

Design and Experimental Characterization of Resistive Force Transducers Manufactured via Screen-Printing

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Abstract

This paper presents a systematic methodology for the development of resistive force transducers (RFTs), tailored for robotics, particularly for applications in assistive technologies such as exoskeletons. RFTs are sensors that alter their electrical resistance in response to applied force, pressure, or mechanical stress. Their adjustability, flexible design, cost-effectiveness, and ability to be easily positioned at contact points without compromising user comfort make them ideal for mapping pressure distributions over defined and limited areas. To this end, the current study aims to leverage screen printing, a scalable and cost-efficient manufacturing technique—to enable high-precision customization of sensor structures and conductive inks with tailored properties. The fabricated RFTs were integrated into Co-Ex, a bipedal exoskeleton equipped with a lower-body framework designed to assist individuals with mobility impairments. The performance of the custom RFTs was rigorously evaluated in realistic testing scenarios and benchmarked against commercially available RFTs of comparable size and specifications. Key performance metrics, including center of pressure (CoP) measurements, demonstrated that the custom RFTs exhibited performance comparable to their commercial counterparts, with CoP measurements showing strong agreement. This work highlights the potential of custom RFTs as cost-effective, flexible solutions for advanced robotics and assistive technologies.

Keywords

resistive force transducer, center of pressure, exoskeleton

Introduction

The recent developments in contemporary robotics triggered a paradigm shift from industrial manipulators to service robots [1]. In particular, practical solutions to long-lasting force control problems [2, 3] enabled the robots to leave the well-controlled laboratory or automation environments and adapt to dynamic human environment. Force control played a pivotal role in providing safe and dependable human-robot and robot-environment interaction capabilities as it is implemented to various robotic systems ranging from human-friendly manipulators to legged systems, and exoskeletons [4, 5, 6].

While implementing force control, the use of load cells or 6 axis F/T sensors may introduce many deficits. They are relatively heavy, fragile against impacts, and could alter the mechanical impedance of the robot due to their structural stiffness [7]. Alternatively, the use of Resistive Force Transducers (RFTs) could remedy these issues. Despite their nonlinear behavior, it was demonstrated that the use of proper calibration techniques elevate their performance and their dynamic response possess favorable characteristics [8]. Accordingly, they were applied to force control of several advanced robotic systems, e.g., exoskeletons [5] and legged robots [6, 9]. Taking these factors into account, this paper proposes the use of screen printing, a scalable and cost-effective manufacturing technique, to fabricate custom RFTs. The following subsections provide a concise review

of the relevant literature and outline the contributions of this study. The rest of this paper is organized as follows: Section 2 discloses the proposed methodology and describes the materials used in the study. Section 3 details the experimental results and provides a comprehensive discussion of their implications. Finally, the paper is concluded in section 4.

State-of-the-art

Flexible pressure sensors have gained considerable attention due to their promising applications in wearable electronics, robotics, and healthcare devices. Early developments in flexible sensors focused on various transduction principles. For flexible sensors based on printing technology, mechanical stimuli such as pressure, force, and vibration are

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converted through four main mechanisms: piezoresistiveness of the sensitive layer, capacitance of the pressure-sensitive structure, piezoelectricity caused by mechanical deformation, and triboelectricity [10]. Each of these mechanisms offers unique advantages and limitations that have driven extensive research into improving the sensitivity, flexibility, and durability of these sensors. Piezoresistive sensors operate by converting mechanical deformations into changes in resistance, which can be measured via an external circuit. These sensors are favored for their high sensitivity, wide detection range, simple structure, and low energy consumption [11]. Typically, materials such as carbon nanotubes, graphene, and conductive nanoparticles are employed in these sensors, as they allow for enhanced mobility of charge carriers through structural deformations. Recent advancements in the use of carbon-based composites and nanowires have demonstrated significant improvements in the sensitivity and stability of piezoresistive pressure sensors [12].

Capacitive sensors function by transducing pressure into changes in capacitance. The capacitance value, which depends on the dielectric constant of the material, the surface area of the electrodes, and the distance between them, alters in response to mechanical deformation. These sensors are known for their high sensitivity, low power consumption, and strong environmental independence [13]. Innovations such as the use of interdigital electrode configurations and micro-structured dielectric surfaces have further improved their spatial resolution and overall performance [14, 15]. Piezoelectric pressure sensors leverage the piezoelectric effect, where mechanical stress induces the generation of electrical charges in certain materials. These sensors are highly responsive, energy-efficient, and capable of self-powering, making them suitable for a wide range of applications [16].

However, traditional piezoelectric materials, such as lead zirconate titanate (PZT), are rigid and brittle, limiting their application in flexible devices. To overcome this limitation, flexible polymers like polyvinylidene fluoride (PVDF) have been introduced, offering greater mechanical flexibility and biocompatibility [16]. Triboelectric sensors, based on the coupling of contact electrification and electrostatic induction, generate charges when two materials come into contact and then separate. This contact-induced polarization creates a potential difference, which can be harnessed for energy generation [17]. Triboelectric sensors are particularly compatible with screen printing technologies, making them highly adaptable for the production of flexible devices [17].

RFT sensors are devices that can measure both static and dynamic forces acting on a contact surface [18]. RFT fabrication usually requires a two-foil manufacturing process with electrodes on one foil and a conductive material on the other foil [19]. A percolation effect within the pressure sensitive layer provides the basis for the pressure sensitivity. When in the unloaded state, the sensor exhibits infinite conductivity. The applied pressure reduces the gap between the conductive particles within the polymer matrix, thereby decreasing the layer's resistance. In other words, as the force applied to the sensor's surface increases, the two layers compress, increasing the contact area and reducing electrical resistance [20, 8]. The primary advantages of RFT sensors include their adjustability, flexible shape and size

characteristics, cost-effectiveness, and the capability to be easily positioned at contact points without compromising user comfort. Moreover, their defined and limited areas make them suitable for mapping pressure distribution on interfaces. However, RFT sensors typically encounter drift issues due to prolonged pressure and exhibit lower resistance to bending and tearing. They may also suffer from poor repeatability [21]. Since RFT is a type of conductive polymer, it possesses non-linear characteristics such as hysteresis, stress relaxation, and creep, which impact its overall sensing performance. This means that the sensor cannot maintain a constant reaction force under the same strain or a constant strain under the same pressure. Consequently, multiple measurements conducted under identical conditions can yield varying results [22].

Emerging advances in printed RFTs have positioned these sensors as versatile tools in both academic research and commercial domains. A wide array of printed RFTs, including those from Interlink Electronics, Tekscan (FlexiForce series), and LuSense (PS3 family), have been deployed across robotics, biomedical devices, and wearable systems due to their low cost, flexibility, and ease of integration [23]. These printed commercial sensors are available in multiple form factors—such as round, strip, or square—and typically operate over force ranges of 1–10 N with resistive outputs varying from $1\text{ M}\Omega$ to $10\text{ k}\Omega$. Scientifically, printed RFT-based devices have been implemented in rehabilitation systems, robotic grippers, and exoskeletons [24, 25, 26], showing notable performance when properly calibrated, despite their inherent nonlinearity. The introduction of inkjet and screen printing technologies using MOD silver inks and flexible substrates (e.g., PET, SiliteX) has enhanced the spatial resolution, mechanical adaptability, and manufacturing scalability of printed RFTs, enabling custom geometries suited for plantar sensing, surgical microtools, or textile-embedded applications [27, 28, 29]. These developments support the relevance of printed RFTs for high-performance force sensing in dynamic environments when engineered with proper materials, calibration protocols, and substrate compatibility.

