Technical Analysis for Electro-Sensory 3D Foot Scanning in a Shoe

Denys J.C. Matthies
Technical University of Applied Sciences Lübeck
Lübeck, Germany
Fraunhofer IMTE Lübeck
Lübeck, Germany
denys.matthies@th-luebeck.de

Maximilian Kasbohm
Ilmenau University of Technology
Ilmenau, Germany
Fraunhofer IGD Rostock
Rostock, Germany
maximilian.kasbohm@tu-ilmenau.de

Gerald Bieber
Fraunhofer IGD Rostock
Rostock, Germany
gerald.bieber@igd-r.fraunhofer.de

Troy Nachtigall
Eindhoven University of Technology
Eindhoven, Netherlands
Amsterdam University of Applied Sciences
Amsterdam, Netherlands
t.r.nachtigall@hva.nl

Figure 1: The process of building a 3D foot scanning shoe begins with preparing materials and design templates (a) and progresses to creating a transparent mold (b) for precise shaping. The inner lining (c) is integrated with conductive elements, ensuring both comfort and functionality. Conductive ink electrodes are then embedded onto the shoe's lining in specific patterns (d) to enable advanced sensing capabilities. Finally, the fully assembled shoe (e) combines ergonomic design with innovative sensing technology, resulting in a wearable prototype.

Abstract

This paper explores the application of electro-sensory technologies for three-dimensional foot scanning within a shoe. This research investigates resistive and capacitive sensor technologies, assessing their suitability for identifying foot pressure points, ensuring ergonomic fit, and indicating shoe wear status. Experimental findings support the potential for integrating advanced sensory systems into footwear, providing significant benefits in preventing foot injuries and improving patient outcomes, particularly for individuals with conditions like diabetes mellitus and peripheral arterial disease.

CCS Concepts

• **Applied computing** → **Life and medical sciences**; *Electronics*; • **Hardware** → *Hardware validation.*

PETRA '25, Corfu Island, Greece

ACM ISBN 979-8-4007-1402-3/25/06
https://doi.org/10.1145/3733155.3733210

Keywords

Electro-sensory technology, 3D foot scanning, ergonomic footwear, pressure sensors, diabetic foot syndrome

ACM Reference Format:
Denys J.C. Matthies, Maximilian Kasbohm, Gerald Bieber, and Troy Nachtigall. 2025. Technical Analysis for Electro-Sensory 3D Foot Scanning in a Shoe. In *The PErvasive Technologies Related to Assistive Environments (PETRA '25), June 25–27, 2025, Corfu Island, Greece.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3733155.3733210

1 Introduction

Foot health is essential for overall well-being, yet the feet are subject to constant stress, leading to issues such as deformation, injury, and complications from conditions like diabetes mellitus and peripheral arterial disease. There are approximately 540 million people worldwide [12] diagnosed with diabetes, 7 million of which were in Germany alone [19]. Compared to 1980, this corresponds to a doubling of the number of people affected. This trend continues, particularly in industrialized countries, so that a decline in the number of cases is not to be expected. Diabetes is a metabolic disease in which the pancreas is unable to produce enough insulin, or the body is unable to use the insulin produced. This means that the body can no longer reliably control its own blood sugar levels [29]. This particularly results in a damage to the nerves (neuropathy) and the arterial vessels (peripheral arterial occlusive disease, PAD), leading to less sensation in feet. This is also called Diabetic Foot syndrome (DFS). The term DFS summarizes foot complications that lead to infection and tissue death (ulcer) [6]. Therefore, it is important to identify when the foot rubs to hard at the shoe wall. Addressing this challenge necessitates the development of ergonomic footwear tailored to individual needs. However, existing technologies for foot assessment, such as foam impressions and external 3D models, are limited in their ability to provide real-time, in-shoe pressure analysis.

The significance of foot interfaces in technology dates back to the world's first wearable computer—an instrumented shoe with a toe-operated switch designed to communicate casino roulette outcomes [38]. Since then, foot interfaces have evolved significantly, transitioning from basic input devices, such as Engelbart's "Mole," an alternative to the mouse [11], to advanced systems leveraging ubiquitous computing and miniaturized electronics [30].

Commercial innovations such as smart-shoes and insoles have penetrated the market, focusing on gait analysis, step counting [34], fall detection [3], and ulcer prevention [36]. Meanwhile, research has expanded the capabilities of foot interfaces to detect gait [17, 22], body posture [9, 33], terrain [26], stress [10], and leg length discrepancies [25]. Actuation technologies such as vibrotactile feedback and electrical muscle stimulation (EMS) [39] have further broadened applications to include tactile augmented reality [42], navigation [27], rehabilitation [43], and virtual reality [37].

The integration of biomechanical and sensory capabilities with advanced sensing and feedback systems has transitioned foot interfaces toward foot augmentations, which can enhance human abilities [8]. By leveraging the unique properties of the feet, such as their stable contact with surfaces and ample space for embedding sensors, foot augmentations offer opportunities to influence posture, balance, and overall locomotion in ways distinct from augmenting other body parts.

Despite the growing body of research [32] and commercial developments, most foot interfaces remain focused on narrow applications, leaving broader opportunities in human augmentation unexplored [8]. This paper addresses these gaps by presenting a novel approach to 3D foot scanning within a shoe, leveraging electro-sensory technologies to measure foot position dynamically. By integrating resistive and capacitive sensor systems, this research aims to set a foundation for future advancements in ergonomic footwear and broader human augmentation applications.

2 Related Work

2.1 Historical Evolution of Foot Interfaces to Future Foot Augmentation

From the first wearable computer [38] to modern wearable interfaces, foot interfaces have undergone a significant evolution. Early designs focused on foot-operated input devices for computers, such as Engelbart's experiments with alternatives to the mouse [11]. As technology advanced, wearable foot interfaces became more compact and capable, leading to innovations in smart-shoes and insoles for activity tracking [7], fall detection [3], and health monitoring [36].

The integration of foot biomechanics with sensory technologies has enabled foot augmentations to enhance human capabilities [8]. Feet, being in constant contact with stable surfaces and offering ample space for embedding sensors, provide unique opportunities to influence locomotion, balance, and posture. However, most developments remain confined to specific applications, underscoring the need for broader, multi-functional systems [41].

Despite the steady growth in research and commercial outputs [8], a unified research agenda is essential to unlock the full potential of foot augmentations. This study contributes by setting a foundation for future advancements in 3D in-shoe scanning and its integration into ergonomic and augmentative systems.

