**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 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. Additionally, the limitations of the current materials and technologies are discussed, as well as the key challenges and the future direction of how a wearable sensing glove will be used in conjunction with a sensory transfer device. 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 begin to integrate technology into wearable devices to measure, enhance, and improve the interaction 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, a wearable sensing glove is used measure the interaction between one’s hands and the environment. A wearable sensing glove is a wearable device worn on the hand that includes sensors to measure the interaction between our hands and the surrounding environment. Many sensors can be put on a wearable sensing glove to measure some of the following parameters: motion, position, temperature, pressure, contact, and relative finger location. Numerous applications have arisen over the past thirty years that require the use of a wearable sensing glove to achieve their goal.

However, there has been a growing need for a device to be used in conjunction with a wearable sensing glove; a device to transfer or replicate the sensory information from the wearable sensing glove to another part of the body. The need for this device combination 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, amputee patients face a similar issue with their prosthetics, which are currently unable to sense or feel. 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, resulting in the reduced use of the limb or rejection of the prosthetic all together [Design and evaluation of a sensory...][7].

A sensory feedback device provides another form of feedback to compliment the visual feedback for users with a form of sensory impairment. 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 to them [4]. The need for a device that can communicate the sensory and physical states of a sensing-less limb is evident.

Overall, we provide an extensive survey of all the technologies used in wearable sensing gloves and sensory feedback devices to provide readers with a broad overview on how these technologies can be used in tandem. Additionally, we hope to inform the non-specialist reader who is interested in using a wearable sensing glove and sensory feedback device for their application. The motivation for writing this paper is that the important information on wearable sensing gloves and sensory feedback devices are scattered across numerous engineering, commercial, and scientific literature. The main objective of this paper is to identify the advantages and drawbacks of each technology and identify potential room for improvements.

**2. Wearable sensor glove**

This portion of the paper focuses on the recent advancements in wearable sensing glove technology as well the applications that they are used for. There are a few literature reviews conducted on wearable sensing gloves. A literature survey conducted by Dipietro in 2008 provides a broad overview of wearable sensing gloves, their characteristics, and their application (Dipietro et al. 2008). As technology is being integrated into wearable sensor gloves more often nowadays, a more focused literature review is required, as a wearable sensing glove can include a sensor to measure anything from detecting fentanyl (Barfidokht et al. 2019) to detecting diverse biomarkers (Bariya et al. 2020). If the reader is looking for an application-specific survey for wearable sensing gloves, there are few resources to guide readers. A literature survey conducted by Pasquale in 2018 focuses on how wearable sensing gloves can be used for medical applications (Pasquale 2018). A literature review conducted by Rashid and Hasan in 2019 reviews how wearable technologies are used for hand joint monitoring for rehabilitation (Rashid and Hasan 2019). A literature review conducted by Ahmed in 2018 reviews how wearable sensing gloves are used for sign language recognition between 2007 and 2017 (Ahmed et al. 2018). A literature review conducted by Chen in 2020 reviews how wearable sensing gloves are used for hand pose estimation (Chen et al. 2020). Although there are numerous sensors this paper could review, this paper is focused on reviewing wearable sensing gloves that use pressure, temperature, and strain sensors. These sensors measure the main interactions patients with sensory impairment disorders need to have transferred to another part of their body. Overall, a wearable sensor glove is the optimal wearable device for this application as it is a noninvasive wearable, it increases the accuracy and repeatability of measurements, and it improves the complexity of the measurements taken to simultaneous measure different sensors (Pasquale 2018).

The focused breadth of this section will concentrate the discussion and enable a more in-depth review of these technologies. 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 in this research domain. After reviewing the sensors used in existing applications, the future direction of wearable sensing gloves will be discussed to guide readers in their research development.

**2.1. Application of wearable sensing gloves**

Wearable sensing glovesare used in a multitude of applications, and the number of applications continues to grow as the technology used to make them has rapidly improved. In 2008, Dipietro created a summary table to detail the many applications for wearable sensing gloves and the rationale to use a wearable sensing glove, alternative device instead of a wearable sensing glove, and the purpose to use the wearable sensing glove. Dipietro divided the applications into two main categories: classical and recent applications. 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 formed by building from this previous work and expanding on it by including more applications due to recent technological advances. The “classical” application category has been redefined to the following: design & manufacturing, information visualization, arts & entertainment, sign language recognition, and computer. The “recent” application category had been modified to include the following: virtual reality, health care diagnostics, prosthetics, robotics, and artificial intelligence.

