**Recent Advances of a Wearable Sensing Glove and Sensory Feedback Device for Rehabilitation and Improved Control of Impaired Upper Limbs and Prostheses**

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**Abstract**

Recent technological advancements in soft actuators, flexible electronics, and data acquisition systems have enabled the creation of a portable, low cost, and unobtrusive wearable sensing glove that is can be used in conjunction with a sensory feedback device. The combination of a wearable sensing glove and a sensory feedback device advances the status quo in healthcare, prosthetics, robotics, and virtual reality applications. This application has emerged as a promising paradigm to enhance the care provided to patients with neurological and musculoskeletal conditions. This paper includes the most up-to-date materials, sensors, actuators, and system-packaging technologies used to develop a wearable sensing glove and sensory feedback device. Details of the mechanical, electrical, system architecture, and material properties are discussed regarding their application in healthcare, prosthetics, and rehabilitation. The limitations of the current methods and technologies are discussed, as well as the key challenges and the future direction of these technologies. Overall, this paper presents an all-inclusive review of the technologies used to develop a wearable sensing glove and a sensory feedback device.

**Keyboards:** Wearable sensor glove, Sensory transfer device, Sensor glove, Data glove, Feedback device

**1. Introduction**

During the last half century, technology has rapidly advanced allowing us to build wearable devices to measure, enhance, and improve the interactions between our body and the environment. Out of all our body parts, our hands are one of the most important tools we use to interact with and manipulate our environment. For that reason, researchers have developed a wearable sensing glove (WSG), which is a wearable device worn on the hand that includes sensors to measure the interaction between our hands and the surrounding environment. A WSG can utilize a sensor to measure some of the following parameters: motion, position, temperature, pressure, contact, relative finger location, and various other variables.

Numerous applications have arisen over the past thirty years that require the use of a WSG. However, there is a large and growing need for a device to transfer or replicate the sensory information read from the sensors on the WSG to another part of the body. The need for this device, used in conjunction with a WSGs, arises from users who have a form of sensory impairment. Sensory impairment is a symptom of a variety of neurological conditions such as spinal cord injuries (SCI), cerebral palsy, peripheral neuropathy, sclerosis, and diabetes. Additionally, individuals with a prosthetic who have had a limb amputation face a similar issue as those with a form of sensory impairment; they are currently unable to sense or feel using their prosthetic. The lack of tactile, proprioceptive, and temperature feedback from a limb (whether human or artificial) often leads to a feeling of disembodiment over the limb. This results in the reduced use of the limb or rejection of the prosthetic all together [Design and evaluation of a sensory...][7].

Currently, patients with a form of sensory impairment rely solely on vision as a feedback mode to determine the state of their limbs, which can be very cumbersome for them [4]. To combat these problems, researchers have developed a sensory feedback device (SFD), which transfers and/or replicates the sensory feedback experienced on one part of the body to another part of the body. This feedback mechanism compliments a user’s visual feedback to enhance their experience while interacting with their environment. The need for a device that can communicate the sensory and physical states of a sensing-less limb is evident.

This literature review provides an extensive survey of all the technologies used in WSGs and SFDs to provide readers with a broad overview on how these technologies can be used in tandem. Additionally, this literature review identifies the advantages and drawbacks of each technology and the potential room for improvements. The motivation for writing this literature review stems from the observation that the important information on WSGs and SFDs are scattered across numerous engineering, commercial, and scientific pieces of literature. Overall, we hope to inform the non-specialist reader who is interested in using a WSG and SFD for their application.

**2. Wearable sensor glove**

The first portion of this literature review focuses on the recent advancements in WSG technology. To provide some context the reader, a WSG is the optimal wearable device to monitor the interaction between user’s hands and their environment. It has the ability to simultaneously measure different sensors to increase the accuracy and repeatability of measurements (Pasquale 2018). WSGs have been around since the 1980s with one of the first commercial products being the Nintendo Power Glove releasing in 1989 (Francisco 2020). To document the advancements in WSGs, literature reviews, like the one you are reading, have been conducted throughout the decades. The first prominent literature survey on wearable sensing gloves was conducted by Dipietro in 2008 (Dipietro et al. 2008). Since then, there has been a rapid acceleration in the technology used to make WSGs. For this reason, there is a growing need for literature reviews on WSGs to be more focused, as they can be used to detect anything from fentanyl (Barfidokht et al. 2019) to diverse biomarkers (Bariya et al. 2020). If the reader is looking for an application-specific survey for WSGs, there are few resources available to guide their research. The following literature surveys on WSGs for specific applications are available for review: medical applications (Pasquale 2018), hand joint monitoring for rehabilitation (Rashid and Hasan 2019), sign language recognition between (Ahmed et al. 2018), hand pose estimation (Chen et al. 2020), hand gesture recognition (Premaratne 2017).

To provide readers with a more focused literature review, this paper is focused on reviewing WSGs that implement pressure, temperature, and strain sensors. These sensors measure the main interaction individuals with sensory impairment disorders need to have transferred to another part of their body. This paper will survey academic papers, commercial products, and Do-It-Yourself (DIY) projects to highlight the manufacturing method, application, and characteristics of the sensors used. The advantages and drawbacks of the technologies used are highlighted to identify potential room for improvements and the future direction of WSGs will be discussed to guide readers in their research development.

**2.1. Wearable sensing gloves applications**

WSGsare used in a multitude of applications, and the number of applications continues to grow as the technology used to make them improves. In 2008, Dipietro created a summary table to detail the uses for WSGs. This table documents possible applications, fields, rationale for their use, the device used instead of a WSG, and their purpose. Dipietro divided the applications into two main categories: classical and recent. In the classical category, Dipietro choose to select the following applications: design and manufacturing, information visualization, robotics, arts and entertainment, and sign language recognition. Dipietro choose to categorize healthcare and computers in the recent category (Dipietro et al. 2008). **Table 2** is an updated version of this prior work and it includes more modern applications that have arisen from technological advances. The “classical” application category has been redefined to the following list: design & manufacturing, information visualization, arts & entertainment, sign language recognition, and computer. The “recent” application category had been redefined to the following list: virtual reality, health care diagnostics, prosthetics, robotics, and artificial intelligence. As the commercially available, DIY, or academic version of the WSGs are discussed, their application is described.