2.2 Sensing Foot Position

The common method for dynamically analyzing the plantar position of the foot are pressure plates. They consist of a matrix of pressure sensors that record, process, and combine data to create detailed pressure distribution maps, enabling the detection of misalignments and the design of supportive insoles [24]. Optical systems, such as video recording, can supplement this by analyzing gait and identifying irregularities linked to health issues, but they lack objectivity without additional data collection. Stationary camera sensing has been previously explored [2, 35]. Gulgin et al. [16] used small markers on shoes to model foot movements precisely, but such systems are labor-intensive and often distorted by unnatural walking conditions in laboratory settings.

To address these limitations, various wearable systems have been developed to measure plantar pressure and gait using sensors embedded in or on shoes. For example, Nguyen et al. used laser scanners to map the environment in 3D [28], while Bauer et al. [5] and Konttila et al. [21] employed hydro and air-filled cells in shoe soles for pressure or weight measurement. These systems, while functional, are often too large for practical use. Piezoelectric sensors offer a compact alternative, as seen in Lin et al.'s lightweight smart insoles that detect activities like walking or stair climbing and identify gait abnormalities [23]. However, these sensors are prone to drift during prolonged measurements and are less suitable for static analysis. Hausdorff et al. [18] addressed this by combining piezoresistive and resistive sensors to analyze gait phases and cadence.

Earlier studies, such as those by Kljajic and Krajnik [20], used strain gauges to measure pressure on the foot. While effective, these prototypes were bulky and impractical, weighing 600g per shoe. Although strain gauges have since become more compact and accurate, modern systems primarily rely on resistive and capacitive sensors embedded in insoles or socks for precise static and dynamic gait analysis [13, 14, 23, 40].

2.3 Other Applications with Novel Wearable Foot Interfaces

2.3.1 Sensing Technologies. Research has expanded the utility of foot interfaces to enable diverse sensing capabilities, such as for gait analysis like CapWalk, a research that analyzes foot pressure patterns to identify gait dynamics [17]. Further, researchers explored sensing posture and balance, such as proposed in GymSoles that assesses body posture and balance using embedded sensors [9].

Table 1: Evaluated compositions of conductive ink/paste. *Sample 5 was recreated followed by Phillips et al. [31].

	Mixture			Test Results			
Sample	**Copper powder (weight in %)**	**Swellable resin powder (weight in %)**	**Organic carrier substance (weight in %)**	**Crack formation**	**Chipping of the ceramic**	**Metallizability**	**Solderability**
1	85	0 (–)	15	Yes	No	Sufficient	Sufficient
2	85	0.5 (Urethan)	14.5	Yes	No	Sufficient	Sufficient
3	80	1 (Urethan)	19	No	No	Sufficient	Sufficient
4	85	5 (Urethan)	10	No	No	Sufficient	Sufficient
5	85	5 (Acryl*)	10	No	No	Sufficient	Sufficient
6	94	1 (Urethan)	5	No	No	Sufficient	Sufficient
7	90	5 (Urethan)	5	No	No	Sufficient	Sufficient
8	80	10 (Urethan)	10	No	No	Sufficient	Sufficient
9	80	15 (Urethan)	5	Yes (Cavity)	No	Insufficient	Insufficient
10	95	1 (Urethan)	4	The formation of the paste is not possible in this composition			
11	75	10 (Urethan)	15	Yes (Cavity)	No	Average	Average

Another sensing capability includes detecting terrain and stress. Here, the work entitled CapSoles identifies surface types with high accuracy [26], while StressFoot monitors acute stress levels [10]. The vast majority, however, regards medical applications. Those systems aid in detecting leg-length discrepancies [25], with additional capabilities for rehabilitation [43].

2.3.2 Actuation and Feedback Technologies. Foot interfaces not just provide detection capabilities, but also actuation, which leverage modalities such as Vibrotactile Feedback. It is commonly used for navigation and tactile augmented reality [27, 42]. Another actuation technology includes Electrical Muscle Stimulation (EMS), which enables kinesthetic feedback for training and performance enhancement [39]. These technologies have expanded foot interfaces beyond real-world rehabilitation applications [1], such as to virtual reality applications [37] .

3 Implementation

3.1 Materials Selection

To achieve the research objectives, the selection of sensor materials and electrode designs was guided by key criteria: accuracy, compactness, durability, and ease of integration into shoes. The materials were chosen based on their performance in previous studies and adaptability to the experimental setup.

3.1.1 Copper Tape. Copper was selected for its excellent electrical conductivity and adaptability. It can be formed into thin films (<1 mm) to ensure flexibility and minimal interference with shoe dynamics (*see figure 5a*). The material was cut into small, foot-contour-specific shapes to serve as electrodes for both resistive and capacitive sensors.

3.1.2 Conductive Textiles. The material we used is Zebra Fabric (HITEK) and EeonTex fabric were chosen for their flexibility, durability, and consistent electrical properties (*see figure 5b*). These fabrics offer low resistance (20 kΩ/cm²) and are easily embedded into shoe interiors without compromising comfort. The predefined size and pattern of the conductive pathways restricted customizability, necessitating careful alignment during the experimental phase.

3.1.3 Conductive Paint. Utilizing conductive paint shows great versatility, such as for forming custom electrodes on shoe materials, adhering well to curved or irregular areas (*see figure 5c*). We investigated 11 different mixtures for conductive paint - see table 1. We found that excessive application led to cracking, which was addressed by applying thin, even layers. Conductive ink, made from ink and graphite or copper powder, is inexpensive and simple to produce, often used by beginners with microcontrollers like Arduino to create basic circuits. While this ink can work on materials like paper, its application on felt or similar fabrics for shoe electrodes proved unsuccessful due to poor adhesion and wear resistance. Adding adhesive to improve durability to make it suitable for wearable applications. The created compound must withstand certain impacts and must be somewhat flexible be suitable for our footwear application. While sample 3 to 8 seem to work fine, we finally decided to use Bare Conductive Electric Paint as it seemed slightly more conductive.

3.2 Capacitive Sensing

We evaluated two technologies to determine their suitability for 3D pressure sensing in shoes.

3.2.1 Arduino CapSense Library. We utilized the CapSense library by Paul Badger [4] as it is the most simple and modular design. We simply require a microcontroller board, such as the Arduino micro, bluetooth modem and a battery (*see Figure 2*).

In order to ultimately determine which pull-up resistor is most suitable for this measurement, each of the three sensitivity levels was tested with the three previously mentioned scenarios of rest, touch and pressure and the respective values were recorded. This was done separately for each electrode material.

Table 2: Summary of the advantages and limitations of the material selected.

