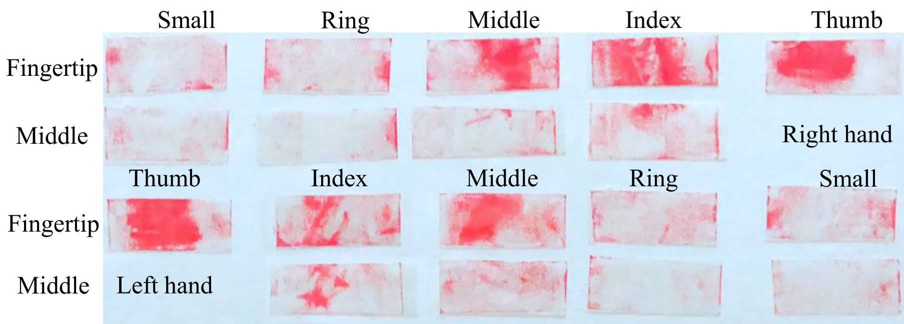

Fig. 8. Left hand mounted post-test contact area, three connections completed

5. Conclusion

Aural feedback from automotive electrical connections typically in the form of a click when the connection has been made successfully is the primary method of informing a worker that a connection has been made successfully. However, due to the loud and highly variable nature of background noise on the assembly floor and differences in worker hearing ability, an incomplete connection or missed hearing of the connection have the chance to cause defects to occur as the worker assumes that they heard correct engagement feedback. Thus, analyzing the hand-process interaction will enable a better understanding of manual assembly processes and in designing wearable process measurement sensor devices.

This work tested a sensor glove for manual automotive assembly tasks and method which measured associate finger engagement interaction and contact force location of a manual electrical connector assembly task. From the presented results, it can be seen that as expected, the index finger and thumb were used very consistently. The middle finger was activated in smaller connectors for the right hand earlier than the left hand which was the non-dominant hand of the users. It was found from video recordings that the side surface of the fingertip was used instead of the center in a number of instances which led to missed finger interactions in the sensor signal.

Fujifilm Prescale material was affixed to a novice associate's hands, and then a connection process was completed once and then three times with separate material. The results agreed with the flexible force sensor and video review while also allowing the recording of the peak force and contact area of areas that were otherwise not sensed, in the case of the flexible force sensor, or occluded, in the case of the video recording.

Continued work for the flexible force sensor will expand the sensed area and incorporate the sides of the fingertips to better prevent missed engagement. Continued work with the Fujifilm Prescale material will improve the coverage of the sensed area of the fingers and expand the number and types of connections. An automated analysis tool is being created to facilitate a more repeatable determination of contact area and peak force reading that will allow for the creation of a contact area fingerprint for each electrical connection type. Novice and experienced assembly associates will be asked to participate in the work so that the variation in finger engagement, contact area, force, and duration of force during manual assembly tasks for both novice and experienced workers can be better understood and applied to future manual assembly human-process interaction modeling.

Future efforts to increase the number, types, complexity, and presentation of connection processes will provide a signature library of finger engagement profiles of varied manual automotive assembly tasks to better understand the human-process interaction and influence the development of future wearable hand-based worker assistance systems. Through the incorporation of additional sensing modalities, these future systems could be used to model the human-process interaction recognition and feedback system and readily assist users on the factory floor.

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