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Electromyographic Analysis of Tibialis Anterior Muscle Activity During Human Locomotion

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Abstract:

This study investigates the electrical activity of the Tibialis Anterior (TA) muscle to identify significant frequency bands during specific bodily movements in normal and pathological subjects. The TA muscle is critical for foot movements, particularly dorsiflexion, and plays an essential role in regulating functional reach and overall locomotion. Electromyography (EMG) signals were acquired from the TA muscle while subjects performed dorsiflexion and functional reach tasks. The primary analysis utilized Wavelet Decomposition to process the raw EMG data and extract essential features. A comparative study of these features was conducted across the two activities and between normal and diseased muscle conditions. The analysis successfully identified significant differences in muscle activity, particularly within the frequency bands of 62.5–125 Hz and 125–156.25 Hz during dorsiflexion, which showed distinct variations in feature values between normal and pathological subjects. The derived significant frequency bands offer valuable insight into the functional state of the Tibialis Anterior. This research is expected to pave the way for improved diagnostic tools, advanced therapeutic strategies, and more targeted rehabilitation programs for individuals with muscle-related conditions.

Key words: Electromyography, tibialis anterior, wavelet decomposition, Willison Amplitude, Myopulse Percentage Rate, Rehabilitation

1.INTRODUCTION:

Electromyography (EMG) is an indispensable technique in both clinical and research settings, offering a window into the electrical activity of muscles. Its utility spans from fundamental scientific inquiry into kinesiology and motor control to practical clinical diagnostics. Clinically, EMG is a critical tool for diagnosing neuromuscular disorders, providing essential information about the function of nerves and muscles. Beyond diagnostics, EMG signals are vital control inputs for advanced assistive technology, including prosthetic hands, arms, and lower limbs, enabling responsive, functional movement and significantly enhancing the quality of life for individuals with limb loss or paralysis.

Understanding and analysing muscular activity is paramount for accurately diagnosing conditions affecting the neuromusculoskeletal system. Through EMG, researchers can quantify muscle force and analyse both the electrical and mechanical aspects of muscle contraction. This analytical foundation, often supported by complementary techniques like Vibromyography (VMG), allows for the detailed study of specific muscles and their unique functional roles.

In the context of human locomotion and balance, the muscles of the lower limb specifically the gastrocnemius, rectus femoris, and tibialis anterior are frequently examined. Analysing

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their performance during activities like walking, running, or maintaining functional reach provides crucial insights into muscle health, strength, and coordination.

EMG measurement is broadly categorized into two primary methods: Surface EMG (sEMG) and Intramuscular EMG (iEMG). sEMG, being a non-invasive technique, is particularly valuable for monitoring large, superficial muscles close to the skin. By placing electrodes directly on the skin, sEMG captures the summed electrical activity generated by multiple motor units, offering a general yet comprehensive overview of the overall muscle excitation level and its functional contribution to movement. Intramuscular EMG [1], on the other hand, is more invasive and is typically used to measure the electrical activity of deeper or smaller muscles. A needle electrode is inserted directly into the muscle to record data, which allows for more localized and precise measurements of individual motor unit activity. Both methods surface EMG and intramuscular EMG are highly effective depending on the specific needs of the study or diagnosis.

Overall, EMG provides essential insights into muscle function and is a key tool in the diagnosis and study of neuromuscular diseases [2]. It also has significant applications in the development of advanced prosthetic devices, making it an important area of research and clinical practice. Through the use of EMG and related techniques like vibromyography, researchers and clinicians can better understand muscle health, detect abnormalities, and enhance the design of prosthetic limbs that respond accurately to muscle signals.

