Humans interacting with machines is an act that can range from 'flicking a fan switch' to 'using a microwave', and all the way up to 'flying a helicopter'. Interacting with machines can be made easy, comfortable, and accessible by introducing user-friendly interfaces. In the case of wearable devices, their sensors and other interfacing elements are very well within the user’s proximity. Using biopotential signals from within the human body makes interaction seamless for the user if the interfacing technology is imperceptible and unobtrusive – since rigid and cumbersome interfaces can hinder the user experience. This paper reviews the use of soft, flexible, and stretchable materials for the development of biopotential interfaces in wearable human-machine interactive devices. Additionally, attention is brought to the scope of possible applications of soft biopotential interfaces in wearable devices.
Response Letter

Reply to Reviewer 1’s comments.

Dear Prof./Dr./Sir/Madam:

Thank you so much for your time and for providing us with valuable comments. We have revised the manuscript thoroughly according to your comments. Detailed actions and revised parts are discussed next:

Reviewer comments:

In this manuscript, the authors introduce four representative soft biopotential interfaces (EMG, EEG, ECG, and EOG). The manuscript is well-organized and follows logical structure, starting with an introduction and then moving on to the specific biopotential interfaces. Each section is subdivided to address different types of interfaces and technologies. The conclusion and outlook provide a summary and suggest future directions for the field. The article covers a wide range of topics and provides detailed information on the technologies, materials, and applications of soft biopotential interfaces. The depth of coverage is sufficient for a review article. The reviewer believes it is publishable after minor revisions below.

1. It would be better if some brief background on biopotential signals and their importance in human computer interface is added in introduction to provide context for readers who may be less familiar with the field.

RESPONSE:

First, we thank the reviewer for this careful comment. We have revised the manuscript and added some brief background on biopotential signals and their importance in the human-computer interface in the “introduction” part (the red one is revised or added contents). We have also made minor changes to the grammatical and literature errors present.

“With the constant progress in health and lifestyle technologies, there has been a significant rise in wearable devices and their capabilities[5-9]. Wearable devices are essential tools for human-computer interaction technologies that can record an individual’s biological and neural activities through close contact with human skin [10]. All kinds of physical and mental activities in the human body generate electrical potentials, called biopotentials, that provide colossal amounts of information, which can be used for various applications, such as health monitoring and controlling electronic devices[11–16]. For instance, neural activities in the brain can be recorded, analyzed, and used for various purposes. Motor actions that are intention-based such as walking or moving of arms can be monitored in the form of neural activities in the brain. Similarly, when sensory inputs are perceived in the brain such as touch or taste, the associated neural activities can be observed in the brain. The most common technique for non-invasive brain recording is Electroencephalography (EEG)[17]. Although EEG allows the recording of neuronal activity non-invasively, is difficult to isolate and record specific areas of the brain [18]. Neural signals from the brain travel in the human body and branch out to different areas through the nervous system. Similarly, the sensory inputs from the body are sent to the brain via these nervous systems. Apart from EEG, electromyograms (EMG), electrocardiographs (ECG), and electrooculograms (EOG) signals are the major biopotential signals that can be acquired using non-invasive interfaces[19]. Other than acquiring data from these signals, non-invasive interfaces can also perform stimulation-
based applications for specific rehabilitation purposes [20-22].”

“Wearable devices can utilize biopotential signals like EMG (from muscular activity) and EOG (from eye movement) for delivering intention-based output signals to allow applications like gesture control, end-effector manipulation, and prosthesis. Unintentional, or autonomous biopotential signals such as ECG (from heartbeats) can allow for health monitoring applications. In human-computer interaction, such information is valuable in various industries, including medical healthcare, assistive robotics, lifestyle, and more.”

2. I recommend the author to add more description (or definition) of EEG and ECG in the section 2 and section 3, respectively.

**RESPONSE:**

We thank the reviewer for this careful comment. We have revised the manuscript and added more description (or definition) of EEG and ECG in sections 2 and section 3.

“Numerous neurons in the brain are responsible for generating, transmitting, and processing mysterious electrophysiological signals. Electroencephalogram (EEG) indicates recorded neural activities on the scalp surface. Although the resolution limitation of EEG, this non-invasive method of recording brain activities enables various applications, such as monitoring mental conditions and controlling machines. To
effectively identify the recorded weak biopotentials, most of the EEG interfaces follow an international standard for electrode placement known as the 10-20 system[61]. Thanks to brain computer interface (BCI) technology, By acquiring EEG signals, the brain can interact directly with the outside world without the intervention of the peripheral nervous system[43-45].”


“Electrocardiography (ECG) is a non-invasive technique used for obtaining data of a heart’s electrical activity through small electrical changes caused by the continuous depolarization-repolarization cycle of the cardiac muscle[92]. In layman’s terms, ECG is the recording of the heart’s electrical activity. This technique provides information of on the autonomic nervous system responsible for the heart’s electrical activity[93,94]. An ECG signal has multiple waves that represent the specific state of the heart during a heartbeat cycle. This signal or wave is called the PQRST wave] where P indicates atrial contractions, QRS indicates ventricle contraction and T indicates ventricle expansion[95]. Abnormalities in PQRST intervals can indicate heart-related problems. ECG recordings have been extensively used in the medical field to record or monitor the heart’s electrical activity in patients[96]. Abnormalities in ECG readings have proven to be essential for medical experts to determine the patient’s health condition[97].”


3. Discussion on limitation or challenges in the development and application of soft biopotential interface would provide more balanced perspective.

**RESPONSE:**

We thank the reviewer for this careful comment. We have revised the manuscript and added discussion on limitation or challenges in the development and application of soft biopotential interface in the ‘Conclusion and Outlook’ section.

“Non-invasive biopotential recording techniques, such as EMG, EEG, ECG, and EOG play a crucial part in establishing effective communication between users and machines. These biopotential signals are recorded non-invasively and often require skin contact, allowing for wearable device applications. These soft biopotential interface technologies have successfully demonstrated human-machine interaction, but further research is necessary to maximize their potential in advanced materials, energy technology, and signal processing. Several limitations and challenges are still present in the current soft biopotential interface technologies that prohibit their immediate adoption in consumer devices. Even though soft interfaces allow miniaturization and improve conformability, their integration with conventional solid-structured electronics that are required for signal processing act as a barrier to achieving complete softness and flexibility of the device. With various soft materials and structural designs, another challenge that soft interfaces face is standardizing to the industry-ready parameters, often leading to ineffective large-scale production. Another major issue to be considered is that human skin is constantly subjected to tiny wear and tear, leaving almost scars and cuts on the surface of the skin that might be invisible to the naked eye. This phenomenon can cause
several issues such as irritation, infection due to material type, loss of adhesion, and inefficiency in healing.”

4. Reference list has many errors such as ‘%’ from the ref#45. Author should carefully go through the list and correct them.

RESPONSE:

We thank the reviewer for the comment. We have gone carefully through the references and corrected every error.
Reply to Reviewer 2’s comments.

Dear Prof./Dr./Sir/Madam:

Thank you so much for your time and for providing us with valuable comments. We have revised the manuscript thoroughly according to your comments. Detailed actions and revised parts are discussed next:

Reviewer comments:

This article reviews the use of soft, flexible, and stretchable materials for the development of biopotential interfaces in wearable human-machine interactive devices and the possible applications of soft biopotential interfaces in wearable devices. However, there are many formatting errors and grammatical mistakes, and the whole paper is not sufficiently rigorous, and there are some contents that need to be supplemented. This work can be published after a major revision. Specific comments are as follows.

1. The abstract does not overview the main content of this review paper properly, please revise carefully.

RESPONSE:

First, we thank the reviewer for this careful comment. We have made considerable changes to the abstract and revised the manuscript. We added relevant information to the “abstract” part (the red one is revised or added contents).

Humans interacting with machines is an act that can range from ‘flicking a fan switch’ to ‘using a microwave’, and all the way up to ‘flying a helicopter’. Interacting Human interaction with machines can be made easy, comfortable, and accessible by introducing user-friendly interfaces. In the case of wearable devices, their sensors and other interfacing elements are very well within the user’s proximity. Using biopotential signals from within the human body can make interaction seamless for the user. Since biopotential signals can be accessed from the surface of the human skin, users can have seamless interaction with wearable human-computer interactive devices. If the interfacing technology is imperceptible and unobtrusive—since rigid and cumbersome interfaces can hinder the user experience, rigid interfaces can hinder the user experience and therefore the need for soft biopotential interfaces is important. Imperceptible and unobtrusive soft biopotential interfaces will drastically enhance many aspects of human-computer interaction. This paper reviews the use of soft, flexible, and stretchable materials for the development of biopotential interfaces in wearable human-machine interactive devices. Additionally, attention is brought to the scope of other possible applications of soft biopotential interfaces in wearable devices.