Researchers in the field of virtual reality are using wearable sensing gloves to allow users to interact with their computer-generated environment and perform digital movements in a more natural way. In the field of health care, they allow researchers to take measurements easily and directly between the user’s hand and the surrounding environment. In the field of prosthetics, they allow the user to improve the control and adoption of the prosthetic by providing a form of feedback to the user. In the field of robotics, they provide a way to measure the interaction between the robotic hand and the surrounding environment. This will provide a closed feedback loop for robotic systems. In the field of artificial intelligence, they provide users with the ability to perform object detection and gesture recognition and model human interactions. In the next few sections, the application that the commercially available, DIY, or academic version of the wearable sensing glove is designed to target is mentioned.

**2.2. Commercially available wearable sensor gloves**

While numerous glove designs have been proposed over the past 30 years, only a few products have become commercially available and viable. A literature review conducted in 2008, provides a thorough description of wearable sensors gloves from the 1970s to 2008 (Dipietro et al. 2008). Today, there are commercially available wearable sensing gloves that integrate a myriad of different sensors. A few notable examples of wearable sensing gloves that use different sensors that will not be discussed in this literature review are the Noitom Hi5 VR Glove (Noitom 2021) that uses an internal measurement unit (IMU), the Workaround ProGlove (Workaround 2021) that uses an industrial bar-code reader, and the SenseGlove that provides force-feedback for VR training (SenseGlove 2021). Rather, this section will focus on commercially available products that implement either temperature, pressure, or strain sensors into a wearable sensing glove.

The commercial wearable sensing gloves that integrate temperature sensors are represented below. The SensPro 8108 by Holik International use an infrared thermometer and contact temperature sensors located in a protective glove. An image is shown in Fig. 3K and this glove is primary used to warn firefighters of the temperature of certain objects before they touch them (SensPro 2021).

The commercial wearable sensing gloves that integrate pressure sensors are represented below. The Pliance Glove by Novel GmbH uses 256 capacitance pressure sensors and can record at a measurement frequency of 20,000 samples per second and an image is shown in **Fig. 3A**. This glove is primarily used to model the human interaction between users and manufacturing and production tools. Additionally, it can be used for assessing manipulations and hand rehabilitation during physical therapy practice (Novel 2021). The Finger TPS by Medical Tactile Inc includes a capacitance pressure sensor on the fingertip of the glove and an image is shown in **Fig. 3I**. This glove is primarily used to optimize a product’s ergonomics by quantifying the user interaction’s with the product (PPS 2021a). The TactileGlove, also by Medical Tactile Inc, includes capacitance pressure sensors throughout the entire glove – fingers to palm. An image is shown in **Fig. 3J** and it is primary used to map human movements and quantify the user’s hand interactions to optimize the ergonomics of a product (PPS 2021b). 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). An image of the glove is shown in **Fig. 3M** and it primarily used for computer interaction control and VR applications (Peregrine 2021). The Glove Pressure Mapping System (GPMS) by Vista Medical, Ltd is a wearable sensor glove with various pressure sensors mounted on the hand in different locations. An image of the glove is shown in Fig. 3P and it is primarily used for to quantify human movements and quantify the user’s hand interactions to optimize the ergonomics of a product (Vista Medical).

The commercial wearable sensing gloves that integrate strain sensors are represented below.

