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i-JaMCSIIX
2023

EXTENDED ABSTRACT BOOK

Publication Date: 30 March 2024
ISBN: 978-967-15337-0-3

https://jamcsiix.uitm.edu.my

INTERNATIONAL JASIN MULTIMEDIA & COMPUTER SCIENCE INVENTION AND INNOVATION EXHIBITION (I-JaMCSIIX) 2023

EXTENDED ABSTRACT

ISBN: 978-967-15337-0-3
i-JaMCSIIX
Universiti Teknologi MARA Cawangan Melaka Kampus Jasin 77300, Merlimau, Melaka

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Recent Studies of Human Limbs Rehabilitation using Mechanomyography Signal: A Survey

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Abstract. In rehabilitation and medical offices, mechanomyography (MMG) is a non-invasive, painless technology that can be applied for a number of goals. The goal of this study is to present a thorough overview of recent studies on mechanomyography-based human limb rehabilitation. The present study illu- minates the utilization of distinct transducers, including accelerometers, piezoe- lectric contact sensors, and condenser microphone sensors. Furthermore, it un- derscores the diverse results that these investigations have yielded. The main findings of this review, which apply to all of these forms of mechanomyogra- phy sensors, are that the ratio of sensor mass to muscle mass under observation is the most crucial factor in sensor selection. Therefore, it is believed that accel- erometers are the most trustworthy devices for spotting MMG signals during both voluntary and induced muscular contraction.

Keywords: Mechanomyography sensor, muscle spasticity, rehabilitation.

1 Introduction

The human body's general functionality depends heavily on the muscles, which make up a sizeable component of it. For both voluntary and involuntary limb motions, the skeletal muscles are to blame. They are therefore always at risk of being destroyed, hurt, having an accident, and losing control. Several methods can be used to evaluate how well muscles work including vibrometery, electromyography, sonomyography, and mechanomyography. Based on the particular types of sensors used, mechano- myography can be divided into a number of subcategories, including acceleromyog- raphy, phonomyography, and vibromyography [1].

A methodological approach called mechanomyography (MMG) enables the regis- tration of vibrations caused by stretching and contracting occurrences in the muscles that travel through the surrounding tissue and may be felt on the skin's surface [2].

Mechanomyography (MMG) produces a signal that reflects the mechanical oscillation produced by the spatiotemporal summation of individual muscle fibres [3]. To pro- vide thorough profiling of muscle contracted activity on the skin surface, the MMG signal can be recorded using a MMG electrode patch sensor, as illustrated in Fig. 1. MMG is a novel investigative instrument in the field of muscular examination, with the potential to outperform electromyography (EMG) in terms of user-friendliness, cost-effectiveness in setup, streamlined procedural steps, signal acquisition reliability, and high compatibility with muscle physiology principles.

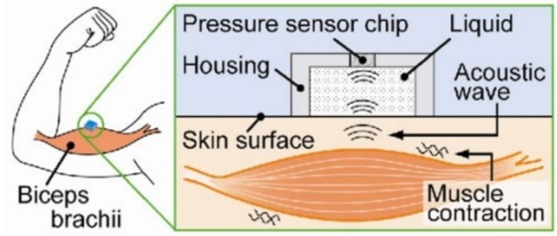

Fig. 1. Mechanomyography Sensor Working Principle

The praiseworthy benefits of mechanomyography (MMG), such as minimum skin preparation requirements, negligible skin impedance influence, and greatly reduced susceptibility to external noise, make this technology a feasible option for electromyography (EMG) [4]. The utilization of expertly designed transducers, including accelerometers, piezoelectric contact sensors, and laser distance sensors, establishes MMG as a dependable and enduring modality for evaluating the mechanical operation of contracting muscles [5]. There are three main mechanisms at play during muscle activation that contribute to MMG: (i) extensive lateral movements of the muscle, as it approaches or recedes from its tension line during both the contraction and relaxation phases; (ii) the resonant frequency induces slight lateral vibrations in the muscle; and (iii) alterations in the dimensions of active muscle fibres. MMG is classify as a new method in measuring muscle spasticity but compared to other methods, it still not stable to be commercialize due to lack of the existing related research. Currently, researchers are examining the approach employed for assessing muscular spasticity with the aim of enhancing its accuracy. The goal of this review is to compile the find- ings from contemporary research on human musculature rehabilitation utilising sever- al mechanomyography sensor types, each of which yields somewhat varied levels of precision in its findings. This paper discusses the survey on the several types of MMG sensor where distinctive sensor-based measurements have been used to measure human musculatures tabulated in Table 1.

