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RESEARCH ARTICLE

Mechanomyography in Assessing Muscle Spasticity: A Systematic Literature Review

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ABSTRACT - Mechanomyography (MMG) has gained significant prominence in the domain of scientific inquiry, exhibiting widespread applications in diverse areas including sensor advancement, signal processing methodologies, characterization of muscle spasticity, diagnosis of neurological disorders, and as a valuable tool in medical rehabilitation. However, despite the considerable body of existing MMG research, there remains a paucity of comprehensive investigations in these domains in the past. The primary objective of this systematic review is to conduct a comprehensive analysis of the available literature pertaining to the evaluation of muscle spasticity assessment using mechanomyography (MMG) in a systematic and categorical manner. By applying the pre-established search criteria to five prominent databases, a total of 63 pertinent studies that met the inclusion criteria for our review. Through a thorough scrutiny of the 10 meticulously selected records, we unveiled the extensive diversity in protocols and parameters employed in the assessment of muscle spasticity using mechanomyography (MMG). Accelerometers and piezoelectric sensor used for mechanomyography (MMG) are currently in the nascent phase of their development, as evidenced by the findings of this systematic review. Notably, this review also highlights the influence of sensor placement on muscles as a potential factor affecting the acquired signal. In consideration of these findings, it can be concluded that further research is warranted to advance MMG, particularly in the domains of sensor refinement, with specific attention to accelerometers, and the refinement of signal processing techniques. Additionally, future investigations should aim to expand the scope of MMG applications in clinical settings and rehabilitation practices.

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1.0 INTRODUCTION

Musculature constitutes a substantial portion of the human physique and is susceptible to various forms of injury arising from fortuitous incidents, excessive exertion, inflammatory processes, pathological conditions, infectious agents, as well as untoward effects of specific pharmacological substances [1]. Muscles can be impacted by an array of complications and disorders, thereby giving rise to debility, discomfort, and impairment of locomotion or even paralysis. Certain afflictions pertaining to muscular tissues can manifest as protracted bouts of distressing agony. Consequently, the acquisition of an accurate diagnosis assumes paramount significance in the endeavor to ascertain and address these muscular ailments.

When describing the symptoms of the upper motor neuron syndrome, Lance first coined the term "spasticity" in 1980 to describe a motor disorder characterised by a velocity dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyperexcitability of the stretch reflex [2], [3]. Spasticity is described here in terms of its consequences on involuntary movements, but its impact on intentional actions is ignored. Spasticity, characterized by heightened muscle stretch reflexes, increased resistance to passive movement, clonus, involuntary movements, and simultaneous activation of antagonistic muscle groups, represents a prevalent concern affecting individuals across the lifespan, encompassing both pediatric and adult populations [4]. This condition arises from a spectrum of neurological disorders, including but not limited to cerebral palsy, traumatic brain injury, spinal cord injury, multiple sclerosis, and stroke. Studies have shown that an impressive proportion of stroke patients, specifically around 42%, encounter spasticity within a mere six months after the stroke incident. Furthermore, spasticity is found to impact

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approximately 65% of individuals diagnosed with multiple sclerosis, and a staggering 70% of those individuals who are enduring a spinal cord injury [5]. It is characterized by increased muscle tone and involuntary muscle contractions, which can cause pain, difficulty with movement, and other problems [6]. Spasticity can have a significant impact on a person's quality of life, and it can be a major challenge for both patients and caregivers.

Traditional clinical scales, such as the Modified Ashworth Scale (MAS) and the Australian Spasticity Assessment Scale (ASAS), remain the gold standard for measuring spasticity in clinical practise [7]. In addition, the clinical assessment tools for assessing spasticity included the Spinal Cord Assessment Tool for Spastic Reflexes (SCATS), Fugl-Meyer Assessment (FMA), the Penn Spasm Frequency Scale (PSFS), and the Modified Tardieu Scale (MTS) [8], [9]. However, the contemporary approach to evaluating muscle spasticity involves subjective assessments made by therapists [10]. Despite the expertise of the practitioners, there exists potential variability in demarcating distinct categories of severity levels in the condition. The assessment of spasticity frequently involves employing the Modified Ashworth Scale (MAS). In the procedural implementation of the MAS, the evaluator engages in passive maneuvers and assigns spasticity grades to the relevant joints based on the perceived degree of muscular resistance encountered during passive stretching [11].

Electromyography (EMG) has been around for quite some time and can be used to record electrical muscle activity however, there are a number of restrictions on its use outside of a therapeutic setting. Also, EMG is easily affected by noise and changes in resistance, which means it is not reliable in different environments or when collecting data for long periods of time, like when someone is sweating [12]. Sensors like microphone or accelerometer are used to assess muscle vibrations (mechanical activity) as an alternative to an EMG which known as Mechanomyography (MMG) [13]. MMG is a method of recording muscle activity based on vibrations caused by the mechanical contraction of muscle fibres which illustrated in Figure 1. When compared to EMG, this method has yet to gain widespread acceptance, especially in clinical settings. In spite of this, mechanomyography has a wide range of potential uses, from controlling prosthetic devices and recognising gestures in human machine interfaces (HMIs) to studying the underlying physiological mechanisms of the neuromuscular system in scientific research [14]. The MMG method is more convenient than EMG because it doesn't need any special preparation, amplification, coupling gel, or skin contact. The MMG responses can be used in a variety of medical contexts, including the clinical evaluation of neuromuscular tissue, biofeedback rehabilitation, and neural/myoelectric prosthetic control.