Location of the surface electrode is essential since electrodes placed near the tendon area may cause more variation in signal amplitude [3-7]. Foot dorsiflexion plays a vital role in control of balance and gait cycle. The tibialis anterior muscle is the most important dorsiflector muscle, and an upsurge in this muscle's ability is affiliated to the decrease in the falling risk. Studies show that heel strike and swing phases are the two main phases with high tibialis anterior activity, the foot is dorsiflexed at the talocrural joint and inverted at the subtalar joint by the tibialis anterior. By supporting the ankle joint when the foot strikes the floor and lifting it off the ground as the leg moves forward, it serves as vital for walking, trekking, and kicking the ball. [8-9]. Dysfunction of this dorsiflexors results in drop foot. Dorsiflexion is also very important when running and walking. The weight moves from the hind foot to the mid foot and finally to the forefoot during the stance phase of the gait. Dorsiflexion can be clearly seen throughout this weight change. The gait pattern will be impacted by any impairment in the dorsiflexors. [10].

It is evident that walking slower with lesser potency shall be associated with variations of the tibialis anterior muscle [11]. Research has been done regarding the isometric [12-13] and isotonic [14] contractions of tibialis anterior muscle at different intensities. EMG signals provide insights on various aspects of muscle function, such as muscle fatigue, pathology [15-18] and prosthesis control [19-22]. Intramuscular pressure increases proportionately with muscle activity that occurs in response to the nerve stimulation. This proves useful for detecting drug action over specific muscles being examined and also helps in analyzing aging effects on the muscles [23]. The researchers have put forth that tibialis anterior is an important muscle that is necessary for dorsiflexion and plantar fexion of the foot. The muscle contracts for both the foot movements and stress of the muscle can be prominent when these foot movements are produced. The EMG analysis of this muscle helps us to determine angles of dorsiflexion as well as of plantarflexion, as muscle stress is higher as the angle become higher. Nerve disorders and other cases of myopathy can be detected by analysing the EMG waves from tibialis anterior. Comparative study among the normal and abnormal individuals

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can yield us useful results for improvising diagnostic methodologies in the field of rehabilitation. This research lays emphasis on analyzing the EMG of tibialis anterior muscle during dorsiflexion and functional reach, which paves the way for diagnosis of muscle dysfunction and enhances categorization of normal and abnormal subjects based on the level of the muscle response during specific activities.

Essential features that signify muscular fatigue are extracted and associated with the muscle action for both normal and abnormal subjects during the two activities. Comparative study among the features is performed for different subjects enabling further analysis of muscular action, during two specific activities, thereby making the technique useful in sports medicine and rehabilitation.

2.METHODOLOGY:

EMG signals of the tibialis anterior muscle during dorsiflexion and functional reach were obtained from the database. For functional reach activity, ten normal subjects were considered, performing three trials each. For dorsiflexion, myopathy and neuropathy subjects were considered. The signals of each subject are pre-processed, decomposed into constituent frequency bands, reconstructed and then analyzed through feature extraction process.

2.1. Pre-processing**:** A butter-worth band-pass filter of 10-500Hz is applied to remove the unwanted frequency or noise. The sampling frequency of EMG signal is 4000Hz for dorsiflexion and 2000Hz for functional reach activity.

2.2. Wavelet decomposition**:** Wavelet decomposition is particularly valuable across various fields because it allows for the analysis of both the frequency components of signals and the time at which those frequencies occur. Discrete Wavelet Transform is applied to the original signal, so that, necessary coefficients can be obtained, from which the respective reconstructed signals can be obtained. The bands used for analysis of EMG were extracted from 50-200Hz. Feature values were obtained for the bands studied. The four significant bands considered are 15.625Hz-31.25Hz, 31.25Hz-62.5Hz, 62.5Hz-125Hz, 125-156.25Hz.

2.3. Feature Extraction**:** Features that are essential for studying muscular function during different activities are extracted from the reconstructed and filtered original signals. The relevant features considered are:

Mean frequency**:** Mean Frequency is the average frequency of the EMG signal and is obtained as the sum of the product of the power spectrum and the frequency, divided by the total sum of spectrogram intensity as in Eq. (1), where Pk is the frequency of spectrum at frequency bin k.

$$Mean\ Frequency = \left(\sum_{k=1}^{M} fk.Pk\right)/\sum_{k=1}^{M} Pk \tag{1}$$

Median frequency**:** It is the frequency at which the EMG frequency spectrum is divided into two regions with equal power and can be obtained from Eq. (2) where Pk is the EMG power spectrum at bin k and MF represents median frequency of the EMG signal.