2. The format of the full text and the labeling of some chemical substances need to be carefully checked and uniformly revised, for example, indentation for the first line in Line 32 and the name of a chemical substance in Line 117, etc.

RESPONSE:

We thank the reviewer for the comment. We have gone carefully through all the text, punctuation, and grammar throughout the manuscript and corrected every minor error.
3. Please check the inconsistent use of parentheses in the description in Figures 1 - 4.

**RESPONSE:**

We thank the reviewer for the comment. We have gone carefully through all the text, punctuation, and grammar throughout the manuscript and corrected every minor error.

4. The author mentions silver electrodes several times in the text and compares some of the reported soft interfaces with Ag/AgCl electrodes. It is also suggested that a suitable amount of performance data be added to the performance comparison.

**RESPONSE:**

We thank the reviewer for the meticulous comment. We have made the changes in the manuscript and compared some of the qualitative performance data of the soft biopotential interfaces with that of Ag/AgCl electrodes in terms of wearable device requirements.

“When direct comparisons are made to the standard Ag/AgCl electrode interface, the performance of these soft biopotential sensors has shown comparable or even better results. For instance, low skin-electrode contact impedance is an important factor for biopotential interfaces attached to the skin’s epidermal layer for recording signals. The flexible sEMG electrode by Zeng X. et al. was fabricated using hydrographic printing and showed an impedance value of around 10 KΩ at 500 Hz, whereas the traditional electrode interface had a value of around 14 KΩ at 500 Hz. Moreover, at lower frequencies, the flexible interface showed significantly lower impedance. Additionally, Li G. et al. reported that the SNR values were comparable between their semi-dry EEG interface and conventional ‘wet’ EEG electrodes. Both devices showed SNR values of around 7 dB in the eyes open/close paradigm experiment. The semi-dry electrode interface performed slightly better in other Steady-state visually evoked potential (SSVEP) paradigms. The Gecko-inspired dry ECG electrode displayed its adhesion capability by achieving over 30 cycles of adhesion to the skin. Moreover, the adhesion force was comparable to those of wet adhesive, ~1.3 N/cm². Qualitative analysis is made between traditional and soft biopotential interfaces with respect to their wearability in Table 1.”

<table>
<thead>
<tr>
<th>Interface type</th>
<th>Type</th>
<th>Conformability</th>
<th>Stretchability or Flexibility</th>
<th>Period of usage</th>
<th>Electrolyte Gel</th>
<th>Bulkiness</th>
<th>Signal quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag/AgCl Electrode Interface</td>
<td>Low</td>
<td>Absent</td>
<td>Short</td>
<td>Present</td>
<td>Medium</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Soft Interface</td>
<td>EMG</td>
<td>High</td>
<td>Present</td>
<td>Long</td>
<td>Absent</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>EEG</td>
<td>Average</td>
<td>Present</td>
<td>Long</td>
<td>Semi</td>
<td>Avg.</td>
<td>Avg.</td>
</tr>
<tr>
<td></td>
<td>ECG</td>
<td>High</td>
<td>Present</td>
<td>Long</td>
<td>Absent</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>EOG</td>
<td>High</td>
<td>Present</td>
<td>Long</td>
<td>Absent</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Table 1: Qualitative performance comparison of traditional vs soft biopotential interfaces w.r.t. wearable device requirement.
5. Please carefully check the format/style of the target journal. For example, the reference format. The journal name needs to be abbreviated.

**RESPONSE:**

We thank the reviewer for the comment. We have carefully revised through the references and corrected every error.

6. References: Flexible electrodes and soft electrode interfaces are developing rapidly, and it is recommended to cite recent literature, such as J. Mater. Chem. A, 2022, 10, 1248-1256;

**RESPONSE:**

Thank you for these great references. We have checked the paper you mentioned and appropriately cited it as a reference.

7. English writing of the manuscript needs further polishing.

**RESPONSE:**

We thank the reviewer for the comment. We have carefully revised all the contents of the manuscript and polished the literature.
Reply to Reviewer 3’s comments.

Dear Prof./Dr./Sir/Madam:

Thank you so much for your time and for providing us with valuable comments. We have revised the manuscript thoroughly according to your comments. Detailed actions and revised parts are discussed next:

Reviewer comments:

This manuscript reviews the use of soft, flexible, and stretchable materials and possible applications for the development of biopotential interfaces in wearable human-machine interactive devices. However, the reviews of the soft biopotential interfaces for wearable human-machine interfaces have some questions need to be revised.

1. The Ag/AgCl electrodes are the gold standard for conducting tests and research in the medical and bioinstrumentation industry, however, what are the pros and cons of the flexible or stretchable electrodes and what conditions do flexible electrodes need to meet for replacing the Ag/AgCl electrodes? Above problems should be elaborated in detail.

**RESPONSE:**

We thank the reviewer for this fundamental comment. When it comes to wearability and wearable devices, the human-machine interface is a very important aspect to consider since the interfacing occurs on the user’s body i.e., human skin. When adhering to the wearability aspect, the advantages that soft interfaces offer are numerous in comparison to Ag/AgCl electrodes. Skin conformability, transparency breathability, long-period usage, and re-usability are a few advantages that soft biopotential interfaces can offer. Moreover, miniaturization and transparency of these interfaces are also available options, which can play an important role in enhancing user experience. However, completely replacing the traditionally used Ag/AgCl electrodes is still a challenge. One of the biggest challenges is scaling up the fabrication and production to meet industry standards. Material acquisition, logistics, and developing fabrication/production lines to mass-produce soft-material-based interfaces are obstacles needed to overcome to be consumer-ready. Moreover, the cost of raw materials and the additional cost of materials used during synthesizing or fabricating the soft interfaces increases the overall device cost. Cost-effective solutions are necessary to allow soft biopotential interfaces to seamlessly enter the wearable devices market. Lastly, making soft biopotential interfaces easy to integrate with the existing signal acquisition and processing equipment can fast-track its way to replacing the traditional interfaces.

2. For this review, the four primary biopotential signal interfaces (EMG, EEG, ECG and EOG) have been simply discussed in the aspect of application. However, what kind of materials and processes are utilized to achieve the four biopotential signal interfaces? And their disadvantages? How did researchers solve these problems?

3. From the perspectives of materials and the synthesis process of materials, what are the challenges for soft biopotential interfaces utilized in wearable human-machine?

**RESPONSE TO 2 & 3:**

We thank the reviewer for this meticulous comment. This review focuses on the use of soft biopotential interfaces from the perspective of their need in wearable devices. In the paper, we have
mentioned the materials used in the reviewed soft biopotential interfaces individually. We have quoted a few below:

“This sEMG was fabricated using polyimide film as the base substrate, with gold as the electrode material.” (Line 111)

“It was fabricated using a 2D material called Titanium Carbide (Ti3c2Tx) Mxene that is encapsulated in Parylene-C.” (Line 123)

“The electrode was made by coating thin polymer bristles with silver-based conductive ink” (Line 270)

Most of these biopotential interfaces utilize the same process as traditional biopotential interfaces for signal acquisition. A small electrical signal is recorded on the surface of the skin due to the difference in electrical potential between the main and reference electrodes. Using a similar method, these carefully designed soft biopotential interfaces record small electrical activity. The disadvantages that lie in the traditional non-invasive electrodes such as low resolution and low-quality signals when compared to invasive techniques, are also present in the soft biopotential interfaces. Since non-invasive interfaces can be used readily in wearable devices without the need for surgical implantation, it is favored over invasive techniques. If Ag/AgCl electrode interfaces are directly compared to soft biopotential interfaces, one of the major disadvantages of soft interfaces is not having standardized large-scale production scalability. Additionally, various soft materials of different performance characteristics are utilized to develop these soft biopotential interfaces, making it difficult to develop an industry-standard device. However, researchers are putting in efforts to develop interfaces by using widely-accepted and popular soft materials such as PDMS and PEDOT:PSS. By using such materials, the transition from experimental use to commercial use can be made smoother.

As mentioned in response 1, from the perspective of materials and the synthesis process of materials, one of the biggest challenges is scaling up the fabrication and production to meet industry standards. Material acquisition, logistics, and developing fabrication/production lines to mass produce soft-material-based interfaces is a big challenge. Moreover, the cost of raw materials and the additional cost of materials used during synthesizing or fabricating the soft interfaces increases the overall device cost. Cost-effective solutions are necessary to allow soft biopotential interfaces to seamlessly enter the wearable devices market.

4. As described in Figure 3, all the cited references come from before 2020, how do you make sure the review in this field keep up with the development trend closely?