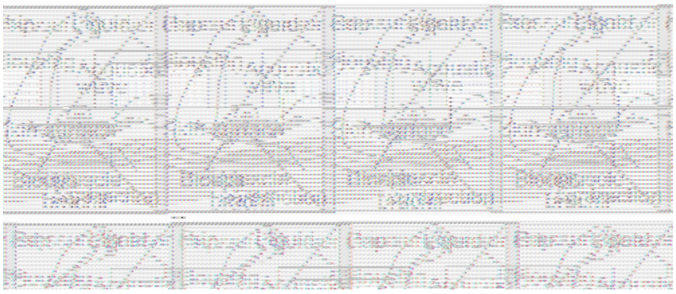

Figure 1. The working principle of Mechanomyography.

MMG encompasses distinct modalities, such as acceleromyography, phonomyography, and vibromyography, which are delineated based on the specific sensors employed for signal acquisition. MMG represents a recent advancement within the realm of muscle research, offering notable advantages over EMG in terms of equipment handling convenience, cost-effectiveness in setup, streamlined procedural steps, signal reliability, and physiological congruence with underlying muscle mechanisms. The mechanomyogram, derived from MMG, serves as a mechanical representation of the comprehensive dynamics of the entire musculature. Given its novelty, MMG warrants comprehensive exploration encompassing equipment refinement, sensor enhancements, diverse application domains, and in-depth investigation of the intricate muscular movements that can be effectively elucidated through this technique [15].

MMG sensors offer a range of advantages over alternative techniques such as EMG. These benefits encompass a superior signal-to-noise ratio, reduced sensitivity in sensor placement, lightweight equipment, and straightforward setup procedures, all while ensuring reliable data acquisition [16]. Notably, MMG obviates the requirement for skin preparations, as it solely pertains to the detection of mechanical vibrations. Consequently, concerns related to skin impedance are rendered inconsequential in MMG applications. The employment of skilfully crafted transducers, encompassing accelerometers, piezoelectric contact sensors, and laser distance sensors, establishes MMG as a reliable and long-lasting modality for assessing the mechanical functioning of contracting muscles [17]. Moreover, MMG can provides valuable insights into the inherent physiological and biomechanical characteristics of scrutinized muscles [18].

This review endeavors to achieve the following objectives: (1) develop a systematic categorization framework for assessing muscle spasticity through the utilization of Mechanomyography (MMG) signals, (2) discern prevalent MMG parameters frequently employed to assess distinct sign of muscle spasticity, and (3) analyse the outcomes associated with all pertinent compartments as per the specified protocol and the specific type of muscle spasticity being investigated. Within the confines of a particular experimental design, the dynamics exhibited by temporal and spectral characteristics of MMG signals are intricately linked to diverse manifestations of muscle spasticity. Moreover, the findings of this study serve to endorse the utilization of Mechanomyography (MMG) in clinical investigations encompassing the domains of medicine, rehabilitation, prosthetic control, as well as applied research pertaining to athletics and sports. Consequently, MMG presents itself as a viable substitute for Electromyography (EMG) across diverse clinical contexts, including but not limited to rehabilitation practices, conditions associated with muscular pathology, and instances of muscle atrophy.

2.0 METHODS

2.1 Identification of Studies

A comprehensive literature search of studies that assessed the muscle using mechanomyography (MMG) was conducted. Five different databases, namely Scopus, IEEEXplore, ScienceDirect, ProQuest and SpringerLink were searched for article on assessment of muscle spasticity using mechanomyography (MMG) using different keywords and periods from January 2014 to Disember 2023 due to limit of database. Our search strategy was deliberately designed to encompass a wide scope, incorporating the combined search terms: #1 (mechanomyography) AND #2 (muscle) AND #3 (spasticity) which been apply to Scopus (2014-2023) and IEEE (2014-2023) while for ScienceDirect (2014-2023), ProQuest and SpringerLink, the keywords that been used was #1 (mechanomyography) AND #2 (muscle) AND #3 (spasticity) AND #4 (assessment) from 2014 to 2023. By employing this comprehensive approach, we aimed to ensure a thorough exploration of the relevant literature pertaining to mechanomyography in relation to muscle spasticity. The examination of potential eligible studies encompassed a meticulous scrutiny of various scholarly sources, including journal articles, conference papers, clinical reports, and book chapters, in adherence to the predefined criteria. An additional step involved meticulously screening the reference lists of all pivotal articles identified during the search process, broadening the scope of the review even further.

2.2 Study Inclusion/Exclusion Criteria

The exploration of five databases using the set of keywords yielded a total of 53 studies. Supplementary to this, ten additional articles were acquired from alternative sources, including medical journals and databases other than the previously mentioned five databases. Eligibility was assessed by reviewing the abstract of the article in the databases, ensuring that it specifically addressed spasticity or, more generally, muscle tone, and was conducted on a population with neurological injuries. Out of the total of 63 studies, 10 records were excluded for the duplicates. The first screening be made based on the following criteria: (1) publication in only English language, (2) focus on neuromuscular physiology and pharmacology, or (3) discussion of a technique other than MMG which exclude 28 records. Subsequent screening resulted in the exclusion of 15 more articles due to the following reasons: (1) absence of muscle assessment description in the manuscript, (2) insufficient findings pertaining to the muscle, (3) inadequate clarity in describing the utilized protocol within the article and (4) absence of muscle spasticity description in the manuscript. Following the elimination of duplicate entries, extended versions, and studies with insufficient information, a final selection of 10 articles conforming to the inclusion criteria was ultimately obtained, as illustrated in Figure 2.

