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INVESTIGATION OF SOUNDS PRODUCED BY HEALTHY AND DISEASED
HUMAN MUSCULAR CONTRACTION

THE UNIVERSITY OF ARIZONA

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INVESTIGATION OF SOUNDS PRODUCED BY HEALTHY
AND DISEASED HUMAN MUSCULAR CONTRACTION

by

Brian Alan Rhatigan

A Thesis Submitted to the Faculty of the
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College
THE UNIVERSITY OF ARIZONA

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STATEMENT BY AUTHOR

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APPROVAL BY THESIS DIRECTOR

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May 10 1984
Date

DEDICATION

To God and my family, especially Pamela and Paul, all of whom have stood by me.

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ABSTRACT

Muscle sounds were recorded from the medial bicep of 37 subjects as they pulled against a stationary object. The recordings were then analyzed with a digital computer system for frequency content. Twenty subjects had some diagnosed neuromuscular disorder, while seventeen had no known muscle impairment.

The average peak frequency was determined for normal subjects, normal subjects under sixty years old, subjects with neuromuscular disorders, and subjects under 60 years old with neuromuscular disorders. The means and standard deviations were 13.861 ± 4.092 Hz, 15.061 ± 4.152 Hz, 11.055 ± 1.558 Hz, and 11.212 ± 1.617 Hz, respectively.

A significant difference was observed between normal subjects and subjects with neuromuscular disorders ($p < .05$). When only the data from subjects under 60 years old were analyzed, the difference became even more significant ($p < .01$). Possible sources of the sound and reasons for the difference are discussed.

INTRODUCTION

It is not generally known that muscle contractions produce an audible sound. Not much research has been performed on this phenomenon even though the first published reference to muscle sounds can be found over 300 years ago. At that time, Grimaldi (1665) attributed the sounds to the motion of animal spirits.

The next mention of muscle sounds occurred two centuries later, when Wollaston (1810) described two methods he used to estimate the frequency of the sound. The first method he used to obtain the muscle sounds was to place his thumb in his ear and clench his fist. He compared this sound to the noise produced by rubbing a stick over a notched board. By knowing the spacing of the notches and approximating the rate of the rubbing, he could estimate the frequency of the sound. The second method he used was comparing the muscle sounds to the distant rumbling of a horse drawn carriage. At the time, the streets of London were composed of regularly spaced bricks. Again, by estimating the rate of the carriage, he was able to approximate the frequency of the sound. From both methods he estimated the frequency of the sound to be between 20 and 30 Hz.

Still using crude comparison methods, Herroun and Yeo (1885) compared the sounds from voluntary contractions with those produced by electrical stimulation. Their results were similar to Wollaston's. Moreover, they found no difference between the sounds produced by the two methods of muscular contraction. In their paper, they supported the idea that the first heart sound is actually produced by the muscles of the ventricles as they contract.

Recently, Oster and Jaffe (1980) used an electronic stethoscope and an auto-correlator to determine the major frequency of the sound to be 25 ± 2.5 Hz (MEAN $\pm$ S.D.). In their study, six athletic individuals lifted various weights as a contact microphone was affixed over their biceps. The frequency of the sound remained constant over the range of loads used (0 to 10 kg). However, the amplitude of the sound was shown to be linearly related to the force exerted. Additional tests were performed on other skeletal muscles, with the same results.

Another aspect of their study was the investigation of sounds produced by stimulated muscle contractions. They confirmed Herroun and Yeo's results, finding no difference between the sounds produced by the two methods of contraction.

In order to investigate the possibility that the sounds were being produced by the microphone rubbing against the skin, a test was performed with the arm submerged in a

water tank and the microphone placed 1 cm from the arm. This arrangement was employed since water is superior to air as a transmitter of low frequency noise. Further tests eliminated blood flow and temperature effects on the sound produced by muscular contractions.