$$Median\ Frequency = \sum_{k=MF}^{M} Pk = 1/2 \sum_{k=1}^{M} Pk \tag{2}$$

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Average Amplitude Change(AAC)**:** It is the change in the average of magnitude of all instantaneous values in the EMG signal. Using Eq. (3), AAC is determined for the EMG signals, where N denotes length of the signal and $1 \leq i \leq N - 1$.

$$AAC=\frac{|x(i+1)-x(i)|}{N} \tag{3}$$

Root Mean Square**:** RMS is an average value of root mean square of the EMG signal amplitude, which defined as in Eq. (4), where L denotes the length of the signal and *xl represents* the EMG signal in a segment *l*.

$$RMS=\sqrt{\frac{1}{L}\sum_{l=1}^{L} xl^2} \tag{4}$$

Mean Absolute Value(MAV)**:** It is an average of the absolute value of the EMG signal amplitude, and is obtained by using the Eq. (5), where L denotes the length of the signal and *xl represents* the EMG signal in a segment *l*.

$$MAV= \frac{1}{L}\sum_{l=1}^{L} |xl| \tag{5}$$

Maximum Fractal Length(MFL)**:** It is defined as the measure of the intensity of muscular contraction. MFL incorporates logarithmic scale, hence making it less noise sensitive. From Eq. (6), we can obtain the feature, where N denotes length of the signal.

$$MFL= log_{10}\left(\sqrt{\sum_{n=1}^{N-1}(x(n+1)-x(n))^2}\right) \tag{6}$$

Simple Square Integral(SSI)**:** Simple square integral denotes EMG signal energy and can be obtained from Eq. (7), where N denotes length of the signal.

$$SSI=\sum_{j=1}^{N} |xj|^2 \tag{7}$$

Willison Amplitude(WA)**:** The amount of times the change in EMG signal amplitude exceeds a threshold value and is obtained from Eq. (8), where f(x)=$\begin{cases} 1, if\ x > threshold \\ 0, otherwise \end{cases}$ and N denotes length of the EMG signal.

$$Willison\ Amplitude=\sum_{n=1}^{N} f(|xn - xn + 1|) \tag{8}$$

Variance: Variance is defined as an average of the square values of the deviation of that variable and is obtained by using the Eq. (9), where L denotes the length of the signal and *xl* represents the EMG signal in a segment *l*.

$$Variance = \frac{1}{L-1}\sum_{l=1}^{L}(xl)^2 \tag{9}$$

Standard Deviation (SD): It represents the distance between each value in the EMG signal dataset and the data set's mean value, and is obtained from Eq. (10) where N denotes length of the signal and $1 \leq i \leq N - 1$.

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$$SD=\frac{x(i+1)-x(i)mean}{N-1} \tag{10}$$

Myopulse Percentage Rate: It denotes the percentage quantity of the EMG signal amplitude exceeding the given threshold where N denotes length of the signal. It is useful in fatigue analysis of the muscle and is obtained by Eq. (11).

$$MYOP=\frac{1}{N}\sum_{i=1}^{N} f(|xi|), \quad f(x)=\begin{cases} 1, x \geq threshold \\ 0, otherwise \end{cases} \tag{11}$$

Graphical representations are obtained so as to enable comparison between features obtained. Cross correlation analysis was performed between different trials of each subjects while performing functional reach activity.

3. RESULTS

In this study, the activity of the tibialis anterior muscle during dorsiflexion was analysed under three different conditions: normal, myopathy, and neuropathy. Each of these conditions presents unique characteristics in terms of muscle behaviour. In the normal condition, dorsiflexion is marked by a smooth cycle of contraction followed by relaxation when the external load is released, indicating typical muscle function. In contrast, the myopathy condition is characterized by clinical myotonia, where there is a delay or difficulty in relaxing the muscle after a forceful contraction. This prolonged state of contraction is a hallmark of myopathic disorders. Lastly, the neuropathy condition is associated with persistent contraction, muscle spasticity, and stiffness due to underlying nerve damage. These symptoms result in a contracted state that does not easily relax, highlighting the impaired neuromuscular function caused by nerve injury.