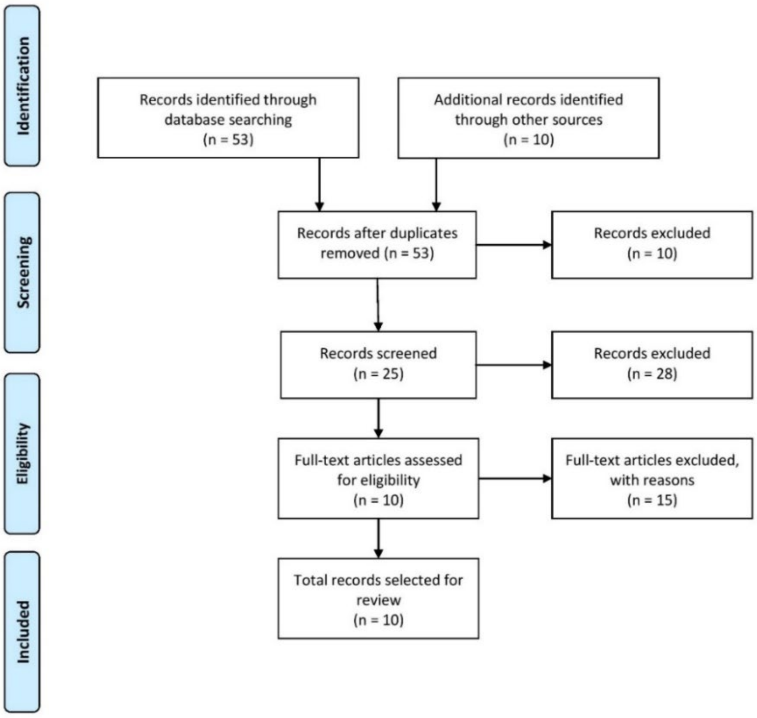

Figure 2. Process of conducting a comprehensive literature search and subsequent selection of studies.

2.3 Data Extraction

Ten articles that successfully met the inclusion requirements were subjected to a thorough and thorough analysis. The following crucial data was then extracted from each article using a methodical and rigorous data collection process: (1) author names and the year of publication; (2) specific details of the sensor used, including the model; (3) thorough information regarding the subjects under investigation; (4) precise identification of the targeted muscle for examination; (5) detailed description of the various parameters relating to muscle mechanomyography (MMG) that were investigated; (6) comprehensive summary of the obtained findings and outcomes; and (7) in-depth elucidation of the system.

2.4 Data Analysis

The organisation of the MMG-based assessment of muscle spasticity in this systematic literature review (SLR) paper was achieved through narrative analysis. The assessment was divided into subsections that covered the types of muscles observed, the specific transducers used in MMG, and the parameters considered during the assessment process.

2.5 Validity Assessment

The data that was gathered from the relevant papers was carefully analysed by Muhamad Aliff Imran and the research team, with the primary goal of minimising the possibility of information bias. In order to maintain the honesty and rigour of this systematic review, as well as to reduce the possibility of publication bias, the inclusion criteria were primarily concentrated on journal publications that have been subjected to scientific evaluation by other researchers.

3.0 RESULTS

The pool of records that were considered to be eligible, which consisted of 10 investigations, included thorough categorizations relating to the measurement of muscular spasticity using mechanomyography (MMG). The quadriceps muscle, biceps brachii, and wrist flexors or extensors were the three types of muscles that could be assessed using MMG-based evaluations of muscle spasticity. These records could be categorised into these three distinct and broad categories.

3.1 Quadriceps Muscle

The literature encompasses a corpus of five studies that have focused specifically on the evaluation of muscle spasticity pertaining to the quadriceps muscle [19], [20], [21], [22], [23] (Table 1). A study by Tsuji et al. [19] used portable mechanomyography (MMG) and electromyography (EMG) devices in order to objectively assess the patellar tendon reflex hyperreflexia. Three sensors were carefully positioned on the quadriceps muscle area while the subjects were seated upright with their knees at 70° and their hips at 80°. The EMG and MMG devices were meticulously affixed to the thigh using adhesive tape. The findings in the muscles of rectus femoris (RF), vastus medialis (VM), and vastus lateralis (VL) demonstrated a notable elevation in root mean square (RMS) amplitudes and a concomitant decrease in mean power frequency (MPF) across both EMG and MMG signals during both maximal and sustained force contractions. Particularly noteworthy were the results in patients with cervical and thoracic myelopathy, where the receiver operating characteristic (ROC) curve analysis showed moderate to very high areas under the curve (AUC) for all EMG-RMS, EMG-MPF, MMG-RMS, and MMG-MPF values, indicating the diagnostic potential of these measures in discerning patellar tendon hyperreflexia.The research indicates that EMG and MMG may have potential therapeutic applications and aid in the diagnosis of a variety of neurological disorders. Particularly advantageous may be MMG in clinical settings involving patients with spinal pathologies and other neurological disorders. MMG is a simple and desirable method for quantifying the patellar tendon reflex, showing significant differences between hyperreflexia in patients with pathologies and normal participants. Nevertheless, clinical implementation faces obstacles such as the scarcity of research involving healthy subjects exhibiting heightened tendon reflexes and the difficulty of distinguishing between pathological and healthy hyperreflexia. It will be critical for the wider implementation of MMG and EMG in clinical settings to surmount these challenges.

