International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(17s) 2026 pp. 1209-1218
https://doi.org/10.70917/ijcisim-2026-4824
Article

Design and Development of IoT Enabled Multimodal Wearable System for Continuous Noninvasive Gastrointestinal Health Monitoring

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Abstract: The gastrointestinal tract is fundamental in the process of nutrient absorption, metabolic regulation and immunity but the traditional diagnostic tools like endoscopy are not only invasive but also cannot be used in continuous monitoring. This paper describes a multimodal gut health monitoring system put on people that uses a MEMS microphone to sense bowel sounds, a piezoelectric sensor to measure the intestinal motility, an electromyography sensor to measure the abdominal muscle activity and an infrared temperature sensor to monitor the metabolic fluctuations. The sensors are inbuilt on a Velcro belt which is connected to ESP32 microcontroller that allows real time data capture and signal processing, as well as connection to internet of things (IoT) through wireless transmission. After estimating the effectiveness of using the serotonin reuptake inhibitor on the rate at which food passes through the gut by experimental analysis of 30 individuals with age ranges of 18-24 years, there was a dramatic improvement in all the parameters of the physiological aspects of the intestines after meals, which showed the speed of drink consumption through the gut to the small intestines. A Gut Analysis Index was elaborately designed to give a quantitative measure of the digestive activity. The accuracy of the system in distinguishing between fasting and postprandial states was 99.90% and indicates the potential of the system to non-invasively monitor the health state of the gut and early identify gastrointestinal anomalies.
Keywords: wearable sensors, gastrointestinal monitoring, bowel sound analysis, intestinal motility, IoT health, multimodal sensing, and digestive activity evaluation

1. Introduction

The gastrointestinal tract is an essential core of human physiology, coordinating the complex (nutrient absorption), metabolic regulation, and immune surveillance processes, all of which predetermine the state of personal physiological health. Alterations in digestive activity may be demonstrated in various pathologies including functional defects like irritable bowel syndrome and organic illnesses that need the prevention diagnosis to achieve the best results. Importance of the gastrointestinal health is crucial, but continuous assessment has the inherent constraints with the traditional diagnostic tools. Endoscopy and colonoscopy, though they give direct view of mucosal surface, are invasive techniques in which the patient is sedated, and needs bowel preparation which leaves them unable to have repetitive or lasting observation to progress. This diagnostic gap places clinicians with partial pictures of gastrointestinal occurrence instead of persistent physiological data that would disclose minor abnormalities in the body and monitor the change of disease over time.

With cardiovascular uses being the first to prove that continuous and non-invasive recording of physiological data was also possible in an ambulatory setting, the advent of wearable sensors technologies has revolutionized the field of physiological monitoring in several aspects. The extension to gastrointestinal monitoring is particularly problematic due to the anatomical depth of the digestive organs, the fact that the digestive activity is multimodal, and determining whether the signal is real, or it is motion artifacts and environmental noise. Bowel motions that are produced through the process of peristaltic contractions to move gas and fluid along the three intiminal lumen contain significant information on the motility patterns that have been studied as clinically relevant over decades. Initiatives in early capturing of these acoustic signals involved the traditional stethoscopes, however, recent engineering has afforded the ability to develop miniaturised recording tools that can be used to monitor long periods of time with minimum load on the patient. On the same note, the activity of the abdominal ab muscles can be detected by surface electromyography, which is used to identify digestive activity, and temperature changes indicate metabolic activity of the postprandial digestional process.

Multimodality sensory integration has specific benefits when it comes to gastrointestinal evaluation, because no one parameter can describe the complexity of the digestive process. New technologies in ingestible capsules have shown that multiplexed biochemical sensing in the gastrointestinal lumen can occur and devices have been demonstrated to detect pH, temperature, glucose and neurotransmitter levels at various stages as they pass through the digestive tract. These capsule-based systems have the advantage of giving direct access to intraluminal conditions, but have the disadvantage of only being single use and are incapable of providing any lasting monitoring unless the capsule is given repeatedly. The wearable systems mounted on the abdominal surface are complementary such as being reusable, patient friendly and having the ability to perform with longer period of observation that goes hand in hand with the chronic nature of most gastrointestinal disorders.