	Advantages	Limitations
Copper Tape	Great conductivity, Electrode shape can be cut to size, Lots of experience (smart soles)	Flexible in one direction only
Zebra Fabric	Great conductivity, Highly flexible, Can be incorporated directly into the shoe	Electrode shape determined, High Costs
Conductive Paint	Great conductivity, Electrode shape and size can be individually adjusted	Limited flexibility for thick layers

Low sensitivity:

- The sensor reacts at a distance of 0mm between the finger and the electrode
- Electrode covered with Eeontex fabric to avoid direct contact
- 820kΩ Resistor

This corresponds to the case where the electrode is attached to the inside of the inner leather and is only separated from the foot by a very thin layer, e.g. socks.

Medium sensitivity:

- The sensor reacts at a distance of 4mm
- This distance corresponds to the thickness of the usual inner lining
- 1MΩ Resistor

This corresponds to the case where the electrodes are inserted between the inner and outer leather of the shoe and thus the inner leather (d = 4mm) separates the electrodes from the foot.

High sensitivity:

- The resistance was chosen so that the sensor reacts significantly at a distance of 1cm between the finger and the electrode.
- 5MΩ Resistor

The electrodes are located between 4mm and 1cm from the foot (e.g. on the outside of the shoe or in the sole of the shoe).

3.2.2 OpenCapSense: Another rapid prototyping tool that provides stable measurements without requiring external resistors is the OpenCapSense toolkit [15].

Here too, one electrode is required for each measuring point. However, this is not connected directly to an Arduino, but to a port on the OpenCapSense board (*see Figure 3*). This charges and discharges the electrode and determines the time constant t. The measurement result is then transferred to an Arduino, which in turn forwards it to the computer via Bluetooth, where it is saved in a table. The advantage of the OpenCapSense technology in this case is the even more compact design. Far fewer cables are required, but also no separate series resistors. These are already attached to the board and the software is specially adapted to them. The division into the different sensitivity levels is not necessary here. Here too, each electrode type was tested with the three scenarios of rest, touch and pressure and the values were recorded for post-processing comparison.

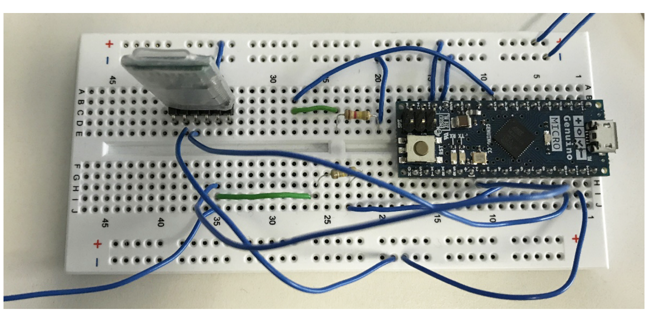

Figure 2: Showing the Arduino CapSense setup with the bluetooth module

3.3 Resistive Sensing

One of the biggest differences between the two capacitive sensors and the resistive technology is that two electrodes are required for the measurement, which are separated from each other by a dielectric (see Figure 4). Measures changes in electrical resistance caused by deformation of the electrodes and the intervening dielectric material. Pairs of electrodes separated by EeonTex fabric were used to create a pressure-sensitive area. The electrodes are connected to a pin on the Arduino, one of which is the transmit pin and the other the receive pin. In this experiment, the area of the respective electrodes is 1*1cm due to the overlap of the 1cm wide strips rotated 90 degrees to each other. The Eeontex fabric from the HITEK Fabric Evaluation Kit is used as the dielectric, as it is very flexible, stretchable, but also easy to compress and has a resistance of 20kΩ/cm² between the top and bottom surfaces across the entire surface. While the capacitance is calculated as follows,

$$C = \epsilon_0 \epsilon_r \frac{A}{d}$$

, here ϵ_0, ϵ_r and A are constant, d is changed during the measurement. If pressure is now applied to the electrodes, the dielectric is compressed, which reduces the distance d between the electrodes. This reduces the capacitance of the capacitor. This change is sent to the Arduino via the receiver pin and is also output as a unitless value

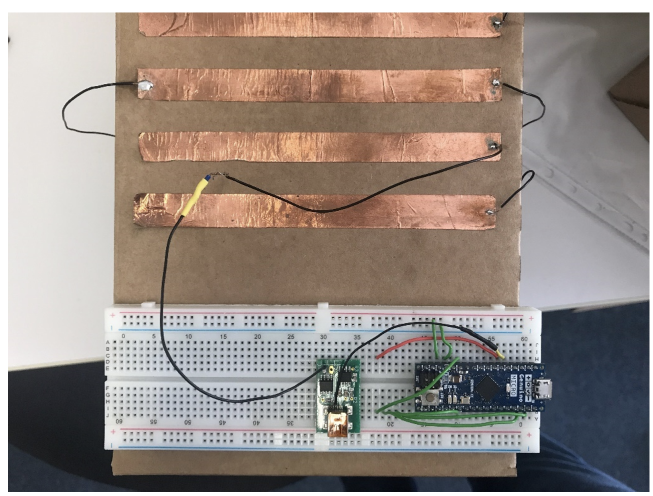

Figure 3: Showing the OpenCapSense Loading Mode Sensor

Figure 4: Showing resistive Sensing setup for copper electrodes. A black velostat material is the buffer layer that is permeable and changes the conductivity at pressure.

between 0 and 1023. A 10kΩ resistor is generally recommended as a series resistor, although resistors of 1kΩ and 5kΩ are also recommended for measurements with lower sensitivity. In order to determine the most suitable resistance for the intended use in a shoe, each measurement was carried out with each of the three resistors. Due to the electrode design, a pressure measurement is only possible on the 1cm² overlap area. Here, too, the three scenarios of rest, touch and pressure were measured. These measurements were carried out three times in total, each time with a different series resistor.

3.4 Experimental Setup

3.4.1 Apparatus. Before integrating the electrodes into a shoe prototype, with placements on the sole, sides, and top to capture comprehensive 3D pressure distributions, we ran an evaluation on a 2D surface (*see figure 5*) identifying the properties of our electrodes and sensing technologies.

In order to compare the electrodes under different sensing conditions, we made them have same dimensions and applied to a material that was electrically well-insulated. Wires connect the electrodes to the microcontroller.

The width of the electrodes was determined by the Zebra Fabric from the evaluation kit, as, unlike the other two materials, this cannot be customized as easily. Its conductive strips are 1cm wide, 15cm long and are 1.2cm apart.

The copper and textile electrodes were also applied to cardboard because they are very easy to attach and the material is well-insulated electrically. The electrodes made of the conductive paint, on the other hand, were applied to felt, as this also has insulating properties and is very similar to the inner material of the shoe. In addition, the flexibility and durability of the paint on this material could be easily tested.

For the resistive sensing, we additionally used a conventional FSR 402 pressure sensor from Interlink Electronics as a benchmark for evaluating the measurement results.

