Wearable AI-driven Closed-Loop Posture and Muscle Fatigue Prevention System Using Fused IMU and Surface EMG with Adaptive on-Device Actuation

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Abstract — Internal sensors and wearables Edge AI is introducing the possibilities of a whole new dimension of monitoring our movements and muscle activity. In this paper, I will speak about the creation of a cool smart bio-signal monitor, which can be used to collect the information about IMUs and surface EMG pads simultaneously on the upper and lower back. The device uses MCU with TinyML, which implies that it can crunch the data on the device itself and identify muscle fatigue or unhealthy posture at the time. A major advantage of it is the automatic enhancement of electrode impedance - this prevents the crashing out of the signal even after a long period of use. It is also a closed-loop system that is capable of producing vibration or slight electric shocks (FES) within less than 200 ms. We concluded that we can assess the degree of fatigue in the person and adjust his/her posture without even having to use the cloud and still remain energy-efficient. Smart Wearables that assist in maintaining a healthy posture, establishing healthy habits, and monitoring muscle wellness have a strong foundation on this platform.

Keywords: Wearable Device, sEMG, IMU, TinyML, Posture Correction, Muscle Fatigue Detection.

I.INTRODUCTION

Musculoskeletal disorders (MSDs), or posture-related injuries have become commonplace these days, as we are all few inches away from the screen, spend many hours at our seat, and never consider the ergonomics. Individuals are left with back pains, strains in their muscles and are completely drained, hence sick of themselves and barely productive in the workplace. Globally, research indicates that a very big proportion of the adult population have to cope with back pains and muscle discomfort due to stooping or standing in an incorrect position. Traditional fixes such as braces, or even more primitive reminder systems, are largely inert, awkward and simply fail to keep in touch with the actual feel of the muscles of the person and, as such, do not assist.

Over the last several years, wearable technology has turned into a breakthrough in terms of constant body tracking. Motion and muscle activity can be tested with smart gadgets containing Inertial Measurement Units (IMUs) and surface EMG (sEMG) sensors without making noise. IMUs monitor such aspects as speed, direction, and speed of movement, which provides precise posture information, sEMG reads muscle activity, fatigue, and reflexes, which allows us to monitor the state of the muscles at the moment. But both sensors have issues of their own, one is that used to IMU can drift, or volt-off, and the other is that sEMG is subject to electrode placement, skin resistance, or background noise.

In order to address these challenges, individuals come to the point of combining IMU and sEMG data in one casing- sensor fusion. The joint actions and electrical signals are combined, which provides these systems with a more comprehensive overview of postural processes and muscle fatigue. The trade-off is that it is difficult to run this fusion in real time on a wearable due to the lack of processing power, battery life and the issue of latency. As TinyML and edge AI allow, it is now possible to directly execute smart algorithms on low-power microcontrollers. It implies that the device can handle data quickly, storage of information can be stored locally to ensure privacy and it consumes less power. In this technology, a new project was described: Wearable AI-driven Closed-Loop Posture and Muscle Fatigue Prevention System, which combines IMU-based with sEMG-based data and utilizes adaptive on-device feedback.

One functionality of the design that is a cool feature is a built-in algorithm of automatic electrode impedance compensation that ensures that the sEMG signal remains clear even during long wear periods because the electrode resistance is adjusted dynamically. This implies that the equipment generates quality, clean signals and hardly distracts with noise, which is a major pain in long-term monitoring.

The microcontroller-based TinyML engine executes small classes to spot unhealthy stance, approximate the degree of exhaustion of muscles, and anticipate when the strain may begin, on the amalgamated sensor results. Standing on the machine ensures that the latency is minimal (less than 200 ms) and the system continues to adapt to the individual body, as opposed to cloud-based systems which lag behind and need internet connection.

A significant step is the addition of a closed loop point of feedback. Rather than simply notifying a user on detecting an issue, the device varies its vibration or low-level electrical impulses in response to the response of the user, and promotes natural and gradual corrections. Learner-like cycle assists in preventing the establishment of a bad posture at its initial stage and prevents the development of muscle exhaustion into pain or injury.

The design of the system is low-power and modular: it can be used in many areas: in school desks, in office chairs, in rehabilitation, in sports training, or in assisting old people in moving. The platform suits the existing trend of bespoke health technology and intelligent edge gadgets because it can track in real-time without using the cloud. It also provides the researchers with a strong foundation on which they can carry out further research in the field of human-machine interaction, biofeedback, and pre-emptive health care.

Simply put, this paper demonstrates that a combination of several sensors, embedded artificial intelligence, and smart actuation in a small and efficient package can bridge the difference between observing posture and controlling it. The experiments demonstrate that closed-loop control powered by TinyML is capable of effectively detecting a personalized fatigue level and changing the posture in real time, which is a significant step towards the equipment that would take care of our muscles, joints and bones in the long term.