Recent research has explored the integration of RFTs in exoskeletons for various applications. In latest research, an exoskeleton was designed to assist with elbow rehabilitation exercises. Low-cost RFTs were integrated into the forearm brace to obtain feedback from the user while the exoskeleton is active [30]. Similarly, another study an exoskeleton was developed to provide mobility support for patients with paraplegia. RFT sensors were placed in the heel and toe areas of the exoskeleton's feet and at the lower ends of the crutches to obtain ground reaction force (GRF) data [31]. Furthermore, a separate study proposed a compact force sensor system for a hip-mounted exoskeleton designed to aid elderly individuals with walking difficulties due to muscle weakness. One of the sensors used is an RFT sensor, which measures the support force as the user walks. The RFT sensor specifically measures the flexion and extension forces of the hip joint caused by hip movement [22].

Contribution

The primary contribution of this work lies in the proposal of a systematic methodology for the development of RFTs.

In contrast to the reliance on commercially available sensors, which come with fixed geometries and limited customization options, our methodology leverages screen printing technology to enable the design and fabrication of custom RFTs with arbitrary geometries and dimensions. This approach provides greater flexibility for optimizing sensor performance, increasing surface area, or tailoring the sensors to fit non-standard surfaces where force measurement is required. The ability to develop sensors in-house eliminates the need to adapt off-the-shelf RFTs, which may not meet specific application needs, and ensures low-cost manufacturing without compromising design freedom.

Another important contribution is the evaluation of our custom RFTs within a realistic and rigorous testing environment. To ensure a fair comparison with existing solutions, we carried out experiments using commercially available RFTs of similar size and specifications alongside our custom sensors. Both types were assessed within a state-of-the-art self-balancing exoskeleton system, where the critical balance metric—center of pressure (CoP)—was evaluated. The results demonstrate that the performance of our custom RFTs is comparable to commercial counterparts, with CoP measurements showing strong agreement. Furthermore, we conducted a dedicated repetitiveness test using an industrial robotic arm (UR5) to verify the sensor's temporal consistency under controlled loading conditions. Comprehensive statistical analyses were also performed on the exoskeleton balancing data, providing robust evidence for the reliability and consistency of our sensor design. These results confirm the feasibility and practical applicability of the proposed sensors.

Materials and Methods

Materials

50 μm Mylar®polyester (PET) films produced by DuPont Teijin Films was used as the substrate for printing the inks and both as spacer layer and dielectric layer. For the fabrication of electrode layer which is the top layer, Henkel AG & Co's Loctite ECI 1010, silver ink having a density of 2.1 g/cm^3 and a viscosity of $6400 \text{ mPa} \cdot \text{s}$ measured at a shear rate of 1.5 s^{-1} and 25°C using a rheometer was used [32]. Loctite NCI-7002 and Loctite ECI 7004-LR which are carbon particle-based piezoresistive inks with adjustable electrical resistance ranges, having densities of 1.270 g/cm^3 and 1.1 g/cm^3 as well as viscosities of $18000 \text{ mPa} \cdot \text{s}$ and $25000 \text{ mPa} \cdot \text{s}$ at a speed of rotation 20 RPM and 25°C after 1 min using a rotational viscometer, respectively, from Henkel AG & Co, were used as supplied by the manufacturer to manufacture the sensing layer which is the bottom layer [33, 34]. These inks were blended together at 80% and 20% ratios, respectively, and mixed mechanically for 10 minutes to obtain a homogeneous ink composition. The electrical conductivities of the silver ink and the carbon ink mixture were evaluated by means of a Windaus Winlab Data Line conductivity meter. Approximately 300 mL of the sample was subjected to the analysis at a temperature of 21°C . The electrical conductivities of the silver ink and the carbon ink mixture were determined to be $1.20 \mu\text{S/cm}$ and $0.61 \mu\text{S/cm}$, respectively. To bind the layers of the fabricated RFT sensor Avery Dennison's laminating adhesive was used.

Design and Fabrication of RFT Sensors

Following the completion of the literature review, it was ascertained that the critical factors for consideration were the line thickness of the electrodes and the spacing between them, rather than the patterns of the electrode layers and sensing layers. In previous studies, several critical design parameters have been emphasized to achieve reliable performance in printed pressure sensors [20]. For instance, interdigital electrodes fabricated on thin polyimide substrates by screen-printing conductive silver inks with a thickness of $\approx 3 \mu\text{m}$ demonstrated that electrode geometry and track thickness directly influence both electrical resistance and sensitivity. A $7 \mu\text{m}$ thick pressure-sensitive ink layer (Loctite ECI 7004LR/NCI7002) further defined the linear response range and saturation behavior, while the use of high-resolution stencils (180 mesh/cm) enabled fine structuring of the tracks, confirming that stencil resolution determines the minimum achievable electrode spacing. Flexible substrates, such as $5 \mu\text{m}$ polyimide foils, also allowed the sensors to conform to curved surfaces with only minor changes in baseline resistance, underlining the role of substrate selection for mechanical compatibility.

Complementary findings were reported in another study, where the influence of track thickness and multiple print coatings on the conductivity of silver electrodes was systematically investigated [35]. Silver tracks of $7 \mu\text{m}$ printed on $100 \mu\text{m}$ PET exhibited 16Ω resistance over a 215 mm line, which decreased to 12Ω and 8Ω with two and three wet-on-wet coatings, corresponding to thicknesses of $12 \mu\text{m}$ and $14 \mu\text{m}$, respectively. The choice of stencil mesh was shown to depend on the ink type, with 100–40 (100 threads per cm , $40 \mu\text{m}$ thick) mesh applied for silver inks and 100–60 (100 threads per cm , $60 \mu\text{m}$ thick) mesh for carbon inks, highlighting the need to adapt stencil resolution to ink rheology and particle size. Additionally, the sensing layer was optimized through blending carbon-based piezoresistive inks (70% NCI-7002 and 30% ECI 7004-LR), achieving an initial resistance of $\approx 150 \text{ k}\Omega/\text{sq}/10 \mu\text{m}$, which provided a balance between conductivity and resistivity. These design considerations ensured not only electrical performance but also mechanical flexibility, with the sensor matrix demonstrating bendability down to a 2 cm radius.

In addition to polymer-based approaches, textile-integrated strategies have also emphasized the importance of geometrical and material considerations [36]. In one work, Ni-coated interdigitated electrodes with finger widths of 0.8 mm and gaps of 0.4 mm were fabricated on polyester fabrics using a mask-assisted electroless deposition method, achieving a minimum line width and spacing of $300 \mu\text{m}$. The textile substrate provided excellent compliance, and the sensors maintained conductivity after 2000 bending cycles with a curvature radius of 20 mm , confirming their mechanical durability. Ni-coated textiles exhibited a sheet resistance as low as $0.7 \Omega/\text{sq}$, while the hierarchical porous CNT/Ni structure enabled high sensitivity (14.4 kPa^{-1} at pressures below 3.5 kPa) due to the enlarged and pressure-dependent contact area. These results underline that track geometry, line resolution, substrate selection, and material morphology are key parameters in achieving the balance between electrical conductivity, sensitivity, and mechanical robustness in printed and textile-based pressure sensors.

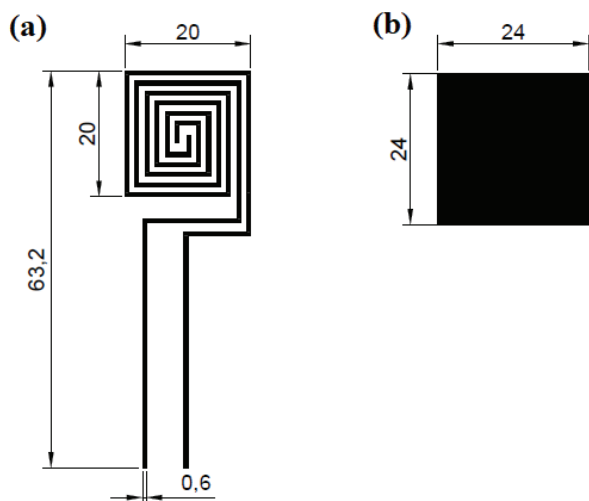


Figure 1. (a) Design of the electrode layers and (b) Design of the sensing layers.