2 Literature Review

2.1 Accelerometer

The accelerometer is used to measure muscle contraction by measuring acceleration, and the resulting signal is known as an acceleromyogram [1]. The accelerometer is available in three configurations: single-axis, dual-axis, and tri-axis, with each axis corresponding to a signal orientated in a distinct direction. A trilateral accelerometer exhibits exceptional proficiency in gauging muscle displacement while undergoing contractions in three diverse dimensions: longitudinal, lateral, and transverse to the muscle fibre. Accelerometers are the most popular mechanomyographic (MMG) sensors because to their ease of use, lightweight structure, and consistent signal capture. Campbell et al. [6] conducted an inquiry into the utilization of digital accelerometers for both wired and wireless mechanomyography applications. This paper aimed to investigate the viability of monitoring MMG reaction with a digital accelerometer. This study demonstrates the use of a digital accelerometer to capture a muscle's MMG response. An analogue accelerometer (ADXL335) and a digital accelerometer (ADXL345) were attached to the mid-belly of the biceps brachii using double-sided tape. In addition, electrical stimulation pulses with a current of 20 mA were used as a stimulant. MP150 BioPac (ADXL335) and Arduino (ADXL345) were the interfaces used by both sensors. The study's findings show that using a digital accelerometer allows for exact assessment of the MMG response, owing to its wider range. A significant advantage of using a digital accelerometer is that it provides not only a direct analogue output, like its analogue version does, but also an inter-integrated circuit (I^2C) and a serial peripheral interface (SPI) digital interface.

In order to objectively evaluate elbow spasticity, Wang et al. [7] examined an investigation on the utilization of support vector machines (SVMs) in conjunction with surface electromyography (sEMG) and mechanomyography (MMG). During passive elbow extension and flexion, signals were collected from the biceps and triceps using surface electromyography (sEMG) and tri-axial accelerometer mechanomyography (ACC-MMG). The recorded sEMG and MMG signals underwent calculations to determine the root mean square (RMS), mean power frequency (MPF), and median frequency (MF). The correlation between the obtained features and the level of spasticity was analysed using Spearman's test. According to the study, by combining MMG and sEMG, SVM can accurately distinguish varied degrees of spasticity. This conclusion is critical in the field of clinical validation for the assessment of spasticity. Next, Kruger et al. [8] was worked on the development of a wearable monitor utilizing mechanomyography (MMG) for the assessment of quasi-isometric muscle fatigue in the context of motor neural prostheses. The main goal of this research was to develop a mechanism for identifying muscular fatigue caused by surface functional electrical stimulation (sFES). The proposed approach was tested in persons with spinal cord injury (SCI) during quasiisometric contractions caused by electrical stimulation in three distinct quadriceps muscle areas, namely the rectus femoris (RF), vastus lateralis (VL), and vastus medialis. To regulate the movement of the knee joint in the sagittal plane, voltage-controlled monophasic square pulses have been utilized at a frequency of 1 kHz (with a duty cycle of 50%) and 50 Hz (with a duty cycle of 15%). During isometric contractions of the quadriceps induced by functional electrical stimulation (FES), it has been suggested by the study that muscle weariness can be identified in real-time through the utilization of MMG as a biomarker. So, MMG could detect fatigue in closed-loop control systems. Other than that, Jo et al. [9] conducted a study investigating the utility of mechanomyography (MMG) in quantifying muscle fatigue resulting from repetitive functional electrical stimulation (FES). The objective of this investigation was to assess the impact of electrical stimulation on muscle fa- tigue by means of analyzing MMG signals via a multitude of techniques, namely ankle joint torque analysis, amplitude-based features, and frequency-based features. To maintain body stability, participants sat in chairs with fixed knee and ankle joints. The choice of the magnitude of the electrical stimulation administered by FES equip- ment available in the market was predicated upon the maximum voluntary contraction (MVC) torque of the ankle joint. The results indicated a linear decrease in convex- hull area, convex-hull volume, and peak-to-peak signal value as muscle fatigue ad- vanced, notwithstanding the presence of a solitary outlier. The MMG signals' mean and median frequencies, however, did not exhibit any significant linearity with re- spect to the occurrence of muscle fatigue.

