

Research Article

A Wearable EMG Sensor for Continuous Wrist Neuromuscular Activity Monitoring

Lalita Chilmakuri¹, Ayush Kumar Mishra², Divyansh Shokeen³, Paakhi Gupta⁴, Harmankaur Harjeetsingh Wadhwa⁵, Karan Dhingra⁶, Saloni Verma⁷

¹Independent Researcher, Telangana, India

²Independent Researcher, Odisha, India

³Independent Researcher, Delhi, India

⁴Independent Researcher, Punjab, India

⁵University of Cincinnati, Ohio, United States of America

⁶Department of Biomedical Engineering, University of Ottawa, Ontario, Canada

⁷Department of Biomedical Engineering, Cornell University, New York, United States of America

Abstract

Carpal Tunnel Syndrome (CTS) is an entrapment neuropathy that affects 3-6% of the adult population globally. About 90% of nerve-damaging diseases are labeled CTS when diagnosed, making it one of the most prominent nerve dysfunctions in the current population metrics. CTS cases have soared in a world where digital gadgets are progressively gaining traction. There is also a high onset of CTS in laborers specializing in fine motor skills. A patient with CTS typically entails symptoms of pain, numbness, and tingling in the wrist. However, accurate diagnosis and consistent checkups for CTS are becoming a bigger issue. In this research paper, we demonstrate the utilization of various diagnostic tests in supporting CTS diagnosis and the necessity for a monitoring system to track wrist neuromuscular activity. By analyzing traditional assessment techniques and identifying their limitations, we can enhance diagnosis, making it easier for patients to deal with the condition. This approach has culminated in the development of our prototype, BracEMG. Through a wearable EMG sensor, our prototype aims to track possible signs of CTS or other nerve dysfunctions at the wrist. The findings gained through an EMG test support our research by outlining the prevalence of CTS across different age groups and illustrating the levels of muscular activity in a graphical format. Our results demonstrate overall muscle activity at the wrist. Since no universally accepted standard for diagnosing CTS exists, we envision our work as the starting point for more extensive research. The limitations of our prototype can become the foundation for future developments in the industry revolving around CTS.

Keywords

Biosensors, Biowearables, Medical Devices, Neuromuscular, Carpal Tunnel Syndrome, Electromyography

*Corresponding author: Divyansh Shokeen

Email addresses:

chilmaxelle@gmail.com (Lalita Chilmakuri), ayushmishra5589@gmail.com (Ayush Kumar Mishra), divyanshudaiveershokeen123@gmail.com (Divyansh Shokeen), paakhigupta012@gmail.com (Paakhi Gupta), harmankaurw@gmail.com (Harmankaur Harjeetsingh Wadhwa), k2dhingra@gmail.com (Karan Dhingra), sv458@cornell.edu (Saloni Verma)

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1. Introduction

An estimate of up to 500,000 cases of carpal tunnel syndrome (CTS) are reported each year in the United States, resulting in over \$2 billion in healthcare costs [1]. In addition to this, we have come to recognize the fact that globally, there is a positive correlation forming between the growing use of technology and the number of CTS cases per year [2]. CTS includes a variety of modalities for measuring nerve function and detecting median nerve compression in the wrist [3]. These methods include nerve conduction studies and muscle response to nerve stimulation electromyography (EMG) [4]. Ultrasound and magnetic resonance imaging (MRI) modalities provide extensive anatomical information about the wrist and its surrounding structures, which can help with differential diagnosis and therapy planning. These instruments have improved dramatically in recent years, owing to developments in medical imaging technology and neurophysiological testing techniques. They aim to correctly measure the severity of nerve compression and help choose the best course of treatment. Furthermore, substantial research has been conducted on the impact of ergonomic interventions and workplace improvements on CTS risk reduction, emphasizing the need for early detection and proactive management measures.

Among all diagnosis tests, the electrodiagnostic tests (EDX), including Nerve Conduction Studies (NCS) and EMG, are considered a reliable method. Although EDX has its respective pitfalls in diagnosing CTS, it plays a significant role in confirming the diagnosis by eliminating other pathologies [5]. EDX acts as a measure to determine the severity of CTS, making it the current gold standard [6]. It is instrumental in pinpointing nerve root involvement and determining the specific nerves affected in cases of CTS. It also identifies functional irregularities in the nerve roots without the need for invasive procedures [7]. One such non-invasive method is surface EMG.

We are using Surface EMG to study the muscle action potential of individuals within a selected sample of

individuals. This non-invasive electromyography tracks neuromuscular activity using liquid gel electrodes connected to a wearable EMG sensor that is directly attached using electrode cables to a microcontroller board and monitored using an IDE (Integrated Development Environment) which enables the analysis of neuromuscular activity. Through these results, designing a prototype will be made much easier. Our prototype, BracEMG, uses surface EMG to record neurophysiological data. The BracEMG combines two different functionalities into one - It primarily works as a monitoring system that can be used by neurophysiologists or doctors to keep track of patient data and additionally provides relief to the wrist by acting as a common wrist brace. This prototype is a form of non-invasive monitoring method for patients with mild CTS thereby reducing the annual costs of surgeries.