Next, de POL et al. [20] investigated application of punctual mechanical oscillation (PO) with different protocols and the magnitude of their effects. Two interventions were administered to all participants, with a time interval of 7 to 15 days between the initial and subsequent interventions, aiming to assess two distinct approaches for the application of oscillation in the modulation of Bicep Brachii (BB) muscle spasticity. The primary objective of this study was to examine the impact of punctual mechanical oscillation (PO) on spasticity in children diagnosed with cerebral palsy. Two distinct intervention protocols were used: Intervention 1 involved applying PO to the spastic muscle's tendon, while Intervention 2 focused on applying PO to the spastic antagonist muscle's muscle belly. The impacts of these interventions were assessed through the application of the Modified Ashworth Scale (MAS), with simultaneous recording of mechanomyographic (MMG) signals. The approach was to evaluate the effectiveness of PO in modulating spasticity in children with cerebral palsy which providing a comprehensive assessment of muscle tone changes**.** Data collection occurred before the interventions and at various time intervals thereafter. The results demonstrated that both intervention protocols resulted in a statistically significant reduction in MAS values following the interventions. However, when the MMG values were examined in both the temporal and spectral domains, no consistent pattern emerged. Furthermore, no significant differences were observed between the two protocols in terms of their effects on MAS, MMG mean frequency (MMG_{MF}), and MMG root mean square (MMG_{RMS}). In aggregate, this study posits that the application of PO exhibits promises as a noteworthy therapeutic modality for modulating spasticity in pediatric individuals diagnosed with cerebral palsy. Although the promise of MMG in clinical practice was apparent, further research will be required to investigate the underlying mechanisms and improve the application of PO. Furthermore, it helps to address the obstacles that hinder the widespread clinical implementation of MMG, such as the requirement for specialized training in signal interpretation and the availability of equipment.

Other than that, Pan et al. [21] proposed a novel approach by developing mechanomyography (MMG) sensors using PVDF piezoelectric electrospinning specifically for lower limb rehabilitation exoskeletons. The study introduces an innovative MMG sensor fabricated through near field electrospinning technology and applies it to detect human body motion in the context of a lower limb exoskeleton robot (LLRE). The MMG sensors demonstrated exceptional sensitivity, enabling the direct capture of muscle movement signals, even during subtle motion intentions. The main objective of the research was to develop a motor control technology integrated with a highly sensitive physiological signal sensor to accurately capture physiological signals. Through the integration of the newly developed MMG sensor signals with motor control, the utilization of the LLRE aims to enhance the efficiency of patient movement. In the comparative analysis, commercial electromyography (EMG) sensors were included alongside the as-made MMG sensors. The maximum signal amplitude recorded by the commercial EMG sensor was approximately 0.2 V, whereas the MMG sensor achieved an amplitude of around 2.8 V. Furthermore, the signal-to-noise ratio (SNR) of the EMG sensor was approximately 4, whereas the MMG sensor demonstrated an SNR of approximately 25. This novel sensor technology effectively improved sensitivity in driving the LLRE by capturing physiological signals using the MMG sensor during human walking with the LLRE system. Moreover, the sensors offer superior sensitivity and amplitudes for assessing muscle activity, making them valuable for diagnosing muscle spasticity. MMG provide more precise motion signals than EMG, making it more accurate and reliable for clinicians to utilized in physiological sensing application.

Besides that, a study conducted by Jun et al. [22] aimed to assess spasticity in individuals with brain lesions through the utilization of mechanomyography (MMG). The main aim of the investigation was to ascertain the association between MMG and the Modified Ashworth Scale (MAS) in individuals who exhibit minimal levels of spasticity. The aim of the study was to establish a more objective clinical parameter for the evaluation of spasticity. Sensor 1 was placed on the vastus lateralis (VL) muscle's dermis, 50% of the femur's span, while Sensor 2 was on the semitendinosus (ST) muscle's skin near the distal point. Both sensors were securely affixed to the skin using 3M foam tape and medical tape to ensure minimal oscillation. At the same time, three medical practitioners meticulously evaluated the passive stretch reflexes of all participants and verified the existence of spasticity. The study found that physician consensus was mostly non-significant. MMG and EMG showed a statistically significant difference in the proportion of normalized hull area between typical and spastic muscles (p=0.01, p=0.02). The discovery of a finding indicating that the antagonist muscle movement surpassed that of the agonist muscle, thus implying the presence of spasticity, was denoted as 'less than one point'. A statistically significant correlation was established between the ratio of the normalized hull area and the mean data of MAS provided by the examiners (r=0.69, p=0.01). However, the correlation between the EMG data and the average MAS data did not produce a statistically significant outcome (r=-0.09, p=0.71). The correlation between standardized hull area and average mean absolute spasticity depends on spasticity severity. Normalized areas for minimal passive contraction of agonist and antagonist muscles were 0.28, while maximal passive contraction measurements were 0.32 and 0.33. The study shows that MMG was a valuable tool for assessing spasticity in patients with brain lesions, offering a quantitative evaluation of muscle activity. When paired with EMG data, MMG enhances the objectivity of assessment. However, the broader use of MMG in clinics faces obstacles due to the requirement for specialized training and equipment for healthcare professionals to interpret and utilize MMG data effectively.

A research study on the assessment of spasticity in the hamstrings muscles through the application of mechanomyography (MMG) with a focus on the antagonist muscular group had been examined by Krueger et al. [23]. The primary aim of this research was to introduce an innovative method for assessing spasticity in the hamstrings muscles by considering the activity of the antagonist muscular group in volunteers with spinal cord injuries (SCIV). MMG sensors were meticulously situated on the muscle belly of the rectus femoris (RF), vastus lateralis (VL), and vastus medialis (VM) muscles using double-sided adhesive tape. More specifically, the sensor affixed to the RF muscle was positioned equidistantly between the anterosuperior iliac spine and the apex of the patella. The sensor situated over the VL muscle was placed equidistantly between the greater trochanter and the lateral condyle of the femur. Additionally, the sensor positioned over the VM muscle was situated within the medial third of the distal thigh region. The study outcomes revealed a statistically significant elevation in the MMG integral (MMG_{INT}) for muscles under consideration, specifically the RF (p = 0.004), VL (p = 0.001), and VM (p = 0.007), when comparing Modified Ashworth Scale grade 1 (MAS1) to grade 0 (MAS0). These results suggest that MMG successfully identified an augmentation in muscular tonus within the antagonist muscular group, notably the quadriceps femoris, among individuals with spinal cord injuries. In conclusion, MMG may be a potential approach for identifying and measuring antagonist muscle tone in spinal cord injury patients. The subjectivity of standard evaluation methods like the Modified Ashworth Scale may prevent broad clinical use of MMG for spasticity assessment.