**2.2. Commercially available wearable sensor gloves**

While numerous WSG designs have been proposed over the past 40 years, only a few products have become commercially viable. The WSGs on the market today integrate a myriad of different sensors. A few notable examples of WSGs that use sensors that are worth mentioning, but are not applicable for this literature review, are the Noitom Hi5 VR Glove (Noitom 2021) that uses an internal measurement unit (IMU) for motion recording, the Workaround ProGlove (Workaround 2021) that uses an industrial bar-code reader for inventory tracking, and the SenseGlove that provides force-feedback for VR training (SenseGlove 2021). Rather this section of the literature review will focus on commercially available products that implement either temperature, pressure, or strain sensors into a WSG.

There are a very limited number of commercially available WSGs that integrate temperature sensors. The SensPro 8108 by Holik International use an infrared thermometer and contact temperature sensors. These sensors are built into a protective glove for firefighters to warn them that the temperature of objects they are touching is too hot (SensPro 2021). The lack of commercially available products that integrate a temperature sensor highlights a potential market opportunity.

Unlike wearable sensing gloves that integrate temperature sensors, there are numerous commercially available WSGs that integrate pressure sensors. **Fig. 3** is provided to help the reader visualize what products are available. Most WSGs that integrate pressure sensors are designed to quantify the ergonomics of a product. The “Pliance Glove” by Novel GmbH, shown in **Fig. 3A,** uses 256 capacitance-based pressure sensors and it records data at a sampling rate of 20,000 samples per second. Tt can additionally be used during physical therapy to assess the severity of a patients injury and aid the patient’s rehabilitation (Novel 2021). The “Finger TPS” by Medical Tactile Inc includes a capacitance pressure sensor on the fingertip of the glove (PPS 2021a). The “TactileGlove,” also by Medical Tactile Inc, includes capacitance pressure sensors throughout the entire glove – fingers to palm, as shown in **Fig. 3G** (PPS 2021b). The “Glove Pressure Mapping System” by Vista Medical, Ltd is has various pressure sensors mounted on the hand at different locations. An image of the glove is shown in **Fig. 3L** (Vista Medical). The “Peregrine Glove ST” by Peregrine has 17 touch point contact sensors (5 touch sensors per long finger and 2 touch sensors on the small finger) as shown in **Fig. 3I**, and it primarily used for computer interaction and VR applications (Peregrine 2021).

The bulk of the commercial WSGs integrate strain sensors for various applications. The largest applications for WSGs that use strain sensors are virtual and augmented reality and computer control, and the following products are designed for these applications. The “VMG 8” by VRealities LLC uses one embedded strain sensor per finger to accurately measure the finger movements as shown in **Fig. 3B** (Virtual Realities 2018). The “MoCap Pro” by StretchSense uses multi-segmented splay sensors to detect the bending of each knuckle as well as the lateral spread as shown in **Fig. 3C** (StretchSense 2021). The “CaptoGlove” by CaptoGlove Inc includes a bend sensor for each finger as shown in **Fig. 3E** (CaptoGlove 2020). The “Manus Prime II Haptic” by Manus VR includes a bend sensor in each finger and provides haptic feedback, as shown in **Fig. 3J** (Manus-VR 2021). The “5DT Data Glove 5 Ultra” by 5DT Technologies includes a bend sensor on each finger as shown in **Fig. 3K** (5DT 2021). The “BeBop Forte Data Glove” by BeBop Sensors includes a bend sensor on each finger and has haptic feedback in the glove, as shown in **Fig. 3F** (BeBop 2021). There are a few products that target different applications. The “Flexpoint USB Glove Kit” by Flexpoint Sensor Systems includes a dual segment bend sensor for each finger as shown in **Fig. 3D**. This glove can be used for a variety of medical applications; determining a patient’s level of monitor skill, post-surgery evaluation, and assisting the disabled (Flexpoint 2021). The “Smart Glove for Home” by Neofect USA includes a bend sensor for each finger. This glove is primarily used as a medical device to quantify the movements of one’s hand to better promote repetition to improve motor function for stroke patients and those suffering from sensory impairment (Neofect 2021). The “MiMu Gloves” by Mi Mu Gloves Limited includes a bend sensor in each finger as shown in **Fig. 3H**. This glove is used as a wearable musical instrument for expressive creation, composition, and performance (MimuGloves 2021).

These commercially available WSGs provide the reader with a broad overview of what features and sensors have been implemented in WSGs at a production level. Additionally, this section should assist the reader by allowing them to understand what WSG they could purchase to accomplish their research goal.

**2.3. Do-It-Yourself wearable sensor gloves**

This section of the paper focuses on Do-It-Yourself (DIY) versions of WSGs, and the manufacturing methods engineers and artist use to make these devices differs dramatically from commercial and academic versions. With hand tools and minimal equipment, these designers are still able to build a WSG that accomplishes their proposed task. **Fig. 4** is provided to help the reader visualize what WSGs are possible to make without expensive equipment. These projects should provide readers with an interest perspective on what is possible using a WSG.