2. Methods

2.1. Pathophysiology of CTS

2.1.1. Mechanism Of Median Nerve Compression

When the median nerve becomes trapped in the carpal tunnel between the transverse carpal ligament and the carpal bones, it becomes compressed. This compression can result in many symptoms, including numbness, tingling, and pain in the hand, particularly in the thumb, index, and middle fingers [8][9]. Excessive bending of the wrist or movement during certain activities can raise fluid pressure and damage the median nerve. This can occur in a variety of ways, such as when the blood vessel-nerve barrier in the carpal tunnel breaks down, thickening the blood vessels due to fibrosis, or when the small blood vessels malfunction, causing swelling inside the nerve. There may be compression if there is obstruction of carpal tunnel by a wrist injury. A lot of the things are based on pressure on the wrist or the carpal tunnel which is measured

*Corresponding author: Divyansh Shokeen

Email addresses:

chilmaxelle@gmail.com (Lalita Chilmakuri), ayushmishra5589@gmail.com (Ayush Kumar Mishra), divyanshudaiveershokeen123@gmail.com (Divyansh Shokeen), paakhigupta012@gmail.com (Paakhi Gupta), harmankaurw@gmail.com (Harmankaur Harjeetsingh Wadhwa), k2dhingr@gmail.com (Karan Dhingra), sv458@cornell.edu (Saloni Verma)

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in mmHg (millimeters of mercury). Normal pressure in the carpal tunnel has been recorded to range from 2 to 10 mmHg. In the normal wrist posture, the average pressure that is registered in our carpal tunnel is 32mmHg but when the wrist is flexed, the pressure reaches 94mmHg [10]. Using a wrist splint at night while in a neutral position can relieve pressure in areas like the carpal tunnel where median neuropathy could

occur. Alternatively, the compression of the median nerve can be relieved through the enlargement of the tunnel by expansion of space. Taking regular breaks, and making ergonomic adjustments can help reduce pressure on the median nerve. Pathophysiology is the decompression of the median nerve at the carpal tunnel level.

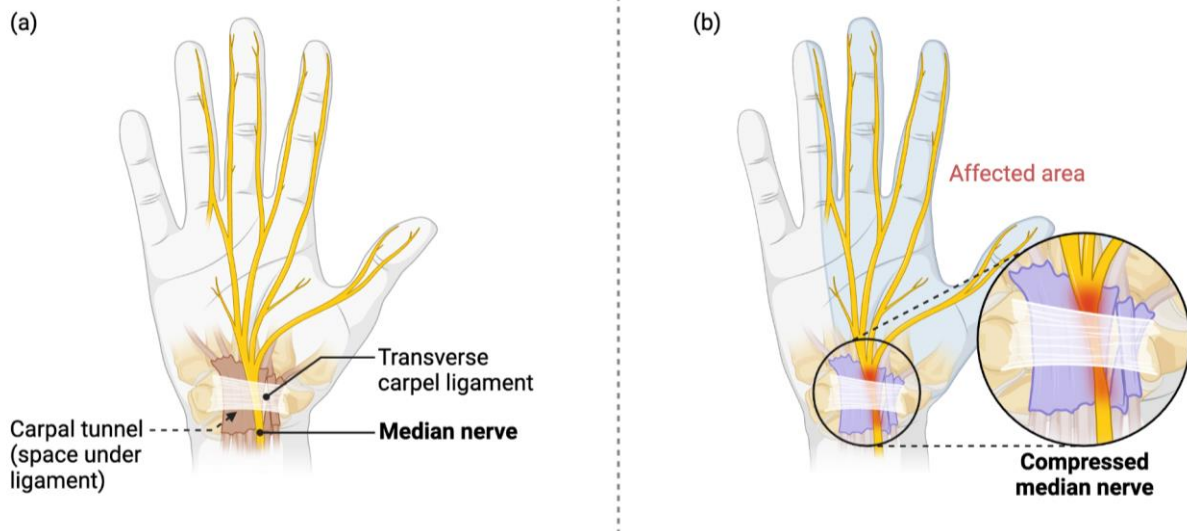


Figure 1. (a) Normal carpal tunnel. (b) Carpal tunnel syndrome. Created with BioRender.com.

Many things can cause median nerve entrapment. The two vital compression areas are at the tunnel's outer area under the flexor retinaculum roof, and the hamulus of hamate. When the carpal tunnel experiences high pressure, compression can occur, often due to the synovial tissue around the tendons in the forearm becoming enlarged. This enlargement is usually caused by overuse, wrist injuries, or conditions like arthritis that trigger inflammation.

When young patients below the age of 20 years experience a high-energy trauma or elderly patients over the age of 50 years experience a low-energy trauma, it can cause the lunate bone to shift into the carpal tunnel, leading to a blockage [11]. This can happen from falling on an outstretched hand or a car accident. While not very common, this displacement can trap the median nerve. Studying the causes of the well-known and easily noticeable CTS pathophysiology is extremely important. However, talking about the less obvious night pains that can worsen CTS symptoms is equally crucial. A lot of people experience more pain at night when they are not active. This happens for a couple of reasons. When individuals lie down on their backs, fluid in their limbs gets redistributed, which puts more pressure on the affected area. Additionally, the lack of interstitial drainage in this area is caused by the absence of muscle pump and movement. This further adds to the increased pressure due to the lack of clearance. It is

common for individuals to flex their wrists during the night, and this prolonged flexion puts even more pressure on the tunnel roof, pressing against the median nerve [12].