Table 1. Overview of MMG Sensor in Quadriceps Muscle Performance.

Studies Found	Types of MMG Sensor	Muscle	Subjects	Study	Used Parameters
[19]	Force transducers, accelerometers, and motion analysis	Quadriceps and tendon	12 healthy subjects	Utilize portable MMG and EMG devices for objective assessment of patellar tendon reflex hyperreflexia.	Root mean square (RMS), mean power frequency (MPF)
[20]	Triaxial accelerometer	Spastic antagonist muscle	7 children with medical diagnosis of cerebral palsy (CP) and ICD (International Classification of Diseases)	Examine diverse punctual mechanical oscillation (PO) protocols and assess their respective impacts.	Root mean square (RMS), mean power frequency (MPF)
[21]	Piezoelectric Sensor	Thigh muscles	Not stated	Develop advanced motor control technology with a highly sensitive physiological signal sensor for exceptional signal capture sensitivity.	MMG amplitude and signal-to-noise ratio (SNR)
[22]	Triaxial accelerometer	Vastus lateralis muscle (agonist) and	10 subjects	Correlate muscle MMG with Modified Ashworth Scale (MAS) in low spasticity patients.	Signal vector magnitude (SVM) and spearman correlation
[23]	Triaxial accelerometer	Semitendinosus muscle (antagonist)	4 subjects	Correlate MMG and MAS in low spasticity patients.	MMG integral (trapezoidal rule integration) and Mann-Whitney

3.2 Bicep Brachii Muscle

A total of four studies were dedicated to the investigation of muscle spasticity specifically in the biceps brachii muscle [24], [25], [26], [27] (Table 2). E et al. [24] had conducted research of comparative analysis of muscle mechanomyography (MMG) signals that obtained from the flexor and extensor muscles in two distinct groups, namely, six athletes with spasticity and six non-impaired individuals. Employing MMG was an option to quantitatively acquire accelerometer-based muscle vibrations. Two MMG sensors were precisely positioned on the skin surface of the volunteer. Sensor 1 was positioned at the motor point of the wrist flexors, whereas Sensor 2 was situated at the motor point of the wrist extensors. Concurrently, the MMG signals were captured and subsequently archived for subsequent analytical examination. The mean equivalent MMG_{RMS} voltage values of MMG signals for the cerebral palsy (CP) cohort were ascertained to be 0.4058 mV for the muscles of the left wrist flexors and 0.4258 mV for the muscles of the left wrist extensors. Furthermore, the corresponding values were determined to be 0.4215 mV for the muscles of the right wrist flexors and 0.4529 mV for the muscles of the right wrist extensors. Conversely, the mean modulus values of MMG_{RMS} signals for the non-impaired (NI) group were noted as follows: 0.3694 mV for the left wrist flexor muscles, 0.3945 mV for the left wrist extensor muscles, 0.3503 mV for the right wrist flexor muscles, and 0.3728 mV for the right wrist extensor muscles. Moreover, the mean 3D modulus of the MMG_{RMS} signals was observed to be higher in the CP group in comparison to the NI group. These results signify the capacity of MMG to discern vibrational disparities among muscles in individuals exhibiting spasticity and those without, thereby facilitating the discrimination between individuals with a healthy neuromuscular profile and those presenting spasticity.

The feasibility of using digital accelerometers for wired and wireless applications in mechanomyography (MMG) was then investigated by Campbell et al. [25]. The study's main goal was to determine whether it was feasible to record a muscle's MMG response using a digital accelerometer. An analogue accelerometer (ADXL335) and a digital accelerometer (ADXL345) were both used in this investigation. They were both taped firmly to the mid-belly of the biceps brachii muscle. The stimulating substance was given as electrical stimulation pulses with a 20 mA current strength. The MP150 BioPac interface was used by the ADXL335 and the Arduino interface by the ADXL345 to interface the two sensors in separate ways. The study's findings show that using a digital accelerometer made it easier to quantify the MMG response accurately, mainly because of its wider range of sensitivity. Notably, the use of a digital accelerometer offered a number of benefits, including the availability of digital interfaces like the inter-integrated circuit ($\mathrm{I^2C}$) and serial peripheral interface (SPI), as well as direct analogue output, similar to that of its analogue counterpart. The used of MMG was to dignosed muscle spasticity as it reflects the mechanical activity of single motor units, aiding in identifying muscle fiber composition and mechanisms underlying force generation in muscles. By utilizing the accelerometer as the transducer of MMG, it can provide a detailed representation of muscle activity during contractions and stimulations. It also has potential as a non-invasive technique for assessing muscle performance, making it valuable for clinical applications such as anaesthetic monitoring and prosthetic control. The lack of knowledge and acceptance of MMG technology in medical environments could hinder its extensive utilisation. Integrating digital accelerometers into existing data collecting systems may necessitate the use of extra hardware and interfacing, which could lead to more complexity and cost.