User ‘Zack Freedman’ on Thingiverse was able to build the “Parametric Data Glove” by 3D printing ring-like fixtures to secure off-the-shelf (OTS) flex sensors on the back of the finger. This design exposes the fingers and the palm, and this low friction design maximizes the user’s maneuverability as one can see in **Fig. 4A** (Freedman 2016). User ‘vu2aeo’ from Instructables built a low-cost WSG using OTS flex sensors on the back of the hand. An Arduino then reads the flex sensors and controls a robotic hand to mimic the movements of the user’s hand as shown in **Fig. 4B** (vu2aeo 2021). User ‘Will Donaldson’ from Instructables used velostat as a piezoresistive material to build strain sensors to measure how much each finger bends as shown in **Fig. 3G**. An Arduino Lilypad is used to read the strain sensors and manipulate a robotic hand to mimic his hand movements (Donaldson 2021). User ‘Rachel Freire’ built a low-cost WSG using flex sensors made from resistive fabric as shown in **Fig. 4H**. These fabric sensors were read by a microcontroller on the back of the hand to control LEDs (Freire 2021a). User ‘Rachel Freire’ decided to expand on her previous project’s technology by integrating a Vive Tracker into her WSG to interact with virtual reality environments as shown in **Fig. 4E** (Freire 2021b).

User ‘Brian Benchoff’ on Instructables took a creative approach by building a WSG that can be used as a musical instrument. By blowing in a tube that is connected to a pressure sensor that is mounted to the thumb, he can increase or decrease the amplitude of a musical note. To change the musical note, he moves his fingers towards his palm and measures this movement by using OTS flex sensors on the back of the hand (Benchoff 2011). User ‘Plusea’ on Instructables built a low-cost WSG with pressure sensors on each fingertip as shown in **Fig. 3F**. The pressure sensors were made using piezoresistive Eeonyx fabric and stretchable conductive fabric. The goal of this WSG was to build a device that helps piano teachers teach children to visualize the difference between soft and hard touches (Plusea 2021). User ‘DanielE58’ on Instructables built a low-cost WSG with OTS strain sensors on each finger as shown in **Fig. 3I**. This device was designed to be used as a gesture-based input device to control one’s computer (DanielE58 2021).

User ‘emcnany’ on Instructables built a low-cost wearable sensing glove with OTS flex sensors on the back of each finger and conductive fabric to detect fingertip touches as shown in **Fig. 3D**. This WSG is designed to be used as a general I/O device and it includes haptic feedback in the palm of the hand (Emcnany 2021). User ‘Shja7942’ on Instructables built a low-cost WSG with OTS flex sensors on the back of each finger as shown in **Fig. 3C** (Shja7942 2021). This glove is designed to assist individuals who have difficulty communicating using speech. The glove recognizes hand gestures and American signed language letters and converts it to speech using a speaker (Shja7942 2021).

Overall, the DIY versions of WSGs demonstrate how artists, designers, and engineers are applying this technology to their own creative applications. The technology they use is not cutting edge, however, they are a using WSGs to solve novel problems.

**2.4. Academic advancements in sensor technology for sensor gloves**

Researchers have been developing sensors for years, however they have just recently started putting these sensors onto gloves to create WSGs. Recently, the sensors that researchers are integrating into WSGs are made using nano-manufacturing techniques and novel nano materials. These sensors have better sensitivity and mechanical properties than the sensors integrated into commercially available products. The sensors that researchers have developed for WSGs should be evaluated in detail. These prior works should assist researchers develop a WSG to meet their unique application, and hopefully companies can commercialize this technology to bring it to market.

**Fig. 1** depicts the relationship and future direction of WSG technology for the integration of a WSG with a SFD. Each section contains examples of an academic version of either a pressure, temperature, or strain sensor. The ideal properties of these sensors are listed in the inner ring and the examples presented in each section are discussed in detail later in this paper. **Table 1** provides a summary of the performance specifications these academic sensors that are used on WSGs. In this table, the material, mechanical, and electrical properties of the sensor and the application of the WSG are documented.

Through the process of conducting this literature review, it is evident that the idealized version of a WSG is an artificial ‘skin’ with flexible, stretchable sensors integrated into a thin membrane. **Fig. 2J** is an example of this artificial ‘skin’ and it contains pressure, strain, and temperature sensors made from single crystalline silicon nanoribbon (Kim et al. 2014). However, the current limitation of this type of sensor is that it cannot detect complex stimuli such as surface textures and object shape. Additionally, a large number of receptors are necessary to provide a more natural feel for prosthetics (Chortos et al. 2016). Literature reviews conducted by Chortos et al. and Li et al. provide a summary on the advances in artificial skin. These reviews provide an in-depth review of skin-inspired multifunctionality devices using flexible electronics and mechanical compliant biometric sensing platforms. Additionally, it details new materials and fabrication strategies to make these multi-functional skintronics (skin-like electronics) (Chortos et al. 2016) (Li et al. 2020a).

**2.4.1. Strain sensor**

A strain sensor is used to detect how much each finger bends when it is implemented into a WSG and there are many examples of strain sensors in academic literature. This section will detail the different methods researchers have used to make strain sensors.

A strain sensor is manufactured from a composite material made of fragmentized graphene foam (FGF) and polydimethylsiloxane (PDMS). The graphene foam is disintegrated into 200-300 um sized fragments. It shows a high sensitivity with a gauge factor of 15 to 29, high stretchability over 70%, and high durability over 10,000 stretching-releasing cycles (Jeong et al. 2015). A highly flexible, stretchable, and sensitive strain sensor based on the nanocomposite of silver nanowire (AgNW) network and PDMS elastomer in the form of a sandwich structure. This sensor has a gauge factor ranging from 2 to 14 and a stretchability up to 70%. This strain sensor was integrated onto a glove for motion detection of fingers to control an avatar in a virtual environment (Amjadi et al. 2014). A strain sensor is made from carbon paint on PDMS material with a PU encasement. Copper tape is attached to the PDMS and conductive thread is used to attach the strain sensor to the circuit elements. The entire system was constructed with less than $100 and did not require access to a cleanroom for completion. These sensors were used to wirelessly translate the American Sign Language (ASL) into text that is displayable on a computer or smartphone (O’Connor et al. 2017). A strain sensor is build using a double layer textile-based goniometer. This double layer configuration provides insight into the sample’s flexion angle independent of its bending profile. A WSG utilizes three KPF goniometers to track flexion and extension movement of the metacarpophalangeal joints of the thumb, index, and middle fingers (Carbonaro et al. 2014). A polymer-enhanced highly stretchable conductive fiber strain sensor is developed using P(VDF-TrFE) polymer nanofibers mat and silver nanowires layer. The conductive fiber sensors exhibit a high gauge factor of 5.326, rapid response of 20 ms, and an outstanding durability after 10,000 strain cycles. Additionally, the fiber strain sensor has the ability to detect bend and torsion deformation with a board sensing range as shown in **Fig. 1B** (Chen et al. 2016).