2.2. Electrodiagnostic Evaluation and Grading of CTS

CTS is the most common factor, prompting a referral to EDX [13]. CTS patients commonly observe Subjective Symptoms such as tingling, numbness, pain, etc., however, oftentimes these lack support from objective findings. EDX studies such as NCS and EMG are consistent, valid, and reliable sources of solidifying the diagnosis of CTS. These EDX studies help to provide evidence and a means to confirm the diagnosis suggested through subjective observations [14]. While EDX tests are not viable for gross or generalized problems such as diffused muscle pain or fatigue, they can provide more detailed and accurate solutions to more specific questions [15]. Hence, EDX studies complement the clinical grading in the assessment of the severity of CTS with the help of useful parameters such as amplitudes. Amplitudes, conduction velocities and nerve action potential depict the functionality of axons [16]. Nerve Conduction Study is a tool used for testing sensory and motor fibers of certain nerves. It tests the distal nerve and late responses, H-reflexes, and F-

wave latencies, providing more information about the proximal segment [17].

In Motor NCS, a nerve is stimulated at two or more points on its path with supramaximal stimulation which ensures that all axons are activated. The placement of the electrode is in two places: (1) Active electrode: placed at the nerve belly. (2) Reference electrode: placed distal to the active electrode. A waveform, namely Compound Muscle Action Potential (CMAP) is recorded as a response. Parameters such as latency, amplitude, and Motor conduction velocity (CV) are measured [18]. In sensory NCS, electrodes are placed over a sensory or mixed nerve. The stimulation can be either antidromic or orthodromic. To measure nerve conduction delay and antidromic sensory potentials an electrode is placed near the base of the ring finger and the median nerve is stimulated 13 cm proximal to the recording electrode. Hence, the CV from elbow to wrist is measured using surface electrodes [19], [20].

2.2.1. Sensitivity and Specificity

The utility of NCS as a tool for diagnosing CTS has always been debatable. It is important to look at its sensitivity and specificity to facilitate this discussion on the utility of NCS and potential as a gold standard. Multiple factors affect the sensitivity and specificity of a diagnostic test: (1) In a population where a condition or disease is widespread, the sensitivity and specificity of the test could be falsely elevated, giving an inaccurate description of its accuracy. (2) Reference Standard got NCS is also a key factor in determining the sensitivity and specificity. A restrictive definition such as entropy of the thenar eminence atrophy will lead to decreased sensitivity while a broader definition like hand pain or hand numbness will elevate the sensitivity. (3) Threshold values of Distal Sensory Latency (DSL) and Distal Motor Latency (DML) also impact the sensitivity and specificity of the test. Lower cut-off values of DSL and DML can increase sensitivity while Higher cut-off values of DSL and DML can increase specificity. In many studies, tools like Receiver Operating Characteristic (ROC) curves are used to optimize and balance the sensitivity and specificity of a diagnostic test [21]. As stated by Masahiro Sonoo in his review, 'NCS has a sufficiently good sensitivity/specificity of NCS adopted in his study, 69%/97% or 92%/63%' [22],[23],[24].

2.2.2. Challenges in NCS

Proper techniques, recognition of pitfalls, and correction of these issues that may arise during this process are important for NCS. Common potential errors while conducting NCS include electrode placement, distance measurement, stimulation site, cathode-anode orientation, stimulus intensity, and filter setting - These errors must be identified and rectified in real time as these errors are not usually recognizable after

the collection of data analysis [25]. Additionally, The latency of conduction velocity could be delayed due to lower temperature. Therefore, skin temperature should always be $\geq 32^{\circ}\text{C}$ [26],[27]. Another potential pitfall in the process is false positive/ false negatives. To minimize false diagnosis of CTS, conducting a minimum of two comparative tests with relatively prolonged median nerve latencies is important. Sometimes asymptomatic cases in workers, diabetics, or people with demyelinating neuropathies. In these cases, CTS should be named 'median neuropathy at the wrist' instead [28]. To validate the results, it is crucial to consider both physiological and technical factors. Moreover, abnormalities are only discernible by observing the relative differences in latencies [29]. It is important to comprehend these limitations as it will significantly aid our understanding of the diagnostic process and its inner workings. This will help us conduct better research.

2.2.3. NCS versus EMG

EMG is the study of muscles through electric signals. The muscles that make up the body have a certain electric potential i.e. the work required to transfer an electric charge from one point to another point on an electric field hence the alternative name - muscle action potential [30] [31]. The application of electrodes in understanding muscle action potential divides EMG into 2 types.

EMG can be distinctly categorized into 2 - surface EMG & needle EMG. While Surface EMG is a non-invasive means of conducting neuromuscular studies by placing electrodes over the surface, the needle EMG entails the use of needle electrodes inserted through the skin and into the muscle to record the electrical impulses occurring within the muscle as it relaxes and contracts [32]. Needle EMG is used while directing NCS to identify and understand neuropathy within the muscles. Thus, it is an intramuscular means of gathering the required data pre-diagnosis. Surface EMG, on the contrary, involves the use of gel electrodes that are placed on the skin where neuromuscular activity is being monitored.