Additionally, features that represent muscle fatigue were analyzed during the functional reach activity for individuals in all three conditions. The muscle fatigue analysis provided valuable insights into how these conditions affect muscle performance over time. As part of the broader investigation, data was also collected from nine additional normal subjects who performed the functional reach activity. The purpose of this data collection was to further analyse the activation patterns of the tibialis anterior muscle across a range of healthy individuals, allowing for a comparison between normal muscle activity and that seen in diseased states.

From the data gathered across all conditions, graphical representations were created to examine trends in key muscle activity features across different frequency bands. These graphical analyses helped in identifying distinct patterns in muscle behaviour, offering insights into how muscle function varies between normal, myopathic, and neuropathic conditions. By focusing on specific frequency bands, it became possible to study how various muscle features, such as fatigue and activation levels, change under different conditions.

Further analysis involved calculating the correlation coefficients for subjects performing the functional reach task. The correlation coefficients were used to assess the consistency and reproducibility of muscle activity across multiple trials. For two of the subjects, an almost equal level of correlation between all three trials was observed, indicating consistent muscle performance across repetitions. However, one subject displayed both positive and negative correlation patterns, suggesting variability in muscle activation or possible underlying differences in muscle function during the task.

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As the number of subjects in this study is expanded, it is expected that more distinct characteristics of muscle activity will emerge. By increasing the sample size, it will be possible to more closely analyze the feature values and correlation patterns associated with different conditions. This larger dataset would allow for a more detailed investigation into how the tibialis anterior muscle behaves across normal, myopathic, and neuropathic states, as well as during functional reach activity. The findings from these analyses could provide a deeper understanding of muscle function, with potential applications in diagnosing and treating neuromuscular disorders.

Fig 1 and 2 present the mean and median frequency values of EMG recordings during dorsiflexion. These figures are instrumental in assessing the fatigue state of the tibialis anterior muscle, as shifts in frequency values are commonly linked to muscle fatigue. Specifically, Fig 1 highlights the mean frequencies, while Fig 2 displays the median frequencies, both providing a comparative overview of muscle activation under different conditions. Monitoring these frequencies helps in understanding how muscle performance deteriorates over time, which is crucial for evaluating neuromuscular health, especially in pathological conditions. Fig 3 illustrates the variation in Maximal Fractal Length (MFL) across two significant frequency bands: cA3D1, which corresponds to the 62.5-125 Hz range, and cD3A1, which pertains to the 125-156.25 Hz range. The labels cA3D1 and cD3A1 represent the 4th and 6th levels of the detailed wavelet coefficients within these specified frequency bands. These coefficients help to capture subtle changes in the EMG signal that are otherwise difficult to detect, allowing for a more nuanced analysis of muscle activity. MFL is an important metric in this context, as it helps assess the complexity and variability of the EMG signal, often correlating with the underlying state of muscle health or fatigue.