Subsequently, a series of preliminary investigations were conducted, varying the thicknesses and patterns of the electrodes [18, 20, 35, 36]. During the preliminary studies, another factor that was taken into consideration was the placement of the sensors on the sole of the foot, which is the intended site of use. In this regard, the dimensions of the layers were modified to ensure that eight sensors could be suitably placed. The determined design of the electrode layers and sensing layers are presented in Figure 1. The electrode layer has a 20 mm X 20 mm design area with 0.6 mm line thicknesses and a 63,2 mm length in the vertical direction, while the design of the sensing layer is designed as a 24 mm X 24 mm square.

In addition, to ensure functional reliability, electrode geometries were designed by considering both sensitivity and short-circuit risks. Narrower electrode gaps can increase sensitivity; however, excessively small dimensions may result in electrical bridging during printing. To experimentally define the feasible resolution, different electrode layouts were printed on PET substrates with silver inks, and it was observed that a minimum electrode spacing of approximately 0.5mm could be achieved without short circuits. Furthermore, PET films with thicknesses of 50, 75, and 190 μm were tested, and 50 μm substrates were selected as they provided better mechanical flexibility and printing resolution. These design considerations guided the final geometries, balancing electrical performance, printability, and compatibility with the targeted application.

The designs of both the electrode and sensing layers were transferred to a stencil with a mesh size of 140 mesh per centimeter. For the screen-printing process, the MHM Single Print double pallet (MACHINES HIGHEST MECHATRONIC GMBH, Mühlgraben, Austria) screen-printing machine shown in Fig. 2. was employed. The screenprinting process was carried out by means of a flood bar, squeegee and a stencil with the patterns required as shown in Fig. 2(b). In the scope of this study, as the first step of the screen-printing process, PET film was placed on the pallet. Then, with the help of the control panel, the stencil was positioned on the PET film's surface and the ink was distributed homogeneously over the surface of the screen

with the forward movement of the flood bar. As a sequential operation, by the backward movement of the squeegee with certain pressure, the stencil was stretched and transferred the ink to the substrate by passing it through the sieve mesh according to the determined design. The squeegee speed was set to 30% of the maximum speed of the screen-printing machine. Illustration of the printing process can be seen in Fig. 3.

After completion of transferring the designs of the electrode and sensing layers to the PET film by printing them apart at different times, the PET films were cured separately in the Memmert Universal Drying Oven UN55 using thermal treatment. The curing temperatures and times suitable for the inks used in the designs of electrode and sensing layers were determined as 2 minutes at 150 °C for the silver ink and 7 minutes at 120 °C for the carbon inks, respectively, based on the manufacturer's recommendations [37, 38, 39].

The curing temperatures applied during the fabrication process (120 °C and 150 °C) exceed the typical glass transition temperature (T_g) of PET films, which lies in the range of 75–85 °C, and may approach their crystallization temperature (T_c), reported to be between 120–160 °C with a peak around 145 °C [40, 41, 42]. Moreover, melting temperatures for PET films are typically observed between 220 °C and 270 °C. However, the thermal exposure was deliberately kept short (2–7 minutes) to prevent any adverse effects on the substrate. In addition to this, the PET films used in this study are commercially available, thermally stabilized and low shrinkage substrates designed to withstand short-term thermal treatment processes from -70 to 150 °C [43, 44, 45, 46, 47]. This type of thermally stabilized films provide excellent registration and flatness [45, 46, 47, 48].

To ensure the dimensional stability and surface integrity of the substrates, post-curing inspections were carried out in the study. These included visual evaluation, which confirmed that the PET films retained their original flatness and were suitable for subsequent sensor performance evaluation. No visual or structural deformation such as warping, shrinkage, or discoloration was observed on the PET films during or after the curing process, indicating that the thermal treatment did not compromise the physical integrity of the substrate. Therefore, under the specific curing conditions applied in this study, no detrimental thermal effects on the PET substrates were identified. After curing, the thickness of the silver ink on the PET film was measured as 1 μm , while the thickness of the carbon ink layer was measured as 3 μm . No delamination, cracking, or visual deformation was observed after the curing process, and both layers maintained good adhesion to the PET substrate, ensuring their suitability for subsequent processing and functional performance.

The fabrication of the RFT sensor consists of four layers of polyethylene terephthalate (PET) plastic substrate stacked on top of each other. The electrode pattern was printed on the bottom PET layer with silver ink. Two PET films were used in the middle layer to provide a buffer zone. On the top PET layer, a pressure sensing layer with carbon ink, which was printed by screen printing method, was added. An adhesive layer was added between all layers to hold them together. AEON NOVA7 laser cutting machine was used to define the contours of the sensors as a final process to obtain the sensor structure with sharp edge lines. After the final process, the

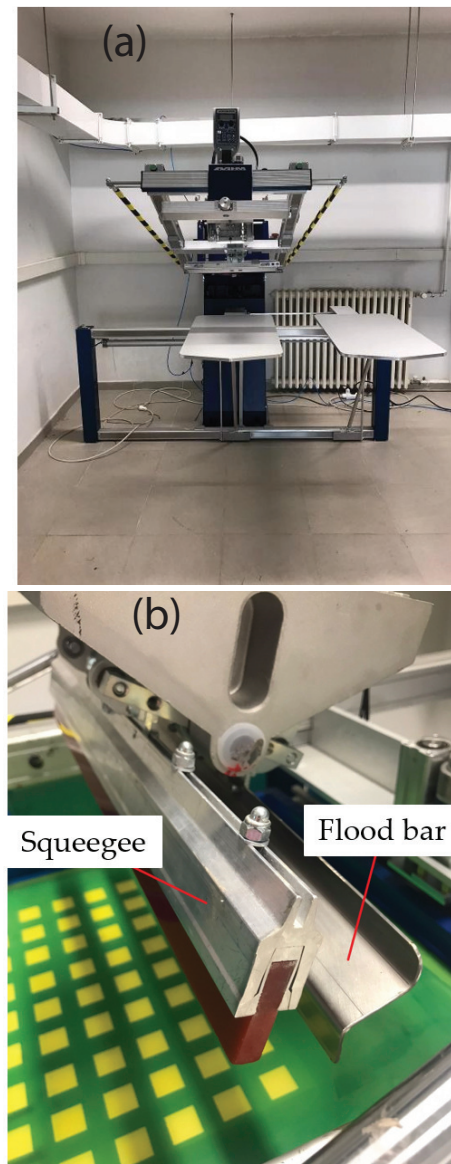


Figure 2. MHM Single Print double pallet screen-printing machine (a) front view, (b) side view.

sensor has thickness of $120\ \mu\text{m}$. Fig. 4 provides a schematic representation of the fabrication process.

Characterization and Analysis of RFT Sensors

Within the scope of the calibration studies, firstly, by applying a known force to the surface of the sensors, its relationship with the resistance was observed. Force data were obtained with an Electric motor SJY-1000-700 dynamometer which is capable of measuring 0-1000 N mounted on a translational stage and resistance data were obtained with a GW Instek LC-6020 LCR meter. Signals were collected using a DAQ (NI cDAQ-9174 from National Instruments) to monitor the mass dependent voltage variation in real time. All experiments were carried out at room temperature.