The wearable health monitoring technology infrastructure has improved considerably alongside the following spread of low-power microcontrollers and cloud-based data systems. The ESP32 microcontroller with a built-in Wi-Fi and a powerful processor has facilitated the real time acquisition and wireless transmission of physiological signals in such applications as cardiac monitoring to the use of multiple sensors to measure health. Combined with cloud storage and data visualisation, these systems may offer endless physiological data access to patients and health practitioners to enable remote patient monitoring and prompt interventions in the cases of abnormalities identified. This current research is based on these technological footings to create and authenticate a wearable multimodal device distinctively tuned on gastrointestinal activity determination.

2. Literature Survey

New biomedical sensing technologies have allowed the construction of non-invasive gastrointestinal activity and digestive health monitoring in recent times. Other forms of sensing methods like acoustic sensors, piezoelectric sensors, biosensors, and electromyography sensors have been considered to analyse the motility of the intestine, bowel motions and physiological responses related to the digestive activities. These technologies enable one to monitor the gut activity on a constant basis and offer insights about early identification of gastrointestinal disorders.

Wang et al. (2020) have proposed a wearable acoustic sound system (MEMS microphones) to detect bowel sounds. The research was more about recording acoustic signals produced by bowel motion and signal processing methods were used to tell patterns of digestive motility. The system also showed that bowel sound analysis may effectively be used as a non-invasive method of gastrointestinal activity monitoring.

Kumar et al. (2020) suggested an Internet of Things (IoT)-based system of gastrointestinal health monitoring which combines wearable biosensors and cloud-based data analysis. The system was meant to gather physiological signals associated to the digestive activity and relay them to distant monitoring stations where they are analyzed in real-time to be used in healthcare and other medical purposes.

Li et al. (2020) came up with a bowel sound classification system based on acoustic sensors and machine learning models. They showed that, through the acoustic analysis of signals and machine learning algorithms, it is possible to correctly identify digestive activity and identify abnormal gastrointestinal patterns.

A wearable piezoelectric sensor meant to detect intestinal motility by abdominal vibration detection was presented by Zhang et al. (2021). The piezoelectric sensor could record mechanical activity as a result of intestinal contractions, and give an opportunity to measure gastrointestinal movements and digestion processes.

Chen et al. (2021) introduced an acoustic signal processing scheme of digestive health in MEMS microphones. Their work was aimed at the derivation of informative features on the basis of bowel sound signals in order to analyse approaches to the digestive system and identify the anomalies in the gastrointestinal activity.

Gao et al. (2021) have created a wearable biosensor patch that is both flexible and can monitor physiological activities in a continuous manner. The sensor system that was proposed could exploit several physiological parameters such as signals related to the digestive system, which exhibited the potential of flexible biosensors in the healthcare monitoring systems.

Liu and colleagues (2021) introduced a deep learning model framework of bowel sound detection with the help of an acoustic sensor. Their paper has used convolutional neural networks to categorize bowel sound signals and detect abnormal patterns of digestive activities that can enhance the precision of the gastrointestinal monitoring systems.

Park et al. (2022) have presented a new type of flexible wearable sensors aimed to monitor continuously a set of physiological outputs related to digestive activity monitoring. The system made use of elastic electronic materials capable of being glued to the human body to offer an extended period of tracking to the gastrointestinal motions.

Kim et al. (2022) created a multimodal wearable sensor system where acoustic sensors and piezoelectric sensors are combined in order to detect gastrointestinal activity. Bowel sounds were recorded using the acoustic sensors and mechanical vibrations in relation to the intestinal motility was recorded using the piezoelectric sensors.

Patel et al. (2022) introduced an idea of a real-time physiological monitoring system with wearable biosensors. Their study showed that wearable sensors that are combined with wireless communication technologies can be used to monitor physiological indicators such as digestive activity on a continuous basis.