A strain sensor was fabricated using poly-vinylidene fluoride (PVDF) electro-spun nanofiber on a flexible liquid crystal polymer substrate. PVDF nano fibers have the highest piezoelectric coefficient among polymers, outstanding mechanical strength, very low acoustic impedance, a flat frequency response and a broad dynamic response, and a good chemical and moisture resistivity. Copper foil tapes were fixed on the edge of the sensors to form the electrodes and laminated by adhesive film as shown in **Fig. 2E** (Khan et al. 2018). A novel stretchable strain sensor was made by using silver nanowires (AgNW) and Polydimethylsiloxane (PDMS) conductor and poly(3-hexylthiophene) nanofrils (P3HT-NF) and PDMS semiconductor nanocomposites as shown in **Fig. 2D**. This material exhibits reliable reversible sensing capability, high gauge factor of 32, high linearity (R2 > 0.996), and a low hysteresis < 12% response at a mechanical strain of up to 100% (Kim et al. 2018). A capacitance-based strain sensor is composed of a sensing material made from silicone elastomer and expanded graphite composite material. The conductive electrode layers were made by incorporating expanded intercalated graphite into the silicone elastomer layer at a loading of 10% by weight with the aid of an organic solvent (McCaw et al. 2018).

A biocompatible, flexible strain sensor is fabricated with polydopamine-coated nanocomposites of nitrile butadiene rubber (NBR) and carbon black (CB) particles as shown in **Fig. 1C**. The CB particles were embedded into a NBR matrix using a dissolving-coating technique, and the obtained NBR/CB composite was coated with polydopamine (PDA) to preserve the CB layer. The strain sensors made from uncoated CB/NBR films possess a high sensing range with a strain of 550% and good sensitivity with a gauge factor of 52.2. Whereas the PDA/NBR/CB films shows a somewhat reduce sensing range with a strain of 180%, but a significantly improved sensitivity with a gauge factor of 346 (Qu et al. 2020). A resistance-based strain sensor is made from ethylene propylene rubber (EPR) using the Scotch Electrical Sem-Conducting Tape 13 made by 3M Company as the sensing material as shown in **Fig. 1A**. EPR will have elastic deformation when elongation is less than 2%, however stretched skin may reach 40%. To avoid permanent plastic deformation, a rubber structure made from Eco-Flex material is used to encapsulate the sensing material to separate stretch from bending. Silver-plated nylon thread by Less EMF Inc is used to connect the sensor to the circuit (Shen et al. 2016). A stretchable strain sensor is made using aligned millimeter-long multiwalled carbon nano tubes (MWCNTs). These MWCNTs are unidirectionally aligned and sandwiched between an elastomer layer as shown in **Fig. 2F**. This stretchable strain sensor can be stretched up to 200%, exhibits a short sensing delay less than 15 milliseconds, and has a high sensitivity with a gauge factor of 10 (Suzuki et al. 2016).

A WSG was built using 10 OTS strain gauges (Omega KFH-20-120-C1-11L1M2R) that are attached to a latex glove using double-sided tape. This WSG with the help of a neural network is used for hand gesture recognition to detect ASL (Zhang et al. 2019). A WSG was designed to tackle hand paralysis, which is one of the most common complications in stroke patients. OTS flexible and bendable strain sensors are employed on each finger to measure the finger’s bending angle. This WSG is used for gesture detection and object detection (Chen et al. 2021).

**2.4.2. Pressure sensor**

A pressure sensor is used to detect the force exerted on each finger when it is implemented into a WSG and there are many examples of pressure sensors in academic literature. There are a couple literature reviews that focus on the recent advancements in the development of flexible pressure sensors (Xu et al. 2018). Another literature review was conducted focusing on flexible pressure sensors for the objective assessment of motor disorders. They investigate flexible pressure sensors that utilize resistance, capacitance, inductance, or transistor-based technology for healthcare measurements. In this paper, Table 1 shows the advantages and limitations of the different sensing mechanisms (Amit et al. 2020). This section will detail the different methods researchers have used to make pressure sensors that are applied to WSGs.

A pressure sensor is implemented on a WSG by using a pressure transducer to detect fluidic pressure changes in the flexible tubing that is sewn throughout the WSG. When an external force is applied to the hand, the flexible tubing constricts and causes a pressure increase. This WSG is used for real-time hand pose reconstruction, environment sensing, and task classification (Hughes et al. 2020). Another WSG uses an OTS pressure sensor made from a Force-Sensitive Resistor (FSR), Interlink model 402 sensor. This pressure sensor makes it possible to detect physical loads between 0 and 100 N. Conductive thread was selected to connect the FSR to the main circuitry as shown in **Fig. 1E** (Francés et al. 2019).