3.4.2 Data Acquisition System. We utilized Arduino boards programmed with CapSense the library [4] and the OpenCapSense toolkit [15] for capacitive sensing, and custom scripts for resistive sensing. We particularly used a battery-operated system to ensure portability as we know that using a power supply can impact the results. We used a Bluetooth module for wireless data transmission to a computer, where data was logged and analyzed.

3.4.3 Testing Environment. Tests were conducted under controlled laboratory conditions to minimize environmental noise. All sensors were calibrated before each test to ensure consistency.

3.4.4 Evaluation Parameters. We primarily looked at the SNR to assess the clarity of the sensor's output relative to background noise. It is defined as the ratio of the power of the signal to the power of the noise. Further we measured the variance / consistency of the sensor readings under identical conditions. A low variance indicates high reliability and repeatability. Lastly, we looked at the durability and flexibility, particularly after repeated cycles of bending and loading to simulate real-world shoe usage.

3.5 Test Protocol

To evaluate the performance of the sensors and materials, experiments were conducted under three scenarios:

3.5.1 Static Testing (Idle).
Purpose: Assess baseline readings and identify noise levels in the absence of external pressure.

Procedure: Sensors were left undisturbed for 10 seconds while readings were recorded.

3.5.2 Proximity Testing (Hover).
Purpose: Measure sensor response to a nearby body part without applying pressure.

Procedure: A finger was held close to the electrode (with a 3d-printed spacer at 4 mm distance) to simulate hover / proximity without contact.

3.5.3 Contact Testing (Touch).
Purpose: Evaluate sensor response under contact with human body.

Procedure: The experimenter touched the covered electrodes the index finger with moderate pressure, aiming to simulate a toe or foot to moderately touching the wall of a shoe.

3.5.4 Pressure Testing (Pressure).
Purpose: Evaluate sensor response under controlled pressure.

Procedure: A calibrated 1.1 kg weight was applied to the electrodes, simulating in-shoe pressure from walking or standing.

4 Results

The analysis focuses on key performance metrics, including signal-to-noise ratio (SNR), variance, accuracy of pressure mapping, and overall feasibility.

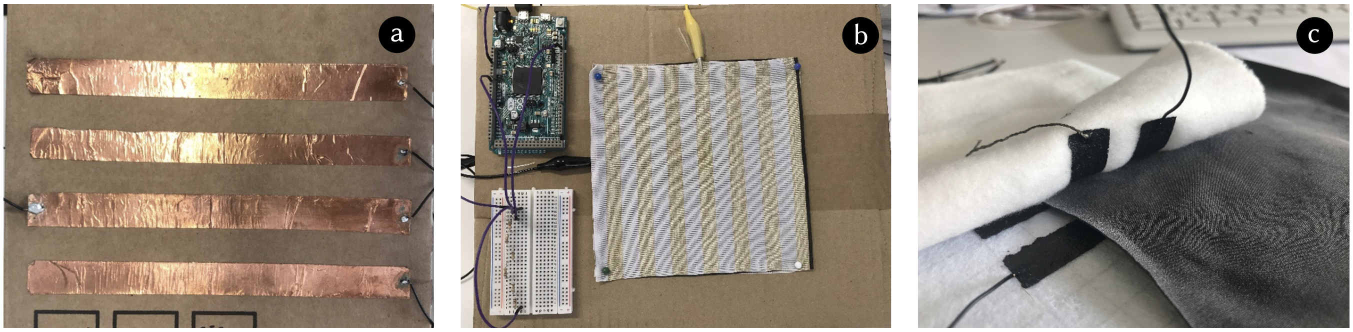

Figure 5: Showing all three types of electrodes we evaluated: a) Copper tape, b) Zebra Fabric (HITEK) and EeonTex fabric, and c) Conductive paint, which we mixed by ourselfes (see Table 1).

4.1 Comparison of Sensor Technologies

4.1.1 Capacitive Sensing (CapSense and OpenCapSense). The first investigation regards the performance of Capacitive Sensing. In table 3 we compared the Signal Energy, SNR, and Variance of Arduino's CapSense Library for three sensitivity levels.

Table 3: Measured values for different conditions (idle, hover (4mm) , touch, pressure) and sensitivities (low,medium,high) for Capacitive Sensing using Arduino's CapSense Library. Every displayed value represents the average of 1000 values.

	Idle	Hover	Touch	Pressure
Low Sensitivity (820kΩ):				
Signal Energy	68.14	703.03	20923.78	20949.87
SNR	12.65 dB	22.32 dB	40.43 dB	40.33 dB
Variance	3.7	4.12	1.9	1.94
Medium Sensitivity (1MΩ):				
Signal Energy	3.17	33.47	8973.88	8976.32
SNR	-0.11 dB	10.53 dB	37.43 dB	22.47 dB
Variance	3.25	2.96	1.6203	1.6
High Sensitivity (5MΩ):				
Signal Energy	148.16	2770.26	390953.89	391501.73
SNR	7.63 dB	18.89 dB	36.68 dB	37.17 dB
Variance	25.60	35.84	83.94	75.14

Sensitivity: CapSense achieved excellent proximity detection, responding reliably at distances of up to 3 cm in our high sensitivity setup. The best signal-to-noise ratio was achieved by the conductive inc electrodes at high sensitivity M=36.68 dB at touch (peak to peak = 22.42 dB - 41.07 dB), whereby high sensitivity also results in increased variance of M=83.94. The smallest variance, however, occurs when measuring with the textile electrodes at low sensitivity (M=40.43) while touching. In this series of tests, the copper electrodes, and especially the textile electrodes, were very susceptible to interference, especially at high sensitivity, which is also reflected in a very high variance. A one-way ANOVA revealed significant differences between all three sensitivities for Signal Energy (SE) ($F_{2,\,297} = 1.437{\times}10^{11}, p < 0.001$). A post-hoc Tukey tests confirmed significant differences between all touch conditions. Similar results are also observable with the idle, hover, and pressure condition.

OpenCapSense offered similar sensitivity with slightly more stability due to its integrated hardware optimizations.

Noise and Drift: Capacitive sensors were susceptible to environmental noise, particularly from ambient electromagnetic fields, resulting in occasional signal drift during extended static tests. A one-way ANOVA also revealed significant differences in Signal-to-Noise Ratio (SNR) ($F_{2,\,297} = 23.83, p < 0.001$) for the touch condition. A post-hoc Tukey tests confirmed all significances apart from medium to high sensitivity. A one-way ANOVA showed significant differences in Signal-to-Noise Ratio (SNR) among all other sensitivity groups ($F_{2,\,297} = 4187.70, p < 0.001$); while a post-hoc Tukey tests confirmed significant pairwise differences between all pairs of idle, hover and pressure.