Meanwhile, Liu et al. [10] evaluated an assessment of hand gesture recognition utilizing a wearable device based on mechanomyography (MMG). Sequential forward selection (SFS) was employed to discern the most crucial factors in augmenting classification precision and curtailing processing duration following the extraction of features from temporal signals and coefficients generated by wavelet packet decomposition (WPD). Classifiers such as k-nearest neighbors (KNN), support vector machines (SVM), linear discriminant analyses (LDA), and deep neural networks (DNN) underwent evaluation and comparison of their respective outcomes. The sensor was placed on the wrist flexors and extensors. The 3-axis accelerometer is safely positioned within a 3D-printed watch casing rather than being directly attached to the skin. A base made of Polylactic Acid (PLA), which is a plate that measures 1 millime- ter in thickness, has been utilized in the watch case in order to facilitate the transmis- sion of the MMG signal. The watch case is subsequently positioned on the flat surface of the posterior ulna bone, thereby assuring a continuous connection between the watch case and the skin. The current study tested participants' ability to do a variety of hand gestures, including clapping, finger flicking/snapping, coin flipping/shooting, wrist extension/flexion, and fist forming. Among the classification algorithms tested, KNN with 7 nearest neighbours had the greatest classification accuracy of 94.56% for the eight gestures.

2.2 Piezoelectric Contact Sensors

Piezoelectric sensors are also one of the elements in mechanomyography (MMG) to measure muscle performance. Several research presented the human musculature measurement using piezoelectric sensors. In a recent work, Esposito et al. [11] used a force-sensitive resistor (FSR) to construct a non-invasive sensor capable of precise quantification of muscle contraction. The sensor that has been developed detects the mechanical force that is generated by the contracting muscles that lie beneath the skin. This sensor is affixed to the skin with a rigid dome, ensuring maximum accuracy in its readings. However, it has been determined that through appropriate FSR condi- tioning, the output drift that arises from FSR creep may be constrained, leading to a stable voltage across the FSR and an output voltage that is commensurate with the applied force. The MMG sensor not only records the larger contraction signals, but also the smaller vibrations that occur during muscle contraction. It was determined that the FSR sensor had a wide enough frequency response to reliably measure the MMG signal. A noteworthy correlation (Pearson's r > 0.9) was discovered between the FSR output and the linear envelope of the electromyography (EMG), ascertained through the concurrent recording of signals emanating from the flexor carpi ulnaris.

Next, Szumilas et al. [12] looked at the potential of using a linked piezoelectric sensor in the creation of mechanomyography (MMG)-based human-machine interfac- es. The MMG sensor incorporates two piezoelectric discs that are firmly connected within a single enclosure. To test the sensor's functionality, a static assessment of the force-to-MMG connection was performed and a gesture classification system based on neural network methods was used. The transmission of mechanical waves, which is initiated by the MMG signal at the surface of the skin, particularly in the forearm, elicits stimulation of the piezoelectric discs in two distinct manners, namely directly and indirectly. The external disc is pressed firmly against the target area of skin to initiate direct transmission. On the other side, a coupler is what makes an indirect gearbox conceivable. The external disc is supported throughout its periphery by a base ring while the middle portion of the internal piezoelectric disc makes contact with a hollow pin resulting in four evenly distributed points of support. As a result, the internal disc begins to deform. The coupler is constructed with flexible hinges, allowing the sensor to self-align when attached to the subject. The data revealed ex- ponential correlations between measured MMG signals and the corresponding applied force which extended to as much as 60% of the subject's maximal voluntary contrac- tion. Furthermore, using MMG signals obtained from a single site placed at the fore- arm, a remarkable classification accuracy of 94.3% was attained for eight separate hand motions.