A capacitance-based pressure sensor is built into an artificial skin by sputtering a thin film of silver (Ag) on a polyethylene terephthalate (PET) frame to form an Ag serpentine-shaped electrode frame. This sandwich structure consists of Ag/PET/PDMS films encapsulated in Eco-flex material. The pressure sensor compresses the PDMS material which causes a change in capacitance. It has a pressure sensitivity value of 1.45 MPa-1 and it has the ability to stretch up to 70% (Zhao et al. 2015). Another capacitive-based soft pressure sensor is made by using conductive fabric and a microporous dielectric layer. The combination of the conductive knit electrode and higher dielectric porosity yields a higher sensitivity of 121 x 10-4 kPa-1. This capacitive sensor is embedded into a textile glove to make a WSG for grasp motion monitoring (Atalay et al. 2018). A pressure sensor is made from potassium iodide and glycerol solution (KI-Gly solution) as shown in **Fig. 1D**. This pressure sensor contains micro-cylinders filled with this solution to achieve high linearity, 5.3% hysteresis at 1 Hz, and a sensitivity of 100% resistance change when a 5 N load is applied (Xu et al. 2019).

A pressure sensor is made using microchannels filled with Galinstan liquid metal as shown in **Fig. 2G**. This pressure sensor has a sensitivity as high as 0.0835 kPa-1. The microchannels were molded in PDMS material and this sensor can undergo strains of over 200% without failure. This WSG is used to provide comprehensive tactile feedback when the user is touching or holding objects (Gao et al. 2017). Another pressure sensor that utilizes microchannels filled with Galinstan liquid metal is demonstrated by Hammond et al. as shown in **Fig. 1F**. The soft pressure sensor can detect pressures in the range from 0 – 165 kPa under a tensile strain of at least 30%. The microchannels are formed in Eco-Flex silicone rubber that is capable of high strains up to 900% (Hammond et al. 2014). Another pressure sensor is developed using microchannels filled with Galinstan liquid metal. Silver electrodes were printed on a 50 µm thick PET substrate. The functionalized PET substrate and platinum cured silicone elastomer layer were adhered together, and the conductive Galinstan liquid metal is injected into the microstructure and sealed to form the pressure sensor (Yeo et al. 2016).

A transparent pressure sensor is made from an active-matrix array of air-dielectric, amorphous oxide semiconductor as shown in **Fig. 2I**. This design offers a rapid and reliable response as the pressure sensors can detect pressures from 200 Pa to 5 MPa. The transistor was made using amorphous indium gallium zinc oxide (a-IGZO) as the oxide semiconductor material due to its high electron mobility (Ji et al. 2020). An inductance-based flexible pressure sensor is developed using a soft ferromagnetic elastomer and a 17 µm thick coil fabricated on a 50 µm thick flexible polyimide sheet. The soft ferromagnetic elastomer is made using eco-flex and iron nanoparticles, and the higher the ratio of eco-flex to iron nanoparticles, the better the response of the sensor due to saturation. The pressure sensor was able to measure up to 39 kPa before saturation (Ozioko et al. 2018). A flexible/wearable multifunctional sensor array is fabricated using PET-based Ag serpentine-shaped electrodes consisting of the following sandwich structure: PDMS/Ag/Ecoflex/Ag/PDMS. This sensor array is implemented for static and dynamic mapping of spatial contact pressure distributions with a detection limit of 6 Pa, stretching up to 70%, and a sensitivity of 1.45 MPa-1 (Zhao et al. 2015). A pressure sensor is made from anti-static sheets and conductive woven fabrics as shown in **Fig. 2H**. This pressure sensor has a stable and linear response able to measure pressure in the range from 1 to 70 kPa (Pizarro et al. 2018).

A pressure sensor can also be used to detect object slip. This is implemented by making an artificial skin on top of a resistance-based pressure sensor. The geometry of the artificial skin has silicone ridges that are placed on top of the pressure sensor. This allows one to detect slippage and quantify the slippage speed to provide the user with a form of tactile feedback information (Damian et al. 2010).

**2.4.3. Temperature sensor**

A temperature sensor is used to detect the temperature each finger feels when it is implemented into a WSG and there are many examples of temperature sensors in academic literature. This section will detail the different methods researchers have used to make temperature sensors.

Some WSGs utilize OTS temperature sensors. One paper utilizes the LM35 temperature sensor by Texas Instruments as shown in **Fig. 1B**. The LM35 temperature sensor has a small package size (4.30 mm x 4.30 mm), temperature range from -55°C to 150°C, and an analog output with a 10 mV/°C scale factor (Hughes et al. 2020). Another paper utilizes an OTS temperature sensor in their WSG using a temperature sensor IC, TC77, as shown in **Fig. 1H**. This chip has a ±1 °C accuracy from +25 °C to + 65 °C while offering 13 bits of resolution 0.0625 °C/Bit (Polishchuk et al. 2016).

A temperature sensor is made by synthesizing AgNW ink to form a flexible paste with a fractal serpentine layout to form a stretchable form of conducting interconnectors. This temperature sensor has a linear response of 3.8 Ω/°C (Kim et al. 2019). A temperature sensor is integrated into an artificial skin was developed with multi-modal sensing capability as shown in **Fig. 1J**. Silicon nano ribbons (SiNR) sensors are fabricated and passivated by polyimide and withstand greater applied strains, and thereby have large dynamic range, but exhibit reduced sensitivity. To measure temperature, SiNRs are doped twice to form p-n junctions and they have a significant advantage in their construction, owing to their nonlinear characteristics. The temperature sensor design with large curvature enables reliable temperature monitoring under various applied pressures (Kim et al. 2014). A temperature sensor made from intrinsically strain-insensitive, hypereleastic temperature-sensing fiber with compressed micro-wrinkles for integrated textronics (textile electronics) as shown in **Fig. 2C**. The fiber exhibits a sensitivity of 0.93 % °C-1 and a high strain insensitivity until 60% tensile strain. The fiber was coated with thermosensitive conductive paste composed of poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS) and single wire carbon nanotubes (SWCNTs). The thin-layered matrix of PEDOT:PSS and SWCNT has a high temperature-resistance dependence, resulting from the corresponding temperature coefficient of resistance (TCR) and electron hopping at the interface between PEDOT:PSS and SWCNTs (Lee et al. 2020).