Dynamic Response: Both, the CapSense libraries and the OpenCapSense toolkit performed well during dynamic pressure tests, with response times below 200 ms.

Table 4: Measured values for different conditions (idle, touch, pressure) and sensitivities (low,medium,high) for resistive sensing (SNR / Variance). As resistive sensing requires some type of touch, a hover state cannot be detected.

	Idle	Touch	Pressure
Low Sensitivity (1kΩ):			
Copper Tape	- / 0	43.58 dB / 0.25	58.89 dB / 0.59
Zebra Fabric	- / 0	52.87 dB / 2.12	74.71 dB / 0.29
Conductive Ink	- / 0	48.14 dB / 0.45	71.86 dB / 0.6
FSR (control)	- / 0	46.41 dB / 0.63	69.62 dB / 1.92
Medium Sensitivity (5kΩ):			
Copper Tape	- / 0	50.89 dB / 0.71	68.14 dB / 2.17
Zebra Fabric	- / 0	65.88 dB / 1.135	78.5 dB / 0.49
Conductive Ink	- / 0	60.07 dB / 7.72/	77.76 dB / 1.06
FSR (control)	- / 0	62.14 dB / 5.98	76.36 dB / 0.81
High Sensitivity (10kΩ):			
Copper Tape	- / 0	62.21 dB / 17.51	73.37 dB / 5.94
Zebra Fabric	-5.72 dB / 0.27	54.54 dB / 1.34	62.03 dB / 0.66
Conductive Ink	- / 0	62.2 dB / 0.5	78.99 dB / 1.13
FSR (control)	/ 0	68.12 dB / 10.87	78.09 dB / 6.77

Table 5: Measured values for different conditions (idle, touch, pressure) and sensitivities (low,medium,high) for the OpenCapSense Toolkit (SNR / Variance).

	Idle	Hover	Touch	Pressure
Arduino CapSense Library (avrg across all sensitivity levels):				
Copper Tape	-10.36 dB / 10.86	1.03 dB / 2.14	21.2 dB / 30.07	21.21 dB / 30.06
Zebra Fabric	-9.73 dB / 9.4	19.66 dB / 120.61	25.75 dB / 114.02	25.73 dB / 113.69
Conductive Ink	-9.49 dB / 8.9	14.27 dB / 153.59	37.47 dB / 9.57	37.55 dB / 9.49
OpenCapSense Toolkit				
Copper Tape	- 2.81 dB / 1.91	-0.28 dB / 4.47	7.14 dB / 73.18	7.42 dB / 89.75
Zebra Fabric	- 4.89 dB / 3.09	9.12 dB / 16.43	12.76 dB / 44.2	13.4 dB / 92.88
Conductive Ink	-2.1 dB / 1.62	11.45 dB / 5.34	24.55 dB / 127.81	24.45dB / 128.63

4.1.2 *Resistive Sensing.*

The second investigation regards resistive sensing using four different electrode / material setups. We similarly selected three sensitivity levels.

Accuracy: As seen in table 4, the recorded precise pressure readings with minimal noise, achieving the highest SNR of up to M=78.99 dB among the tested methods. The resistive measurements consistently delivered sufficient good results in terms of both SNR and variance. Between the touch and pressure conditions, there is a significant difference for low sensitivity ($t(6) = -6.83, p < 0.01$) medium sensitivity ($t(6) = -4.77, p < 0.01$) and high sensitivity ($t(6) = -2.76, p < 0.005$). This indicates with SNR to significantly raise with increased pressure. This technology seems to be resistant to external interference, mainly because no electric field is sensed. Thus, in contrast to capacitive sensors, fluorescent tubes on the ceiling or movements of the arm in close proximity to the electrodes, for example, did not cause interference even at high sensitivity.

Robustness: Apart from the noise signal artifact at the high sensitivity condition with the zebra fabric, resistive sensors are considered robust and unaffected by proximity artifacts, making them ideal for scenarios requiring direct pressure measurement. While we deployed the off-the-shelf FSR 402 as a gold-standard to check the signal quality, we could see that there are significant (p<.05), but negligible differences. Also to note is that the conductive ink electrodes consistently delivered sufficiently results, which are very similar to those of the FSR 402.

Limitations: Required precise calibration to account for variations in electrode overlap and dielectric thickness.

4.2 Performance of Sensor Materials

In table 5 we summarize the overall performance for our material selection: Copper Tape, Zebra Fabric, and Conductive Ink.

4.2.1 *Copper Tape.*

Signal Energy: Copper electrodes provided the highest signal strength among the tested materials, with minimal interference during static and dynamic testing.

SNR: It exhibited a sufficiently high SNR of approximately up to approx. 21 dB in touch & proximity tests, indicating excellent sensitivity to touching and nearby objects. ANOVA repeated measures revealed a significant difference between Arduino CapSense and OpenCapSense ($F_{3,\,396} = 244.21$, $p < 0.001$). Post-hoc Tukey's HSD test indicated significant differences ($p < 0.001$), evidencing Arduino CapSense to work somewhat better on copper an OpenCapSense.

Pros/Cons – Durability: Copper Tape maintained structural integrity under repeated pressure and bending. However, their single-direction flexibility limited their adaptability to curved surfaces inside the shoe.

4.2.2 *Conductive Textiles (Zebra Fabric and EeonTex).*

Signal Energy: The fabric showed a sufficiently high signal energy, although not as high as the signal energy from conductive paint.

SNR: Zebra Fabric demonstrated moderate consistency in signal energy, with an SNR of around 25 dB in static touch and hover conditions and a slightly higher variance compared to copper electrodes. Also here, an ANOVA revealed a significant difference between the both sensing technologies ($F_{3,\,396} = 760.22, p < 0.001$). The post-hoc Tukey's HSD test confirmed a significant difference revealing the Arduino CapSense Library to be better in terms of SNR than the OpenCapSense Toolkit.

Pros/Cons – Flexibility & Availability The inherent flexibility of the fabric made it well-suited for embedding into shoe interiors, particularly in areas prone to deformation. The material is readily made and purchasable off the shelf, which is a huge pro. However, the correct alignment of the conductive pathways in Zebra Fabric is critical to ensuring accurate measurements. EeonTex's compressible nature proved advantageous in resistive sensing.

4.2.3 *Conductive Ink (Bare Conductive Electric Paint).*

Signal Energy: Surprisingly, conductive ink constantly showed the highest signal energy among all conditions and across all technologies.

SNR: While providing sufficient sensitivity, the paint exhibited slightly higher noise levels compared to copper or textile electrodes with OpenCapSense. An ANOVA also revealed a significant difference to the Arduino CapSense Library ($F_{3,\,396} = 22.94, p < 0.001$). The post-hoc Tukey's HSD test confirmed a significant the Arduino CapSense library to have a signficantly better SNR than the OpenCapSense toolkit using conductive ink electrodes.