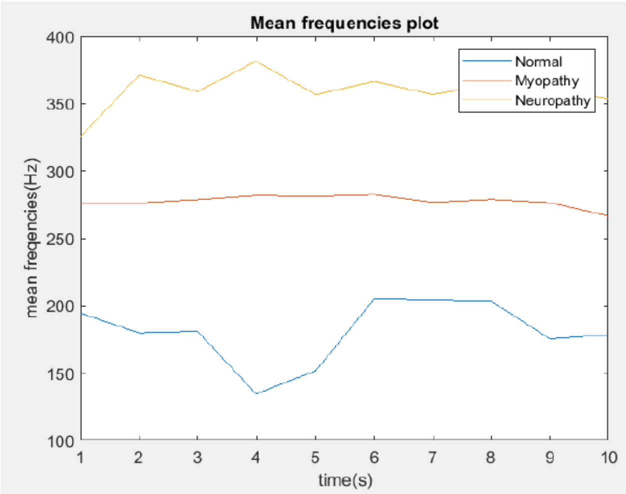

Fig 1. Mean frequencies for dorsiflexion

Fig 4 provides a visual representation of the Myopulse % Rate variation during dorsiflexion for the same two frequency bands, cA3D1 (62.5-125 Hz) and cD3A1 (125-156.25 Hz). Myopulse % Rate is a key feature for understanding muscle contraction patterns, especially in relation to conditions like myopathy and neuropathy. The figure clearly shows how the Myopulse % Rate changes in these critical frequency bands during dorsiflexion, offering insights into the level of muscle engagement and fatigue. Fig 5 focuses on the mean and median frequencies of EMG signals during the functional reach task. Similar to the analysis for dorsiflexion, this figure aids in evaluating the fatigue and activation levels of the tibialis

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anterior muscle during a different type of movement. By comparing the frequency data between dorsiflexion and functional reach, one can better understand how different movements place varying demands on the muscle.

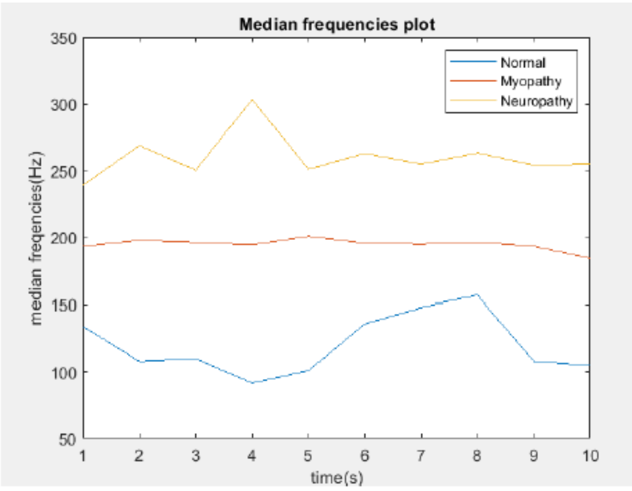

Fig 2. Median frequencies for dorsiflexion

Fig 6 showcases the variation in MFL during the functional reach activity across four frequency bands: 15.625-31.25 Hz, 31.25-62.5 Hz, 62.5-125 Hz, and 125-156.25 Hz. This figure offers a detailed breakdown of how MFL changes across these bands, providing a comprehensive view of the muscle's behavior during functional reach. The inclusion of multiple frequency bands enables a more thorough analysis of muscle activity, revealing patterns that might be missed if only a single frequency range were considered.

Additionally, cross-correlation coefficients between the three trials performed by each subject during functional reach were calculated. These coefficients measure the degree of similarity between two EMG signals, indicating how consistently the muscle behaves across multiple trials. This consistency, or lack thereof, can be a useful metric in assessing muscle performance and the reliability of the recorded EMG signals. The cross-correlation results provide valuable insight into the reproducibility of muscle activity patterns, which is essential for understanding both normal and pathological muscle function. By analyzing these correlations, researchers can gain a better understanding of the underlying neuromuscular processes at play during functional reach.

4. DISCUSSION

In the analysis of dorsiflexion across three different conditions normal, neuropathy, and myopathy it was found that both mean and median frequency values were highest in subjects with neuropathy. When compared to the neuropathy condition, these frequency values were lower in individuals with myopathy, and the lowest values were observed in normal subjects. Specifically, the mean and median frequencies for the normal condition were significantly lower than those for both neuropathy and myopathy. Furthermore, the features such as Root Mean Square (RMS), Mean Absolute Value (MAV), Mean Frequency Level (MFL), and Myopulse % Rate also followed this trend, with the highest values recorded for neuropathy

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subjects, intermediate values for myopathy cases, and the lowest values for normal subjects. This clear pattern indicates that neuropathy exhibits the most pronounced muscle activity, while normal muscle activity is the least, with myopathy falling between the two.