A temperature sensor is made using multiwalled MWNTs/PDMS fibers as shown in **Fig. 1I**. The well-tunable, stretchable, and thermal-sensitive MWNTs/PDMS fibers are fabricated using a cost-effective one-step extrusion method. This temperature sensor has a linear response with a resistance change of 0.55% °C-1 with a correlation coefficient of 0.998 in the range of 0-100 °C. Temperature recognition is of significant importance for the auxiliary perception and protection of patients from secondary damage (Li et al. 2020b). A temperature sensor was made using liquid metal Galinstan in microchannels formed in PDMS and covered in epoxy as shown in **Fig. 2A**. This Galinstan material was used to monitor the temperature of a wearable heater glove (Ota et al. 2016). Another temperature sensor is made from silkworm fibers that are embedded with a mixture of carbon nanotubes (CNTs) and an ionic liquid ([EMIM] Tf2N. This material has a sensitivity of 1.23% °C-1. This fiber is constructed by wrapping silk fibers around supporting yarn. Then CNTs in an ionic liquid saturate the yarn to form a temperature sensor. This material can then be weaved into textiles during the construction of gloves as shown in **Fig. 1G** (Wu et al. 2019).

**2.5. Limitations and challenges**

Although the WSGs developed by researchers have improved the status quo, they are lacking in many different areas. Many examples presented in this paper are bulky and cumbersome to use. They require a thick membrane (fabric, plastic, or leather) to attach these sensors to a user’s hand. However, these gloves tend to feel hard and tight because of the bending sensors and hard glove fabrics. Additionally, the users’ hands tend to become sweaty after long-term use as most gloves do not utilize breathable fabric. A thinner membrane made from breathable material is required to improve the user interaction. Also, flexible circuit boards can be utilized to improve the flexibility of the data collection technology.

Aside from the physical interaction, there is a lot of room to improve the data acquisition system for these systems. Most examples present a small sensor with a large, bulky data acquisition system. Sometimes, this data acquisition system is wired to a computer requiring a cable to provide power to the wearable sensing glove. This presents a poor user interaction and inhibits the user from freely using the glove. WSGs should start to implement Bluetooth modules to transmit the data collected from the various sensors on the sensor glove. Finally, the last major drawback of WSGs is the size and weight of the battery. However, until the energy density of batteries is dramatically improved, the battery will be the largest inhibitor for seamless user interaction.

**3. Sensory feedback device**

People with sensory impaired or artificial limbs are unable to determine the current state of their limbs at any given time and rely on vision and memory to manipulate their limbs. Dexterous limb manipulation relies on a closed loop control comprised of motor output and incoming sensory feedback [6]. For instance, when ordered to grasp an object, the brain outputs a motor signal to the hand which uses memory to anticipate the forces and position needed to complete the given task. Once the hand has grasped the object, cutaneous sensation feedback is sent back to the brain and forces and position are adjusted as needed [10]. While a healthy limb would be able to achieve this naturally, a sense-less or artificial limb lacks the ability to adjust to its environment as needed. If the object being grasped requires an unexpected force, a hand unable to sense would likely drop the object as it wouldn’t be able to adapt accordingly. The lack of sensory feedback can also be dangerous as the person is not able to sense when it feels pain, whether it is from encountering a sharp object or a burning surface.

Efforts to tackle this issue include the development of wearable sensory feedback devices which display sensory data cutaneously on a part of the body that is able to sense. The feasibility of such a device has been widely researched throughout the years. Furthermore, these sensory feedback devices have been proven to decrease the cognitive effort required to manipulating an artificial limb, when compared to vision as the sole feedback [18]. Different methods and devices are discussed in further detail in the following sections, focusing on the different ways in which stimulus is created.

**3.1. Feedback modes**

Determining an appropriate feedback method is crucial to the success of the feedback device. Sensory feedback modes are divided into 3 categories, listed from most artificial to most authentic: substitution, modality matched, and somatotopically matched feedback. Substitution feedback doesn’t match the modality of stimulus. This category includes vibrational and electro tactile feedback. Modality matched feedback is congruent to external stimulus. This category includes mechanotactile feedback, or pressure. Somatotopically matched feedback is perceived as if it were on the location where the stimulus is applied. This category involves invasive procedures such as peripheral nerve stimulation and targeted reinnervation. [6]. Naturally, modality matched feedback is preferred as it eases the cognitive burden on the user by being more intuitive [14]. Therefore, a feedback device should be designed to match stimulus modality when possible [7]. \*Add transition

**3.1.1. Electro cutaneous**

Electric stimulation can be an effective and size efficient way to display sensory feedback. Scott et al. Used electric square waves with a frequency of 3 kHz and a rate between 0-60 pulses/sec to display pinch forces measured by strain gauges of an artificial hand. The signal’s rate was mapped to a corresponding force ranging from 0 to 100 N. This method proved to be useful specially when carrying light objects which would otherwise be dropped in the absence of feedback. [2]. Damian et al. Used electrotactile vibrations on the lumbar area to represent the slipping speed of a distant object. The ability of subjects to prevent the object from slipping was studied with visual feedback only, blind feedback that was not proportional to the rate of slip, and blind feedback congruent with slip speed. Slip speed feedback was the most successful for preventing object drop. The study also showed that as the study progressed, there was no learning; meaning that the subject’s ability to control the slipping object completely depended on the feedback display. [19]. This is significant as it reiterates the need of such a device and the importance of designing a device that is wearable and ergonomic.

**3.1.2. Vibrotactile**

Vibrotactile feedback is undoubtedly the most used feedback method due to its affordability and small form factor [20]. Multiple research efforts have investigated vibrotactile displays for manipulation of artificial limbs, control of impaired extremities, and motor learning.