Other than that, Wang et al. [26] carried out a study to investigate the viability of using surface electromyography (sEMG) and mechanomyography (MMG) in support vector machine (SVM) for the objective evaluation of elbow spasticity. MMG works to record low-frequency transverse muscle vibrations and then assess muscular stiffness. The combination of MMG and surface electromyography (sEMG) in evaluating spasticity shows potential due to the complementary nature of the information they provide. The sEMG and tri-axial accelerometer mechanomyography (ACC-MMG) signals from the biceps and triceps muscles were recorded simultaneously during the experiment when subjects passively extended or flexed their elbows. The captured sEMG and MMG signals were then used to extract root mean square (RMS), mean power frequency (MPF), and median frequency (MF) characteristics. The association between the collected features and the degree of spasticity was examined using Spearman correlation analysis. The results of the study indicate that SVM can distinguish and categorise different grades of spasticity with accuracy by combining MMG and sEMG signals. Regarding the clinical validation for the assessment and evaluation of spasticity, this discovery has important ramifications. Additionally, the use of MMG provides detailed biomechanical insights that go beyond the capabilities of sEMG alone. This suggests that using both MMG and sEMG together could improve the evaluation of spasticity. Nevertheless, the effectiveness of MMG may be influenced by parameters such as sensor type and contact pressure, which could pose challenges to its widespread use in clinical settings.

In addition, Santos et al. [27] reviewed a study that looked at the relationship between the Modified Ashworth Scale (MAS)'s numerous degrees of spasticity and the temporal and spectrum characteristics of mechanomyography (MMG) signals. The research utilised MMG as a method to measure muscle tone changes, where higher muscle tone levels were associated with increasing MMG amplitudes. As part of the experimental methodology, the assessment and categorization of spasticity levels in the agonist muscles (specifically, knee and/or elbow joint flexor or extensor muscles) were conducted using the MAS. Both muscle groups mechanomyographic (MMG) signals were captured simultaneously. In order to properly prepare the skin for the implantation of mechanomyographic (MMG) sensors, trichotomy and antisepsis were performed using 70° alcohol. The double-sided tape was used to firmly attach the sensors to the skin. The belly of the agonist muscle group was where "Sensor 1" was placed, while the belly of the antagonist muscle group was where "Sensor 2" was placed. The MMG descriptor that exhibited the highest correlation with the Modified Ashworth Scale (MAS) was found in the time domain, specifically, the MMG_{ME} (mechanomyographic mean envelope). This strong correlation suggests that MMG_{ME} is a robust indicator for evaluating spasticity. Conversely, in the spectral analysis, a moderate correlation was observed between the MMG_{MF} (mechanomyographic median frequency) and MAS, implying that MMG_{MF} may not be a suitable descriptor for spasticity evaluation. These findings suggest that MMG could replace MAS in the future by quantitatively assessing spasticity. MMG provides a more objective, efficient, accurate, and trustworthy tool for measuring spasticity, and its signals could help physical therapy clinics quantify upper and lower limb spasticity. However, more research is needed to evaluate their sensitivity and accuracy to established approaches.

3.3 Wrist Flexors or Extensors

The wrist flexor and extensor muscles were the focus of an experiment on muscle spasticity carried out by Liu et al. [28] (Table 2). The approaches that been used involved with MMG signal that can detect muscle activity periods for real time gesture recognition, which crucial in diagnosing muscle spasticity. It also been used to provide valuable insights into muscle fatigue and torque, showcasing their potential in assessing muscle spasticity. In the research, temporal signals and coefficients obtained through wavelet packet decomposition (WPD) were employed for feature extraction. The identification of the most relevant components was subsequently conducted through the application of sequential forward selection (SFS), with the primary objective of enhancing classification accuracy and expediting processing. It was compared and analysed how well several classifiers performed, including k-nearest neighbours (KNN), support vector machines (SVM), linear discriminant analysis (LDA), and deep neural networks (DNN). The sensors were placed on the wrist flexors and extensors, and a 3-axis accelerometer was contained inside a watch casing that was 3D-printed as opposed to being affixed to the skin. A 1 mm thick PLA (Polylactic Acid) plate was used at the base of the watch case to help transmit the mechanomyography (MMG) signal. The posterior ulna, which provided a flat surface and acted as a stable mounting point for the case, allowed for constant skin contact with the watch case. The study included the evaluation of eight distinctive and unusual movements, including clapping, flicking the index finger, snapping the finger, flipping a coin, shooting, extending the wrist, flexing the wrist, and making a fist. KNN with 7 nearest neighbours achieved the highest classification accuracy of 94.56% for the eight gestures among the four classification methods used (SVM, LDA, and DNN). According to this study, the utilization of MMG signals in wearable devices to recognize hand gestures shows that it can be possible to deploy MMG technology in clinical environments to diagnose muscle spasticity such as prosthesis control, which could benefit patients with limb deficiencies. Moreover, MMG can be useful in diagnosing muscle spasticity in patients with conditions like cerebral palsy or stroke, but challenges in accurately positioning sensors on specific muscle groups may hinder widespread adoption. Further research is needed to optimize signal processing and classification methods.

Table 2. Overview of MMG Sensor in Bicep Brachii and Wrist Flexor or Extensor Muscle Performance.

Studies Found	Types of MMG Sensor	Muscle	Subjects	Study	Used Parameters
[24]	Triaxial accelerometer	Flexors and extensors muscles	6 athletes with spasticity and 6 non-impaired.	Conduct a comparative analysis of flexor and extensor muscle MMG signals.	Root mean square (RMS)
[25]	Triaxial accelerometer, electrical stimulation pulse	Biceps brachii	2 subjects	Explore the use of digital accelerometers for MMG applications.	MMG amplitude
[26]	Triaxial accelerometer	Elbow	39 subjects	Investigate SVM algorithm feasibility for objective assessment of elbow spasticity using sEMG and MMG signals.	Root mean square (RMS), mean power frequency (MPF), and median frequency (MF)
[27]	Triaxial accelerometers	Muscles flexors or extensors (agonists)	22 subjects	Validate the correlation between temporal and spectral features of MMG signals and varying spasticity levels determined by the Modified Ashworth Scale (MAS).	Median frequency, meadian amplitude, kruskal-Wallis, coefficient of determination and spearman correlation
[28]	Triaxial accelerometer	Wrist Flexors or Extensors	35 subjects	Identify key features for enhanced classification accuracy and faster processing.	Time-frequency features, k-nearest neighbors