Other studies have indicated that the sound produced by muscles is actually a high frequency click lasting 5 to 15 mSec. Gordon and Hobourn (1948) used a piezoelectric transducer placed above the eye to detect the sounds. The motor units in the muscle of the eyelid (m. orbicularis oculi) are composed of so few fibers that individual contractions can easily be recognized. It was probably these individual contractions that appear as clicks. In fact, when examining other skeletal muscles, Gordon and Hobourn noted only being able to detect a complex rumbling sound.

Using frog sartorius muscles in vitro, Brozovich and Pollack (1983) confirmed that as the muscle shortened, discrete sound bursts of 400 uSec duration were given off. In their investigation, they utilized a broadband piezoelectric transducer but only examined frequencies between 500 Hz and 250 KHz. The results of their experiments suggest that muscular contraction is not a continuous process, but rather one that occurs in discrete steps.

With the widespread application of electrical instrumentation into medicine, more information is being obtained

about muscle sounds. Earlier studies relied on mechanical stethoscopes which have a limited frequency response somewhere between 75 and 200 Hz. Indeed, with instruments such as the Carotid Phono Angiograph, which uses a microphone to listen to and evaluate the blood flow to the brain, muscle sounds produced in the neck have been a source of interference (Medical Electronic Devices, 1977).

Another advance which has aided the evaluation of muscle sounds is the use of the digital computer and the Fast Fourier Transform (FFT) to obtain a spectral analysis of the signal (Gold and Rader, 1969). This is a graphical representation of the frequencies contained in a signal, along with their relative magnitudes.

The purpose of this study was twofold. The first was to utilize these new methods to examine the sounds produced by healthy muscular contraction. Secondly, those results were compared with results obtained from individuals with neuromuscular disorders. The major objective was to gain a better understanding of the sounds produced. It was, furthermore, hoped that the results would in some way help to provide a non-invasive procedure to diagnose neuromuscular disorders.

MATERIALS AND METHODS

A Narco Biosystems Carotid Phonoangiography microphone was employed for primary detection of the muscle sounds. This microphone is a Wollensak model A-0450 modified with a custom designed Teflon bell-shaped coupling. The microphone output was amplified by a two-stage battery powered amplifier (DC to 8 KHz) and recorded with a Hewlett Packard 4-channel FM tape recorder (model HP 3964) at a tape speed of 15 inches per second (ips). While the signal was being acquired, a pair of high impedance headphones was employed to monitor the quality of the sound being recorded and to insure an accurate microphone placement. The complete data acquisition system is shown in Figure 1.

The recorded signal was played back at 15 ips through a differential amplifier (DC to 1 KHz) and into the analog-to-digital convertor, where it was sampled at 3333 Hz. for 2.5 seconds. A Fast Fourier Transform and Power Spectrum were performed on the sampled data and a graph of the spectrum and scaled relative power values were obtained. Figure 2 shows the entire data analysis system.

With approval of the Human Subjects Committee, data was collected from 37 subjects (age 22 to 86 years); 20 volunteers from the Neuromuscular Clinic at the Arizona

Figure 1. Schematic representation of the data acquisition system.

Figure 2. Schematic representation of the data analysis system.

Health Sciences Center and seventeen normals with no known neuromuscular disease. Ten of the twenty subjects displayed some form of Muscular Dystrophy (Limb-Girdle, Myotonic, or Facioscapulohumeral), while the remaining ten had other diagnosed neuromuscular disorders. Table 1 shows the complete distribution of subjects. Myotonic, Facioscapulohumeral, Limb-Girdle, and Polymyositis are muscular diseases. The remaining diseases are neurological

Sound data was recorded from the medial bicep, with the coupling bell held firmly against the muscle. All subjects were seated, with the forearm horizontal and lifting against a convenient stationary object.

Table 1. Distribution of subjects by neuromuscular disorder.