The VMG 8 by VRealities LLC uses one embedded strain sensor per finger to accurately measure the finger movements and an image is shown in **Fig. 3B**. This glove is primarily used for virtual reality applications (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. An image is shown in **Fig. 3C**. This glove is primarily used for VR/AR applications and motion capture (StretchSense 2021). The Stroke-Rehab Glove by Anthrotronix uses strain sensors to detect finger bending and an image is shown in **Fig. 3D**. This glove is primarily used for healthcare applications as this glove helps patients regain the fine motor control that they may have lost due to brain damage and muscle weakness caused by a stroke (Anthrotronix 2021). The Flexpoint USB Glove Kit by Flexpoint Sensor Systems includes a dual segment bend sensor for each finger and an image is shown in **Fig. 3E**. This glove can be used for a variety of medical applications from determining a patient’s level of monitor skill, post-surgery evaluation, and assisting the disabled (Flexpoint 2021). The CaptoGlove by CaptoGlove Inc includes a bend sensor for each finger and an image is show in **Fig. 3F.** This glove is primarily used for pc gaming and for virtual realities applications (CaptoGlove 2020). The Smart Glove for Home by Neofect USA includes a bend sensor for each finger and an image is shown in **Fig. 3G**. This glove is primarily used as a medical device to quantify even small movements of the upper extremity to better promote repetition, optimal for brain retraining to improve motor function (Neofect 2021). The BeBop Forte Data Glove by BeBop Sensors includes a bend sensor in each finger and has haptic feedback in the glove. An image is shown in **Fig. 3H**. This glove is primarily used for VR and AR applications (BeBop 2021). The Mimu Gloves by Mi Mu Gloves Limited includes a bend sensor in each finger and an image of the glove is shown in **Fig. 3L**. This glove is used as a wearable musical instrument for expressive creation, composition, and performance (MimuGloves 2021). The Manus Prime II Haptic by Manus VR includes a bend sensor in each finger and provides haptic feedback to the user as well. An image is shown in **Fig. 3N** and it is mainly used for motion capture, virtual reality and augmented reality applications (Manus-VR 2021). The 5DT Data Glove 5 Ultra includes a bend sensor in each finger and an image of the glove is shown in Fig. 3O (5DT 2021).

These commercially available wearable sensing gloves provide the reader with an understanding of what features and sensors have been implemented at a production level. Additionally, it should help guide researchers to understand what products they could purchase to integrate with their research. Also, it should help to understand what features are important to implement into a sensor glove. It can be a way to gauge demand and understand where the need for a product is.

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

Do-It-Yourself (DIY) versions of wearable sensor gloves provides an interesting perspective for readers. The manufacturing methods engineers and artist use to make these wearable sensor gloves differs dramatically from the commercial and academic versions. With hand tools and minimal equipment, they are still able to build a wearable sensor glove that accomplishes their proposed task.

Zack Freedman was able to build the Parametric Data Glove by 3D printing ring-like fixtures to secure 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 on Instructables built a low-cost wearable sensing glove using off-the-shelf flex sensors on the back of the hand. An Arduino then read the flex sensors and controlled a robotic hand to mimic the movements of the user’s hand as shown in **Fig. 4B** (vu2aeo 2021). Will Donaldson built a similar device as User vu2aeo as shown in **Fig. 4G**. Donaldson used velostat as a piezoresistive material to build the strain sensors to measure how much each finger bends. He then used an Arduino Lilypad to read the strain sensors and manipulate a robotic hand to mimic his hand movements (Donaldson 2021). Rachel Freire built a low-cost wearable sensing glove 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). Rachel Freire decided to expand on this technology by integrating a Vive Tracker into her wearable sensor gloves. By integrating textile based strain sensors on the back of the hand, she was able to build wearable sensing gloves that can integrate with virtual reality environments as shown in **Fig. 4E** (Freire 2021b).

Brian Benchoff took a creative approach by building a wearable sensing glove that doubles as a musical instrument. Using a pressure sensor and flex sensors on the fingers, he was able to mimic the behavior of 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 (Benchoff 2011).

User ‘Plusea’ on Instructables built a low-cost wearable sensing glove 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 wearable sensing glove was to build a device to help piano teachers teach children to visualize the difference between soft and hard touches (Plusea 2021). User ‘DanielE58’ on Instructables built a low-cost wearable sensing glove with off-the-shelf strain sensors on each fingertip as shown in **Fig. 3I**. User ‘DanielE58’ designed the wearable sensor glove 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 flex sensors on the back of each finger and conductive fabric to detect fingertip touches as shown in **Fig. 3D**. This wearable sensing glove 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 wearable sensing glove with 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 wearable sensing gloves provides the reader with information on how artists, designers, and engineers are applying this technology to their creative applications. The technology they use is not cutting edge, however, it demonstrates how normal people are using this technology to solve the problems they are facing. Hopefully, readers take away the sentiment that there are applications for wearable sensor gloves and many unsolved problems.