Pros/Cons – Customizability & Durability: Paint electrodes allowed for highly customizable shapes, enabling precise placement in areas of interest, such as the ball and heel of the foot. Thin layers showed reasonable performance, but thicker applications became prone to cracking under repeated pressure.

5 Combining Resistive and Capacitive Sensing

We extended the conductive material "sandwich" to operate in *dual mode*. At the start of each sampling frame the firmware temporarily floats the lower electrode and performs a single Capacitive-Voltage-Division (CVD) cycle, yielding a self-capacitance measurement that indicates the foot's approach distance (~0–30 mm). Immediately afterwards the GPIO configuration reverts to the original resistive divider, permitting high-rate load acquisition within the same gait cycle. The entire sequence adds only a 240 µs timing slot and no additional hardware; nevertheless, the 10-bit ADC and coarse timer on the *Arduino Micro* limit proximity resolution to roughly 2 mm and introduce jitter above 5 Hz stride frequencies. To achieve sub-millimeter presence accuracy and stable synchronization at higher cadences we need to migrate to a *PSoC-6* platform, whose 12-bit $\Delta\Sigma$ ADC, hardware CVD engine, and shield-drive GPIO provide the greater precision. More research is needed to implement PSoC based systems for even greater precision and detail in the applications.

Shielding to suppress ground–water artefacts. Capacitive presence sensing depends on fringing electric fields; any nearby conductive or high–permittivity body alters the measured self-capacitance. A thin film of water near the electrode, such as on top of the shoe or beneath the sole, with $\varepsilon_r \approx 80$ and finite conductivity, therefore behaves like a large virtual electrode and causes stochastic proximity events (see figure 6. Placing a driven shield directly under Electrode 2 forces the underside of the sensor to an equipotential, collapsing downward field lines so the external water layer is electrically invisible, while the upward field toward the foot remains unaffected. The dielectric overlays already introduced to reduce electromagnetic noise serve concurrently as mechanical spacing for this shield, so no additional thickness or materials are required.

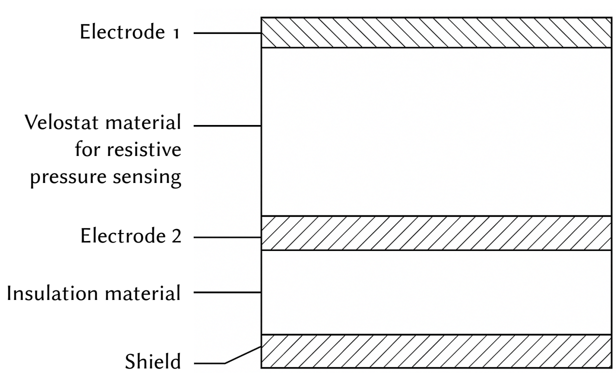

Figure 6: Stack of materials on capacitive and resistive sensing. A shielding electrode can be used to eliminate the impact of foreign signals, such as EM-noise or water.

6 Final Prototype Assembly

From our evaluation, we decided to use conductive ink with a combination of capacitive and resistive sensing. This series of images in figure demonstrates the systematic approach to combining traditional shoemaking techniques with advanced sensing technology, resulting in a functional prototype of a 3D-sensing shoe.

Initial Design and Materials Preparation: Figure 6–a showcases the preparatory stage where various materials and design patterns are laid out on a workbench. You can see different cutouts of fabric or leather, likely intended to form the upper and inner components of the shoe. Additionally, there are templates for shaping the shoe and other tools to assist with precise assembly. The workspace suggests careful planning and prototyping before integrating the sensing technologies.

Creation of the Transparent Mold: Figure 6–b showcases the creation of a transparent mold, which appears to be made of flexible or rigid polymer material. This mold is likely used as a structural framework to shape and align the shoe components accurately. The transparency ensures visual inspection during assembly, ensuring precision in the application of conductive ink or placement of other internal features.

Integration of the Inner Lining: In figure 6–c the inner lining of the shoe is being assembled. The lining is crafted to incorporate sensing elements while maintaining comfort and durability. The close-up provides a view of the stitching or adhesive techniques used, ensuring the integration of conductive ink electrodes within the shoe's structure without compromising the user's comfort or the sensing accuracy.

Embedding the Conductive Electrodes: This figure 6–d illustrates the crucial step of embedding conductive ink electrodes onto the shoe's surface. The electrodes are applied in precise patterns, possibly using screen printing or similar techniques, to create a 3D-sensing wall. The foam or padding visible in this stage suggests efforts to combine functional sensing elements with cushioning to maintain the ergonomic quality of the footwear.

Final Shoe Assembly: The last image, figure 6–e, presents the fully assembled shoe, featuring a polished and wearable design. The shoe integrates all the previously assembled components, including the conductive ink electrodes and 3D-sensing wall, seamlessly into a professional and ergonomic product. A foam last (a model of a foot) is visible in the background, indicating its use during the shoe's shaping process.

7 Discussion

Material Selection and Challenges: Copper electrodes and conductive textiles emerged as the most effective materials, offering a balance of performance, durability, and integration ease. However, copper's limited flexibility restricted its application to flat or mildly curved surfaces, while conductive textiles required precise alignment to maintain consistent electrical properties. Conductive paint allowed for custom electrode shapes but exhibited durability issues under repeated stress.

Sensor Synergy and Technology Gaps: The combined use of capacitive and resistive sensors provides robust pressure mapping by leveraging the strengths of both technologies. However, capacitive sensors were prone to electromagnetic noise and drift in static conditions, necessitating recalibration. Shielding with dielectric layers showed to partially erase this issue. Resistive sensors are reliable for pressure measurements, but struggle when aiming to capture highly localized variations, similar to CapSense also due to resolution constraints.

Prototype Integration and Practical Limitations: The prototype demonstrated the practical viability of embedding electro-sensory systems into shoes for pressure mapping, maintaining wearer comfort and achieving accurate data capture. However, integrating multiple sensor types increased system complexity, and real-time data processing proved computationally demanding for current microcontroller setups. Battery life and cost also posed challenges for long-term, portable applications.

Challenges in the Real-world: In real world contexts, environmental interferences are present. In our experiment, we are able to shield all conductive materials using dielectric layers to minimize electromagnetic interference. Sensors, particularly the capacitive sensors have a sensor drift, which countered by recalibrating the system periodically. Further, we face integration challenges. In our experiment the conductive paint and fabrics were optimized for placement in areas of minimal deformation to avoid cracking or misalignment. In shoes, higher wear through constant deformation might occur. Another aspect concerns foot variations (size, form, arch height,...). Here a calibration could be a solution to adapt to these differences. Lastly, real-time 3D foot scanning over long periods of time may generates large data streams that require efficient processing. Balancing speed and power consumption is crucial for battery-operated wearables.