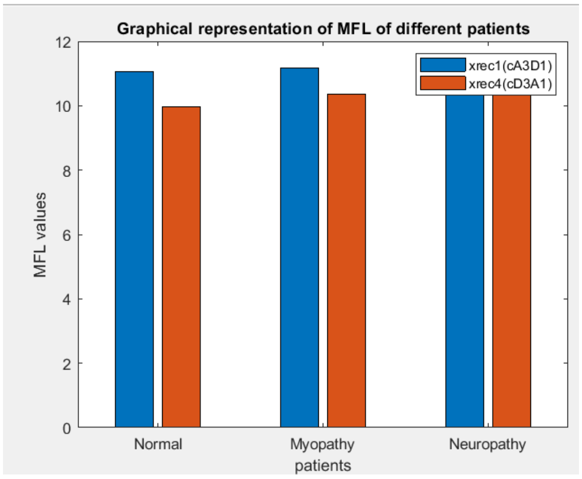

Fig 3. Maximal Fractal Length variation

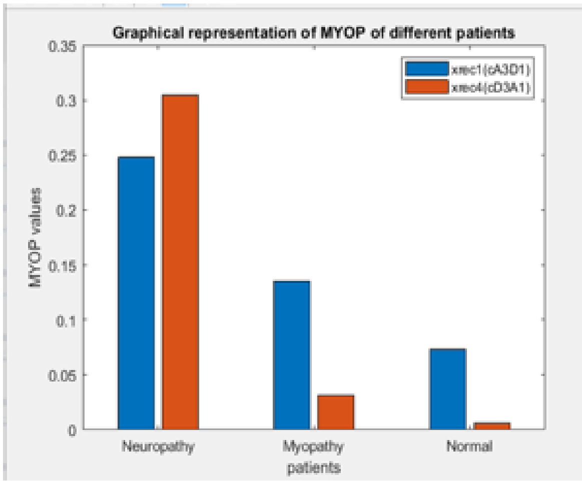

Fig 4. Myopulse %Rate variation

The frequency bands that showed the most notable variations in feature values between normal and diseased muscles during dorsiflexion were identified as 62.5 Hz to 125 Hz and 125 Hz to 156.25 Hz. These frequency ranges appeared to be particularly significant in distinguishing normal muscle function from diseased muscle activity. For the dorsiflexion activity, the average mean frequency recorded for normal subjects was 170.57 Hz, while the average median frequency was 105.92 Hz when it comes to the functional reach activity, the average mean frequency was found to be 114.839 Hz, with an average median frequency of 89.37 Hz in normal individuals. This demonstrates that the mean and median frequency

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values are higher during dorsiflexion compared to functional reach, further emphasizing the greater muscle activity in dorsiflexion.