Normal	17
Myotonic	5
Facioscapulohumeral	1
Limb-girdle	4
Spinal muscular atrophy	3
Friedreich's ataxia	2
Polymyositis	1
Myasthenia gravis	2
Parkinson	1
Motorneuron disorder	1

SYSTEM VERIFICATION

As mentioned before, other studies have shown muscle sounds to be below 100 Hz. Therefore, three frequencies below 100 Hz (10, 30, 90 Hz) were chosen to test the recording and signal analysis system. The outputs from three signal generators were combined and fed directly into the A/D convertor. This signal was also recorded and analyzed. Six tests were conducted (3 direct, 3 from tape). The computer reported the same three peaks for each of the tests (10.2, 28.9, 90.4 Hz).

The system's response to noise was then tested. A white noise-generating chip was obtained (National Semiconductor MM 5837) and a pink noise circuit was constructed (see Figure 3). The white and pink noise responses are shown in Figures 4 and 5, respectively. The response for white noise should be flat, indicating equal power over the bandwidth. Pink noise should exhibit a decrease in power as the frequency increases. However, these waveforms show an oscillation in their peaks. This phenomenon is the result of two deficiencies in the FFT: leakage and the "picket fence effect" (Bergland, 1969). Leakage occurs because the waveform is sampled for a finite period of time. This causes the main lobe to widen and gives rise to an infinite number

Figure 3. Noise generating circuit (from National Semiconductor Handbook, 1980).

Figure 4. White noise power spectrum. -- Note the oscillation in amplitude caused by "leakage" and the "picket fence effect" (see text).

Figure 5. Pink noise power spectrum. -- This spectrum also exhibits the effects of "leakage" and the "picket fence." However, the pink noise characteristic of inversely proportional amplitude with increasing frequency is still evident.

of sidelobes. The "picket fence effect" can be understood by considering the FFT to be a series of overlapping band-pass filters. Some frequencies fall between the center frequencies and therefore will not be of the same amplitude as neighboring frequencies.

In order to test the system's sensitivity to signals in noise, a 25 Hz signal was combined with the white noise and analyzed. The noise amplitude was maintained at 4 volts peak to peak while the 25 Hz signal amplitude was varied from .4 to 2 volts. Figures 6 and 7 show two of the responses. As can be seen from Figure 6, a signal to noise ratio of 1:10 yields a dominant peak at 25 Hz and noise peaks less than 50% of this peak. At a ratio of 1:4, no noise peaks were greater than 5% of the signal peak.

Repeatability was verified by performing 8 tests on the same individual over 3 months on 5 different days. Results of the detected peaks are shown in Table 2. The average peak value was 13.7 Hz, with a standard deviation of 1.1 Hz.

Figure 6. Power spectrum of signal in noise. -- A .4 volt peak-to-peak signal was combined with a 4 volt peak-to-peak white noise signal, and analyzed.

Figure 7. Power spectrum of signal in noise. -- For a 1 volt peak-to-peak signal combined with a 4 volt peak-to-signal noise, no peaks reach 5% of the dominant peak.

Table 2. Repeatability of measurements
conducted on the same individual
over time.

Date	Frequency
2-08-84	13.8
2-15-84	15.0
2-15-84	13.8
3-28-84	12.2
3-28-84	14.6
4-02-84	12.2
4-02-84	13.0
4-02-84	14.6
mean 13.7 Hz	
standard deviation 1.1 Hz	

DATA ANALYSIS AND RESULTS

Earlier studies (Oster and Jaffe, 1980) showed a linear relationship between force and amplitude. Since different forces were exerted depending on the subject, information regarding the amplitude of the data was not processed. In general, the subjects with neuromuscular disorders had an amplitude one-half to one-fifth that of the normals.