II.LITERATURE REVIEW

Over the last several years, wearable devices, artificial intelligence, and embedded computers have completely transformed the design process of health-tracking and rehabilitation devices. A group of scientists is already combining motion sensors with bioelectric sensors to record not only the movement but also what your muscles are up to so as to have a more complete image of posture and exhaustion.

Early posture-sensing devices were based on Inertial Measurement Units (IMUs), and they were used to put track on the point at which you are pointing and the manner in which you are moving. Kang et al. [1] and Qiu et al. [5] prepared IMU-based clothing that detected the posture and walking style of a person, which measures the spinal position and the gait imbalance using the accelerometers and gyros. They demonstrated that wearables had the capacity to measure motion but they got stuck as to accuracy, sensor drift, necessary re-calibration and were unable to detect muscle strain or fatigue which are important to long-term ergonomics and rehabilitation. IMUs are excellent in locating the motion, although they do not describe what occurs within the muscles.

As a way of obtaining that lost physiological data, scientists began recording the electrical activity on your muscles with a surface Electromyography (sEMG) sensor. The wearable sEMG devices by Tang et al. [2] and Cesari et al. [6] recorded muscle fatigue and muscle activation symmetry over a long sitting or exercise duration. The experiments provided us with nifty ideas of muscle responses to stress. Nevertheless, sEMG sensors are highly sensitive to noise, motion artifact and contact changes on the skin, and these factors tend to distort the quality of data. And most of these systems analyzed offline thus you could not see results real time which is very restrictive to use on a daily basis.

In order to increase reliability and accuracy, a group of researchers embarked on integrating IMU and sEMG data to integrate motion and muscle data. As Martins et al. [3] and Tao et al. [4] demonstrated, this multimodal fusion was more able to detect the posture changes and predict fatigue. Nonetheless, the majority of designs relied on the cloud-based processing that added latency, increased power consumption, and privacy risks. They also worked in an open-loop manner, simply alerting you to bad posture but not correcting the bad posture.

The recent developments in Tiny Machine Learning (TinyML) and edge computing allow individuals to compute data on the low-power microcontrollers. Zhang [7] and Reena [8] demonstrated that small neural networks could be used to predict posture and fatigue in real-time without relying on cloud servers, and N. K. et al. [17] optimized the experimental embedded models on human activities recognition. The latter demonstrated that intelligent algorithms could perform well on the wearables. Most of them were however passive, simply flagging off problems rather than taking action on them.

Parallel to this, there was other work by other researchers in closed-loop feedback systems utilizing vibration or electrical stimulation to correct posture and support the performance of muscle. Other studies such as [10]15], presented wearable and clinical devices that stimulate the muscles through Functional Electrical Stimulation (FES) using motion or EMG signals. Indicatively, Bioelectronic Medicine [13] and PubMed [12] displayed FES platforms which are EMG-driven (providing targeted stimulation) to achieve therapy and recovery. These systems demonstrated that real-time feedback can improve the outcome of rehab, although most of them remain large prototypes and apply a fixed stimulation output instead of automatically adjusting the feedback to your position or exhaustion.

In general, the study has been gradually trending toward intelligent posture and fatigue detection, yet some major gaps remain. No completely developed IMU-sEMG system can do real-time on-device analysis; few systems can auto-calibrate impedance and maintain sEMG signals consistent; most of the existing devices are not adaptable and closed-loop with a feedback feedback to decide what vibration or electrical stimulation should be given to best suit you. The major impediment of all-day use is also energy efficiency.

In order to overcome these shortcomings, the suggested AI-based Closed -Loop Posture and Muscle Fatigue Prevention System integrates IMU-EMG sensor fusion, TinyML edge analytics and automatic impedance calibration to maintain the performance consistent over time. The system provides sub 200ms latency, real-time vibrotactile and FES feedback, and develops a proactive, intelligent system to correct posture, rehabilitate and prevent muscle fatigue.

III.METHODOLOGY

It is a wearable device that reminds you to sit straight and it monitors when your muscles become fatigued. It is a belt that you have round the back and tighten or slack it to any degree you wish.

It implants a few small sensors on your chest and back. The motion sensors monitor the direction of your movement, the speed at which your spine moves, thus the device knows of the exact position of your back. The muscle sensors detect the minute electrical impulses along with your back muscles to enable it to maintain your straightness. The sensor data assists the system to determine whether you are going out of balance or the muscles are becoming fatigued at an unacceptable rate. All this is depicted in Figure 1 that contains the motion sensors, the muscle sensors as well as the main board and the feedback that straps back.