Jiang et al. Developed a low-cost haptic display for multiple sclerosis (MS) patients who often experience reduced sensation causing them to overcompensate and use larger than needed forces when lifting objects. The goal was for subjects to apply the same amount of force on each finger to reduce the overall force being used during lifting. Feedback was delivered using small vibrating motors and evaluated using two methods: event cue (ECF) and amplitude-based feedback (ABF). ECF provided vibration only when the measured force went below a given threshold. ABF provided constant feedback proportional to the magnitude of the force applied. The study concluded that feedback improved the subject’s ability to control the forces on their fingers, and the method preferred depended on the level of impairment of the subject. Those most impaired found ABF most useful while those with lingering sensation found ABF overwhelming and unnecessary. [11]. Walker et al. Used vibration to prevent slip of objects in prostheses users. The study found that visual feedback is the extremely important and their main feedback source, but when not available, added feedback is essential to prevent slip. [13].

Vibrotactile feedback is also widely used for corrective feedback. Redd et al. used a smartphone application to provide vibratory feedback to correct gait issues [5]. While Lieberman et al. developed a sleeved vest which provided vibrotactile feedback for motor learning. The suit could be used for improvement of gait issues and even learning how to dance. The suit provided vibrations proportional to the error of the desired movement. The vibrotactile suit made users more aware of their errors and consequently improved performance. The study also found that skin is most sensitive to frequencies around 20 Hz. [12].

\*mention studies comparing vibration to other modalities and how although is it greatly used because it is easy and affordable it may not be the optimal feedback mode since it is not modality matched

**3.1.3. Mechanotactile**

Amongst the discussed feedback modalities, mechanotactile feedback is the only that is modality matched. It’s effectiveness at sensory substitution and its superiority over other modalities has been established by various studies.

**3.1.3. Other novel approaches**

Sdsd

**3.2. Limitations and challenges**

Sdsfs

**4. Conclusions and future perspectives**

In this literature review, we presented a survey of WSGs, as well as a survey of sensory transfer devices. We narrowed the scope of WSGs to focus on three main sensor modes: temperature, strain, and pressure. We presented commercially available, DIY, and academic versions of WSGs that integrate these sensors into a glove form factor. We critically analyzed the technology used to make each sensor on a WSG and detailed the performance of the sensor to allow for direct comparison. Although this literature review only focuses on sensors used in WSGs, there are more ways to manufacture temperature, strain, and pressure sensors that have not been integrated onto a WSG yet. There is room for innovation and improvement in WSG technology, as stretchable, flexible sensors have yet to be integrated into WSGs. The improved mechanical properties of stretchable, flexible sensors can reduce the thickness of the WSG, increase the user’s comfort, and allow the user to interact with their environment in a more natural way. Regarding the sensory transfer device, various methods are presented to translate sensory information from the hand to other parts of the body. We presented background information regarding electro cutaneous, vibrotactile, and mechanotactile feedback methods. These feedback mechanisms have had limited success so far and improvements can be made to reduce the size of these mechanisms and increase the cognitive response to distinguish between various stimuli. Overall, WSGs and sensory transfer feedback devices will greatly improve the status quo in prosthetics, rehabilitation devices, and virtual reality applications.

**Authorship contribution statement**

**Carl Demolder:** Conceptualization, writing – original draft, review, and editing.

**Alicia Molina:** Conceptualization, writing – original draft, review, and editing.

**Frank Hammond:** Conceptualization, writing – review and editing.

**Woon-Hong Yeo:** Conceptualization, writing – review and editing.

**Conflict of interests**

We confirm that there are no known conflicts of interest associated with this publication. There has been no significant financial support for this work that could have influenced its outcome.

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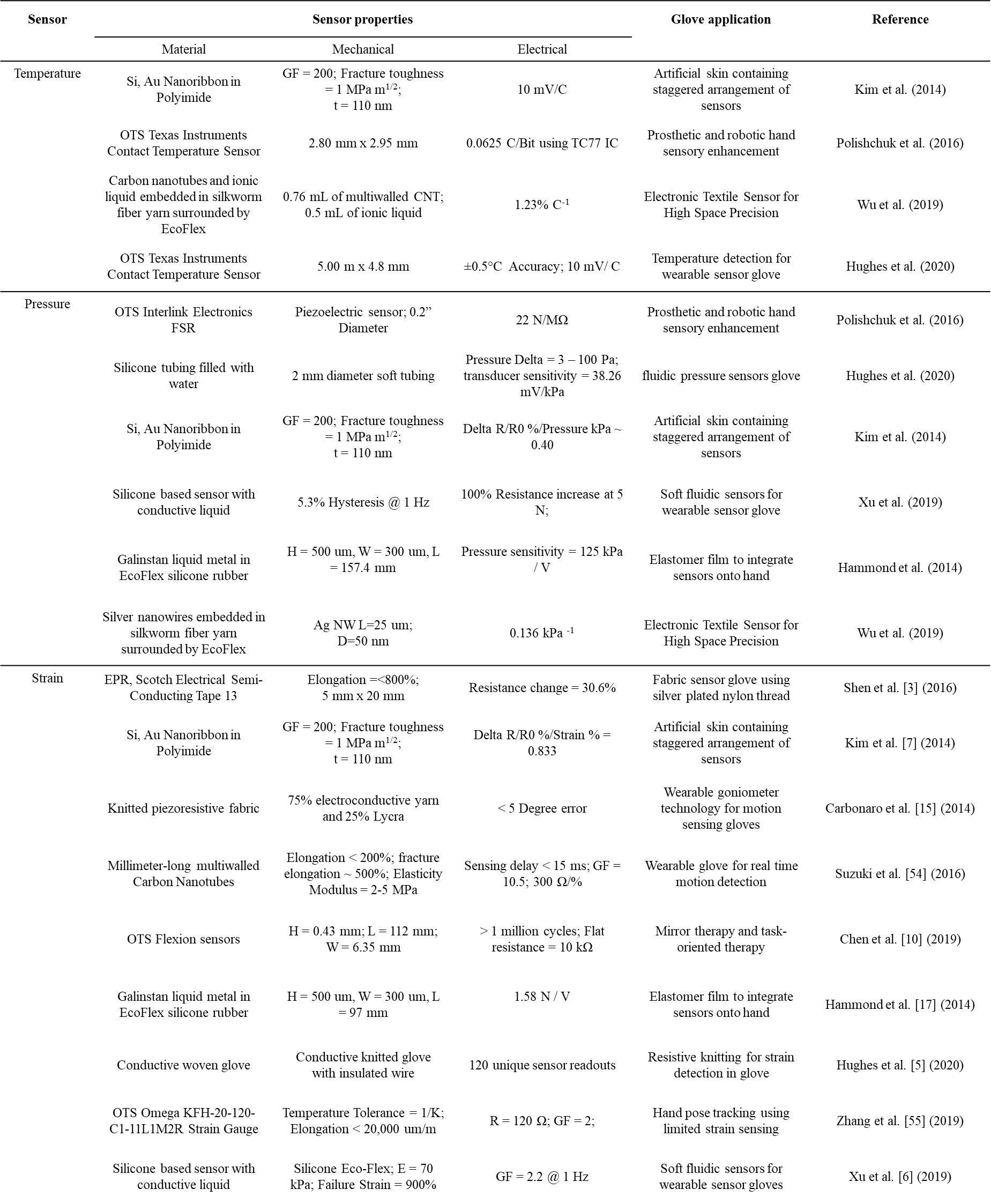
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**Table 1. Academic papers of existing sensor technologies.** Academic papers are separated by sensor type. Characteristics for each sensor node are detailed below to provide a short description of the sensor.