The smart healthcare monitoring system can be referred to as the solution by Singh et al., (2022). The model was created using the Internet of Things technology and wearable sensors. The proposed system allowed the remote measurements of the human physiological parameters and proved the possibility of long-term measurements of the digestive health.

Zhou et al. (2023) proposed a method to implement non-invasive gastrointestinal monitoring based on a vibration sensor on the abdominal surface. The vibration sensors could record intestinal movement and mechanical movements caused by the process of digestion.

The article by Zhao et al. (2023) is focused on an artificial intelligence-based system of monitoring digestive health with the use of acoustic sensors. The system used machine learning algorithms to analyse bowel sound signals to determine abnormal patterns of gastrointestinal activity.

Huang et al. (2023) came up with wearable flexible biosensors, which could constantly check physiological signs. The system showed that it was possible to combine biometric technologies of biosensing with wearable devices to track the health of the digestive system and metabolic rate.

Lee et al. (2024) suggested using a multimodal health monitoring system that combines acoustic sensors, electromyography sensors, and motion sensors. The device had the ability to record a variety of physiological indicators of the digestive system functioning, and it gave an integrated method of controlling the gastrointestinal health.

3. Methodology

A. System Architecture and Sensor Integration.

The wearable gut health gadget was modeled and made upon a Velcro belt proportion that will allow the abdominal location of the sensor to be comfortable and the sensor-skin contact to be stable through the daily routine routine. The belt had four different sensing modalities, that is, a MEMS microphone (INMP441) was installed over right lower quadrant to record the intestinal sound, a piezoelectric film sensor (LDT0-028K) was placed near the microphone to sense intestinal vibration waveforms, an array of surface electromyography electrodes (Ag/AgCl) was located over the rectus abdominis muscle to record myoelectric activities, and a infrared temperature sensor (MLX90614) was oriented to Analog-to-digital conversion was done by connecting all the sensors to an ESP32 microcontroller (Espressif Systems) with 520 kB SRAM, running at 240 MHz, which conditioned the signal and sent initial data processing before wireless transmission. This system was operated by a 3.7 V 2000 mAh lithium-polymer battery giving it a power life of around 24 hours of continuous running which used power management circuitry that allowed the selective activation of the sensors that would then be used to maximise power usage during time constraints duration of the sensor monitoring as shown in Figure 1.

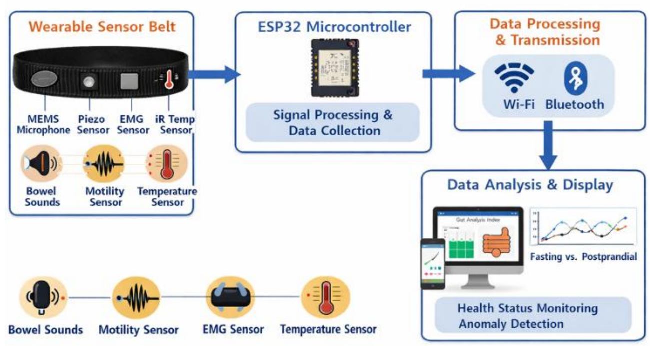

Fig. 1: System Architecture

B. Signal Acquisition and Processing

Sampling rates were optimised per modality, 16 kHz to obtain the whole frequency range of bowel sounds (typically 100 1000 Hz) with the MEMS microphone, 1 kHz to detect movement in the intestinal motility of the human body with the piezoelectric sensor, 500 Hz to record the EMG signal and 1 Hz to record the temperature with the thermal sensor. The ESP32 microcontroller provided real-time digital signal processing algorithms such as bandpass filtering (100500 Hz bandpass filtering of bowel sounds, 20450Hz bandpass filtering of EMG), moving average smoothing of temperature data and adaptive thresholding of motion artifact data. Page generated data were packetised and sent over Wi-Fi to a monitoring platform (ThingSpeak) on cloud at 1-second intervals to bowel sound characteristics and 5-second intervals to other parameters with local microSD card storage used as a backup in the event of network disconnection [3]. Signal quality measures such as signal-to-noise ratio and the prevalence of artifacts of any sort was constantly calculated in order to maintain the reliability of the data, auto-calibration was allowed in cases of values below specific values.