RESPONSE:

We thank the reviewer for this careful comment. As you mentioned, the cited references in Figure 3 are from 2020 and before. We acknowledge that to keep up with the development trend in this field, citing some of the recent works is necessary. With that in mind, we have included some relevant works (between 2020~2022) that align with the topic of this paper and updated the manuscript. These recently cited works use flexible headbands with electrode interfaces and record EEG signals from the forehead. These works are briefly described in Section 2b, along with the other mentioned forehead EEG interface by Guangli Li et al.

We would like to mention our reasoning for not including these works in the manuscript previously – EEG recording generally uses the 10-20 system which requires the interface to be in contact with the scalp. Forehead EEG recordings are subjected to muscle movement artifacts and the signals are weaker when compared to scalp EEG recordings. With this understanding, we chose to include soft systems that follow the 10-20 system in EEG recording and one flexible forehead EEG interface. However, we now acknowledge the importance of including more papers since the forehead
EEG interfaces do offer better wearability options. We would once again like to thank you for your comment.

“Furthermore, Guangli Li et. al. fabricated a unique flexible Ag/AgCl dry electrode array with a sweat-absorbable sponge for frontal EEG monitoring[82]. This coating exhibited exceptional non-polarizability and adhesion performance. Sweat absorption can be substantially aided by the sponge. Furthermore, it uses sweat as the electrolyte, effectively eliminating the risk of cross-interference or short circuits while lowering the contact impedance. All of the findings supported the viability of forehead EEG recording. Forehead EEG recording techniques make wearability more accessible. Golparvar A. et al developed a graphene-based e-textile interface that can record brain waves[83]. This graphene-based textile EEG interface is made with a Dip-Dry-Reduce method. The main materials used are hydrophilic nylon textile and graphene oxide solution. The reliability of this wearable device was demonstrated by comparing it with commercial dry electrodes in EEG recording experiments. Another wearable e-textile EEG recording device developed by Carneiro M. et al contains 11 electrodes for interfacing with the forehead site and an electronic circuit for signal processing[84]. Their design and fabrication process allows this soft latex-based interface to have two open sites, one to contact the epidermis, and the other to allow connection with the electronics. The inclusion of the electronics system along with Lithium-Polymer batteries allows 24 hours of operation time which is favorable for wearable device applications. For a variety of EEG recording and monitoring applications, flexible dry electrodes provide quick setup, user-friendliness, self-application, and wearer comfort.”


Reply to Reviewer 4’s comments.

Dear Prof./Dr./Sir/Madam:

Thank you so much for your time and for providing us with valuable comments. We have revised the manuscript thoroughly according to your comments. Detailed actions and revised parts are discussed next:

Reviewer comments:

This paper reviews the soft, flexible, and stretchable materials for the development of biopotential interfaces in wearable human-machine interactive devices. Interacting with machines can be made easy, comfortable, and accessible by introducing user-friendly interfaces. This may provide biopotential interfaces in wearable human-machine interactive devices development. However, the manuscript should be highly improved before accepted for publication.

1) The current manuscript needs to be polished by a native English speaker or a professional language editing service.

RESPONSE:

First, we thank the reviewer for the comment. We have gone carefully through all the contents of the manuscript and polished the literature.

2) The format of the whole manuscript should be uniform, for example, there is no space at the beginning of the Line 61, there is too much space in Line 195-198, and do on.

RESPONSE:

We thank the reviewer for the comment. We have gone carefully through all the text, punctuation, and grammar throughout the manuscript and corrected every minor error.

3) The resolution of the figures is too low, and the size of the words should be adjusted to make it looks comfortable, for example, the quality of Figure 3 is really bad, and the words in that figure is also not suitable.

RESPONSE:

We thank the reviewer for the comment. We have gone carefully through all the figures and corrected all the possible errors.

4) In the introduction section, the authors need to provide detailed information on current progress in soft biopotential electrode interfaces. There are few references in the introduction.

RESPONSE:

We thank the reviewer for this careful comment. We have revised the manuscript and provided detailed information on current progress in soft biopotential electrode interfaces in the “introduction” part. We have taken note of the referencing in the introduction section and have cited additional relevant articles. (the red font is revised or added contents).

“Integrating interfaces and sensors on wearable HCI devices requires embedding soft and advanced materials. Soft materials can improve the physical attributes of these
electrode interfaces such as conformability, safety, size, attachment, adaptability, efficiency, accuracy, ergonomics, and more, while advanced engineering materials can improve conductivity, reliability, stability, and more; some of the attributes that the current technology lacks[29–31]. Figure 1 illustrates the possible HCI applications that can be controlled via wearable soft biopotential interfaces. Recent progress in areas like soft material designs[32], nanomaterials[33], stretchable electronics[34–37], energy harvesting[38,39], and wireless communication[40,41] have shown promising results in improving the wearability and portability of wearable HCI devices.

Kwon Y.T. et. al. developed a fully equipped soft biopotential EMG wearable device that consists of a stretchable serpentine-designed interface and embedded bioelectronics[42]. Their work displayed excellent EMG recording capabilities by using machine learning algorithms and also demonstrated real-time wireless control of other devices. 3D printing technologies have opened up a new realm of possibilities by allowing rapid prototyping of soft interface structures and enabling suppliance-specific designing[43–45]. Zhu Z. et. al. and group have successfully demonstrated direct printing of biomedical devices on live human organs by using an adaptive 3D printing approach[46]. Such innovative methodologies if applied towards the development of soft biopotential interfaces, the human-computer interaction capabilities of wearable devices can reach possibilities that are currently beyond our comprehension.”

43. Wei H, Li K, Liu WG, Meng H, Zhang PX, Yan CY. 3D Printing of Free-Standing Stretchable Electrodes with
5) In Soft EMG Interfaces, there are few introductions in this part, you can add some introductions about the conductivity of EMG Interfaces.

**RESPONSE:**

We thank the reviewer for this careful comment. We have revised the manuscript and added more description with regard to the conductivity of EMG in section 1 along with minor literature changes. (the red one is revised or added contents).

“Electromyograph (EMG) signals are biological signals generated from the electrical activities in the muscles. EMG recording is a technique that provides indirect information on muscle activity and even muscle condition[29–31]. Surface electromyography (sEMG) is one of the most utilized muscle interface methods since it is non-invasive. Due to this method’s reliability to acquire bio-signals while being completely non-invasive, it has been extensively studied for decades[32].

Ag/AgCl electrodes are the norm for analyzing biopotential signals non-invasively. However, while these Ag/AgCl electrodes have been used in several professional industries like medicine and bio-instrumentation, they hold an unimpressive share in the wearable device sector. To pass as a viable biopotential interface in wearable devices, using soft materials along with unique designs show great potential in shaping some of the newer sEMG interfaces. On the other hand, using soft materials can affect the conductivity of the sEMG interface which inherently determines the quality of the output signal. Although recent advances in stretchable and flexible materials satisfy the mechanical requirements which are needed in wearable devices for HCI, it is equally important for these soft interfaces to exhibit competitive electrical performance.”

6) In Soft EEG Interfaces, the specific working mode of this interface is not particularly clear. It is recommended to explain it in detail.

**RESPONSE:**

We thank the reviewer for this careful comment. We have revised the manuscript and added more description with regard to the specific working mode of soft EEG interfaces in section 2.

“Numerous neurons in the brain are responsible for generating, transmitting, and processing mysterious electrophysiological signals[60]. Electroencephalogram (EEG) signal indicates the neural or electrical activity of the brain. Since the brain cells communicate through electrical impulses, the cortex of the brain receives postsynaptic
potential. These biopotential signals can then be recorded on the scalp surface. This non-invasive method of recording brain activity allows real-world applications. Most of the EEG interfaces follow an international standard for electrode placement known as the 10-20 system for recording brain activity[61]. Thanks to brain-computer interface (BCI) technology, by acquiring EEG signals, the brain can interact directly with the outside world without the intervention of the peripheral nervous system[62-64].”


7) In Soft ECG Interfaces, compared with other methods, what is unique about ECG? What are the disadvantages of the existing technology?

RESPONSE:

We thank the reviewer for this careful comment. After reading your comment, we have made efforts to explain briefly about the other methods in comparison to Soft ECG interfaces and also describe the disadvantages of the existing technologies.