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

Researchers at universities have been developing new versions of sensors for years, however they have recently started putting those sensors on gloves to create wearable sensing gloves. The sensors put on wearable sensing gloves integrate different techniques of nano manufacturing techniques. Additionally, the more recent advances in these sensors have start to use different combination of nano materials. These sensors have better sensitivity and better mechanical properties than commercially available products. **Fig. 2** depicts a Venn-diagram where each section of the pie is used to build the center image which is an artificial skin that can measure pressure, temperature, and strain. Each individual image used to conduct the Venn diagram is explained in the sections below. The ultimate wearable sensing glove is a durable, thin membrane that can be worn on the hand that combines all three sensor nodes into one form factor. Through the process of conducting this literature review, it is evident that there is a need for an artificial skin that is a very thin membrane that can be used as a wearable sensor glove. **Fig. 2J** is an example of artificial skin with pressure, strain, and temperature sensors made from single crystalline silicon nanoribbon (Kim et al. 2014). The advances in artificial skin are documents in a literature review conducted by Chortos in 2016 (Chortos et al. 2016). In this literature review, the author details the new materials and fabrication strategies that are being developed to make multifunctional skintronics (skin-like electronics). The combination of pressure, temperature, and strain sensors in a single membrane provides the ultimate wearable sensing glove. However, the current limitation of these sensors is the sense complex stimuli such as surface textures and object shape. A large number of receptors are necessary to provide a more natural feel for prosthetics (Chortos et al. 2016). Another literature review was conducted in 2020 that provides another in depth review of skin-inspired multifunctionality at the prosthetic level using flexible electronics and mechanical compliant biometric sensing platforms. Additionally, this review going into depth about implantable electrodes to connect with exposed neurons. This a great supplementary resource to see where the future of artificial skin can be used to interact with prosthetic devices (Li et al. 2020a). The combines all three major sensing nodes into one glove system.

Another literature review was conduct in 2017 to present the historical development of hand gesture recognition using glove-based control interfaces for computer control (Premaratne 2017).

Although there is only one example of a wearable sensing glove combining all three sensor nodes into one form factor, most of the academic references explore the advancements in sensor technology in one sensor node. **Table 1** provides a summary of the sensors used on wearable sensing gloves. The material, mechanical, and electrical properties of the sensor used are documented and the application that the wearable sensing glove is used in is documented. Each reference is explained in detail in their corresponding sensor section below.

**2.4.1. Strain sensor**

A strain sensor was composed from fragmentized graphene foam. This strain sensor is manufactured from a composite 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 glove capable of wirelessly translating the American Sign Language (ASL) into text displayable on a computer or smartphone. A strain sensor is placed on the knuckles of each finger (two strain sensors per finger, 1 strain sensor for the thumb). These strain sensors are 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 (O’Connor et al. 2017).

A wearable kinesthetic glove using knitted piezoresistive fabric sensor technology. The sensing glove is endowed by three KPF goniometers that are used to track flexion and extension movement of metacarpophalangeal joint of the thumb, index, and middle fingers. The sensor consists of a double layer textile-based goniometer starting from the electromechanical characteristics of a single layer piezoresistive sensor. This double layer configuration provides insight into the sample’s flexion angle independently by their bending profile (Carbonaro et al. 2014).

Polymer-enhanced highly stretchable conductive fiber strain sensor used for electronic data gloves. A 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 (Chen et al. 2016).

A sensory glove was designed to tackle hand paralysis, which is one of the most common complications in stroke patients. Off-the-shelf flexible and bendable sensors are employed on each finger to measure their bending angles. This sensing glove can be used for gesture detection and object detection (Chen et al. 2021).