2.2.4. CTS Grading

The neurophysiological scale on which the grading of CTS takes place, is designed to provide clarity and treatment strategies to doctors and patients alike. Oftentimes, deciding the severity of CTS is a struggle due to the methods of diagnosis; these diagnostic methods include clinical and EDX. Despite being labeled as a collection of symptoms & signs, CTS remains an enigma with an unidentified cause. It generally exists alongside an asymptomatic median nerve dysfunction at the wrist (MNW) where it passes through the carpal tunnel. [33]. While diagnosing CTS clinically,

electrodiagnostic testing merely acts as a supportive measure. The objective of EDX is, most importantly, to “confirm a clinical impression for carpal tunnel syndrome” [34]. It is often debated as to whether EDX is a necessary measure if CTS has been confirmed through clinical means. Additionally, a substantial number of patients with malignant clinical symptoms but little to no abnormalities gathered from electrodiagnostic testing and the utter contrast which is seen in other patients where the presence of extreme neuropathy was identified through EDX but no symptoms were identified, is proof of how EDX can complicate grading, even as it exists as a supportive measure. However, EDX still exists to aid a neurophysiologist in developing a prognosis by taking a part in deciding the severity as it remains the gold standard for the diagnosis of carpal tunnel syndrome [35].

CTS is graded using a myriad of grading systems. Deciding the neurophysiological severity is crucial for a disease that remains a mystery in the world of science. A proper scale must be established with properly calibrated gradations that indicate how mild/moderate/severe a case might be. These gradations are merely a means to decide future outlook and are created to convey the severity in adequate increments. A grade of 1 to 6 is most suitable. A popular grading scheme developed by Bland shows how Grade 1 represents the mildest level of neuropathy and Grade 6 depicts the worst on the neurophysiological scale. A grade of 1 or 2 indicates proper splinting of the hand and possible local corticosteroid injections initially. This is followed by Grade 3 patients who are given a choice of either medical or surgical treatment strategies. A Grade of 4, 5, or 6 suggests the need for immediate surgery, and as the severity increases the prospects of complete recovery decrease. Much like the scale made by Bland in the UK, Stevens from the US shows a scale that conveys the same through non-standard measurements i.e. the scale labels the same grading system in different terms - mild, moderate, and severe [36].

A closely-related review article published by ScienceDirect, ‘Nerve conduction studies and EMG in carpal tunnel syndrome: Do they add value?’ presents their treatment strategies based on a completely different neurophysiological scale. In summary of their ‘Suggested Management Principles’, a table indicates the CTS severity of EDX findings and possible intervention; a case of CTS without MNW shows no electrodiagnostic findings and can be treated through symptomatic treatment. A mild case shows abnormalities in sensory nerve conduction studies (sensory NCS) and is also treated through symptomatic treatment. Their grading scheme showed prolonged distal motor latency to the APB (abductor pollicis brevis) with normal amplitude. Like grade 3 on Bland’s scale, this requires injections or ‘surgery with progression’. Severe CTS shows findings of moderate grading

along with ‘either reduced median to APB CMAP amplitude and/or abnormal needle EMG in the thenar muscles’. It can be treated through surgery but is usually contraindicated [37].

2.3. Electrodiagnostic Accuracy for CTS Diagnosis

2.3.1. Combined Sensory Index

When compared to single NCS, the combined sensory index (CSI) has been shown previously to have superior sensitivity and specificity for diagnosing carpal tunnel syndrome (CTS). The CSI involves summing the latency differences of three comparison tests, with a CSI score of ≥ 1.0 considered abnormal, demonstrating a sensitivity of 83% and a specificity of 95% [38]. This index has the highest test-retest reliability when compared with ring-diff, thumb-diff, and palm-diff. Therefore, scientists propose the use of the CSI as not only an accurate but also a reliable method for diagnosing carpal tunnel syndrome. CTS can be a tricky diagnosis due to its overlapping symptoms with other conditions [39]. The symptoms of CTS mimic various conditions. Other nerve compression syndromes that compress other nerves in the hand or wrist, like pronator teres syndrome or radial tunnel syndrome, can mimic CTS symptoms [40]. Additionally, CTS mimics C6 radiculopathy. A patient with C6 radiculopathy usually feels pain or numbness from the neck to the radial side of the biceps, forearm, the dorsal web space of the hand between the thumb and index finger, and to the tips of those fingers and a patient with CTS feels the same tingling and numbness but in palm, thumb, or first two fingers [41] [42]. Common conditions such as Repetitive Strain Injury (RSI), Thyroid, Arthritis, and Diabetes are often misdiagnosed as CTS, and vice versa. RSIs can cause pain and inflammation in the hand and wrist, similar to CTS [43]. However, the pain from RSI is usually more localized and worsens with activity. Diabetes can cause neuropathy (nerve damage) that can manifest with symptoms similar to CTS. Diabetes can cause carpal tunnel syndrome [44] [45].