“ECG monitoring can play a vital role as a wearable device. With the increased awareness of physical health and lifestyle maintenance, keeping track of the body’s everyday performance has become a necessity[98]. Many wearable technologies such as smartwatches and fitness bands already include heart-rate monitoring systems, however, most of these technologies have a different method for detecting these biopotential compared to the traditional ECG technique[99,100]. These devices generally use photoplethysmography (PPG) optical sensors that detect the change in blood volume during a cardiac cycle. These wearable devices have effectively shown impressive results as wearable heart-rate monitoring technology[101]. However, the PQRST wave cannot be precisely determined by this method and a lot of vital data can go unmonitored. To record such delicate information, the ECG interfacing device should be placed on the skin. The inclusion of soft ECG interfaces can provide critical information in applications where detailed and accurate readings of heart activities are needed for detecting cardiac abnormalities in a subject under intensive care[102].”

8) There is too little content about Soft EOG Interfaces, it is suggested to add content about the specific manufacturing method, process, characterization and application of EOG. Please refer the following paper:


RESPONSE:

Thank you for your comment. We have added additional information to the Soft EOG interfaces section and made changes to the manuscript as well.

a. Flexible and Stretchable EOG interfaces

This electrooculography electrode developed by Won et al. is fabricated using a plant-based bioplastic – polylactic acid (PLA), and poly(3,4-ethylenedioxythiophene)
polystyrene sulfonate (PEDOT:PSS)[112]. The conductive element, PEDOT:PSS is sandwiched between two substrate PLA layers. These materials allow the interface to be soft, transparent, conductive, and biocompatible. Using fabrication techniques like spin coating and laser cutting, thin Y-shaped kirigami patterned voids are created which allow not only multidirectional stretchability and high areal coverage but also breathability. The fabrication process also allows rapid and scalable fabrication since it eliminates the use of time-consuming chemical-dependent patterning and etching processes generally used in microfabrication. Since there are no sacrificial layers, this soft device can be easily peeled off from the substrate. To accommodate external electrical contact, gold was deposited and used as a contact pad on PEDOT:PSS. The group demonstrates the human-machine interaction capability of the interface by integrating it with a signal processing unit and switching various electric devices on and off by eye movements of the user wearing the soft electrode interface.

Thank you for this reference. We checked the paper you mentioned and appropriately cited it as a reference (We have even included the work in Section V of our review paper)

9) The review paper is too short, and the quality of this review paper should be highly enhanced by citing more papers from Zhenan Bao, Rogers, etc. There are at least 10 figures for such a topic.

RESPONSE:
We thank the reviewer for this notable comment. We have made considerable changes to the manuscript, including its total length and quality. We have added an additional section that showcases different strategies in soft interfaces for wearable applications that aim to tackle current limitations. Additionally, we have cited more relevant articles by more authors (including the ones you mentioned) where deemed suitable.

V. Innovative strategies for improved wearable soft interfaces

Soft biopotential interfaces in wearable devices can benefit from technologies like soft electronics and optimized energy systems. Since wearable devices require a portable source of energy to operate, most of the systems use battery systems. These battery systems face limitations when scaled down in size and can make the system bulky. Innovative strategies such as energy harvesting systems and self-powered systems have been integrated into these soft biopotential interface technologies to enhance wearability.

Li W. et al. developed a poly(vinylidene fluoride) based self-powered wireless flexible wearable device that helps in overcoming the limitations of the battery system in wearable devices[116]. Apart from displaying high stretchability (1500% of its original length), this PVDF-ionogel device has the ability to convert external pressure into electricity which enables it to power itself. The electricity generated by this piezoelectric property is enough to charge a 4.7 μF 50 V capacitor to 0.7 V within 225 seconds. Although this device was used to measure different body movements, the inclusion of self-powered technology enhances its wearability aspect. The inclusion of such technology in soft biopotential interfaces can improve long-term usage in health monitoring.

Since biopotential interfaces are vastly used in healthcare and health monitoring areas, a slight imprecision in the electronic reading can result in an inaccurate diagnosis of the user’s health. Stretchable devices containing electronics often have limited strain capabilities so as to not compromise the electronic performance. Wang W. et. al. along
with Bao. Z. developed a strain-insensitive intrinsically stretchable transistor array[117]. The stretchable device was fabricated using an all-elastomer process for applying local stiffness using styrene–ethylene–butylene–styrene (SEBS) as the main material. The device achieved stable electrical performance even under large strains. This property allows stretchable devices to have mechanical flexibility without compromising electrical stability. In soft biopotential interfaces, introducing such technology can make signal recording more precise and accurate. Figure 6(i) shows PVDF-ionogel self-powered soft and wearable device and Figure 6(ii) shows the strain-insensitive intrinsically stretchable transistor array under strain.


Figure 6. (i) Schematic of the PVDF-ionogel self-powered wearable device. (ii) Output voltages due to bending. (iii) Rectifier circuit diagram and plot of voltage vs. time curve for charging capacitor. Reprinted (adapted) with permission from Li W. et al. Copyright 2023 American Chemical Society. (iv) Photographs of a transistor array under the original (left) and stretched (right) states. (v) Optical microscope images of one transistor in the array, under 0% (left) and 100% (right) global strain. Reprinted (adapted) with permission from Wang W. et. al.. Copyright 2021 Springer Nature.

With regard to the number of figures, we acknowledge your valuable insight. We made efforts to add more figures to bring it to a total of 6 figures. Since our manuscript is divided into 5 major sections, adding additional figures will not reflect well with the text in our opinion.
Prospects of soft biopotential interfaces for wearable human-machine interactive devices and applications.

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Abstract

Human interaction with machines can be made easy, comfortable, and accessible by introducing user-friendly interfaces. In the case of wearable devices, their sensors and other interfacing elements are very well within the user’s proximity. Since biopotential signals can be accessed from the surface of the human skin, users can have seamless interaction with wearable human-computer interactive devices. Rigid interfaces can hinder the user experience and therefore the need for soft biopotential interfaces is important. Imperceptible and unobtrusive soft biopotential interfaces will drastically enhance many aspects of human-computer interaction. This paper reviews the use of soft,
flexible, and stretchable biopotential interfaces in wearable human-machine interactive
devices. Additionally, attention is brought to the scope of other possible applications of
soft biopotential interfaces in wearable devices.

**Keywords:** Biopotential, Soft interface, Wearable, Interface, Human-machine interface
(HMI), Human-computer interaction (HCI)

**INTRODUCTION**

Human-machine interface (HMI) in layman’s terms is an interactive system designed to
allow communication between humans and machines[1]. Since the dawn of human-
computer interaction (HCI) technologies, it was evident that HMI technology would have
to adapt and evolve to improve its usability[2]. Eventually, wearable devices with HCI
capabilities were introduced to the world, and considering human aspects such as
physical, cognitive, and emotional characteristics of these devices is essential during
their development[3]. Refining designs, configurations, and ergonomics of rigid wearable
devices for HCI technologies would not be enough to enhance the users’ experience.
Therefore, using soft and advanced engineering materials is crucial for making human-
machine interfaces more competent and up to par to pass as a mode of communication
in wearable HCI devices[4].

With the constant progress in health and lifestyle technologies, there has been an uprising
in wearable devices and the features they can offer [5–9]. Wearable devices are essential
tools for human-computer interaction technologies that can record an individual’s
biological and neural activities through close contact with human skin [10]. All kinds of
physical and mental activities in the human body generate electrical potentials, called
biopotentials, that provide colossal amounts of information, which can be used for
various applications, such as health monitoring and controlling electronic devices [11–16].
For instance, neural activities in the brain can be recorded, analyzed, and used for various
purposes. Motor actions that are intention-based such as walking or moving of arms can
be monitored in the form of neural activities in the brain. Similarly, when sensory inputs
are perceived in the brain such as touch or taste, the associated neural activities can be
observed in the brain. The most common technique for non-invasive brain recording is
Electroencephalography (EEG)[17]. Although EEG allows the recording of neuronal
activity non-invasively, is difficult to isolate and record specific areas of the brain [18].
Neural signals from the brain travel in the human body and branch out to different areas
through the nervous system. Similarly, the sensory inputs from the body are sent to the brain via these nervous systems. Apart from EEG, electromyograms (EMG), electrocardiographs (ECG), and electrooculograms (EOG) signals are the major biopotential signals that can be acquired using non-invasive interfaces\[19\]. Other than acquiring data from these signals, non-invasive interfaces can also perform stimulation-based applications for specific rehabilitation purposes\[20–22\]. Wearable devices can utilize biopotential signals like EMG (from muscular activity) and EOG (from eye movement) for delivering intention-based output signals to allow applications like gesture control, end-effector manipulation, and prosthesis. Unintentional, or autonomous biopotential signals such as ECG (from heartbeats) can allow for health monitoring applications. In human-computer interaction, such information is valuable in various industries, including medical healthcare, assistive robotics, lifestyle, and more.