A sensitive and flexible polymeric strain sensor for accurate human motion monitoring. A facile fabrication strategy via electrospinning to develop a stretchable, and sensitive vinylidene fluoride nanofibrous strain sensor. PVDF nano fibers offers the highest piezoelectric coefficient among other polymers. PVDF has been used in a wide range of applications thanks to its flexibility and its other mechanical and electrical properties. PVDF fibers show an outstanding mechanical strength, very low acoustic impedance, and exhibit a flat frequency response and a broad dynamic response. Additionally, PVDF has a good chemical and moisture resistivity. The strain sensor was fabricated based on PVDF electrospun nanofiber on a flexible liquid crystal polymer substrate. Copper foil tapes were fixed on the edge of the sensors to form the electrodes and laminated by adhesive film (Khan et al. 2018).

A strain sensor based on rubbery semiconductor. This is developed by using a stretchable strain sensor to quantify the large mechanical deformation and strain. The novel stretchable strain sensor made by using a solution-processed rubbery semiconductor as the sensing material to achieve high sensitivity, large, mechanical strain tolerance, and hysteresis-less and highly linear responses. Specifically, the rubbery semiconductor exploits nano-fibrils to yield semiconducting nanocomposite with a large mechanical stretchability, although a P3HT is a well-known non stretchable semiconductor. The fabrication strain sensors exhibit 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%. AgNW/PDMS conductor and P3HT-NF/PDMS semiconductor nanocomposites are utilized to construct the strain sensor (Kim et al. 2018).

A wearable sensing glove utilizes flexible sensors use material softness and elasticity to allow for high conformability, low risk of injury or discomfort, and ease of integration into other flexible materials such as clothing. These soft capacitive strain sensors for measuring finger bending and fingertip pressure, while leveraging low-cost components. Capacitance based sensors measure changes in bulk sensor geometry. As a result, they are less susceptible to material degradation that can result in long-term signal drift in resistive sensors. The sensor was fabricated using the following way. The sensor presented here are composed of platimum-cure silicone elastomer and a silicone elastomer and expanded graphite composite material. The sensors are constructed as parallel-plate capacitors. To manufacturer the conductive electrode layers, expanded intercalated graphite was incorporated into the silicone elastomer at a loading of 10 wt% with the aid of an organic solvent. The dielectric layer was constructed by preparing unmodified silicone elastomer and rod-coating over the electrode layer in the same fashion (McCaw et al. 2018).

A biocompatible, flexible strain sensor fabricated with polydopamine-coated nanocomposites of nitrile butadiene rubber (NBR) and carbon black (CB) particles. The CB particles were embedded into an NBR matrix via a dissolving-coating technique, and the obtained NBR/CB composite was coated with polydopamine (PDA) to preserve the CB layer. These strain sensors showed that an 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. NBr/CB and PDA/NBR/CB composite films can be utilized to produce wearable and flexible sensing systems for real-time monitoring of body motions (Qu et al. 2020).

Another 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. When the material is bent or stretched, the resistance of the material will change. EPR will have elastic deformation when elongation is less than 2%, however stretched skin may reach 40%. To avoid permanent, plastic deformation, an EcoFlex rubber structure 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).

Stretchable strain sensors made using rapid-response, widely stretchable sensor of aligned millimeter-long multiwalled carbon nano tubes (MWCNTs). These MWCNTs are unidirectionally aligned and sandwiched between elastomer layers. This stretchable sensor can be stretched up to 200%, exhibits a short sensing delay less than 15 ms, and a high sensitivity with a gauge factor of 10 (Suzuki et al. 2016).

A sensing glove uses 10 off-the-shelf strain gauges (Omega KFH-20-120-C1-11L1M2R) attached to the latex glove using double-sided tape. The change in resistance is measured using a strain gauge measurement circuit utilizing a Wheatstone bridge amplifier with an Arduino Mega board. This setup is utilized for hand gesture recognition to detect ASL using an neural net (Zhang et al. 2019).

**2.4.2. Pressure sensor**

A robotic hand is equipped with artificial ridged skin over top of a resistance pressure sensor was used to detect slip. The geometry of the silicone ridges that is placed on top of pressure sensor allows one to detect slippage and to quantify the slippage speed. This information can be relayed back to the user as a form of tactile feedback information (Damian et al. 2010).