Other than that, Pan et al. [13] innovatively devised mechanomyography (MMG) sensors utilizing PVDF piezoelectric electrospinning for the purpose of lower limb rehabilitation exoskeletons. This research offers a unique MMG sensor that was cre- ated using near field electrospinning technology. The sensor was then utilised to de- tect human body motion while it was being performed by a lower limb exoskeleton robot (LLRE). The MMG sensors displayed an impressive degree of sensitivity which made it possible for direct collection of muscle movement signals even during more minor motion intents. The primary objective was to develop a motor control technol- ogy that could be employed in tandem with a highly sensitive physiological signal sensor to consistently acquire physiological signals. Through the integration of newly developed MMG sensor inputs with motor control, the utilisation of LLRE aims to realise improvements in the efficacy of patient movement. During the course of the research, both as-made MMG sensors and commercial electromyography (EMG) sensors were evaluated side by side. A maximum signal amplitude of 0.2 V was recorded by a standard EMG sensor while 2.8 V was recorded by a MMG sensor. Incorporating further, while the signal-to-noise ratio (SNR) for the EMG sensor persisted at around 4, the MMG sensor yielded an exceptional SNR of over 25. The utilization of advanced sensor technology has significantly enhanced the sensitivity of the LLRE while monitoring physiological data during human gait with the aid of the MMG sensor.

2.3 Condenser Microphones

Comparing to an accelerometer, a condenser microphone provides less signal-to-noise ratio in the mechanomyography (MMG) signal during dynamic contractions muscle [14]. Previous studies have focused on the comprehensive monitoring of motion and muscle activation by combining inertial sensing and MMG techniques, resulting in an innovative fusion approach [15]. This particular research has introduced a distinctive methodology for the simultaneous measurement of motion and muscle activity over a day's duration in an unregulated environment with minimal preparation and effortless assimilation into one's daily routine. The mechanical impulses related to skeletal muscle contractions can now be quantified thanks to the combination of a MMG sensor and specialised inertial measurement unit (IMU) in this system. This study aimed to prove the usefulness of the developed system by correctly recognising activities in six healthy volunteers with an impressive 98% success rate. In addition, a single-leg am- putee and a person with cerebral palsy were monitored over time to see how their mobility and muscle strength evolved. The sensor was placed just above the superfi- cial muscles on the skin's surface. The bespoke MMG and IMU sensors demonstrated outstanding precision in monitoring both motion and muscle activity during straight- forward movements when compared to the existing gold standard.

Other than that, Meagher et al. [16] presented significant advancements in mechanomyography (MMG) sensor technology and signal processing, focusing on the assessment of the validity and intra-rater reliability of muscle recordings. The goal of this work was to design and construct a wearable device containing MMG sensors for arm rehabilitation in stroke patients. The results from the MMG sensors were compared to the data from the electromyography (EMG) sensors. The MMG sensors used in the investigation were a Knowles SPU1410 microphone and a conical chamber 5 mm in height and 7 mm in diameter enclosed by a Mylar membrane. In these MMG sensors, employment was made of a diminutive silicon microphone (Knowles SPU1410LR5H-QB) which encompasses an acoustic sensor, a low noise input buffer, and an output amplifier. The MMG sensor was attached to the extensors of the wrist, while the EMG sensor was linked to the flexors. The study's findings indicated a good level of reliability in MMG onset detection with an intraclass correlation coefficient (ICC) value of 0.78. The MMG was equivalent to the reliability of EMG which had an ICC value of 0.79. There was also a substantial association between force and MMG with an R^2 value of 0.94. These findings show that the MMG device can con- sistently record valid and reliable signals of mechanical muscle activation throughout numerous testing sessions.