The most widely accepted and used interface for recording biopotentials are silver/silver-chloride (Ag/AgCl) electrodes\[23\]. These electrodes are the gold standard for conducting tests and research in the medical and bioinstrumentation industry\[24\]. Their performance has been constantly under study and their parameters are well-defined, displaying remarkable consistency\[25\]. However, Ag/AgCl electrodes, due to their use of electrolyte gel, cannot be used for long term, which is an important consideration for producing convenient wearable devices. Moreover, the materials used have a short life cycle. Other issues such as inelasticity, obtrusiveness, and non-reusability make them unfit for integration with wearable HCI devices\[26–28\]. Integrating interfaces and sensors on wearable HCI devices requires embedding soft and advanced materials. Soft materials can improve the physical attributes of these electrode interfaces such as conformability, safety, size, attachment, adaptability, efficiency, accuracy, ergonomics, and more, while advanced engineering materials can improve conductivity, reliability, stability, and more; some of the attributes that the current technology lack\[29–31\]. Figure 1 illustrates the possible HCI applications that can be controlled via wearable soft biopotential interfaces. Recent progress in areas like soft material designs\[32\], nanomaterials\[33\], stretchable electronics\[34–37\], energy harvesting\[38,39\], and wireless communication\[40,41\] have shown promising results in improving the wearability and portability of wearable HCI devices.

Kwon Y.T. et. al. developed a fully equipped soft biopotential EMG wearable device that consists of a stretchable serpentine-designed interface and embedded bioelectronics\[42\].
Their work displayed excellent EMG recording capabilities by using machine learning algorithms and also demonstrated real-time wireless control of other devices. 3D printing technologies have opened up a new realm of possibilities by allowing rapid prototyping of soft interface structures and enabling supplication-specific designing\cite{43-45}. Zhu Z. et. al. and group have successfully demonstrated direct printing of biomedical devices on live human organs by using an adaptive 3D printing approach\cite{46}. Such innovative methodologies if applied towards the development of soft biopotential interfaces, the human-computer interaction capabilities of wearable devices can reach possibilities that are currently beyond our comprehension.

The paper reviews some recent works in soft biopotential electrode interfaces and discussion of their abilities with regard to wearability and possible HCI applications. For this study, we separate the four primary biopotential signal interfaces (EMG, EEG, ECG, and EOG) into their main sections and survey different types of soft electrode/interface technologies developed in the sub-sections. Each biopotential interface technique will be briefly explained in terms of its working methodology, its use, and the limitations of current technology. Finally, each sub-section will discuss recent works and their possible applications.

![Figure 1. A graphical representation of the possible wearable HCI applications controlled via wearable soft biopotential interfaces.](image-url)
I. Soft EMG Interfaces

Electromyography (EMG) signals are biological signals generated from the electrical activities in the muscles. EMG recording is used as a technique that provides indirect information on muscle activity and even muscle condition\[^{47-49}\]. Surface electromyography (sEMG) is one of the most utilized muscle interface methods since it is non-invasive. Due to this method’s reliability to acquire bio-signals while being completely non-invasive, it has been extensively studied for decades\[^{50}\].

Ag/AgCl electrodes are the norm for analyzing biopotential signals non-invasively. However, while these Ag/AgCl electrodes have been used in several professional industries like medicine and bio-instrumentation, they hold an unimpressive share in the wearable device sector. To pass as a viable biopotential interface in wearable devices, using soft materials along with unique designs show great potential in shaping some of the newer sEMG interfaces. On the other hand, using soft materials can affect the conductivity of the sEMG interface which inherently determines the quality of the output signal. Although recent advances in stretchable and flexible materials satisfy the mechanical requirements which are needed in wearable devices for HCI, it is equally important for these soft interfaces to exhibit competitive electrical performance. Figure 2 shows a variety of soft EMG interfaces. Using soft materials along with unique designs has proved to be of great potential in shaping some of the newer sEMG interfaces to become more user-friendly and comply with the requirements needed in wearable devices for HMI.

a. Flexible EMG interface

One of the critical features required for an sEMG interface to operate as a sensor on a wearable device is flexibility. Besides that, durability, biocompatibility, and size are some factors that are necessary as well.

SLIP (Sub-Liner Interface for Prosthetics) electrode developed by Yeon et al, is a prime example of a flexible sEMG interface with HMI capabilities\[^{51}\]. This sEMG was fabricated using polyimide film as the base substrate, with gold as the electrode material. The thickness of this electrode is around 80~100 μm. Since this electrode is developed using flexible PCB manufacturing techniques, it has good reproducibility. The group successfully demonstrated the human-machine interaction of the SLIP electrode by performing clinical trials on humans with lower-extremity amputation. While demonstrating walking using a prosthetic limb, it was found that the electrode’s
flexibility and sleek design played a vital part in comfortable signal acquisition.

Another example of a flexible sEMG interface is the high-density surface electromyography (HDsEMG) electrode developed by Murphy et al. This sEMG interface is particularly interesting, showcasing a high-density, gel-free flexible electrode, a fitting candidate for wearable devices. It was fabricated using titanium carbide (Ti3c2Tx) Mxene encapsulated in Parylene-C. This electrode has demonstrated some desired characteristics such as decent skin conformability, hydrophilic surface terminations, excellent conductivity, low interfacial impedance, flexibility, and being around 8 μm thick with 16 recording channels. Since it is gel-free, unlike the Ag/AgCl electrodes, it has the potential to perform as a sensor in wearable devices. This array-based sEMG electrode can eventually support multiple wearable applications as already demonstrated by the group. In Driscoll et al, with slight changes to the fabrication process, a similar MXene-based bioelectronic interface was developed. Here, they performed not only high-fidelity biopotential signal recording but also demonstrated the stimulation capability through in-vivo experiments.

b. Soft-stretchable EMG interface

Human skin has a low modulus and therefore is stretchable and flexible. Skin can also be dry and uneven, which adds some non-contact points between the electrode and the skin resulting in insufficient coverage over the sensing area, lower resolution, and loss of reliable data. Although flexible sEMG electrodes can bend, their inability to stretch and precisely conform to the surface of the skin can affect their performance. Therefore, it is important for the interfacing electrode to adapt to the constant stretching movement it is subjected to when attached to the surface of the skin.

Stretchable sEMG interfaces are sometimes called ‘e-skin’ due to their ability to stretch like skin. Yu et al developed a stretchable sEMG electrode using inkjet-printing technology, using multiple custom-developed nanomaterial inks. Although this sensor can sense multiple signals, we focus on its bio-signal acquisition and wearability performance. This stretchable interface uses PDMS as the base substrate and demonstrates high stretchability and good mechanical compliance. In addition, this inkjet-printed, four-channel, three-electrode, serpentine-structured sEMG array electrode has the capability to recognize certain hand gestures after applying various machine learning algorithms. It has a wide range of wearable HMI applications such as gesture-
controlled IoT devices or robotic limbs.

Another type of a stretchable and flexible sEMG electrode, developed by Zeng et al, uses a hydrographic printing technique\[53\]. This technique allows the electrode to be directly transferred to the skin like an artificial tattoo. Since the electrode is essentially printed on the skin, the skin acts as an efficient stretchable natural substrate. In terms of recording sEMG signals, this electrode matched the performance of an Ag/AgCl electrode. When it comes to wearability, this electrode shows high conformability and long-term usage. The electrode is gel-free which gives it an upper hand compared to the commercial electrodes, and upon detachment, it does not leave any distinctive marks such as redness or swelling.

c. Textile-based EMG interface

Integrating sensor technology with existing clothing can enhance the user-friendly aspect of wearable devices. Apart from the physical aspect like wear-ability and comfort-ability, it improves the psychological aspect of wearable devices\[57\]. Since wearing clothes is a daily activity, built-in textile-based sEMG sensors can go unnoticed by the user, hence reducing the consciousness of wearing sensors.