An example of the muscle sounds and corresponding power spectra can be found in Figures 8 and 9. None of the power spectra contained significant frequencies above 100 Hz. From the tests of signal in noise, it was observed that a signal to noise ratio of 1:7 would produce a measurable peak. Figure 9 does not exhibit a peak in this range. Since other studies only examined frequencies below 100 Hz, further tests were performed to confirm the hypothesis that the predominant frequencies lie below 100 Hz. Eight subjects' data were reanalyzed by filtering through two differential amplifiers in series, each with their upper and lower cutoffs set at 100 and 1000 Hz, respectively. In the power spectra output, the frequencies below 150 Hz were set to zero and the remaining spectrum was scaled as before. Figure 10 shows a typical response. The spectra obtained by this

Figure 8. A sample of muscle sound obtained from the medial bicep produced by pushing against a table.

Figure 9. Power spectrum of sound shown in Figure 8. -- Note the peak in the tremor range of 5-12 Hz. Also, no peaks are observed above 120 Hz.

Figure 10. Power spectrum of muscle sound processed through two bandpass filters. -- All frequencies below 150 Hz were set to zero before scaling the spectrum.

method have the same characteristics as "pink noise"; that is, decreasing power with increasing frequency.

Since less than 3 seconds of data are necessary for analysis and 20 to 30 seconds of data were acquired, two separate sections of the tape were analyzed for each subject. These two values were then averaged and counted as a single data point. A measure of the repeatability within the sample can be obtained from the mean and standard deviation of the differences, which were 2.77 ± 2.92 Hz, respectively.

Table 3 contains the statistical values derived from the data. Comparison of means tests were performed using the "student's t-distributions." Prior to the comparison, the "F-test" was performed and corrections to the degrees of freedom were made when necessary. Results of the various comparisons are in Table 4. Since aging has a direct effect on muscle mass, innervation, contractile strength and other factors (Kenney, 1982; Shepard, 1979; Grimby and Saltin, 1983), comparisons were also conducted eliminating subjects over 60.

No difference was found between Males and Females or Normals < 60 and Normals > 60. Among subjects with neuromuscular disorders, no difference was found between groups. However, comparing all normals and all subjects with neuromuscular disorders, a significant difference was found ($p < .05$). Furthermore, when subjects over 60 were elimin-

Table 3. Sample size, means, and standard deviations of different groups in this study.

Name	Number		Standard Deviation
Male (normal)	13	14.769	4.090
Female (normal)	4	10.913	2.687
All normal	17	13.861	4.092
Normal < 60	12	15.061	4.152
Normal > 60	5	10.980	2.210
Myotonic	5	10.380	1.728
Limb-girdle	4	11.550	1.585
S.M.A.	3	10.083	1.522
Other neuromuscular ¹	7	11.193	0.873
Muscular dystrophy ²	10	11.250	1.931
All neuromuscular	20	11.055	1.558
Muscular Dystrophy < 60	9	11.411	1.975
All neuromuscular < 60	17	11.212	1.617

1. Friedreich's Ataxia, Polymyositis, Myasthenia Gravis, Parkinson and Motorneuron Disorder.

2. Myotonic, Limb-girdle, and Facioscapulohumeral.

Table 4. Results of the comparison of means tests. -- A significant difference was observed between the normal and neuromuscular groups ($p < .05$). When age was considered, a significant difference was observed between normals < 60 and MD < 60 ($p < .05$); and between normals < 60 and neuromuscular < 60 ($p < .01$).

Comparison Groups	T	t _{.95}	t _{.99}
Males vs Females	1.751	2.131	2.947
Normal < 60 vs Normal > 60	2.053	2.131	2.947
Myotonic vs Limb-girdle	1.045	2.365	3.499
MD vs S.M.A.	0.952	2.201	3.106
MD vs Others	0.073	2.148	2.947
Normal vs MD	1.887	2.063	2.787
Normal vs Neuromuscular	2.840	2.086	2.845
Normal < 60 vs Neuromuscular < 60	3.487	2.154	2.998
Normal < 60 vs MD < 60	2.428	2.114	2.861

ated from both groups, the difference became even more significant ($p < .01$).