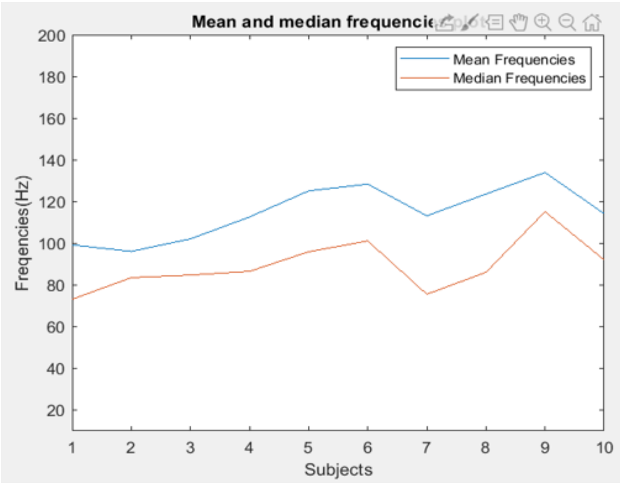

Fig 5. Mean and Median frequencies for functional reach

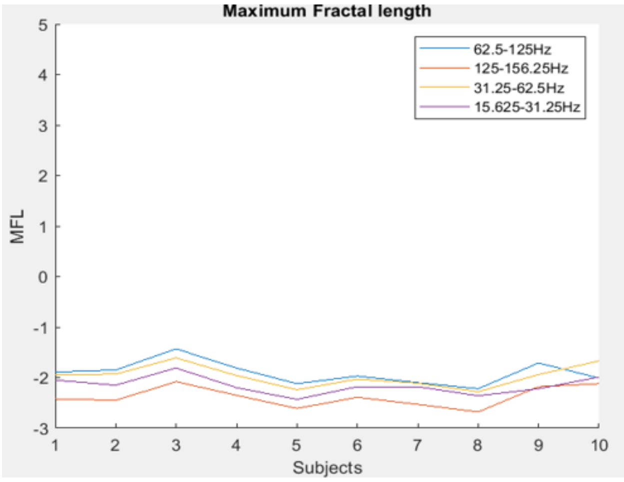

Fig 6. MFL variations for functional reach

In the analysis of frequency bands, the highest values for MFL were observed within the 62.5 Hz to 125 Hz range, while the lowest MFL values were noted in the 125 Hz to 156.25 Hz band. When examining Myopulse % Rate, the lowest values were recorded in the 125 Hz to 156.25 Hz range, and the highest values were found in the 15.625 Hz to 31.25 Hz range, indicating a clear band-specific variation in muscle activity. Regarding the Willison Amplitude feature, the lowest values were detected in the 15.625 Hz to 31.25 Hz band, while the maximum range was found in the 62.5 Hz to 125 Hz band, reflecting the varying characteristics of muscle activity across different frequency bands. When comparing MFL values during dorsiflexion, it was observed that normal subjects exhibited significantly higher MFL values across all four frequency bands, indicating a robust muscle response in healthy individuals. The average Myopulse % Rate value during dorsiflexion was also higher than the corresponding value during functional reach, further supporting the conclusion that dorsiflexion elicits greater muscle engagement in the tibialis anterior.

Additionally, the RMS and MAV values recorded for dorsiflexion were consistently higher than those recorded during functional reach. These findings provide clear evidence that the activity of the tibialis anterior muscle is significantly greater during dorsiflexion than during functional reach. This heightened activity during dorsiflexion, as reflected in the increased feature values across various metrics, underscores the greater demands placed on the muscle during this movement compared to the functional reach task. These insights have important implications for understanding muscle function and could be applied in clinical and sports settings to assess muscle health and performance.

5. CONCLUSION

The tibialis anterior muscle in the lower limb has been studied to assess its activity during two specific tasks: dorsiflexion and functional reach. The findings indicate that the muscle is significantly more engaged during dorsiflexion compared to functional reach. This suggests that dorsiflexion requires a higher level of muscle activation, possibly due to the nature of the movement and its demands on the tibialis anterior. Along with the activation levels, various features related to muscle fatigue were also examined. These features were evaluated in specific frequency bands, which showed distinct patterns. By identifying and analyzing the feature values in these significant frequency bands, deeper insights into muscle performance and fatigue can be obtained.

Moreover, increasing the number of participants from both diseased and healthy groups is expected to enhance the reliability and accuracy of the feature values. The larger sample size would allow for a more robust comparison, helping to fine-tune the understanding of muscle function in these different populations. Conducting a correlation analysis on the expanded dataset would likely yield further valuable results, revealing trends and variations in feature values across individuals. These trends could then be used to better understand how muscle fatigue and activation differ between healthy and diseased individuals, offering critical information for diagnosis and treatment.

For this study, EMG signals for the dorsiflexion task were recorded using a needle electrode, while for the functional reach task, surface electrodes were employed. The use of different types of electrodes introduced variations in the magnitude of the recorded feature values. This difference in electrode type likely affected the precision of the EMG data, as each electrode type captures signals in a slightly different way. To mitigate this inconsistency and improve accuracy, it is recommended that the same type of electrode be used for all subjects when collecting EMG data across multiple tasks. By doing so, the data would be more consistent and reliable, facilitating a clearer comparison of the results across participants.

Additionally, the analysis of feature values within different frequency bands holds great promise for practical applications. The insights gained from studying these features could be beneficial in fields such as sports medicine and rehabilitative medicine. By understanding the variations in muscle activation and fatigue, professionals can develop strategies to differentiate between healthy and diseased muscles more effectively. This knowledge could then be applied to designing better training programs, rehabilitation techniques, and diagnostic tools, ultimately improving patient outcomes and enhancing athletic performance.

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