A stretchable and flexible nanofiber carbon film-sensing electrode is developed by Huang and Chiu, which can perform EMG and ECG monitoring\[58\]. We focus on the EMG part. This textile-based EMG interface uses carbon as its conductive material, giving it an upper edge compared to metal-based conductive fabrics. This particular EMG interface has some excellent wearable parameters which can seamlessly blend into clothing such as chemical resistance, washability, good skin contact, and wear resistance. Their experiments demonstrated various EMG applications, such as recording signals of upper and lower limb movement as well as finger movements. Such wearable EMG technology can provide multiple functions and applications ranging from healthcare monitoring to HMI applications such as gesture-controlled devices. This textile-based electrode could be used for long-term usage compared to Ag/AgCl.

d. Soft microneedle EMG interface

Microneedle EMG interfaces are not entirely non-invasive but can still be implanted on the skin without surgical techniques. In addition, microneedle EMGs have benefits over sEMG electrodes in acquiring more accurate biosignals. This is due to the micro-needle-like structures penetrating the skin and effectively reducing the impedance.
A polyimide-based microneedle array (MNA) developed by Li et al, is a soft EMG interface that can record high-quality biopotential signals\cite{59}. Apart from excellent electrode-skin contact, using flexible material to fabricate this electrode allows it to have features like long-term-wearability, bio-compatibility, and inexpensive manufacturing. The performance of this flexible MNA is noteworthy in terms of wearability aspects which were demonstrated through clinical studies. The electrode was used for long periods of time (8 hours/night for 44 nights) by multiple healthy subjects for the sleep-monitoring type of data accumulation. This successful study proved that these electrodes have the potential to substitute conventional clinical standard Ag/AgCl wet electrodes. Upon repeatedly penetrating the MNA electrode in the skin up to 100 times, no fractures we observed on the skin, and no inflammation, or any other reactions were noticed. Some slight penetration marks are seen upon electrode detachment from the skin; however, they tend to fade within hours. Since microneedle EMGs can provide better quality signals compared to surface EMG, their use can be extended to a wide range of wearable applications where near-accurate EMG signals can be beneficial.

![Figure 2. EMG](image-url)

(i) Gel-free flexible HDsEMG electrode array. Reproduced with permission from Murphy et al\cite{52}. Copyright 2020 WILEY - VCH Verlag GmbH & Co. KGaA, Weinheim (ii) Stretchable and flexible hydrographic-printing-based EMG electrode\cite{53}. (iii) Textile-based stretchable and flexible wearable EMG electrode interface. Reprinted (adapted) with permission from Huang et al\cite{58}. Copyright 2021 American Chemical Society. (iv) Flexible Microneedle biopotential electrode array\cite{59}.
II. Soft EEG Interfaces

Numerous neurons in the brain are responsible for generating, transmitting, and processing mysterious electrophysiological signals\[^{[60]}\]. Electroencephalogram (EEG) indicates recorded neural activities on the scalp surface. Although the resolution limitation of EEG, this non-invasive method of recording brain activities enables various applications, such as monitoring mental conditions and controlling machines. To effectively identify the recorded weak biopotentials, most of the EEG interfaces follow an international standard for electrode placement known as the 10-20 system\[^{[61]}\]. By acquiring EEG signals, the brain can interact directly with the outside world without the intervention of the peripheral nervous system\[^{[62-64]}\].

Generally, BCIs are implemented for various applications including acquiring and amplifying signals, extracting, and classifying features, controlling signals, and providing feedback\[^{[65-67]}\]. These types of interfaces are categorized into invasive and non-invasive branches based on signal acquisition methods or contact between the electrode on the patient’s scalp\[^{[68]}\].

Among the non-invasive techniques such as magnetoencephalography (MEG), near-infrared spectroscopy (NIRS), functional magnetic resonance imaging (fMRI), (MRI), and electroencephalography (EEG), EEG is considered one of the most non-invasive, realistic, and practical BCIs\[^{[69]}\].

Due to the advantages of the EEG technique compared to other signals, such as direct measuring the cerebral activity, high-resolution mobility (1 ms) for use in clinical settings, ease and portability to clinical use, long-term stability, and adapting to multiple experimental paradigms, they are commonly used for measuring signals of different brain activities\[^{[70,71]}\].

These types of non-invasive BCIs have been divided into wet, dry, and semi-dry electrodes according to the issue of whether the conductive gel is required for the electrode or not. However, it is important to note that most dry electrodes have unacceptably high contact impedances, while wet electrodes require lengthy setups and conductive pastes or gels to be used. Hence, semi-dry electrodes have been invented as a 3\(^{\text{rd}}\) type of electrode to moderate the disadvantages of the two previous groups.
Figure 3 shows a variety of flexible, semi-dry, and soft EEG interfaces. In the following, each type of electrode with its pros and cons will be addressed.

a. *Wet flexible EEG interface*

In literature, this kind of electrode requires electrolytic substances to improve the conductivity of the scalp-electrode. In the commercial stage, these electrodes are composed of Ag/AgCl disk and an infiltration substance i.e., conductive gel which contains electrochemical potential stability and infiltration ability. Due to the advantages mentioned above, wet electrodes are currently prevalently used. However, a list of drawbacks exists that should be considered and solved. One of the common problems is the time-consuming procedure of cleaning up and controlling the amount of conductive gel for each electrode point. Another critical issue is reducing the moisturizing level of gel during the experiment which results in poor EEG signal quality as an increasing impedance\textsuperscript{[72]}.

To mitigate these problems, dry and semi-dry electrodes were suggested.

b. *Dry flexible EEG interface*

Dry flexible electrodes are leveraged to overcome wet electrodes’ inconvenience and unstable recording conditions, as mentioned before. Indeed, dry electrodes make dry connections with skin that do not require conductive gel or any skin preparation and are desirable for portable and wearable electronic devices\textsuperscript{[73–75]}. However, in addition to these benefits, dry electrodes have several drawbacks, including the fact that they are bulkier, more costly, and more prone to movement aberrations because there is no liquid contact\textsuperscript{[76]}.

Due to the lack of humid and electrolyte media in dry electrodes, an array of structural designs is implemented for improving the contact area including the spongy\textsuperscript{[77]}, nanowire\textsuperscript{[78,79]}, microtip, and variable structural designs, or achieving highly flexible and stretchable structures and deformable conductors.

A wide range of brain-computer interactions can be performed using flexible dry EEG electrodes, as described by Grozea et al\textsuperscript{[80]}, including recording alpha rhythms in the occipital region, testing event-related potentials using an oddball auditory paradigm, and implementing sensory-motor rhythms-based event-related desynchronization paradigms.

The electrode was made by coating thin polymer bristles with silver-based conductive
ink. Its bristles almost flex as easily as those in toothbrushes and it is hard enough to pass through hair and reach the surface.

Compared to gel-based electrodes, the bristle sensors produced almost the same signal in the recorded frequency range between 7 to 44 Hz. Furthermore, it maintained mechanical and electrical contact which is recommended for long-term usability. Compared to both gel-based electrodes and arrays of pin electrodes, this electrode demonstrated excellent comfortability.

To overcome the drawbacks of wet electrodes a novel flexible dry electrode was proposed by Wang et al. which did not need any conductive gel and skin preparation\[81\]. This PDMS-based flexible electrode with pins structure indicated superior contact impedance compared to a standard wet electrode without skin preparation, while it was higher than that with a skin preparation. This flexible dry electrode is safer and more comfortable and can meet the requirement of high-quality EEG measurement.

Furthermore, Guangli Li et al. fabricated a unique flexible Ag/AgCl dry electrode array with a sweat-absorbable sponge for frontal EEG monitoring\[82\]. This coating exhibited exceptional non-polarizability and adhesion performance. Sweat absorption can be substantially aided by the sponge. Furthermore, it uses sweat as the electrolyte, effectively eliminating the risk of cross-interference or short circuits while lowering the contact impedance. All of the findings supported the viability of forehead EEG recording.

Forehead EEG recording techniques make wearability more accessible. Golparvar A. et al. developed a graphene-based e-textile interface that can record brain waves\[83\]. This graphene-based textile EEG interface is made with a Dip-Dry-Reduce method. The main materials used are hydrophilic nylon textile and graphene oxide solution. The reliability of this wearable device was demonstrated by comparing it with commercial dry electrodes in EEG recording experiments. Another wearable e-textile EEG recording device developed by Carneiro M. et al. contains 11 electrodes for interfacing with the forehead site and an electronic circuit for signal processing\[84\]. Their design and fabrication process allows this soft latex-based interface to have two open sites, one to contact the epidermis, and the other to allow connection with the electronics. The inclusion of the electronics system along with Lithium-Polymer batteries allows 24 hours of operation time which is favorable for wearable device applications. For a variety of
EEG recording and monitoring applications, flexible dry electrodes provide quick setup, user-friendliness, self-application, and wearer comfort. In general, the flexible dry electrodes presented rapid setup, user-friendliness, self-application, and wearer comfort for various applications of EEG recording and monitoring.

c. Semi-dry soft EEG interface

Several non-invasive electrode types, such as spring-like, porous, or sponge-like structures, as well as materials consisting of elastomers and hydrogels, are known as semi-dry or quasi-dry electrodes\cite{85–88}. The self-storage and gradual release of electrolytes make this type of electrode stand out from wet and dry electrodes\cite{89}. Indeed, Semi-dry electrodes release electrolytes at a slower pace than wet electrode types, depending on the particular structural design or substance. Therefore, this value will have an impact on preserving low contact impedance and preventing short-circuit interference between electrodes. Despite these advantages, large-scale manufacture is limited due to specific structural designs or particular materials.