8 Conclusion

In this paper, we demonstrated the integration of 3D foot-scanning technologies into footwear using conductive ink electrodes to create a functional and versatile sensing wall. We investigated the feasibility of using copper electrodes and conductive textiles, and conductive ink with advanced sensor synergy through capacitive and resistive sensing. The findings highlighted the opportunities and limitations of these technologies. Embedding sensors in a 3D-way, by integrating electrodes into the wall, allows potential applications in medical diagnostics, sports performance, and human augmentation. Despite challenges in material durability and scalability, this research may lay the foundation for future advancements in electro-sensory systems, emphasizing their transformative potential for personalized and data-driven footwear solutions.

9 Future Work

In the future, smart soles and shoes are expected to become an integral part of our everyday lives, particularly also for elderly care environments due to their advanced sensing capabilities. By unobtrusively integrating standardized tests—such as the Timed Up and Go Test, Sit-to-Stand Test, and 4-Balance Test—these systems can assess the quality of activities of daily living, which serve as key health indicators.

Beyond elderly care, electro-sensory footwear holds promise for a range of applications, including medical diagnostics (e.g., diabetic foot monitoring), sports performance analysis, and human augmentation. These developments pave the way for advanced, multi-functional footwear solutions that go far beyond conventional use.

To this end, we have also explored a dual-mode sensing strategy combining resistive load cell measurements with self-capacitance proximity detection. Future work should expand on this by implementing controlled scan sequences for CVD measurements, enabling estimation of approach distances (~0–30 mm) before switching to pressure sensing. This two-modality approach—capturing both proximity and pressure within a gait cycle — could offer pre-touch awareness, guide users before contact, and minimize false activations, particularly in loose-fitting footwear.

However, realizing this potential will require overcoming several key challenges, including material optimization, signal noise reduction, and improvements in energy efficiency. Addressing these issues is essential for transitioning from prototype systems to widespread real-world adoption, and ultimately for unleashing the full capabilities of smart, sensor-integrated footwear.

References

[1] Gabriel Aguirre-Ollinger, J Edward Colgate, Michael A Peshkin, and Ambarish Goswami. 2011. Design of an active one-degree-of-freedom lower-limb exoskeleton with inertia compensation. *The International Journal of Robotics Research* 30, 4 (2011), 486–499.

[2] Jamie J Allan, Shannon E Munteanu, Daniel R Bonanno, Andrew K Buldt, Simon Choppin, Alice Bullas, Natalie Pearce, and Hylton B Menz. 2023. Methodological and statistical approaches for the assessment of foot shape using three-dimensional foot scanning: a scoping review. *Journal of Foot and Ankle Research* 16, 1 (2023), 24.

[3] B-Shoe. 2015. Balancing Shoes to Prevent Fall. Retrieved October 3, 2024 from https://b-shoe.com/.

[4] Paul Badger. 2012. CapSense Library. http://playground.arduino.cc/Main/CapacitiveSensor. Accessed: 2025-01-05.

[5] S. J. M. Bamberg, A. Y. Benbasat, D. M. Scarborough, D. E. Krebs, and J. A. Paradiso. 2008. Gait analysis using a shoe-integrated wireless sensor system. *IEEE Transactions on Information Technology in Biomedicine* 12, 4 (2008), 413–423.

[6] R. Brandl and H. Stiegler. 2015. Das diabetische Fußsyndrom–Pathogenese, Diagnostik, Therapie und Prävention. *DMW-Deutsche Medizinische Wochenschrift* 140, 08 (2015), 593–602.

[7] Digitsole. 2020. We walk you through life. Retrieved October 3, 2024 from https://digitsole.com.

[8] Don Samitha Elvitigala, Jochen Huber, and Suranga Nanayakkara. 2021. Augmented foot: a comprehensive survey of augmented foot interfaces. In *Proceedings of the Augmented Humans International Conference 2021*. 228–239.

[9] Don Samitha Elvitigala, Denys JC Matthies, Löic David, Chamod Weerasinghe, and Suranga Nanayakkara. 2019. GymSoles: Improving squats and dead-lifts by visualizing the user's center of pressure. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–12.

[10] Don Samitha Elvitigala, Denys JC Matthies, and Suranga Nanayakkara. 2020. StressFoot: Uncovering the potential of the foot for acute stress sensing in sitting posture. *Sensors* 20, 10 (2020), 2882.

[11] Douglas Engelbart. 1984. Doug Engelbart Discusses Mouse Alternatives.(May 1984). *Retrieved March* 3 (1984), 2014.

[12] International Diabetes Federation. 2025. Diabetes Facts and Figures. https://idf.org/about-diabetes/diabetes-facts-figures/ Accessed: 2025-01-05.

[13] Sensoria Fitness. 2017. Sensoria Fitness Socks and Anklet. http://store.sensoriafitness.com/sensoria-fitness-smart-socks. Accessed: 2017-11-23.

[14] K. Fukahori, D. Sakamoto, and T. Igarashi. 2015. Exploring Subtle Foot Plantar-based Gestures with Sock-placed Pressure Sensors. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 3019–3028.

[15] Tobias Grosse-Puppendahl, Yannick Berghoefer, Andreas Braun, Raphael Wimmer, and Arjan Kuijper. 2013. OpenCapSense: A rapid prototyping toolkit for pervasive interaction using capacitive sensing. In *2013 IEEE International Conference on Pervasive Computing and Communications (PerCom)*. IEEE, 152–159.

[16] H. Gulgin, K. Hall, A. Luzadre, and E. Kayfish. 2018. 3D gait analysis with and without an orthopedic walking boot. *Gait & Posture* 59 (2018), 76–82.

[17] Marian Haescher, Denys JC Matthies, Gerald Bieber, and Bodo Urban. 2015. Capwalk: A capacitive recognition of walking-based activities as a wearable assistive technology. In *Proceedings of the 8th ACM International Conference on PErvasive Technologies Related to Assistive Environments*. 1–8.

[18] J. M. Hausdorff, Z. Ladin, and J. Y. Wei. 1995. Footswitch system for measurement of the temporal parameters of gait. *Journal of Biomechanics* 28, 3 (1995), 347–351.

[19] Christin Heidemann, Yong Du, Elvira Mauz, Lena Walther, Diana Peitz, Anja Müller, Maike Buchmann, Jennifer Allen, Christa Scheidt-Nave, and Jens Baumert. 2024. Healthcare and health situation of adults with type 2 diabetes in Germany: The study GEDA 2021/2022-Diabetes. *Journal of Health Monitoring* 2

(2024). https://www.rki.de/EN/Content/Health_Monitoring/Health_Reporting/GBEDownloadsJ/Focus_en/JHealthMonit_2024_02_Healthcare_diabetes_GEDA.pdf?__blob=publicationFile Accessed: 2025-01-05.