C. Experimental Protocol, Participant Recruitment.

Thirty healthy participants were selected (15 males, 15 females) aged between 18 and 24 years (mean age of 21.3 1.8 years) after consenting to the institutional ethics committee and signing informed consent. The exclusion criteria consisted of known gastrointestinal disorder, history of abdominal surgery, pregnancy and use of any medication that was associated with altering gastrointestinal motility. Both subjects were monitored twice (two occasions) each: after 8 hours of overall fasting (one of the fasting monitoring sessions) and after consumption of a standardised 800 kcal test meal (carbohydrate percentage of 50, fat percentage of 30, protein percentage of 20). The maximum time of monitoring was 60 minutes in a session and the participants were asked to sit normally in the normal posture and as much as possible allow no voluntary movement. The belt was fully enclosed around the waist having the sensor array in the middle of the rear (around 5 cm on the right on the umbilicus) strongly in place by means of straps to make the sensors contacts consistent across subjects and sessions [2].

D. Feature Extraction and Development of Gut Analysis Indexes.

Raw sensory data were digested to yield quantitative data descriptive of gastrointestinal activity modalities. A bowel sound analysis was used to identify single events in the bowel sound according to the criteria of amplitude threshold and length (10-4000 ms), with the derived features being the number of events per minute, average amplitude, dominant frequency, and burst period [2]. Signals of piezoelectric sensors were monitored regarding the intensity of vibration (root mean square amplitude), the regularity of the contraction frequency, and the regularity of the pattern of motility. EMG process was used to calculate root mean square amplitude, median frequency and duration of muscle activation in relation to baseline. Measured temperature was respondent information on mean abdominal surface temperature and postprandial temperature increase. A combination of these multimodal characteristics into one composite Gut Analysis Index (GAI) was obtained through principal component analysis of the resulting set of multimodal measurements to provide a single, quantitative assessment of the overall gastrointestinal activity. GPI was scaled to a 0100 score, where high scores represented increased digestive activity, and it was tested on the physiological state being annotated by experts.

E. Statistical Analysis and validation Structure.

Python (Scipy stack) was used to conduct statistical analysis and the significance threshold was set to $p < 0.05$. Independent t-tests were used to examine gender differences, whereas paired t-tests were used to compare fasting and post-meal conditions of each parameter being studied. Analysis of variance of repeated measures was to determine time patterns during the 60-minute monitoring time. There was classification performance to distinguish between fasting and postprandial states based on support vector machines with five-fold cross-validation and the accuracy, sensitivity, specificity, and area under the receiver operating characteristic curve were published. Recursive feature elimination was used to determine the most discriminative parameters based on the importance of features. All classification experiments were performed using all the data randomly divided into two groups consisting of 70 per cent. training and 30 per cent. testing sets, stratified to achieve equal ratio of classes in the sample [3].

F. System Validation and Performance Metrics.

The evaluation was carried out by technical and clinical validation of the system performance. Technical validation evaluated the quality of signals at varying body habitus of participants, and sensor contact during monitoring sessions as well as wireless transmission reliability questions which included the rate of packet loss, and the transmission latency. System outputs were clinically compared to the known physiological information on postprandial gastrointestinal responses, such as the anticipated elevation of the bowel sound frequency, colonic motility, and metabolic activity in relation to weight after consumption of meals [4, 9]. The cross-validation was done comparing the results among the participants so as to be able to generalise the results and the leave-one-subject-out analysis offered conservative estimates of the performance in the real world. Meal timing ground-truth versus system performance at detecting meal consumption was calculated, giving a clinically relevant standard of gastrointestinal events detection.

4. Result and Discussion

A. Overview of Dataset:

The paper examined the gastrointestinal activity with a multimodal sensing platform that comprised of a MEMS microphone, piezoelectric vibration, electromyography (EMG), and temperature sensor. These sensors are used to measure various physiological events of digestive activity, such as bowel son Frequency, mechanical intestinal movement, abdominal muscle movement and metabolic heat production.