Pressure is detected using fluidic pressure changes in fibrous flexible tubes. These flexible tubes are sewn throughout the gloves and a tube is used per finger and one is used for the palm. Through the use of pressure transducers, the pressure change is measured and used for real-time hand pose reconstruction, environment sensing, and task classification (Hughes et al. 2020).

Another example of artificial skin integrating strain and pressure sensors is conducted by sputtering an Ag thin film on a PET frame to form Ag serpentine-shaped electrode frame. This sandwich structure consists of Ag/PET/PDMS films encapsulated Ecoflex 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).

A capacitive-based soft pressure sensor based on a 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. For a practical application, the capacitive sensor is embedded into a textile glove for grasp motion monitoring during activities of daily living (Atalay et al. 2018).

An off-the-shelf pressure sensor was selected that utilizes low-cost technology using a Force-Sensitive Resistor (FSR) using an Interlink model 402 sensor. This FSR 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 (Francés et al. 2019).

There are a couple papers that have developed pressure sensors that use microchannels filled with Galinstan liquid metal. Gao et al. developed a pressure sensor with a sensitivity as high as 0.0835 kPa-1. The microchannels were developed in PDMS material and this sensor can undergo strains of over 200% without failure. This sensor was integrated into a PDMS glove to provide comprehensive tactile feedback of a human hand touching or holding objects (Gao et al. 2017).

Another paper that demonstrates the capabilities of microchannels filled with Galinstan liquid metal is demonstrated by Hammond et al. to measure up to hundreds of Newtons of interaction forces. Experimental data was able to demonstrate the sensitivity of the soft pressure sensor in the range from 0 – 165 kPa under a tensile strain of at least 30%. The microchannels are formed using Eco-Flex silicone rubber that is capable of high strains up to 900% (Hammond et al. 2014). An image of the sensor is shown in Figure 1F.

Moving aside from pressure sensors made using capacitive and resistance-based methods, an unconventional approach is taken through the fabrication of an active-matrix array of air-dielectric, amorphous oxide semiconductor transistors for transparent, wearable pressure sensors by Ji et al. This design offers a rapid and reliable response as pressure sensors for an extensive range of pressures from 200 Pa to 5 MPa. The transistor was made using a-IGZO a the oxide semiconductor 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 higher the ratio of eco-flex to iron nanoparticles, the better the response of the sensor. This behavior is because the increase in the amount of iron particles in the polymer reduces its compressibility and causes the sensor to saturate faster. When pressure was applied to the sensor, it was able to measure pressure up to 39 kPa before saturation (Ozioko et al. 2018).

Another pressure sensor is developed using microchannels filled with Galinstan liquid metal by J.C. Yeo et al. Silver electrodes were printed on a PET substrate of 50 µm thickness. 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 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).

There are a couple in depth reviews for flexible pressure sensors. A review was conducted by Xu et al. in 2018 where the researchers focus in depth on flexible pressure sensors (Xu et al. 2018). Another review was conducted by Amit et al. in 2019, where they focused on flexible pressure sensors for objective assessment of motor disorders. More specifically, they investigate flexible pressure sensors based on resistors, capacitors, inductors, or transistors regarding healthcare measurements. In this paper, a summary table is provided, Table 1, to show the advantages and limitations of the different sensing mechanisms (Amit et al. 2020).

**2.4.3. Temperature sensor**

A fully soft, wearable glove uses an OTS temperature sensor, LM35 temperature sensor by Texas Instruments, which is used for environment sensing. 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).

The e-glove system was built off of a commercial stretchable nitrile glove by applying epoxy on the surface to provide adhesive support. A conductive AgNW ink was screen-printed onto the surface of the glove to act as the interconnects between the sensors and the testing elements. The temperature sensors are made of Au (100 nm thick\_ and filamentary serpentine interconnectors (Au, 300 nm thick) ADD MORE TO THIS (Kim et al. 2019).