To monitor the measurement values, an interface has been developed on LabVIEW to take instant measurements from the produced RFT sensors. Via LabView and NI Daq, the user can monitor the voltage change continuously depending on the change in the measuring resistor (RM) resistance

and the mass placed on the RFT sensors. RM ranging from 560 to $4.7\text{k}\ \Omega$ were used to find the range in which the RFT sensors manufactured can work well. Each RFT sensor had its own RM resistor value. To obtain the voltage-force characteristics of the RFT sensors, measurements were taken by changing the RM resistors in the circuit and placing six 200 g masses on the RFT in order. The reason for changing the resistor here is to help producing the desired output voltage with the op-amp. The correct selection of the feedback resistor determines the sensitivity, accuracy, and noise level of the measured signal. In addition, 8V was given for the circuit to operate, and the resulting change could be monitored instantly on the front panel. When the measurement was finished, the data were saved and the voltage changes corresponding to the mass were taken from there. Afterwards, these data were processed via Excel and voltage-force graphs were obtained by graphing commands via MATLAB. A schematic representation of the test setup is given in Fig. 5.

The force-resistance relationship obtained by the characterization studies can be observed in Fig. 6. Due to the fact that each sensor has its own resistivity, starting and ending resistance points of sensors vary. To prevent this, resistance values can be mapped between 0 and 1 and as a result the Force vs Resistance curves were obtained; see 6(a). Considering 8 RFT sensors fabricated, the dead-zone end threshold occurs approximately at 30N (6(a)) while saturation begins approximately at 900 N (Fig. 8). As seen in this figure, resistance values of each sensor show a decreasing trend as applied load increases. The custom-made sensors behave similarly to the commercial sensor [19], which is also shown in Fig. 6. The sensors generally exhibit a *semi-linear* behavior for load values ranging from 0 to 100 N. Here, *semi-linear* refers to an initially linear response followed by a slight nonlinearity, which is still predictable and shows measurable variance. The RFT sensor is composed of pressure-sensitive carbon ink, sandwiched between conductive polymers. At low forces, the contact area is small. As the force increases, more microcontacts engage, and the resistance drops rapidly. Therefore, there is a steep response at the beginning. Besides, the sensing material, a polymer composite, also exhibits viscoelasticity, which contributes to the nonlinearity.

At high forces, the sensors approach a saturation point because most contact pathways have been established, and additional forces will not significantly affect the resistance. This semi-linear behavior and saturation after a certain point of force are common in both custom-made and commercial sensors. While it was not possible to consistently acquire measurements at extremely low forces because of experimental limitations, the tested force range aligns well with the usual loading conditions encountered during exoskeleton operation. Additionally, the sensor's response within this range correlates well with data from commercial resistive force transducers, demonstrating the practical reliability of the sensor design and its measurements. Beyond 100 N, the sensors tend to become less sensitive to additional loading, with their resistance values converging to a range of $0\text{--}2.5\text{k}\ \Omega$. It is crucial to note that while the sensors yield similar results, each sensor has unique characteristics.

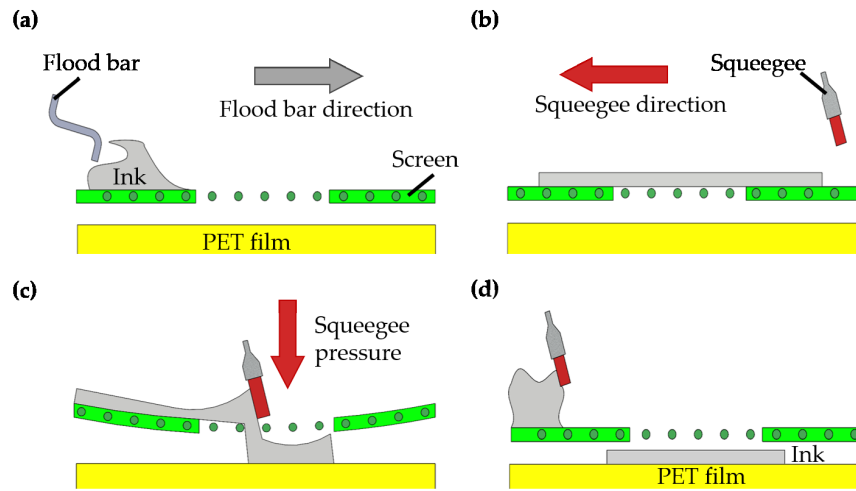


Figure 3. Schematic of the production procedure with screen printing machine: (a) flood bar spreads the ink over the stencil, (b) squeegee makes its motion along the opposite direction of the flood bar, (c) In the specified pattern region, ink penetrates through the opening in the screen and passes onto the PET film, (d) printing procedure completed and residual ink taken away by the squeegee.

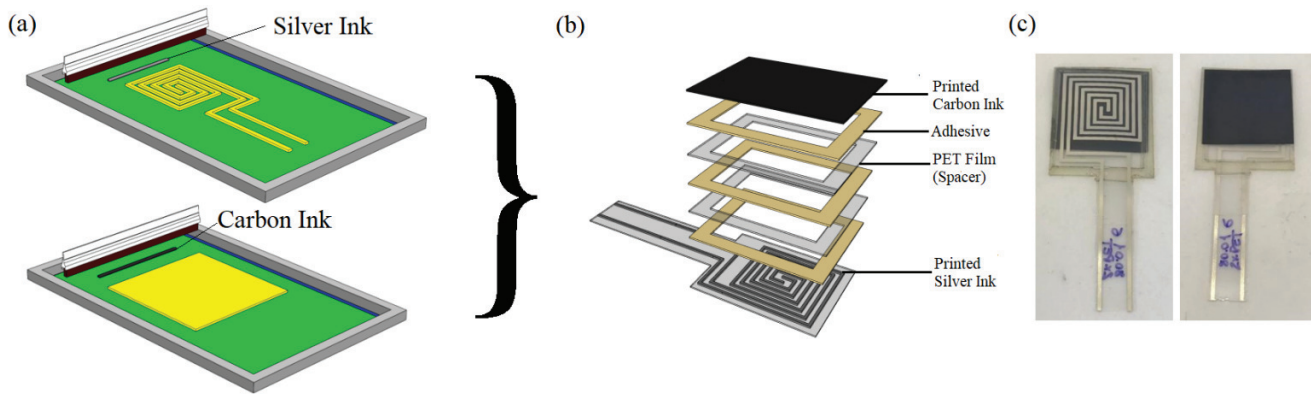


Figure 4. Fabrication of RFT sensors: (a) Screen printing on PET layers using carbon ink and silver inks, (b) Merging the layers with adhesive and spacer PET films cut using laser cutter, (c) Front and back view of the fabricated RFT sensors.

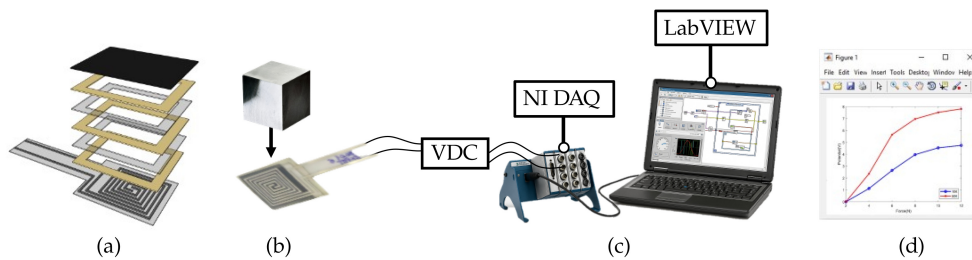


Figure 5. Test Set-up of RFT sensors: (a) Layers of RFT sensors, (b) Putting mass on the RFT sensors, (c) Connecting the RFT sensor to the voltage divider circuit (VDC), collecting data with NI Daq and displaying it in LabVIEW via PC, (d) Saving the obtained data as an excel file, plotting the voltage value corresponding to the force graphically via Matlab.