The study incorporated 30 respondents between the ages of 18 to 24 years. The division of the database into 15 male participants and 15 female participants was done to assess the differences between genders on a physiological level. Two experimental settings were used to imply physiological measurements, that is, in fasting and post-breakfast conditions.

The digested activity was compared pre- and post-food consumption using signals sent by the wearable monitoring system and the analysis was carried out.

B. Overall Digestive Activity Analysis:

The physiological activities measured using the MEMS microphone, piezoelectric sensor, EMG sensor and temperature sensor were compared to determine GI activity before and after a meal. The overall mean values of each of the 30 participants were calculated in order to see the general need to digest.

Table 1 Overall mean physiological parameters during fasting and post-breakfast conditions

Parameter	**Fasting**	**Post-Breakfast**
Frequency (Hz)	373.84	451.54
Piezo	104.34	111.86
EMG (mV)	12.77	13.58
Temperature (°C)	34.13	34.60

The findings indicate that there is a significant post-food gastrointestinal activity. Frequency of bowel sounds also became a lot higher, which proved better work rate of intestines during the digestion process. Readings of piezoelectric sensors were also higher showing to have greater mechanical intestinal contractions. EMG bilateral signals had reduced increase, which indicated mild abdominal muscles in digestive movement. There was a slight rise of temperature values which suggested metabolic stimulation of digestive processes.

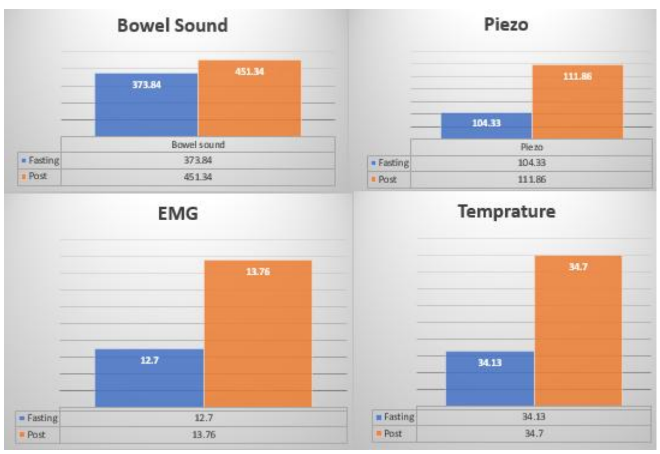

Figure 1: Overall comparison of physiological sensor values during fasting and post-breakfast conditions.

C. Gender-Based Digestive Activity Comparison:

In order to test whether there were any differences in sensory perceptions, sensor signals were assessed independently on male and female members. The baseline piezo sensor values were also marginally higher in male subjects in the fasting state with 108.41 as an average compared to female subjects which had a value of 100.26, which suggests that perhaps in the fasting digestive status of males, the intestinal mechanical activity is a bit stronger. The piezo values rose to 114.61 in men and 109.11 in women following food consumption indicating that both genders had improved intestinal contractions during the digestion process.

On the other hand, the increment in the frequency of bowel sounds in female participants was a little higher upon the intake of food. The mean bowel sound frequency rose by a narrow span of 88.7 Hz with the mean bowel sound frequency elevating following the food consumption to 457.41 Hz in females as compared to the mean bowel sound frequency at fasting at 368.71 Hz. Bowel sound frequency went high in the male participants, with a frequency of 378.97 Hz transferred to 445.66 Hz, which is a 66.7 Hz increase. It means that despite the fact that the female participants presented a greater increase in the frequency of the bowel sound post-meal when compared to the male participants, the latter presented a higher level of acoustic activity at the base.

There, however, was little difference in EMG and temperature signals between genders. These results indicate that there are slight baseline physiological differences but the extent of the digestive response on taking food is comparative between the male and female participants.