2.3.2. Tracking and Trending

EMG is a vital tool in the diagnosing and monitoring of CTS. Serial EMG tests, conducted over time, can help track the progression of CTS. It's usually used in conjunction with a physical examination and other tests like NCS [46]. While needle EMG isn't always mandatory for diagnosing CTS, according to the American Academy of Neuromuscular and Electrodiagnostic Medicine (AANEM), it can be a helpful tool in confirming distal conduction block and Axonal loss [47].

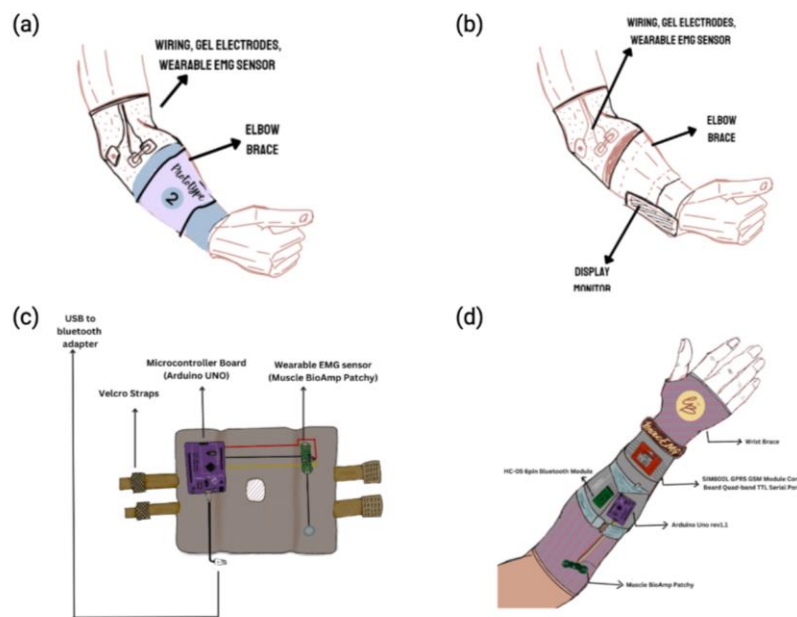


Figure 2. (a) Initial placement of EMG brace on body. (b) Optimized EMG brace with reduced hardware. (c) Electrical connectivity. (d) Final prototype design of EMG brace..

2.4. Wearable EMG Monitoring System

2.4.1. Prototype Design

The Prototype is a modified elbow brace with a system for EMG monitoring wirelessly. It utilizes a wearable EMG sensor. The monitoring of muscle activity using the system enables the diagnosis of neuromuscular disorders, including muscle dystrophy or paralysis. This system can be during exercise or other activities to improve performance and prevent injuries Figure 2 depicts the progression of our prototype from Figure 2a to 2d. Figure 2a had bulky components like the display monitor adding significant mass and discomfort, hence it was removed in the current design. Figure 2b depicts a refined prototype design where the monitor was eliminated, and the wrist brace features Velcro straps for convenience. To resolve the issue of protruding wires, we switched the USB connection with a USB-to-Bluetooth adapter, as shown in Figure 2c. Figure 2d depicts our latest model, it establishes several enhancements to improve functionality : (1) The addition of an HC-05 module facilitates Bluetooth connectivity, and a SIM-GSM module

that allows transmission of alerts and data directly to the patient's phone via SMS; (2) Snap buttons, along with Velcro straps, have been integrated to enhance user convenience.

2.5. Experimental Setup

For this research, we used an Arduino Uno, gel electrodes, skin-prep gel that exfoliates the dead skin and removes dirt, thereby the Muscle BioAmp Patchy (further elaborated in the next section), alcohol swabs, and Arduino IDE, a software application to develop code to view results (table 1). To begin the setup, using the skin preparatory gel and either the alcohol swab or wipes, the area of the forearm over the ulnar nerve must be cleansed neatly. This enhances the contact between the electrodes and the skin to optimize recording measurements when applied. After applying gel electrodes over the skin and securing the BioAmp Patchy to the electrodes, connect the Muscle BioAmp Patchy to the Arduino Uno via jumper cables as shown: OUT to A0, GND to GND, VCC to 5V and connect the Arduino Uno using a USB to display results on the laptop to be interpreted.

Component or Material	Description	Purpose
Wrist Brace/Elbow Brace	Acts as the base of the prototype.	Provide support, comfort, and aid to the pain.

Velcro Straps and snap buttons	Allows individual adjustments, increasing comfort and functionality.	To provide a secure structure to the prototype.
Arduino Uno	Serves as the microcontroller for the prototype.	Processing electrical signals.
BioAmp Patchy	A surface-mount, biopotential signal acquisition board.	To monitor electrical signals.
HC-05 Bluetooth module	A serial Bluetooth converter.	Enables the prototype to send statistics wirelessly.
Sim GSM Module	Enables GSM (Global System for Mobile Communications) network connectivity.	Allows the prototype to send stats and warnings to the patient's phone via SMS.
Ultrasound gel	Acts as a replacement for gel electrodes.	Reduces cost and increases the comfort of use.

Figure 2. Materials and components used in the prototype design.