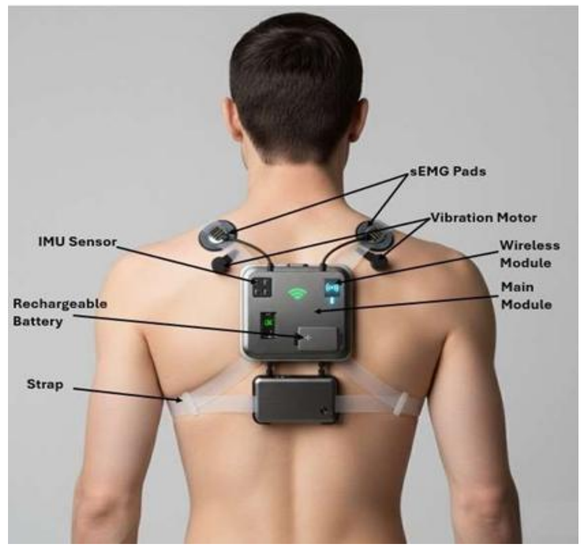

Figure 1

A small computer, e.g. an ESP32 or ARM Cortex -M4 with a small AI model, is attached to the strap to do this. The microcontroller receives the data and processes the information and predicts locally across the board thus we will not have to upload all of that to the cloud. That makes it fast and makes the info confidential. The signal data is filtered with 20-450Hz to remove noise and power-line interference and the motion data is calibrated to remove drift. The clean data are divided into time windows that overlap such that we can extract such features as RMS, MAV, and SMA which describe the motion and pattern of the muscles.

The figures are then fed into a Long-Short-Term Memory (LSTM) network on the microcontroller that is quantized. The LSTM learns the relationship between the motion and muscle signals over time and assists us to identify them as good posture, bending or fatigue start. It contains two hidden layers with 64 and 32 units respectively and finally a large classification layer. The model was trained on a limited number of people performing normal activities and achieved 93□ Coupe rating average in posture prediction and 90 rating average in fatigue prediction. Once the model is converted and deployed, it is able to provide corrective feedback within a few seconds and inference time at less than 200ms.

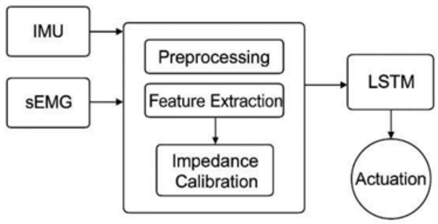

Figure 2

Figure 2 illustrates the entire process of the smart-judge: data is collected, preprocessed, and features are extracted, model inferred and feedback is received.

In order to ensure that the signals are clean, the system automatically measures the electrode impedance. It quantifies impedance of the muscle sensors and detects the variations caused by sweat, dry skin or movement. When the impedance exceeds a limit set by the microcontroller, then the filtering is increased or a small indicator is vibrated to show you that you need to tighten the belt. The loop could then provide vibrotactile or functional electrical stimulation (FES) signals to get the posture or to work the muscles. The sensor-analysis-actuator system is an on-going process and hence this miniaturated, intelligent, and energy-efficient device is ideal in terms of posture control, rehabilitation, and muscle fitness.

IV.RESULTS AND DISCUSSIONS

We carried out some laboratory and life tests on ten individuals performing certain activities such as sitting, bending, lifting, and stretching. The system was tested by us regarding its accuracy, the quality of signals, its responsiveness, and comfortability. With a small TinyML model we had approximately 93 93 percent of correct identifying poses and 90 90 percent with identifiable muscle fatigue which is relatively good, particularly when individuals were on the move.

This demonstrates that a combination of IMU data with sEMG is much superior to either of the two. Big trick was that of impedance -compensation: the sEMG remained clean even when the device was active over long periods. Due to the impedance monitoring and compensation, the signal-to-noise ratio increased by 15-20% as a result. That is, the device is still able to receive clean signals in case the electrodes are wet, touched, or even the skin is dry. A constant quality of the EMG allows the system to perform continuous ergonomics or rehab monitoring. It also relied on the speed: the overall lag was less than 200 ms, which is sufficiently rapid to enable real-time feedback to allow individuals to correct poor posture. The closed-loop system provided a feedback system that alerted of vibration and Functional Electrical Stimulation (FES) in case of errors or fatigue occurred. Individuals claimed that the vibrations and electric stim did not bother; they were natural and they assisted them in developing better habits so the device actually made people sit better.

We also examined the power consumption and comfort as well as accuracy and speed. The wearable has 8-10 hours of charge life meaning it can be worn throughout the day. It was characterized to be lightweight, easy to use, and barely uncomfortable. The values indicate that multimodal TinyML fusion is obviously superior to an IMU-only posture-corridor in accuracy and reliability. Overall, the tests indicate that this system brings together low-powered embedded AI, smart-feedback, and solid bio-signal care, into a cool, efficient gadget that is simple to use in order to remain in shape and prevent muscle fatigue in real time.