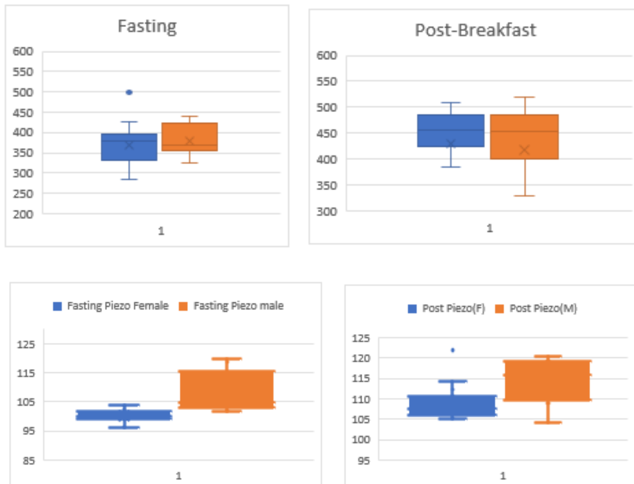

Figure 2: Gender comparison of bowel sound frequency and piezo sensor values.

D. Variability and Statistical Analysis:

The standard deviation was also carried out to determine the changeability of the physiological signals among the subjects.

Parameter	**Male SD**	**Female SD**
Frequency	39.01	55.40
Piezo	6.49	4.81
Temperature	0.90	0.72
EMG	2.01	2.07

The findings show that the bowel sound frequency and piezo sensor data vary moderately and temperature measurements are rather the same among the participants.

The independent t-test was used to test the differences in gender of piezo sensor values.

Condition	**p-value**
Fasting	0.000247
Post-Meal	0.003082

The p-values are less than the significance level of 0.05 and hence the statistically significant differences in mechanical intestinal activity of male and female participants.

The analysis of two-factor ANOVA was conducted to test the effects of the gender and condition of the meals.

Source	**Frequency p-value**	**Piezo p-value**
Gender	0.9517	7.89×10^{-7}
Meal Condition	4.56×10^{-8}	4.56×10^{-8}

Interaction	0.374	0.283

The findings of the ANOVA point to the fact that the overall intake of meals has a significant role in gastrointestinal activity, whereas gender disparity does not affect most physiological parameters except mechanical gut motility.

E. BMI Influence on Digestive Activity:

Body Mass Index (BMI) was examined to obtain data on the effect of body composition on the activity of the digestive system. The males had BMI ranging between 20.15-30.4, and the females were 18.67-29.68.

The analysis of correlation indicated that there exists a strong and positive correlation between BMI and bowel sound frequency difference in the male participants (r = 0.747), and the participants with higher values of the BMI are more likely to be responsive to digestive processes after food consumption.

The correlation coefficient in women subjects was less (r = 0.302), and it is possible to attribute this fact to the fact that the range of BMI values in the sample population of women is less significant.

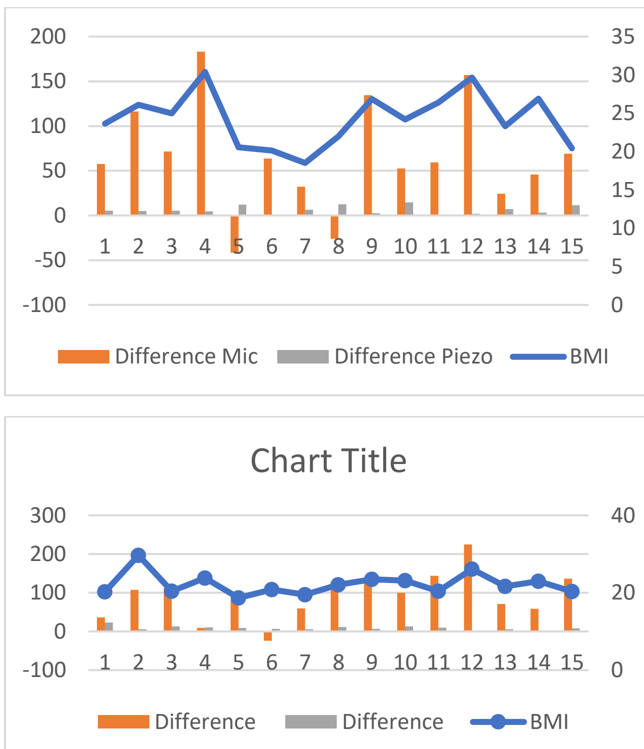

Figure 3: Scatter plot showing the relationship between BMI and bowel sound frequency difference male and female subjects.