Therefore, calibration is essential before deploying these sensors in any application to ensure accuracy and reliability.

As displayed in Fig 7, the analysis of repeatability across the eight sensors indicates that the level of applied force influences variability. At low forces (30–50N), the differences between the sensors are more pronounced, with standard deviations reaching approximately 0.30, which corresponds to nearly 50% of the mean. In the mid-force range (100–200N), the variation decreases, with standard deviation values ranging from 0.03 to 0.08, representing approximately 30–40% of the mean. At higher forces

(500–1000N), the responses from the different sensors converge, resulting in very low variation, with standard deviations falling below 0.01.

As a further investigation, the ohmic characteristic compliance was tested over the values read from the sensors under voltage between -10 V and 10 V; see Fig. 8. In this context, since the product of resistance and current is equal to voltage according to Ohm's law, it is aimed to determine the electrical behavior and performance of the sensor from this equation. The "Current vs Potential" values under different loads show good linearity as depicted in this figure.

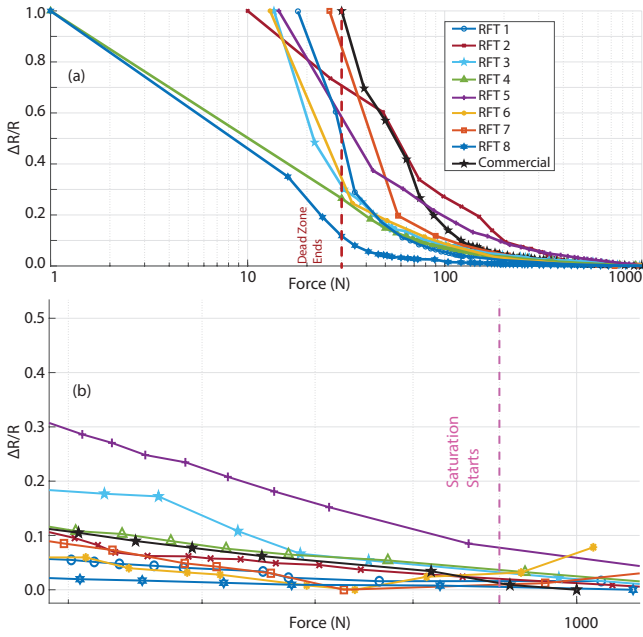


Figure 6. (a) Logarithmic plot of force versus normalized resistance, highlighting the dead-zone region at the low-force end. (b) Logarithmic plot of force versus normalized resistance, showing the onset of saturation.

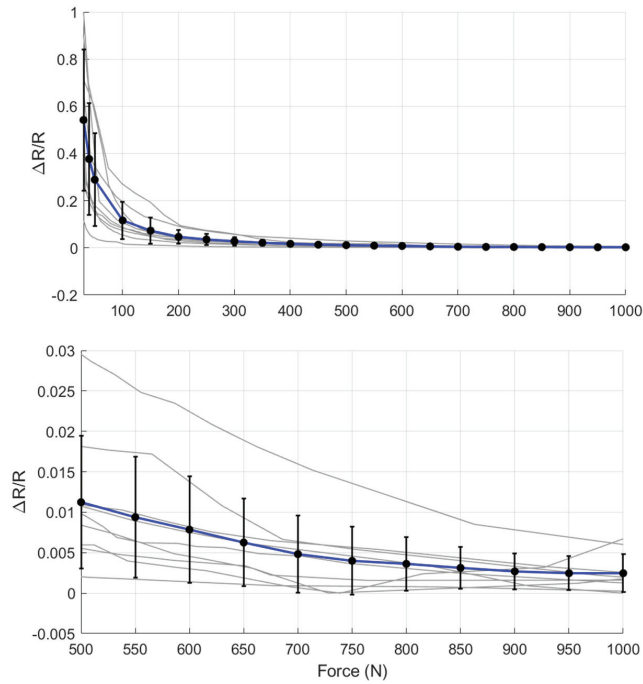


Figure 7. Top: Individual responses of eight sensors (gray lines) and the mean response (blue line) between 30 N – 1000 N. Bottom: Standard deviation values for high forces (> 500 N). Error bars represent the standard deviation across sensors at selected forces, demonstrating measurement repeatability.

To demonstrate the sensitivity of the produced RFT sensors, a finger touch-release motion was practiced on one of the RFT sensors. As can be seen in 9, the touch-release status was successfully displayed on the graph waiting for a certain time interval just after taking the finger off the sensor and also, it can be observed that the RFT sensor can detect finger tap-and-release gestures in rapid succession.

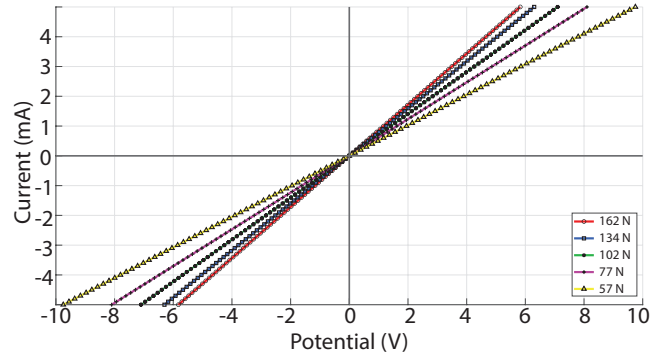


Figure 8. Potential vs Current graph under -10 V to 10 V for a RFT sensor.

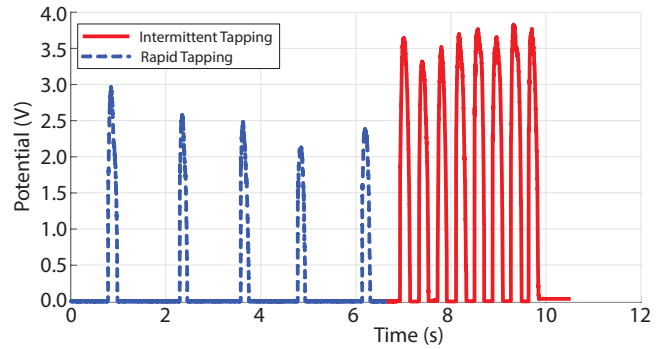


Figure 9. Touch-release status motion performed in certain time intervals and successively in a rapid manner.

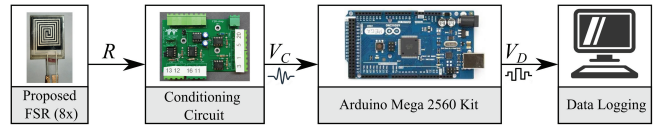


Figure 10. Electronics hardware setup block diagram. The symbol R indicates electrical resistance, V_C refers to continuous voltage, and V_D symbolizes discrete voltage.

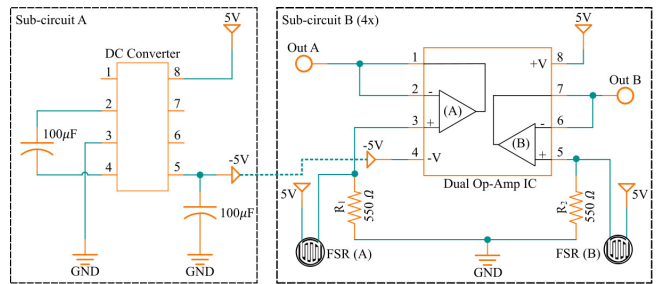


Figure 11. Conditioning circuit schematic diagram.