The Muscle BioAmp Patchy is a wearable muscle sensor designed to record muscle's electrical activity. It is a small-scale version of the EMG which is taken to understand muscle action potential. The sensor is single-channeled, meaning it records electric signals from one muscle at a time, therefore, it is a form of serial EMG. Unlike a Muscle BioAmp Biscute, the patch is directly secured to the skin through the use of disposable gel electrodes thereby skipping the process of adding electrode cables which connect the Biscute to the skin. Using this wearable EMG,

The information gathered on this particular sensor was gathered from the UpsideDown Labs website. The BioAmp patchy is a cost-effective & user-friendly sensor (suitable for students & researchers alike) and has been designed by UpsideDown Labs as a more direct & efficient means of attaching the sensor to gel electrodes, eliminating the necessity of cables and enabling quicker set-up while conducting tests involving it. It delivers high-quality EMG signals for consistent results which overall helps the quality of research being conducted. It allows users to customize hardware & software to a certain extent. However, it has a restricted set of customization options when compared to a professional EMG sensor and is limited to measuring the signals of a single muscle at a time. The 4.5V minimum input voltage is not always compatible with all devices and the sensor can't always tell the difference between signals from nearby muscles or muscle groups that influence each other making it hard for the device to accurately identify the muscles that are affected. During extensive use, the Muscle BioAmp Patchy can cause skin irritation or soreness caused

by the gel and electrodes that are required along with this type of EMG sensor. It is also possible for some people to have an allergic reaction to the materials used. It is important to include this section within our research to inform said individual of the requirements, and the advantages & disadvantages before testing.

3. Results

The baud rate for data transmission is set to 115200 baud. Active Signal: "Value 1" shows an active and periodic signal, which could represent some form of biological or mechanical activity being monitored. Inactive Signal: "Value 2" does not show any activity, implying either a lack of signal or a possible issue with the measurement for this value. The graph shown in Figure 3 (a) shows an age range from 0 to 10 years, during which the wrist is still developing and CTS is not common among individuals in this age group. The age range depicted in the Figure 3 (b) provided is 10 to 20 years old. CTS is prevalent within this age group due to the increased use of technology by teenagers, often involving repetitive wrist movements. Figure 3 (c) shows that individuals between the ages of 20 and 30 have a higher prevalence of CTS, likely because a large number of people working in the IT industry or other technology-related occupations are in this age group. Figure 3 (d) shows data for individuals aged between 30 and 40 years old, which represents the working age group. Many people in this age