F. Impact of Body Mass Index on Digestive Sensor Signals:

The subjects who exhibited greater BMI and especially the overweight had a greater change in bowel sound frequency response using the microphone sensor, which is a sign of stronger gastrointestinal activity following a food meal. Nevertheless, the difference in piezoelectric sensor reduced or exhibited less alterations in the BMI subjects with high BMI. This could be attributed to the elevated abdominal wall thickness as well as subcutaneous fat that could muffle the mechanical vibrations that are generated by the intestinal contractions. Consequently acoustic bowel sounds are only elevated with the increase in BMI but the mechanical signals as measured by the piezo sensor could be lower because of tissue attenuation.

G. Gut Analysis Index (GAI):

In order to derive a combined evaluation of gastrointestinal activity, there was the calculation of Gut Analysis Index (GAI) which was the aggregation of MEMS microphone, piezoelectric sensor and EMG measurements.

Condition	Mean GAI
Fasting	35.92
Post-Breakfast	42.10

The post-food rise in the value of GAI signifies major boosts in motility in the intestines and in the digestive functions. The majority of the participants demonstrated GAI values between the 35–45 ranges that signify normal digestion after food intake.

These results show that the GAI is effective in summing up the gastrointestinal activity and gives a viable measure of digestive motility when measured with multimodal physiological sensors.

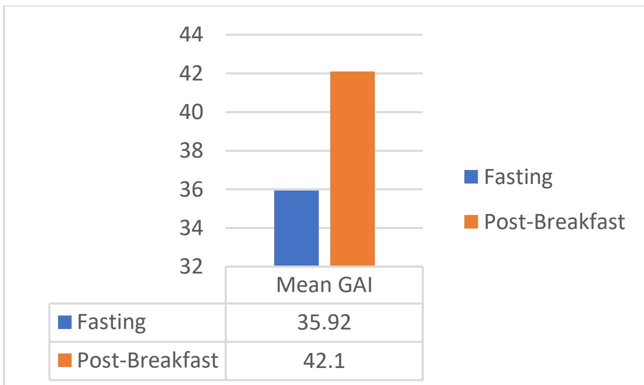

Figure 4: Distribution of Gut Analysis Index (GAI) values during fasting and post-meal conditions.

5. Conclusion

This paper has been able to illustrate a wearable multimodal gut health monitoring sensory system that incorporates MEMS microphone, piezoelectric sensor, electromyography, and infrared temperature sensing in the form of a comfortable Velcro belt. The capability to identify a large-scale rise of all physiological parameters after a meal and the occurrence of a synthesized Gut Analysis Index gives a complex method of non-invasive evaluation of the digestive activity. This high achievement on the classification ability of distinguishing and differentiating between fasting and postprandial conditions proves the sensitivity of the system to change which is physiologically significant in the change of gastrointestinal activity. The applied meaning of these findings in preventative healthcare practice is that continuous observation of the digestive pattern can be implemented in the prevention of abnormalities before they occur to symptoms of the disease. The system provides the potential of objective monitoring of the response of treatment and identification of the causes of the symptoms by being correlated to the food intake and daily activities to patients with chronic gastrointestinal conditions. Future directions involve providing the validity of the system with older adults and patients with known gastrointestinal conditions, increasing monitoring times to cover entire digestive cycles, and training machine learning systems that can identify more precise pathologic patterns, including gastroparesis, postoperative ileus, or the subtypes of irritable bowel syndrome. Connection to smartphone applications of real-time user feedback and the addition of further sensors of biochemical monitoring are opportunities of improving clinical utility. Finally, wearable gastrointestinal monitoring can revolutionize the idea of digestive care, where people have to react to problems which appear after a certain period (i.e. after intermittent testing), to the one where they are guided to react to specific problems based on continuous physiological channels of data delivery.

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