4.0 DISCUSSION

The results of Mechanomyography (MMG) in assessing spasticity in various muscle types utilising various transducers, such as accelerometers and piezoelectric sensors, are summarised in this study. These review's two main conclusions are as follows: The use of mechanomyography (MMG) for the measurement of several muscle types, such as the quadriceps muscle, biceps brachii, and wrist flexors or extensors, is supported by a significant body of research. Second, the review provides strong evidence in favour of using MMG as a practical method for evaluating muscular spasticity resulting from neurological diseases. It would be important to undertake comparative research with properly chosen samples of patients with neurological problems in order to support appropriate rehabilitation approaches. Additionally, our review only included studies with meticulous data presentation, well defined protocols, and thorough examples of research methodologies. As a result, there is small chance of bias in all of the included research.

4.1 Mechanisms of MMG Signal Formation

Multiple MMG signal origins are described in our thorough investigation. The biceps femoris, a muscle that makes up the hamstrings, was connected to the MMG sensors (Piezoelectric) in order to record muscle deformation, according to Pan et al., 2020. Massive deformations in the gait cycle result from the lengthening and subsequent shortening of active muscles (eccentric and concentric contractions, respectively). Triaxial accelerometers were employed by Jun et al., 2018 in order to capture MMG signals at a sampling rate of 1 kHz from the vastus lateralis (VL) and semitendinosus muscles. MMG was evaluated biomechanically while passively isotonically flexing and extending muscles. A triaxial accelerometer was employed by Krueger et al. (2012) as an MMG signal transducer to capture the signal. The MMG sensor successfully picks up the signal after going through a conversion process that turns mechanical vibrations into electrical counterparts. Because of the MMG signal's considerable sensitivity to changes in muscle tone, it is possible to identify and evaluate spasticity in the hamstrings and inadequate relaxation in the quadriceps in people who are otherwise in normal physiological condition.

4.2 MMG Signal Processing

Several research offer several methods to measure muscular spasticity using MMG signal processing. Electromyography (EMG) inquiry employs elements used in MMG recording analysis, such as time and frequency domains, and the wavelet technique, which combines both domain studies [29]. However, various algorithms have been introduced for the joint time-frequency domain representations of the signal, encompassing the short-time Fourier transform (STFT), wavelet transform (WT), and the more recently proposed time-scale representations, due to some useful information that may not be ordinarily evident in time or frequency domain [30]. For example, Santos et al., 2016 used Fast Fourier Transform (FFT) for quantifying the signal processing of MMG sensor to process the MMG median frequency (MF) data. The calculation of the median frequency (MF) involves the utilization of the power spectrum (P(f)) and sampling rate (fs) within the corresponding equation.

To examine potential dissimilarities, the Kruskal-Wallis test was employed to compare the median values of the mechanomyography (MMG) signal across different levels of spasticity as measured by the Modified Ashworth Scale (MAS). To evaluate linearity, the coefficient of determination (R^2) test was employed to scrutinize the correlation between the mean energy of MMG ME and the median frequency of MMG MF values in relation to the outcomes determined by the MAS. Furthermore, the Spearman correlation test was conducted to explore the association between the MMG ME and MMG MF of agonist muscles, as well as the MAS evaluation results, thereby investigating the potential presence of a correlation. Besides, in order to quantify the signal processing of the MMG sensor, Pan et al., 2020 assessed the sensor's maximum signal amplitude and signal-to-noise ratio (SNR) during the lower limb rehabilitation exoskeleton (LLRE) walking process. The maximum signal amplitude and SNR of the MMG sensor were 3 V and 25, respectively, which were 6 and 7 times greater than those of the EMG signals, indicating that it was more sensitive than EMG sensors.

4.3 MMG Sensor Utilization

Ten studies on the issue of developing the platform consists of MMG sensors are included in our narrative-analysis; each paper uses a different type of transducer. In some studies, MMG was combined with other techniques; for instance, Tsuji et al., 2021 combined an accelerometer with EMG and Campbell et al., 2017, an accelerometer with electrical stimulation; the goal of this development was to eliminate muscular shortening. An accelerometer and sEMG were integrated by Wang et al. in 2017. Although sEMG may distinguish between different spasticity patterns using bioelectric data, it is unable to provide biomechanical information on either passive or dynamic movements. MMG, however, can produce a wealth of biomechanical information. As a result, sEMG and MMG may complement each other well when assessing spasticity. The suggested method therefore has the potential to be used for precise and thorough classification of individuals with various degrees of spasm, allowing for reliable assessment of medication efficacy. In addition to employing an accelerometer as a transducer of MMG, Pan et al., 2020 measured muscular spasticity using an EMG and a piezoelectric sensor. The precise collection of dynamic data indicative of the patient's desired movements is made possible by the PVDF piezoelectric properties of the MMG sensors.

4.4 Variability and Potential of MMG Sensor

Variability and potential inconsistencies in MMG findings across studies was not the same due to several factors. Differences in study design, such as MMG transducer types, participant characteristics, muscle group that been examined, and experimental protocols, may lead to variations in MMG outcomes. Specialized transducers like accelerometers, piezoelectric contact sensors, and laser distance sensors enhance MMG's dependability and durability when evaluating the mechanical activity of contracting muscles. Accelerometers are the preferred choice for detecting MMG signals during both voluntary and stimulated muscle contractions due to their advantages in terms of easy setup, lightweight design, and reliable signal acquisition. This makes accelerometers the best option among other sensors and leads to improved outcomes. MMG signals might vary significantly depending on the particular muscle group being studied. In addition, differences in muscle size, composition, and function can affect the mechanical properties related to muscle contraction and relaxation. As a result, the results obtained from research that focuses on different muscle groups may not be easily compared. Methodological variances, encompassing disparities in MMG equipment, electrode placement, signal processing techniques, and data analysis methods, further contribute to variability in findings. Additionally, the heterogeneity of outcome measures derived from MMG signals, along with variations in sample size and statistical power across studies, can yield inconclusive or conflicting results. Publication bias, wherein studies reporting positive or significant findings are more likely to be published, and reporting and interpretation bias, can also impact the consistency of MMG findings. To tackle these challenges, standardizing protocols for MMG data collection, conducting multi-center studies or meta-analyses, performing sensitivity analyses, and transparently reporting methods and results are crucial steps to enhance the reliability and comparability of MMG research across studies.