Furthermore, regarding the usage of soft materials, the mechanical mismatch between electrodes and the human scalp is low\cite{90}. As a result, semi-dry electrodes are advised for prolonged therapeutic usage including sleep monitoring and rehabilitative treatment\cite{91}. In 2019, Lin et al. reported a type of Gel-Free Electroencephalogram Electrode with a high conductivity of 917 S/m due to the surface metallization by the silver nanowires (AgNWs).

Compared to the conventional electrodes that contained conductive gel, the new electrode showed almost the same steady-state visual evoked potential (SSVEP) as that of the conventional one. In conclusion, the cost-effectiveness, simplicity of manufacture, flexibility, robustness, relatively low electrode-skin impedance, and mechanical stability of this electrode were its main strengths.

In addition, Li et al. proposed innovative passive semi-dry electrodes for recording electroencephalography data from the hairy scalp. This ceramic-based electrode was able to attain a low and stable impedance and a steady-state visually evoked potentials
SSVEPs) paradigm. Due to the capillary force through porous ceramic pillars, a regulated amount of saline solution could be released which eliminates skin preparation and gel application. EEG signals were consistent and electrode polarization voltage demonstrated a steady state which was similar to commercial gel-based Ag/AgCl electrodes. Semi-dry electrodes applied to real-world practical EEG applications, such as brain-computer interfaces and wearable technology.

A quasi-dry electrode for electroencephalography (EEG) is fabricated by Mota et. al\cite{76}. This polymer-based electrode was able to discharge 30 µl of a hydrating agent, which decreased the volume of gel needed to simply cover the electrodes' contact sites. Obtained legitimate EEG signals that were comparable to those of commercial Ag/AgCl reference electrodes, demonstrating the electrode's suitability for BCI applications.
Figure 3. Flexible dry and semi-dry electrodes: i) Silver-coated polymer conductive bristles dry electrode instead. Reproduced with permission[80]. Copyright 2011, the Authors. Published by IOP Publishing. ii) Schematic diagram of assembled screen-printed flexible Ag/AgCl electrode array. Reproduced with permission[82]. Copyright 2020, the Authors. Published by IOP Publishing. iii) Photo and schematic diagram of a single semi-dry electrode including porous ceramic pillars (a), a built-in reservoir (b), 3.5% saline solution (c), and sintered Ag/AgCl electrode (d). Reproduced with permission[85]. Copyright 2016, Elsevier. iv) Hollow cylinder electrode consisting of a PVC shell, infiltrated normal saline, and an AgPMS contact and assembled EEG electrode. Reproduced under the terms of an ACS AuthorChoice License[77]. Copyright 2019, Copyright American Chemical Society. (v) Diagram illustrating a semi-dry electrode that expels the hydrating agent. Manufactured polyurethane electrodes. Reproduced with permission[76]. Copyright 2013, Elsevier.

III. Soft ECG Interfaces
Electrocardiography (ECG) is a non-invasive technique used for obtaining data on a heart’s electrical activity through small electrical changes caused by the continuous depolarization-repolarization cycle of the cardiac muscle[92]. In layman’s terms, an ECG signal is the recording of the heart’s electrical activity. This technique provides information on the autonomic nervous system responsible for the heart’s electrical
activity[^93,^94]. An ECG signal has multiple waves that represent the specific state of the heart during a heartbeat cycle. This signal or wave is called the PQRST wave[^95] where P indicates atrial contractions, QRS indicates ventricle contraction and T indicates ventricle expansion[^95]. Abnormalities in PQRST intervals can indicate heart-related problems.

ECG recordings have been extensively used in the medical field to record or monitor the heart’s electrical activity in patients[^96]. Abnormalities in ECG readings have proven to be essential for medical experts to determine the patient’s health condition[^97]. Since ECG is mostly used for health monitoring, factors like long-term usage, high stability, and stable attachment to the epidermal layer are of great importance and should be considered when developing wearable devices. Ag/AgCl electrodes are the industry standard for recording ECG signals, but they lack the wearability aspects mentioned in the previous section.

ECG monitoring can play a vital role as a wearable device. With the increased awareness of physical health and lifestyle maintenance, keeping track of the body’s everyday performance has become a necessity[^98]. Many wearable technologies such as smartwatches and fitness bands already include heart-rate monitoring systems, however, most of these technologies have a different method for detecting these biopotential compared to the traditional ECG technique[^99,^100]. These devices generally use photoplethysmography (PPG) optical sensors that detect the change in blood volume during a cardiac cycle. These wearable devices have effectively shown impressive results as wearable heart-rate monitoring technology[^101]. However, the PQRST wave cannot be precisely determined by this method and a lot of vital data can go unmonitored. To record such delicate information, the ECG interfacing device should be placed on the skin. The inclusion of soft ECG interfaces can provide critical information in applications where detailed and accurate heart activity readings are needed to detect cardiac abnormalities in a subject under intensive care[^102].

### a. Flexible and Stretchable ECG interfaces

Inspired by the adhesion mechanism of a gecko’s feet and the advanced nanomaterials, these ECG electrodes developed by Kim et al. drastically improve the adhesion force on the skin while eliminating the need for an electrolyte gel[^103]. The electrode is manufactured using materials like PDMS and carbon-based nanofillers and is patterned in a carefully fabricated mold. This mushroom-shaped micropillar array electrode also exhibits flexibility and stretchability (>100%) while satisfying the electrical parameters.
To add to its advantages, this bioinspired ECG electrode has a superhydrophobic surface which allows it to work when immersed underwater and also makes it prone to turning into a dusty surface. This property allows the electrode to be cleaned by simply washing it, allowing reusability up to a limit. Various experiments were carried out to demonstrate this electrode’s unique properties, such as adhesivity and superhydrophobicity.

Figure 4(i) shows the Gecko-inspired ECG interface. Such bioinspired ECG electrode interfaces have benefits over traditional ECG electrodes. The ability to adequately perform while being immersed in water and not lose conformal contact while doing so is impressive. Moreover, when the user is in motion, the ECG readings can still facilitate meaningful data in real time thus displaying great stability.

b. Wearable textile-based ECG interfaces

Since health-monitoring wearable devices are meant to deal with extended periods of usage, apart from being imperceptive, it is also necessary to record and deliver data accurately in case of different motions it may be subjected to. Isolating motion artifacts can help provide reliable data, enhancing the reliability of wearable ECG devices. Wearable textile-based dry electrodes are favorable for such long-term applications. However, other factors such as washability and retainment of signal quality are necessary for such a type of soft electrode.

A PEDOT:PSS textile-based ECG electrode developed by Ankhili et al. is a wearable type of interface that can be washed and re-used\textsuperscript{[104]}. The textile material used in this electrode is a polyamide textile fabric that absorbs a modified version of the PEDOT:PSS solution during its fabrication. This electrode was able to deliver ECG signals even after multiple washing cycles. However, it was found out in an experiment that after 50 washes, even though the ECG signals can be clearly monitored, a significant drop in can be seen in the signal-to-noise-ratio (SNR) values. The loss of SNR was inculpated by the fact that after washing the electrode, PEDOT:PSS was lost.

Figure 4(ii) shows the Gecko-inspired ECG interface. Integrating soft sensors in clothing is a promising method for long-term monitoring applications. With significant efforts put into textile-based ECG interfaces, a stable and reliable wearable garment-type device can be developed to assist with athlete performance in real-time or patient health monitoring in real-time without discomfort.
Figure 4. Soft ECG Electrode Interfaces: i) Highly Stretchable and Conductive
Gecko-inspired dry ECG electrode. Reprinted (adapted) with permission from Taehoon Kim, et al. Copyright 2016 American Chemical Society. ii) Washable textile-based ECG electrode interface.