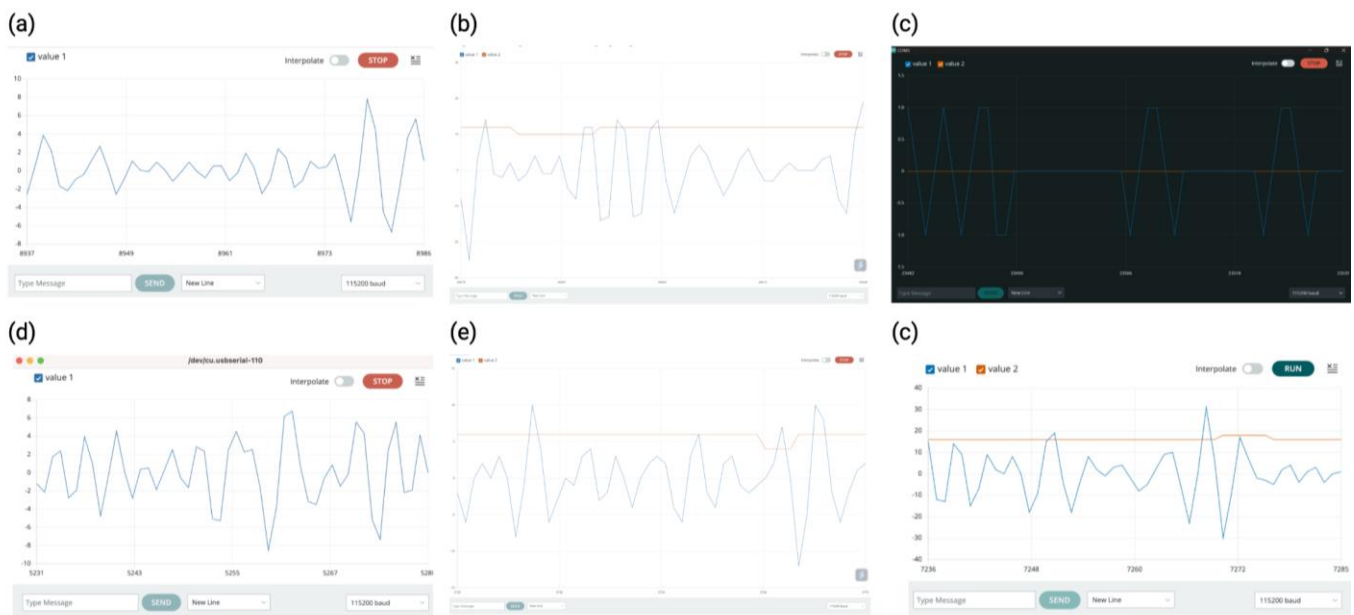


Figure 3. (a) Age group below 10 years. On average, the amplitude goes up to 1.5 and -1.5, "Value 1" exhibits a periodic waveform, oscillating between positive and negative values, while "Value 2" does not change. (b) Age group 10-20 years. The amplitude typically increases from 3.1 to -3.3 on average. The reading remains relatively stable for the majority of the time and occasionally exhibits a consistent pattern. When the muscles are relaxed, the reading remains constant, but during movement, it experiences sudden drops or rises towards either axis. This abrupt increase in amplitude is caused by the continuous movement of the hand, resulting in a high frequency and greater amplitude compared to other age groups. (c) Age group 20-30 years. "Value 1" displays a periodic waveform that oscillates between positive and negative values, while "Value 2" remains constant. The amplitude increases on average to 1.5 and -1.5. "Value 1" displays a periodic, active signal that might be a biological or mechanical activity under observation. "Value 2" displays no activity, suggesting that there may be a problem with the measurement of this value or that there is not enough signal. The "value 1" oscillations imply a recurring pattern that might be a hint of a periodic signal. (d) Age group 30-40 years. The amplitude usually ranges from 4.65 to -5.6 on average. At the end of the x-axis, there is a sudden fall-off. Muscles are always active with no periods of rest that may be prolonged as though in motion. The frequency is about 6-10 Hz and the wavelength is relatively short. (e) Age group 40-50 years. The average amplitude typically falls within the range of 4.7 to -4.6, with the second value remaining relatively stable aside from minor fluctuations. It is worth mentioning that the frequency of occurrence is notably high. (f) Age group 50 years and older. The amplitude typically increases from 5.7 to -6.6 on average. This observation is highly unusual since it is uncommon for individuals in this age group to excessively strain their wrists. Even when the arm is at rest, the muscle movement does not decrease significantly. This indicates a greater amplitude, suggesting a higher overall frequency and wavelength.

range are actively working in their professional careers. Figure 3 (e) shows that individuals between the ages of 40 and 50 are most affected by CTS due to nerve demyelination, which is the deterioration of the protective covering around nerve fibers. This is often linked to the aging process. CTS is frequently observed in individuals within this particular age bracket, displaying high amplitude readings. The age group for Figure 3 (f) is above 50 years. CTS is not very prevalent in this age group as older individuals generally have a lot of wrist movement they want to do. However, this reading was unfavorable when considered because it shows quite the opposite - the possibility of neuropathy indicated by the graph is much higher than assumed.

In the process of gathering our results, we have decided to consider participants of ages ranging from 10 to 80 years. This age bracket was chosen because individuals under the age of 10 years are said to have developing wrist which may affect

the readings we obtain by creating fluctuations in the patterns. This could impact the results. Additionally, the 50 years and above age group was hypothesized to have lower muscle activity compared to other age groups, as this range exhibits comparatively low strain on the wrist. However, according to the results obtained, even this age range suggested more muscle action potential of the wrist leading to unforeseeable outcomes. According to the results we observed, there were inconsistent signal patterns both during rest and at an active stage. This led to our presumption that CTS may be prevalent in this age group challenging our prediction. Following this, we expected CTS to be most occurring from ages 20-50, but this was challenged by the results. Less favorable outcomes were seen in this category taking into consideration factors that CTS may be linked to, namely lifestyle factors such as profession, age, duration of manual labor in particular, and medical factors including presence of neurological deficits, or

alternative neurological disorders, results obtained from a Phalen test, and lastly the duration of symptoms relating to CTS. The diagnosis and monitoring of CTS heavily relies on the raw EMG data, signal processing techniques, and extracted parameters [48]. However, it is important to note that the diagnostic accuracy and outcomes of EMG testing have certain limitations. The initial EMG signal necessitates processing to eliminate interference and improve the signal-to-noise ratio. This may involve employing methods like filtering, amplification, and rectification. The unrefined EMG signal captured from the muscles represents a variance in electrical potential or voltage difference. This signal is frequently marred by interference, including electrical disturbances, muscle irregularities, and motion irregularities. The oscillating pattern that Value 1 displays, fluctuating between positive and negative values, points to a periodic active signal that might be associated with biological or mechanical activity. Yet, Value 2 remains unchanged, mostly, suggesting a potential issue with tracking this particular number or a signal failure. The measurements mostly remain constant, though they do occasionally show a consistent pattern. The measurements stabilize when the muscles are relaxed. The rapid shift in wave size, however, indicates continuous hand movement when there is movement. Individuals in the 30 to 40 age range typically lack any visible pattern and are inherently unpredictable. Their muscle activity shows continuous activation, indicating that they are not resting. High amplitude values are a defining characteristic of Carpal Tunnel Syndrome, a relatively common condition in the 40–50 age range. With only a small deviation before returning to its consistent state, Value 2 is generally stable.