Hardware Setup

The hardware setup block diagram used to establish the interface between the proposed RFTs and a PC is shown in Fig. 10. The shown hardware setup is used to perform the proposed RFTs calibration and experimental verification. Eight proposed RFTs were connected simultaneously to an Op-amp-based, custom-made conditioning circuit. The schematic of the circuit is shown in Figure 11 and is composed of two main sub-circuits:

Sub-circuit A implements a DC voltage inverter using the ICL7660 integrated circuit. This inverter generates a -5 V

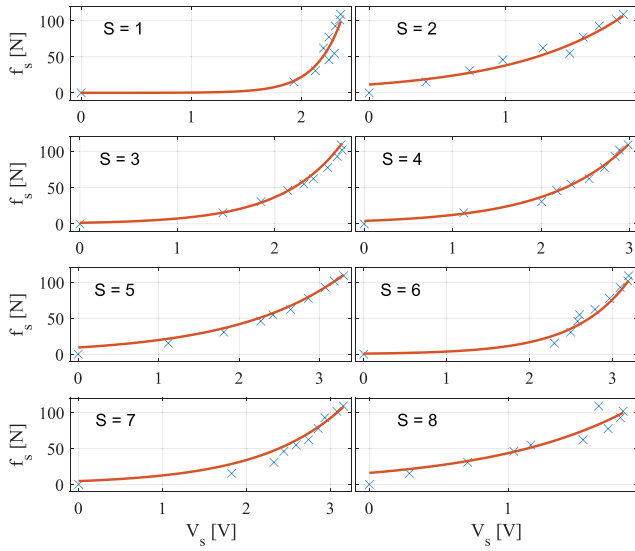


Figure 12. Measured voltage data points versus the applied force and the curve fitted function.

supply from a 5 V input, enabling the use of a dual-supply op-amp configuration. The ICL7660 delivers up to 20 mA, which is well above the ~ 12 mA required by the CA3240EZ op-amp used in the circuit.

Sub-circuit B performs both voltage conversion and signal buffering. Each RFT is connected in a voltage divider configuration with a fixed $550\ \Omega$ resistor. The resistor value was empirically chosen to ensure an optimal balance between voltage sensitivity and current safety across the expected force range (0–100 N). Based on the resistance characteristics of the commercial RFTs (typically $\sim 10\ \text{k}\Omega$ at rest, ~ 50 – $100\ \Omega$ at full load), this configuration results in an output voltage range of approximately 0.2 V to 4.8 V. This range efficiently utilizes the input range of 5 V-tolerant ADCs, maximizing resolution.

The voltage output from the divider is then buffered using a CA3240EZ op-amp configured as a unity-gain follower. This op-amp offers high input impedance and ultra-low input bias current ($\sim 50\ \text{pA}$), ensuring signal stability and preventing voltage drop due to loading. Empirical results confirmed that the proposed RFTs produce an analog voltage signal ranging approximately from 0.288 V to 3.3 V for applied forces up to 100 N.

The conditioning circuit generates analog continuous voltage signal V_c through 8 analog output channels within the (0 $\sim$ 5 V) range relative to the applied forces on the RFTs. The analog signals are transmitted to the 8 analog input terminals on the Arduino Mega 2560 kit; see Fig. 10. The analog input terminals are internally connected to an analog-to-digital converter with a 10-bit resolution and a reference voltage of 5 V. The discretized signal V_D is transmitted to the PC via the USB port at 0.1 Hz. The data are further recorded and monitored using the Data Streamer tool in an Excel worksheet on a PC.

Calibration

Recent studies have found similar exponential behaviors in polymer-based and flexible resistive flexible transducers (RFTs). These behaviors occur because the conductive

Table 1. Fitting equation coefficients (a, b) for each RFT.

RFT	1	2	3	4	5	6	7	8
a	5e-3	11.5	1.5	4.1	9.3	0.8	4.6	16
b	4.2	1.2	1.6	1.1	0.75	1.52	1	1

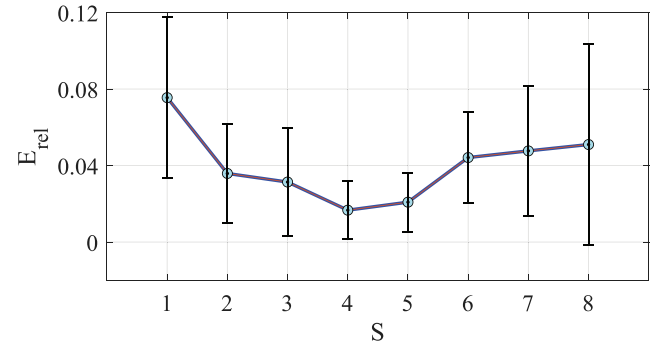


Figure 13. Curve fitting functions relative error.

pathways develop over time and the sensing layer can be compressed, leading to nonlinear electrical responses [49, 50]. When comparing different models, the exponential model is more straightforward than logarithmic models used for thin-film RFTs [50] and power-law models suitable for composite-based transducers near the percolation threshold [49]. The exponential model offers a good balance of simplicity and fit quality. It also reduces the risk of overfitting that can happen with more complex polynomial models, making it a practical choice for applications such as soft robotics and wearable systems.

The RFTs are calibrated by applying different forces using a set of identified weights. The corresponding voltage for every applied force to each RFT is obtained using the previously discussed hardware setup. The resulting measured voltage values corresponding to each applied force are shown in Fig. 12 using blue crosses. The solid orange line shows the fitted curves using an exponential regression function $f_s = ae^{(bV_s)}$, where f_s and V_s are each RFT force and voltage signal, respectively. This exponential behavior reflects the intrinsic nonlinear decrease in resistance of RFTs under applied load, which is typical for this type of sensor. The curve fitting function parameters for every RFT are shown in Table 1.

To evaluate the calibration quality and repeatability more clearly, the relative error for the curve fitting functions concerning the measured values is presented in Fig. 13. In this figure, the circular markers indicate the relative error mean for each regression function, while the error bars represent the standard deviation, thereby providing the requested statistics on repeatability. The obtained relative error average values indicate a maximum value less than 8%, while the maximum error is less than 12%. As a result, the regression functions could successfully model the proposed RFT performance combined with the conditioning circuit.

Results and Discussion

Repetitiveness

To evaluate the repetitiveness capability of the proposed RFT, a series of experiments were conducted using the test

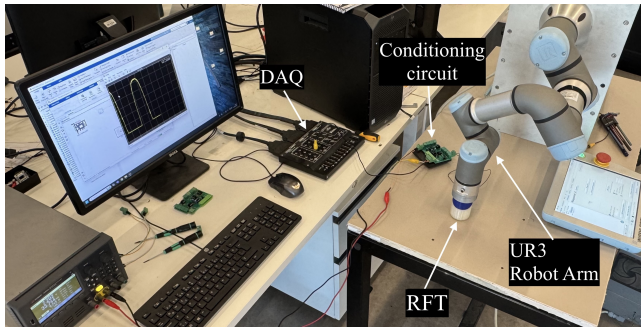


Figure 14. Experimental setup used for repetitiveness testing. The system includes a UR3 robot arm, a rigidly mounted RFT specimen, a conditioning circuit to convert resistance changes into voltage signals, a Quanser data acquisition system, and a host PC for data collection and analysis.