IV. Soft EOG Interfaces
Electrooculography (EOG) is a technique used for recording the corneal-retinal potential difference\cite{105–107}. EOG interface can allow effective communication for people with severe motor disabilities\cite{108,109}. EOG has also seen its use in some of the newer HCI virtual reality systems wherein the user can navigate through a virtual environment using eye movements\cite{110,111}. Using soft technology to develop EOG electrodes can improve their wearability. Since these types of electrodes are attached to the face of the user, being thin and transparent can enhance the user experience.

a. Flexible and Stretchable EOG interfaces
This electrooculography electrode developed by Won et al. is fabricated using a plant-based bioplastic – polylactic acid (PLA), and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS)\cite{112}. The conductive element, PEDOT:PSS is
sandwiched between two substrate PLA layers. These materials make the interface soft, transparent, conductive, and biocompatible. Using fabrication techniques like spin coating and laser cutting, thin Y-shaped kirigami patterned voids are created which allow not only multidirectional stretchability and high areal coverage but also breathability. The fabrication process also allows rapid and scalable fabrication since it eliminates the use of time-consuming chemical-dependent patterning and etching processes generally used in microfabrication. Since there are no sacrificial layers, this soft device can be easily peeled off from the substrate. To accommodate external electrical contact, gold was deposited and used as a contact pad on PEDOT:PSS. The group also demonstrates the human-machine interaction capability of the interface by integrating it with a signal processing unit and switching various electric devices on and off by eye movements of the user wearing the soft electrode interface. Figure 5 shows images of the soft EOG interface showcasing the Kirigami structure, and all its soft properties. There is evident scope for wearable applications using such soft EOG interface technology. Apart from controlling tangible devices in the real world, this type of interface has shown its practicality in controlling graphical user interfaces (GUI) in virtual reality environments\[113]\. Allowing the user to operate and navigate through a virtual environment using just eye movements can heighten the user experience. On the other hand, there might be certain limitations since eye movements can cause fatigue to the user. Some soft EOG interfaces have also been used in sleep monitoring by integrating them into a sleeping mask\[114,115]\. However, users may feel discomfort wearing such masks during sleep and might prefer alternative methods of sleep tracking if needed. However, in some use cases, such technology can benefit patients who require such type of sleep tracking which can provide useful data to a medical expert to provide correct medical advice.
V. Innovative strategies for improved wearable soft interfaces

Soft biopotential interfaces in wearable devices can benefit from technologies like soft electronics and optimized energy systems. Since wearable devices require a portable source of energy to operate, most of the systems use battery systems. These battery systems face limitations when scaled down in size and can make the system bulky. Innovative strategies such as energy harvesting systems and self-powered systems have been integrated into these soft biopotential interface technologies to enhance wearability. Li W. et al. developed a poly(vinylidene fluoride) based self-powered wireless flexible wearable device that helps in overcoming the limitations of the battery system in wearable devices\cite{116}. Apart from displaying high stretchability (1500% of its original length), this PVDF-ionogel device has the ability to convert external pressure into electricity which enables it to power itself. The electricity generated by this piezoelectric property is enough to charge a $4.7 \mu F$ 50 V capacitor to 0.7 V within 225 seconds. Although this device was used to measure different body movements, the inclusion of self-powered technology enhances its wearability aspect. The inclusion of such technology in soft biopotential interfaces can improve long-term usage in health monitoring.

Since biopotential interfaces are vastly used in healthcare and health monitoring areas, a slight imprecision in the electronic reading can result in an inaccurate diagnosis of
Figure 6. (i) Schematic of the PVDF-ionogel self-powered wearable device and the output voltages due to bending (above). Rectifier circuit diagram and plot of voltage vs. time curve for charging capacitor (below). Reprinted (adapted) with permission from Li W. et al. Copyright 2023 American Chemical Society. (iv) Images of transistor array under the original and stretched states (above). Optical microscopic images of one transistor in the array under 0% and 100% global strain(below). Reprinted (adapted) with permission from Wang W. et al. Copyright 2021 Springer Nature.
user’s health. Stretchable devices containing electronics often have limited strain capabilities so as to not compromise the electronic performance. Wang W. et. al. along with Bao. Z. developed a strain-insensitive intrinsically stretchable transistor array\cite{117}.

The stretchable device was fabricated using an all-elastomer process for applying local stiffness using styrene–ethylene–butylene–styrene (SEBS) as the main material. The device achieved stable electrical performance even under large strains. This property allows stretchable devices to have mechanical flexibility without compromising electrical stability. In soft biopotential interfaces, introducing such technology can make signal recording more precise and accurate. Figure 6(i) shows PVDF-ionogel self-powered soft and wearable device and Figure 6(ii) shows the strain-insensitive intrinsically stretchable transistor array under strain.

When direct comparisons are made to the standard Ag/AgCl electrode interface, the performance of these soft biopotential sensors has shown comparable or even better results. For instance, low skin-electrode contact impedance is an important factor for biopotential interfaces attached to the skin’s epidermal layer for recording signals. The flexible sEMG electrode by Zeng X. et al. was fabricated using hydrographic printing and showed an impedance value of around 10 $\Omega$ at 500 Hz, whereas the traditional electrode interface had a value of around 14 $\Omega$ at 500 Hz. Moreover, at lower frequencies, the flexible interface showed significantly lower impedance. Additionally, the SNR values Li G. et al. reported were comparable between their semi-dry EEG interface and conventional ‘wet’ EEG electrodes. Both devices showed SNR values of around 7 dB in the eyes open/close paradigm experiment. In other Steady-state visually evoked potential (SSVEP) paradigms, the semi-dry electrode interface performed slightly better. The Gecko-inspired dry ECG electrode displayed its adhesion capability by achieving over 30 cycles of adhesion to the skin. Moreover, the adhesion force was comparable to those of wet adhesive, ~1.3 N/cm2. Qualitative analysis is made between traditional and soft biopotential interfaces concerning their wearability aspect in Table 1.
Table 1: Qualitative performance comparison of traditional vs soft biopotential interfaces w.r.t. wearable devices requirement.

<table>
<thead>
<tr>
<th>Interface type</th>
<th>Type</th>
<th>Conformability</th>
<th>Stretchability or Flexibility</th>
<th>Period of usage</th>
<th>Electrolyte Gel</th>
<th>Bulkiness</th>
<th>Signal quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag/AgCl Electrode</td>
<td>Low</td>
<td>Absent</td>
<td>Short</td>
<td>Present</td>
<td>Medium</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Soft Interface</td>
<td>EMG</td>
<td>High</td>
<td>Present</td>
<td>Long</td>
<td>Absent</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>EEG</td>
<td>Average</td>
<td>Present</td>
<td>Long</td>
<td>Semi</td>
<td>Avg.</td>
<td>Avg.</td>
</tr>
<tr>
<td></td>
<td>ECG</td>
<td>High</td>
<td>Present</td>
<td>Long</td>
<td>Absent</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>EOG</td>
<td>High</td>
<td>Present</td>
<td>Long</td>
<td>Absent</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

CONCLUSION AND OUTLOOK

Non-invasive biopotential recording techniques such as EMG, EEG, ECG, and EOG play a crucial part in establishing valuable communication between users and machines. Since most of these biopotential signals are recorded non-invasively and require skin contact, several possibilities for wearable device applications emerge. Some of the aforementioned soft biopotential interface technologies have already successfully demonstrated human-machine interaction by controlling certain mechatronic devices. To achieve the full potential of a soft biopotential interface, extensive study is required in the sector of advanced materials, energy technology, and signal processing. Several limitations and challenges are still present in the current soft biopotential interface technologies that prohibit their immediate adoption in consumer devices. Even though soft interfaces allow miniaturization and improve conformability, their integration with conventional solid-structured electronics that are required for signal processing act as a barrier to achieving complete softness and flexibility of the device. With various soft materials and structural designs, another challenge that soft interfaces face is standardizing to the industry-ready parameters, often leading to ineffective large-scale production. Another major issue to be considered is that human skin is constantly subjected to tiny wear and tear, leaving almost scars and cuts on the surface of the skin that might be invisible to the naked eye. This phenomenon can cause several issues such as irritation, infection due to material type, loss of adhesion, and inefficiency in healing. Further development of soft biopotential interfaces to accommodate practical wearable HMI applications is required. Along with soft interfaces, efforts should be made towards minimizing the footprint of signal processing units and energy storage units. Renewable
energy and energy harvesting technologies can be involved in powering these untethered bio-interfaces. Wireless technology can help enable communication between the interface and its processing system and in some cases, even provide power for operation. Besides health monitoring, signal recording, and data accumulation, more research should be carried out with soft non-invasive interfaces for functional electrical stimulation (FES), which can, in a way, provide bidirectional (recording and stimulation) applications in cases of physical rehabilitation. Soft biopotential or neural implants have also been researched or many years. For such invasive technology to penetrate the wearable device market will require extraordinary endeavors towards the biocompatibility, biodegradability, and user-acceptance aspects. Discovering methods to implant soft electrodes and interfaces directly inside a user using minimum-to-no surgical techniques can lead to much more intricate, precise, and useful HCI applications. Lastly, it is definite that the inclusion of soft biopotential electrode interfaces while developing human-computer interaction technologies can provide more options for wearable device applications that are sustainable, credible, and effective. To diminish the need for Ag/AgCl electrodes completely, more efforts will be needed into standardizing the characteristic parameters of soft biopotential interfaces and scaling their manufacturability to the industry level. The fast-paced and promising growth towards these soft biopotential interfaces does assure one thing - “getting used to” the rigid and bulky wearable devices is a phenomenon that our future generations will never have to experience.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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