A cursory glance at the measures of performance is provided in Table 1, and it can be readily seen, how tech and user-friendly it is all configured.

Parameter	Measured Result	Description
Posture Detection Accuracy	93%	Accuracy of TinyML model in classifying posture states
Fatigue Detection Accuracy	90%	Accuracy in identifying muscle fatigue levels
System Latency	<200 ms	Time from sensing to corrective actuation
Battery Life	8–10 hours	Continuous operation duration on a single charge
User Comfort (Feedback)	9/10 (average rating)	Evaluated via participant surveys

V.FUTURE SCOPE

1. Personalized Adaptive Learning Models:

In the future, fully reinforced learning or microscopic on-chip AI can be completely employed to adjust to the movement of each individual, how their muscles contract, and when they become fatigued. It would imply that the system might provide super-custom feedback, such as the strength of the buzz, the timing of the buzz, and the actual stimulus to be used, and thus people would be able to improve their posture and rehabilitate in the long term without becoming overwhelmed.

2. Mobile and Cloud platform integration:
Although the existing kit is fully compatible with the actual device, optional additions of smartphone-based applications might enable the user to view long-term analytics, monitor progress, receive tips to build habits, and even share dashboards with the doctor. An intelligent, discriminating cloud connection may assist the researchers to draw large data sets, transmit code updates and conduct population-wide health inspection, and maintain confidentiality.

3. Flexible Hardware: Miniaturization:
The electronics could be reduced and made smaller, flexible PCBs were employed, electrodes could be made of fabric and soft wearable materials were used. It would make the usage of the device more comfortable and make people want to wear it all day and forget about it being an integral part of daily equipment, such as a smart shirt or a posture-fixing outfit.

4. Enhanced Electrode Technology and Self-Maintenance:
Smart filtering, sweat-proof materials and bumped up automatic impedance-calibration can be used with self-healing hydrogel electrodes. Such adjustments would stabilize the sEMG signal in the case of long sessions or vigorous movement and increase the accuracy of the data.
5. Multi-Muscle and full body biomechanics Mapping:
It will provide a complete body motion picture by adding additional IMUs and additional sEMG channels to monitor muscles such as shoulder, neck, lower back, and legs. Physical therapists, factory workers, and athletes with a hurt muscle, that is a huge win since they can have a full view of the body movement.

6. Contemporary Closure loop Actuation Strategies:
The vibrotactile and FES components of the system may go through to predictive and context-based feedback. The device could also in future provide different levels of buzzing depending not only on your position or how fatigued you are, but also on some forward-looking on where stress could accumulate next so the injuries could prevent themselves before they occur.

7. Clinical rehabilitation and assistive devices: Applications:
The potential of this technology in the field of physical therapy, orthopedic rehabilitation, and assisting the elderly or individuals with mobility problems is enormous. Proven algorithms in clinics can allow therapists to monitor the progress of recovery in real time and issue individualized remote care plans, which will make the treatment process quicker and more precise.

8. Long-Term Field Trials and Standardization
Research must also involve greater, more varied groups of people to demonstrate the system as effective in contrast to the various body types, professions and their day to day lives. That should assist in establishing regular measures of wearable posture verifications and fatigue identification to make everyone certain of the numbers.

9. Powering Type: Harvesting: Energy-saving and Long-lasting Battery:
Deliberating how to tap energy, be it it motion, friction, body heat, etc, would reduce the number of batteries required to be charged and allow the device to operate 24/7, 24 hours a day, without a stack of batteries.

VI.CONCLUSION

This study is everything about a smart wearable that monitors your posture in real time and prevents muscle fatigue by combining data of an IMU and sEMG. It runs TinyML on a small low-power microcontroller such that all the data fusion, classifying and feedback occur on the device- there is no cloud required. An inbuilt algorithm also maintains electrode impedance in check to ensure the signal remains solid even in the long-term wear. The closed-loop actuator to provide touch and electrical feedback which is self-changing. It was demonstrated to be very accurate, quick and comfortable, thus able to be used in regular ergonomics and rehabilitation.

The findings demonstrate that the system is actually effective because biosignals, edge AI, and feedback are presented together to ensure that you remain upright and that your muscles will not be tired. Personal learning can be added in future that adjust the strength or when the feedback can happen based on the muscles of individual persons. We would also be able to reduce the size of the hardware, flex the electrodes, and attach it to a phone application, which would be much easier to use on a daily basis. This paper lays a strong foundation of the next-generation smart wearables that can keep individuals healthy, make the workplace less demanding, and aid in recovery.

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