Diagram

Description automatically generated

**Fig. 1. Wearable sensor gloves using different sensor technology.** (A) Glove with strain sensor made from ethylene propylene rubber (Shen et al. 2016) (B) Glove with strain sensors made from a silver nanowire layer (Chen et al. 2016) (C) Glove with strain sensors made from carbon particles embedded in nitrile butadiene rubber (Qu et al. 2020) (D) Glove with pressure sensors made from potassium iodide and glycerol solution (Xu et al. 2019) (E) Glove with pressure sensors made from Interlink 402 force sensitive resistors (Francés et al. 2019) (F) Glove with pressure sensors made from gallinstan conductive liquid (Hammond et al. 2014) (G) Glove with temperature sensors made from CNTs and [EMIM]Tf2N wrapped in conductive yarn encapsulated in Ecoflex (Wu et al. 2019) (H) Glove with temperature sensors made from off the shelf Ti TC77 ICs (Polishchuk et al. 2016) (I) Glove with temperature sensors made from MWNTs and PDMS (Li et al. 2020b) (J) Artificial skin with pressure, strain, and temperature sensors made from single crystalline silicon nanoribbon (Kim et al. 2014).

Graphical user interface, diagram

Description automatically generated

**Fig. 2. More examples of wearable sensor gloves using different sensor technology.** (A) Temperature sensors made from liquid Galinstan material. (Ota et al. 2016) (B) Temperature sensor made using Ti LM35 ICs (Hughes et al. 2020) (C) Temperature sensors made from strain‐insensitive fiber with compressed micro‐wrinkles (Lee et al. 2020) (D) Strain sensor made from poly nanofibrils percolated in silicone elastomer (Kim et al. 2018) (E) Strain sensor made from vinylidene fluoride nanofibers (Khan et al. 2018) (F) Strain sensor made from millimeter-long multiwalled CNTs (Suzuki et al. 2016) (G) Pressure sensor made from embedded Galinstan microchannels (Gao et al. 2017) (H) Pressure sensor made from anti-static sheets and conductive woven fabrics (Pizarro et al. 2018) (I) Pressure sensor made with an air dielectrics for transparent and wearable pressure sensor array (Ji et al. 2020)

A picture containing sky, different, various, several

Description automatically generated

**Fig. 3. Commercial examples of wearable sensor gloves using different sensor technology.** (A) Courtesy of Novel GmbH (Novel 2021) (B) Courtesy of Virtual Realities, LLC (Virtual Realities 2018) (C) Courtesy of Sensor Holdings Limited (StretchSense 2021) (D) Courtesy of Flexpoint Sensor Systems, Inc. (Flexpoint 2021) (E) Courtesy of CaptoGlove Inc. (CaptoGlove 2020) (F) Courtesy of Bebop Sensors (BeBop 2021) (G) Courtesy of Medical Tactile Inc. (PPS 2021b) (H) Courtesy of MI.MU Gloves Limited (MimuGloves 2021) (I) Courtesy of Iron Will Innovations Canada Inc. (Peregrine 2021) (J) Courtesy of Manus Machinae BV (Manus-VR 2021) (K) Courtesy of 5DT Technologies (5DT 2021) (L) Courtesy of Vista Medical, Ltd. (Vista Medical)

A collage of a cat

Description automatically generated with low confidence

**Fig. 4. Do-It-Yourself prototypes of wearable sensor gloves using different sensor technology.** (A) Courtesy from Thingiverse.com (Freedman 2016) (B) Courtesy of Instructables.com (vu2aeo 2021) (C) Courtesy of Instructables.com (Shja7942 2021) (D) Courtesy of Instructables.com (Emcnany 2021) (E) Courtesy of Instructables.com (Freire 2021b) (F) Courtesy of Instructables.com (Plusea 2021) (G) Courtesy of Instructables.com (Donaldson 2021) (H) Courtesy of Instructables.com (Freire 2021a) (I) Courtesy of Instructables.com (DanielE58 2021)

**Table 2. Application and purpose of wearable sensor gloves.** This figure was derived and adapted from a previous literature review (Dipietro et al. 2008). This figure was updated to reflect the latest advancements in the past decade.