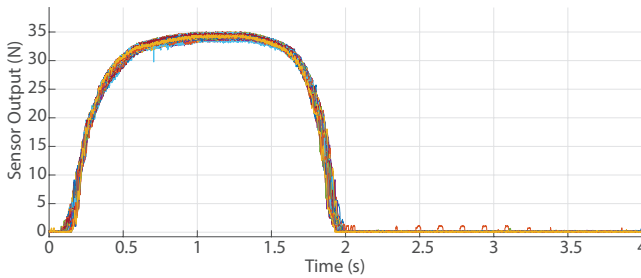


Figure 15. Overlay of force response cycles during repetitiveness testing. The high degree of overlap among cycles indicates excellent consistency in the sensor's response under repeated loading.

setup illustrated in Fig. 14. The setup consists of a UR3 robot arm, a conditioning circuit, a host PC, and a Quanser data acquisition system. One of the RFT specimens was rigidly mounted to allow physical interaction with the robot arm. The conditioning circuit, as described in the previous section, was used to convert resistance variations into voltage signals. These voltage signals were then transmitted to the host PC via the data acquisition system for recording and analysis.

For the repetitiveness test, the robot arm was programmed to apply a vertical downward force of 35 N in a controlled manner—gradually increasing and decreasing over a period of 2 seconds—followed by a 2-second interval with no applied force, resulting in a complete 4-second cycle. The experiment was repeated over an extended duration to ensure the collection of a representative dataset. The results are shown in Figs. 15 and 16, where overlaid force cycles and the corresponding mean $\pm$ SD (standard deviation) values are presented.

As illustrated in Fig. 15, the individual cycles exhibit strong consistency, with no noticeable deviation. The mean root mean square error (RMSE) was calculated as 0.0783 N. In addition, Fig. 16 demonstrates minimal variation across cycles; the mean correlation coefficient was found to be 0.9989. These findings clearly demonstrate the high repetitiveness performance of the proposed RFT.

Co-Ex Description

The proposed RFTs were verified using the built-in-house lower-body bipedal exoskeleton Co-Ex. The robot is shown

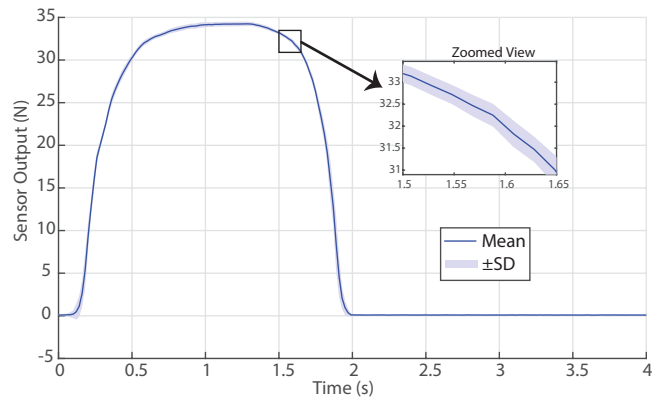


Figure 16. Mean force response with $\pm$ SD bands across multiple cycles. The narrow deviation bands and high correlation values confirm the reliable and repeatable performance of the proposed RFT.

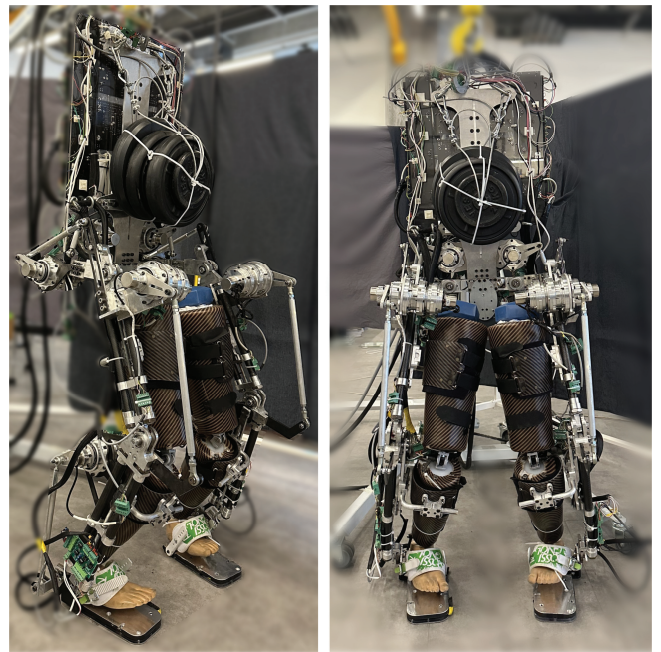


Figure 17. Lower-body exoskeleton Co-Ex, while supporting a dummy manikin with passive joints.

in Fig. 17 while supporting a heavy dummy. Co-Ex possesses four active joints for each leg distributed as follows: two joints rotate along hip abduction/adduction and flexion/extension axes, one joint rotates along knee flexion/extension axis, and one last joint rotates along ankle dorsi plantar/flexion axis. Co-Ex can perform self-stabilized squatting and swaying motions as demonstrated in [51]. Co-Ex has several proprioceptive sensors to measure the joint states and torques, pelvis spatial motion, and contact forces in Co-Ex feet.

Co-Ex foot Structure

Co-Ex foot consists of three main layers sandwiching an array of RFT sensors (Interlink FSR UX 402), which is used to measure the contact force and zero moment point (ZMP); see Fig. 18(a). The RFTs are sandwiched between metal and acrylic plates as shown in Fig. 18(b). A rubber layer is attached to the acrylic plate to eliminate the contact slippage

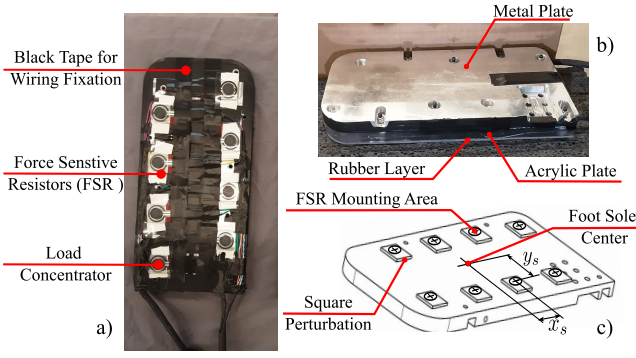


Figure 18. Co-Ex foot structure. Using plexiglass layers, we used a distributed architecture both for the proposed RFTs (middle layer) and for the commercial RFTs (Interlink FSR, outer layer).

between the supporting foot and the ground. The proposed RFTs are compared to the commercial RFTs used in Co-Ex by mounting 8 proposed RFTs in correspondence to the commercial RFTs and sandwiching both by the metal and acrylic plates.

ZMP Computation

The ZMP for the contact foot is computed as a ratio between the vertical contact force F_z and the tangential contact moments M_x and M_y acting in x and y directions, respectively. The contact force components are computed using the RFTs force signal f_s as follows:

$$F_z = \sum_{s=1}^8 f_s, \quad M_x = \sum_{s=1}^8 f_s y_s, \quad M_y = \sum_{s=1}^8 f_s x_s, \quad (1)$$

where x_s and y_s are the distances between each RFT sensor and the foot sole, as shown in Fig. 18(c). Afterward, the ZMP variation is obtained using the contact force components as below:

$$x_{zmp} = \frac{M_y}{F_z}, \quad y_{zmp} = \frac{M_x}{F_z}, \quad (2)$$

where x_{zmp} and y_{zmp} are the Cartesian position of ZMP concerning the foot sole.

Experimental Verification

The proposed RFTs were verified using the Co-Ex's self-balancing squatting capability. The ZMP signal is measured using the commercial and proposed RFTs while Co-Ex performs different squatting motions.