4.5 Challenges and Consideration in MMG Signal Interpretation

MMG technology provides several benefits for muscle function and spasticity assessment, but it also has limitations that need further study. Lower spatial resolution than EMG or ultrasonography is a key drawback. This limitation makes muscular activity difficult to pinpoint, especially in deeper muscle layers or complex muscle groupings. Movement artefacts, skin impedance changes, and mechanical noise can also degrade MMG signal quality and interpretation. Signal shape and amplitude vary across persons, muscle groups, and measurement settings, making it difficult to standardise data gathering and processing techniques, restricting study comparability. MMG offers promise for detecting muscular stiffness and function, but its clinical validity and reproducibility compared to EMG or clinical assessments need to be confirmed. Its clinical usage is limited by the lack of protocols and normative data. Improvements in sensor technology play a crucial role in refining the precision and dependability of MMG measurements, especially in evaluating muscle spasticity. Future sensor designs should prioritize several key areas of enhancement.

Firstly, boosting sensitivity is vital to detect even the slightest changes in muscle activity, particularly in individuals with mild or moderate spasticity. Enhanced sensitivity enables the detection of minor muscle contractions, offering more nuanced insights into muscle function. Additionally, reducing noise interference and optimizing the signal-to-noise ratio are critical. Progress in noise reduction can help mitigate artifacts caused by external factors such as movement artifacts, variations in skin impedance, and environmental noise, resulting in cleaner and more trustworthy MMG signals. Furthermore, miniaturization and portability are essential for facilitating ambulatory monitoring and real-time assessment of muscle spasticity across various settings. Compact sensor designs enable seamless integration into wearable devices, ensuring continuous monitoring without hindering mobility or comfort. Multi-channel MMG sensor arrays present another avenue for improvement, providing spatial information about muscle activity across different muscle groups or regions. This capability enables more comprehensive assessments and targeted analyses of muscle function. Additionally, the development of flexible and stretchable sensor materials allows for optimal sensor-skin contact and accommodates changes in muscle geometry during movement, reducing motion artifacts and enhancing data accuracy.

Integrating wireless data transmission capabilities into MMG sensors facilitates real-time connectivity with external devices, enabling remote data monitoring, analysis, and storage without cumbersome cables. Finally, ensuring long-term stability and durability of MMG sensors is essential for consistent performance over extended periods. Biocompatible materials resistant to degradation ensure reliability during daily activities and rehabilitation exercises. By addressing these advancements in sensor technology, researchers can significantly improve the utility and effectiveness of MMG sensors in assessing muscle spasticity, ultimately enhancing care for individuals with neurological and musculoskeletal conditions.

4.6 Limitation

The present narrative-analysis experienced difficulties in clearly identifying risk factors linked to severe or disabling spasticity due to a small number of studies and a wide range of assessment approaches. The practicality of doing a meta-analysis especially concentrating on stroke sites was hampered by the lack of appropriate data. Similarly, the execution of meta-regression analysis to examine the significant heterogeneity identified was hampered by the paucity of relevant literature. As a result, it was unable to estimate the likelihood of publication bias by a thorough risk analysis. Furthermore, this analysis was unable to determine the prevalence of incapacitating spasticity longer than a year after a stroke because to the lack of long-term follow-up research. It is important to emphasize that these limitations highlight the necessity for upcoming studies to tackle these gaps in the existing literature and offer more substantial evidence for comprehending and handling severe spasticity in stroke patients.

4.7 Potential Future Research

MMG technology offers exciting opportunities to improve muscular spasticity evaluation clinical practice and research. Developing modern MMG sensors with enhanced sensitivity, accuracy, and downsizing is the top priority for more accurate and practical muscle activity monitoring. These sensors can be easily integrated with wearable technologies to assess spasticity in natural settings. MMG can be integrated with other diagnostic modalities as functional MRI, EMG, and ultrasound imaging. This integration may assist identify spasticity causes and generate individualised treatment approaches by evaluating muscle function more thoroughly. Longitudinal studies are needed to track spasticity changes, therapy outcomes, and neurological traumas like strokes. These studies may explain spasticity's typical course and identify factors that impact it. Clinical trials and validation studies are needed to prove MMG-based evaluations' efficacy in monitoring therapy outcomes and guiding treatment choices. Finally, exploring MMG's usage in biomechanical analysis, sports performance tracking, and prosthetic limb control may improve its efficacy and stimulate advances in related fields. By studying these areas, scientists and clinicians can better understand muscle spasticity and develop better management and rehabilitation methods for a variety of patient populations.

5.0 CONCLUSION

In conclusion, our in-depth analysis highlights the potential use of mechanomyography (MMG) as a reliable method for determining muscle spasticity. The results offer strong evidence in favour of using MMG to assess spasticity in a variety of muscle groups. This review also emphasises the significance of MMG as an effective assessment tool for assessing muscular spasticity. In order to further comprehend MMG's potential as an assessment tool for muscle spasticity, additional research is necessary to study its application in comparison studies between healthy people and people with neurological diseases.

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