3. Discussions

Searching for methods of diagnosis and implementing tracking systems for individuals with neuropathy plays a significant role in our research. It includes probing into the details of the use of non-invasive tools for monitoring neurophysiological data; warning individuals in the circumstance where severe abnormalities occur while also assisting physicians in implementing a prognosis; and establishing a properly calibrated scale to determine how mild/moderate/severe the case is, neurophysiologically. Our final objective is 1. to interpret low, high, and moderate threshold activities of the wrist at different postures and 2. to develop a prototype for treatment by evaluating existing treatments and diagnostic guidelines. Our research primarily led to reviewing the pathophysiology of CTS in which the median nerve is compressed within the carpal tunnel. It elaborates on where CTS occurs and explains the anatomy of the carpal tunnel. It is critical to be informed of this as CTS has a major role in affecting everyday activities, especially

activities that are hand-held such as gardening, cooking, knitting... This led to us delving deeper, where we discovered that CTS in simple words is nothing but a collection of symptoms causing numbness and/or tingling pain in the fingers and wrist. These symptoms are evidence of the median nerve which is compressed within the carpal tunnel causing the neuropathy alongside CTS.

After our initial research process, we realized that there is a need for proper evaluation of the guidelines, criteria, and treatment strategies for CTS. This moved us to analyze already existing gold-standard tests such as EDX and NCS, followed by assessing grading schemes and neurophysiological scales suggested by another research article [49]. The CSI was taken into consideration when considering the sensitivity and specificity of EDX and pitfalls were accounted for. A proper examination of EMG led us to combine the insight we gained so far to create our first design for a working prototype that assesses EMG thereby tracking neuromuscular activity. A prior study with healthy participants using a Surface EMG kit provided by UpsideDown Labs discussed outcomes gained when age group, gender, and motion of the wrist were considered. After setting up the experiment, we tested it on a randomized sample with no obvious presence of CTS. To summarize, from the results obtained some were favorable & some unfavorable. Particularly, the 70-80 age group showcased an unfavorable result, as predicted before the experiment. While designing the prototype, we encountered some limitations.

3.1.1. Hardware Limitations

Weight is a very important factor in any wearable technology. It plays a more significant role in this particular prototype as more weight would apply more pressure which could hurt people with muscle neuropathy. With so many different components in the prototype, the initial challenge was to find a way to equally distribute the weight hence, making the device lighter. We eventually decided on eliminating the monitor which was the bulk of the weight. Instead of the monitor, the prototype now has a Bluetooth model where the readings can be directly seen on the 'Arduino IDE application. Furthermore, the issue of rigid components in the prototype persists. As a few components viz. Muscle BioAmp Patchy and the Arduino Uno (Microcontroller Board) are not flexible and can get damaged with the constant movement of the hand over a longer period which could further add to challenges in the Financial part. Lastly, the comfortability of the brace is a considerable issue as all the components of the device could lead to soreness if worn for a long period. This factor could be addressed by lining the inner wall of the brace with additional cushioning. Apart from physical comfortability, the constant requirement to change gel electrodes could make the process more agitating.

3.1.2. Technical Limitations

As the prototype is a consumer-grade device, there could be an issue with the interpretation of the graphs due to the complex nature of the graph. This leads to an issue with the user interface (UI) of the existing 'Arduino IDE application. As there are no other dedicated applications for the analysis of the collected data, the intricate UI of Arduino IDE poses a challenge for the users in data interpretation. Moreover, the lack of options to access records makes it challenging for neurophysicians to monitor trends and formulate a plan for treatment/testing. Furthermore, the prototype is intended to be used without professional equipment or clinical assistance, which raises concerns about the accuracy of the data. The utilization of serial EMG, which measures impulses of one muscle at a time, along with temperature fluctuations, can potentially compromise the accuracy of the data.

4. Conclusion

In our examination of Carpal Tunnel Syndrome, we surmised that there is an urgent need for accurate diagnosis and consistent monitoring. However, finding a diagnostic test with minimal limitations and maximum sensitivity and specificity is a major challenge due to the lack of information regarding the condition itself, its causes, and its symptoms. EDX tests (NCS and EMG) do not serve as standalone tools and hence can only confirm the diagnosis when combined with clinical symptoms. Moreover, NCS and EMG are also responsible for producing false negatives or false positives. Furthermore, Needle EMG is an invasive process that can be extremely uncomfortable and painful. Every method that is currently available has its own set of drawbacks that prevent the existence of a gold standard. Our experiment on CTS was influenced by a limited sample size, which reduced the precision of our findings. Additionally, the result's dependability was decreased as there was no standardization in our Methodology. These limitations underline the importance of bigger, more controlled research to reach solid findings about the diagnosis and course of CTS possibly with lab on chip technology [50]. Future research on the subject may aim to improve the diagnostic techniques' accuracy and efficiency. In conclusion, our prototype represents a significant advancement in healthcare technology, combining data collection capabilities with patient support functionalities. This dual-purpose design positions the device as a potentially valuable resource for both healthcare providers and patients, aligning with the growing trend of personalized and data-driven healthcare. The future outlook of this technology would include improving accuracy, optimizing for scalability, robustness, and further optimization techniques.

Author Contributions

L.C., A.K.M., P.G., D.S., H.K.W., K.D., S.V. - data curation, investigation, methodology, testing, resources, visualization, writing - original draft. H.K.W., K.D., S.V. - validation, writing - original draft. K.D., S.V. - conceptualization, writing - review & editing.

Conflicts of Interest

The authors declare no competing financial interests or conflicts of interest.

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