An artificial skin was developed with multi-modal sensing capability. Silicon nano ribbons (SiNR) sensors are fabricated and withstand greater applied strains, and thereby have large dynamic range, but exhibit reduced sensitivity. SiNRs or gold NRs that are passivated by polyimide. To measure temperature, SiNRs are doped twice to form p-n junctions. SiNR diode temperature sensors 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). The fiber exhibits a sensitivity of 0.93 % °C-1 and a high strain insensitivity until 60% tensile strain. The fiber demonstrates results that are highly repeatable and reproducible for less than 1000 cycles and they exhibit excellent cyclic responses to on/off switching. The fiber was coated with thermosensitive conductive paste composed of PEDOT:PSS and single wire carbon nanotubes (SWCNTs). The compressed micro-wriknles were employed as a temperature-sensing layer on stretchable polyurethane (PU)-based fibers fabricated through a facile dip-coating method using poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS). And single-walled 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 CNTs (Lee et al. 2020).

A smart glove is made based on multiwalled MWNTs/PDMS fibers to be developed for temperature recognition. The well-tunable, stretchable, and thermal-sensitive MWNTs/PDMS fibers are fabricated via a facile and cost-effective one-step extrusion method. They present a linear relationship of resistance change and temperature of 0.55% °C-1 with a correlation coefficient of 0.998 in the range of 0-100 °C. Temperature recognition is of significance for the auxiliary perception and protection of patients from secondary damage (Li et al. 2020b).

A temperature sensor was made using a liquid metal Galinstan in microchannels formed in PDMS and covered in epoxy. This Galinstan material was used to monitor the temperature of a wearable heater glove (Ota et al. 2016).

An off the shelf temperature sensor is used in this flexible sensor glove. In this multi-functional sensory glove, a temperature sensor IC, TC77, was selected to used in the glove. 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).

Silkworm fibers are durable, good heat conductors, insulating, and biocompatible, and are therefore regarded as excellent mediating materials for flexible electronics. To achieve enhanced temperature sensing performance, a mixture of carbon nanotubes and an ionic liquid ([EMIM] Tf2N is embedded which displays top sensitivity of 1.23% °C-1. The fiber is constructed by wrapping silk fibers around supporting yarn. Then CNT in an ionic liquid saturates the yarn to form a temperature sensor. This material can then be weaved into textiles during the construction of gloves (Wu et al. 2019).

**2.5. Limitations and challenges**

Although these wearable sensor gloves 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. Additionally, there is a lot of room to improve the data acquisition system. Most examples present a small sensor with a large data acquisition system. This data acquisition system is occasionally wired requiring a cable to provide power to the wearable sensing glove. This presents a poor user interaction that could use some improvement. With the recent advancements in Bluetooth, the longer range and higher data transfer rates enable sensor gloves to use a small Bluetooth transmission module to transmit the data collected from the various sensors on the sensor glove. The major drawback moving forward for wearable sensing gloves is the size and weight of the battery. Advancements in nano particle manufacturing enable smaller sensors to be manufactured, flexible circuit boards to be thinner and flexible. However, until the energy density of batteries is dramatically improved, the battery will be the largest inhibitor to seamless user interaction.

Finger sweatiness during a prolonged performance was also success-fully eliminated by using a breathable fabric.

Various improvements have been made to the gloves since their introduction to the market, and they are advertised to fit to human hands well because they are stretchable and lightweight. However, these gloves tend to feel hard and tight because of the bending sensors and hard glove fabrics, and users’ hands tend to become sweaty after long-term use; further improvements are highly desirable.