2.4 Constant and variable

Signals from Mechanomyography (MMG) were thoroughly analysed in both the temporal and frequency domains, with the goal of capturing their unique properties. Root mean square (RMS), peak-to-peak (PTP) amplitude, and mean average value (MAV) are just a few of the time domain measures that were analysed to learn more about the temporal characteristics of the MMG signals. The spectrum elements of MMG signals were further investigated by looking at their frequency content and analysing metrics including mean power frequency, median frequency, centre frequency, and frequency variance. Such in-depth study enables a wide range of applications and areas of interest, showcasing MMG's relevance due to its ability to offer delimited characteristics in both the time and frequency domains.

The root mean square (RMS) analysis is a prevalent approach employed in studies involving mechanomyography (MMG). It utilizes the intensity quadratic mean value to quantify the extent of muscle displacement conveyed through its acceleration (RMSa) [17]. The mean frequency feature of the MMG signal is widely favored and commonly employed in studies due to its comparative resilience to the influence of analysis methods. In contrast to the median and peak frequencies, the mean frequency serves as a crucial metric for investigating the underlying mechanical alterations with- in muscle activation [18]. This preference stems from its capacity to provide valuable insights into the broader spectrum of muscle dynamics and the associated changes in muscle mechanics. The frequency domain analysis of MMG signals yields significant insights into the contraction characteristics of targeted muscles, facilitating the explo- ration of muscle fiber types and composition. This approach provides valuable infor- mation regarding the underlying physiological and biomechanical properties of the muscles under investigation [19]. During a muscle contraction, the fluctuations in global firing rate that occur within an unfused activated motor unit can be employed as an indicator by monitoring the frequency content of the MMG signal.

Table 1. Overview Of MMG Sensor Development.

No.	Studies Found	Types of MMG Sensor	Muscle	Subjects	Study
1.	Campbell, 2017	Accelerometer, electrical stimulation pulse	Biceps brachii	2 individuals	To explore digital accelerometer usage in Mechanomyographic applications.
2.	Woodward, 2017	Microphone	Forearm flexors	3 individuals	Creating a versatile mechatronic sensing system for real-world physiological data acquisition.
3.	Wang, 2017	Accelerometer	Elbow	39 individuals	Assessing SVM's viability for elbow spasticity evaluation using sEMG and MMG.
4.	Krueger, 2018	Accelerometer, surface functional electrical	The hamstrings, quadriceps, and	6 individuals	To devise a technique for identifying sFES-induced

		stimulation (sFES)	rotator cuffs		muscle fatigue.
5.	Esposito, 2018	Force-sensitive resistor (FSR)	Biceps brachii	Not stated	To assess muscle contraction with a force-sensitive resistor (FSR) as the measurement tool.
6.	Jo, 2018	Accelerometer, surface functional electrical stimulation (sFES)	tibialis anterior muscle	21 men	Measuring muscular fatigue via electromagnetic stimulation and MMG.
7.	Meagher, 2020	Microphone	Forearm flexors	18 individuals (7 men, 11 women)	Assessing MMG signal accuracy and consistency with new sensor tech and processing.
8.	Liu, 2020	Accelerometer	Wrist	35 individuals	To find factors improving accuracy and reducing processing time.
9.	Pan, 2020	Piezoelectric Sensor	Thigh muscles	Not stated	Developing advanced motor control tech and a sensitive physiological signal sensor.
10.	Szumilas, 2021	Piezoelectric Sensor	Forearm	Single men	Evaluating neural network for gesture classification and force/MMG connection in static conditions.

3 Conclusion

A valuable tool for determining the mechanical counterpart of muscle contractions is mechanomyography. In addition to the numerous literary achievements, MMG is still in its formative years. The major conclusions reached as a result of this review which the ratio of sensor mass to muscle mass under observation is the most important consideration in sensor selection. The accelerometer stands out as the optimal selection due to possessing key criteria which are not present in other sensors. These criteria include a straightforward setup process, a design that is lightweight, and an excep- tional level of reliability in signal acquisition. Hence, accelerometers are regarded as the most reliable tools for detecting MMG signals during both voluntary and stimulat- ed muscle contraction.

4 Acknowledgement

This research was supported by Ministry of Education (MOE) through Fundamental Research Grant Scheme (FRGS/1/2022/TK07/UIAM/02/6).

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2023

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