[20] M. Kljajic and J. Krajnik. 1987. The use of ground reaction measuring shoes in gait evaluation. *Clinical Physics and Physiological Measurement* 8, 2 (1987), 133.

[21] A. Konttila, J. Kaartinen, J. Plomp, R. Toivonen, and L. Hopsu. 2011. Wireless weight measurement shoes. In *Biomedical Engineering and Informatics (BMEI), 2011 4th International Conference on*, Vol. 3. IEEE, 1386–1390.

[22] Feng Lin, Aosen Wang, Yan Zhuang, Machiko R Tomita, and Wenyao Xu. 2016. Smart insole: A wearable sensor device for unobtrusive gait monitoring in daily life. *IEEE Transactions on Industrial Informatics* 12, 6 (2016), 2281–2291.

[23] F. Lin, A. Wang, Y. Zhuang, M. R. Tomita, and W. Xu. 2016. Smart Insole: A wearable sensor device for unobtrusive gait monitoring in daily life. *IEEE Transactions on Industrial Informatics* 12, 6 (2016), 2281–2291.

[24] B. A. MacWilliams and P. F. Armstrong. 2000. Clinical applications of plantar pressure measurement in pediatric orthopedics. In *Pediatric Gait, 2000. A new Millennium in Clinical Care and Motion Analysis Technology*. IEEE, 143–150.

[25] Denys JC Matthies, Don Samitha Elvitigala, Annis Fu, Deborah Yin, and Suranga Nanayakkara. 2021. Mobilld: Exploring the detection of leg length discrepancy and altering gait with mobile smart insoles. In *Proceedings of the 14th PErvasive Technologies Related to Assistive Environments Conference*. 37–47.

[26] Denys JC Matthies, Thijs Roumen, Arjan Kuijper, and Bodo Urban. 2017. CapSoles: who is walking on what kind of floor?. In *Proceedings of the 19th International Conference on MobileHCI*. 1–14.

[27] Anita Meier, Denys JC Matthies, Bodo Urban, and Reto Wettach. 2015. Exploring vibrotactile feedback on the body and foot for the purpose of pedestrian navigation. In *Proceedings of the 2nd international Workshop on Sensor-based Activity Recognition and Interaction*. 1–11.

[28] L. V. Nguyen, H. M. La, J. Sanchez, and T. Vu. 2016. A Smart Shoe for building a real-time 3D map. *Automation in Construction* 71 (2016), 2–12.

[29] World Health Organization. 2016. *Global report on diabetes*. WHO Library Cataloguing-in-Publication Data, Geneva. 6–7 pages.

[30] Glenn Pearson and Mark Weiser. 1988. Exploratory evaluations of two versions of a foot-operated cursor-positioning device in a target-selection task. *ACM SIGCHI Bulletin* 19, 3 (1988), 70–75.

[31] Chris Phillips, Awadh Al-Ahmadi, Sarah-Jane Potts, Tim Claypole, and Davide Deganello. 2017. The effect of graphite and carbon black ratios on conductive ink performance. *Journal of materials science* 52, 16 (2017), 9520–9530.

[32] Nihar Sabnis, Dennis Wittchen, Ata Otaran, Fatima Badmos, Siyi Liu, Aryan Saini, Georg Regal, Vincent van Rheden, Florian 'Floyd' Mueller, Suranga Nanayakkara, et al. 2025. Walking the Future: Bridging Foot Augmentation into Next Steps of Human Augmentation. In *Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*. ACM, 1–7.

[33] Ruben Schlonsak, T. Yang, Marco Torge Gabrecht, and Denys Jörg Christian Matthies. 2024. ShoeTect2.0: Real-time Activity Recognition using MobileNet CNN with Multisensory Smart Footwear. In *Proceedings of the 9th international Workshop on Sensor-Based Activity Recognition and Artificial Intelligence*. 1–5.

[34] Sensoria. 2019. Sensoria Artificial Intelligence Sportswear. Retrieved October 3, 2024 from https://www.sensoriafitness.com.

[35] Jana SIEGMUND, Huangmei LIN, Sybille KRZYWINSKI, Monika RICHTER, and Kathrin SCHÄFER. 2019. Development of a 3D grading method for shoe lasts based on scanned 3D foot data. In *10th Int. Conference and Exhibition on 3D Body Scanning and Processing Technologies*. 119–124.

[36] SoleCooler. 2024. WARNFEET The insole that detects diabetic foot ulcers. Retrieved December 3, 2024 from https://solecooler.com/en_US/.

[37] Paul Strohmeier, Seref Güngör, Luis Herres, Dennis Gudea, Bruno Fruchard, and Jürgen Steimle. 2020. BARefoot: Generating virtual materials using motion coupled vibration in shoes. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. 579–593.

[38] Edward O Thorp. 1998. The invention of the first wearable computer. In *Digest of Papers. Second international symposium on wearable computers*. IEEE, 4–8.

[39] Keigo Ushiyama and Pedro Lopes. 2023. FeetThrough: Electrotactile Foot Interface that Preserves Real-World Sensations. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. 1–11.

[40] H. von Lilienfeld-Toal, S. Morbach, P. Bajorat, and J. M. Asfour. 2007. Entwicklung der „schlauen Socke", einem diagnostischen Instrument zur Verhinderung rezidivierender Fußdefekte durch Evaluation der Druckverteilung der vollständigen Zirkumferenz des Fußes im Schuh. *Diabetologie und Stoffwechsel* 2, S 1 (2007), P84.

[41] Patrick Willnow, Max Sternitzke, Marco Torge Gabrecht, and Denys J.C. Matthies. 2024. SurfSole: Demonstrating Real-Time Surface Identification via Capacitive Sensing with Neural Networks. In *Proceedings of the 9th international Workshop on Sensor-Based Activity Recognition and Artificial Intelligence*. Springer, 1–9.

[42] Dennis Wittchen, Valentin Martinez-Missir, Sina Mavali, Nihar Sabnis, Courtney N Reed, and Paul Strohmeier. 2023. Designing Interactive Shoes for Tactile Augmented Reality. In *Proceedings of the Augmented Humans International Conference 2023*. 1–14.

[43] Junkai Xu, Tian Bao, Ung Hee Lee, Catherine Kinnaird, Wendy Carender, ..., and Peter B Shull. 2017. Configurable, wearable sensing and vibrotactile feedback system for real-time postural balance and gait training: proof-of-concept. *Journal of neuroengineering and rehabilitation* 14 (2017), 1–10.