**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 paper, we presented a survey of wearable sensor gloves, as well as a survey of sensory transfer devices. We narrowed the scope of the wearable sensor gloves to focus on three main categories: temperature, strain, and pressure. We presented commercially available, DIY, and academic versions of sensor gloves that integrate these sensors into a glove form factor. We critically analyzed the technology used to measure these sensor categories, and we mentioned their advantages and drawbacks for each novel technique used. Although this literature review only focused on the sensors used in wearable sensor gloves, there are many different methods to manufacture a temperature, strain, and pressure sensor that have not been integrated onto a wearable sensor glove yet. There is room for innovation and improvement in wearable glove technology, as stretchable, flexible sensors can be integrated into wearable sensor gloves. The improved mechanical properties of these sensors can reduce the thickness of the wearable sensor glove, 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 in 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, wearable sensor gloves and sensory transfer feedback devices will have a 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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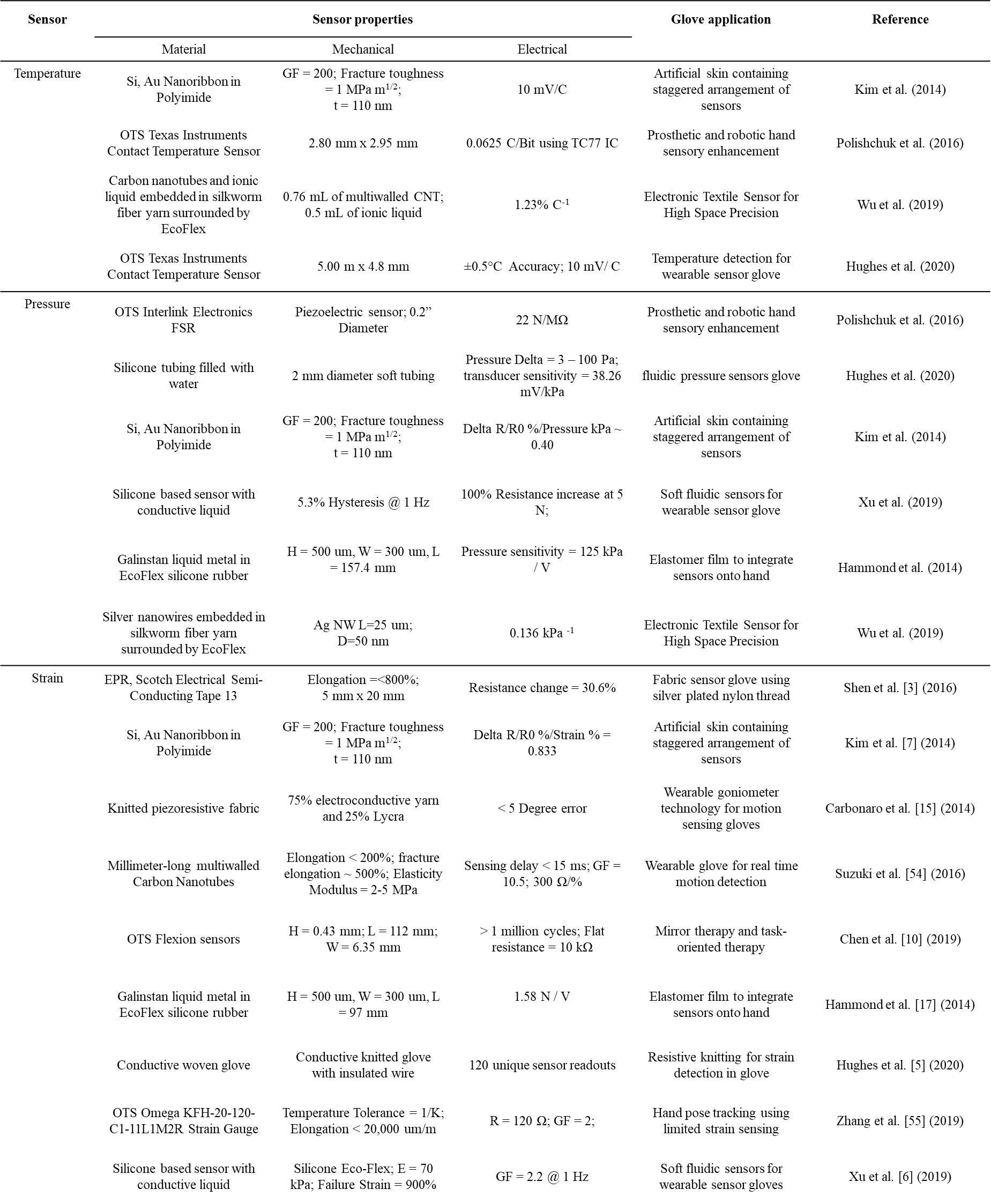
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**Table 1. Academic papers of existing sensor technologies.** Academic papers are separated by sensor type. Characteristics for each sensor node are detailed below to provide a short description of the sensor.



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.