Fig. 19 shows the measured ZMP during a squatting experiment using commercial and proposed RFTs in solid blue and orange lines, respectively. Both signals showed consistent matching performance with minor deviations. As a result, the proposed RFTs can accurately measure the actual dynamic force. Moreover, it showed a good performance while measuring ZMP, which is a crucial measurement for legged robots and a portion of exoskeleton applications.

For thorough verification, the matching between proposed and commercial RFTs ZMP signals for three different squatting motion patterns is evaluated using Pearson's correlation coefficient. The squatting motion patterns were

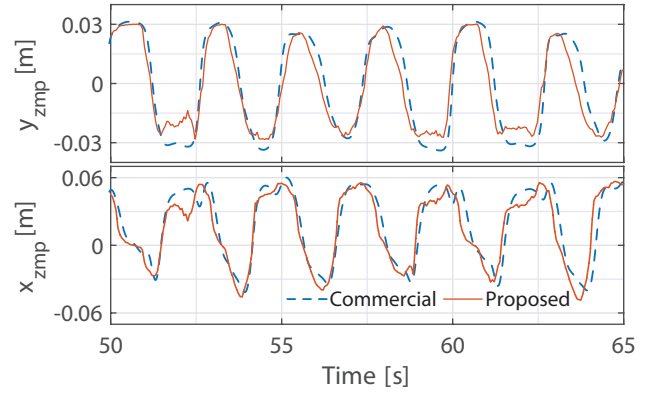


Figure 19. Proposed versus Commercial RFTs measured ZMP.

Table 2. Correlation Coefficient of ZMP matching between proposed and commercial RFTs.

	$r(x_{zmp})$	$r(y_{zmp})$
Amplitude: 3.5 cm	0.82	0.93
Amplitude: 4 cm	0.86	0.90
Amplitude: 5 cm	0.84	0.90

performed at 0.5 Hz and 3.5, 4, and 5 cm amplitudes. MATLAB function *corr2* is used, which returns a scalar value between 1 and -1. As much as a result approaches 1 or -1, the input variables are positively or negatively correlated linearly. The input variables are uncorrelated as long as the function result approaches 0. The resulting correlation coefficient r for the three squatting experiments is tabulated in Table 2. The correlation coefficient r approaches 1 for the measured ZMP in all motion patterns in either x – direction $r(x_{zmp})$ or y – direction $r(y_{zmp})$. Accordingly, the proposed RFTs could provide realistic measurements that match the commercial RFTs' results over a wide range of motion and applied forces.

Statistical Analysis

To evaluate the similarity between the proposed and commercial RFTs, force measurements collected during three squatting experiments were statistically analyzed. The evaluation metric was defined as the average reading of each RFT across the three experiments. A Repeated Measures ANOVA was selected to rigorously assess the consistency of RFT readings across the experiments [52]. This method is appropriate for datasets involving repeated measurements for the same subjects (in this case, RFTs) across multiple experiments.

Given that repeated measures ANOVA assumes normally distributed data, and considering the spatial distribution of RFTs across the foot sole—where the force measured may vary based on each sensor's proximity to the center of pressure (CoP)—the assumption of normality could not be made a priori. Therefore, the Lilliefors test was applied using MATLAB's *lillietest()* function to evaluate the normality of the data.

The results indicated that the readings from the first and second experiments were normally distributed, while those from the third were not. However, both sensor groups exhibited a high degree of similarity even in the third

(excluded) experiment, as evidenced by the correlation coefficients presented in Table 2.

Accordingly, only the data from the first and second experiments were included in the statistical analysis using repeated measures ANOVA, conducted via MATLAB's *ranova()* function at a significance level of $\alpha = 0.05$, to test for significant differences between the two sensor types. The analysis revealed no statistically significant difference between the proposed and commercial RFTs, $F(1, 7) = 0.00116, p = 0.9738$.

Subsequently, a post hoc test with Bonferroni correction was conducted using the *multcompare()* function. An adjusted significance level of $\alpha = 0.167$ (i.e., $0.05/3$) was applied. The results are summarized in Table 3.

The p-Value and t-Value parameters for pairwise comparison is reported in Table 3, columns 3 and 4, respectively. The first and second columns show the mean difference, $\Delta\mu$, and mean squared error, σ_{Δ}^2 , of the two RFTs in comparison. The last two columns display the 95% confidence interval (CI) for the mean difference between the two braces.

The analysis revealed an insignificant change in average metrics values when proposed RFTs ($M = 24.3658, SD = 18.6801$) was used, compared to commercial RFTs ($M = 24.3202, SD = 18.3640$). The results indicate that the proposed RFTs are statistically like the conventional RFTs.

Conclusion and Future Work

In conclusion, screen printing has proven to be a cost-effective and scalable technique for fabricating flexible pressure sensors, offering significant advantages in terms of precision, customization, and large-scale production. By optimizing parameters such as mesh density and squeegee pressure, the performance of the sensors can be fine-tuned to meet diverse application requirements.

In this study, we fabricated the proposed sensors and integrated eight of them into our lower body exoskeleton system to measure the center of pressure, a crucial parameter for maintaining balance. Through a series of self-balanced squatting experiments, the center of pressure measurements obtained using our sensors showed excellent agreement with those from commercialized Resistive Force Transducer (RFTs). This demonstrates the robustness and reliability of the proposed sensors and highlights their broad applicability in wearable robotics, particularly in exoskeleton systems.

The custom RFTs show significant promise for wearable applications like exoskeletons; however, there are several limitations that need to be addressed. One major concern is the sensors' long-term stability under repeated stress and changing environmental conditions, such as temperature and humidity, which could lead to variations in sensor response over time. Additionally, while the current fabrication method works well for prototyping, it may

encounter issues with scalability and consistency in larger production runs, particularly in terms of achieving uniform material distribution and reliable mechanical bonding. Going forward, we will focus on measuring drift and hysteresis through prolonged cyclic testing, as well as refining the formulation and deposition methods for mass production. We also intend to explore encapsulation techniques to improve environmental durability and assess printed or roll-to-roll fabrication approaches to enhance production efficiency.

Moreover, assessing the microstructural characteristics and percolation threshold of the conductive material would yield important insights into the foundational functioning of the sensor. Therefore, SEM imaging, analysis of conductivity versus filler ratio, or dynamic percolation studies will be incorporated into the future research as the material-level factors contributing to sensitivity and nonlinearity are being further investigated. To date, we have focused on the static and quasi-static characterization of the sensors, which is sufficient for our exoskeleton application given the relevant force ranges and loading conditions. However, the dynamic response of our sensors will be evaluated and real-time applications will be explored in future work.

In this study, we focused on analyzing the resistance values obtained from the LCR meter, as these are directly related to the proposed transducer's working principle. However, we did not include the full impedance spectra, which provide information on both magnitude and phase as a function of frequency. Future work will employ impedance spectroscopy to gain deeper insights into the detailed electrical characteristics of the devices. In addition, this study primarily examined the force-response behavior and reproducibility of the sensors, but did not address hysteresis effects. Systematic hysteresis measurements will be included in future research to more comprehensively assess the long-term reliability of individual devices.

Currently, we are investigating various geometric dimensions and material configurations of the RFTs to optimize their sensitivity, durability, and application-specific performance. Future improvements will also explore the integration of these sensors into larger systems—such as exoskeleton braces, medical assistive devices (e.g., smart crutches), robotic grippers, and legged robot feet. These developments aim to enhance long-term stability, and enable scalability for broader production, ultimately contributing to more compact, robust, and functionally integrated mechatronic platforms.

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$\Delta\mu$	σ_{Δ}^2	p-Value	t-Value	Lower bound	Upper bound
0.0457	14.397	0.9738	0.0340	-3.1265	3.2178

Table 3. Repeated Measures ANOVA results comparing the proposed and commercial RFTs.

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