DISCUSSION

It is generally accepted that muscles produce some type of sound. Studies which examined single motor units reported hearing clicks with durations from 5 to 15 mSec for intact human muscles (Gordon and Hobourn, 1948) to 400 uSec for frog muscles in vitro (Brozovich and Pollack, 1983). This can be explained by considering the muscle fiber to be a constant volume cylinder. Upon contraction, the height would shorten and the radius would increase correspondingly. This rapid lateral increase would cause displacement of the surrounding environment and would be detected as a sound burst.

When examining larger skeletal muscles, one can only obtain an averaging effect. Indeed, if the muscle were to contract in a stepwise fashion as current investigators believe (Brozovich and Pollack, 1983; Delay et al., 1981), each step would pull on the elastic connective tissue and give rise to oscillations of the overall muscle body. It is possible that the sounds detected are caused by these oscillations.

It is also accepted that physiological tremor in the range of 5 to 15 Hz occurs in all muscles (Allum et al., 1978; Halliday and Redfearn, 1956; Matthews and Muir, 1980)

and peaks between 8 and 10 Hz for weak contractions. As contraction force increases, the peak shifts upward in frequency (Allum et al., 1978). Lippold et al. (1957) demonstrated that this tremor gives rise to measurable mechanical oscillations. These mechanical oscillations could be detected as sounds.

Oster and Jaffe (1980) cited studies (Larson et al., 1968; Goldspink et al., 1970) which showed oscillations in the mean sarcomere length to have a frequency of approximately 20 Hz. They also cited studies (Huxley, 1974; Taylor and Lynn, 1972; Curtin et al., 1974) which indicated that the cycling of cross bridges occurs at approximately 20 Hz. Both of these phenomena could contribute to the production of the sounds recorded.

Rietz and Stiles (1974) compared normal human limbs to a second order underdamped system. It is quite possible that the driving frequency is different for certain disease conditions and could account for differences in the frequency of the muscle sounds between normal subjects and those with neuromuscular disorders.

As with physiological tremor, there probably are multiple reasons for muscle sounds. Our study shows that there is a significant difference between sounds produced by healthy muscles and by those with neuromuscular disorders. Muscles with some form of disease tend to atrophy and produce

weaker contractions. It is interesting to note the frequency obtained in our study is close to the tremor frequency. In fact, almost all the power spectra contained a significant peak in the 5 to 12 Hz range. It is very likely that physiological tremor plays some role in the sounds produced by muscular contractions and is possibly the major factor for subjects with neuromuscular disorders.

The mean frequency for normals in this study was 15.06 ± 4.15 Hz. This differs from the results of Oster and Jaffe (1980), who obtained 25 ± 2.5 Hz. However, the methods used were very different. Oster and Jaffe used six athletic individuals and analyzed their data with an auto-correlator. In their investigation, subjects lifted known weights. Subjects in this study were asked to push against a stationary object with as great a force as they felt they could produce.

In the future, it might be useful to study the correlation of sound amplitude vs load for neuromuscular disorders. Oster and Jaffe (1980) demonstrated this to be a linear relationship for the athletic subjects in their study. Since the muscles of subjects with neuromuscular disorders atrophy, a greater percentage of the muscle is recruited for smaller loads. The amplitude vs load curve might contain more information about the condition of the muscle.

The findings reported in this study do not indicate a statistically significant difference between ages. However, the sample size was small and as can be seen from the data, results are very close to being significant. As mentioned earlier, the effects of aging are similar to, but not as rapid as the effects of neuromuscular disorders (atrophy of the muscle). Further studies on age might therefore shed more light on this issue.

In analyzing the data, only the highest peak was chosen from the spectrum. Further analyses of the spectrum might also provide useful information. Other analyses could examine the bandwidth of the spectrum. If the sounds are produced by various factors, then their relative contributions to the muscle contraction could be determined by their relative peaks in the power spectrum.

Since almost all the spectra contained a significant "tremor peak" (the peak between 5 and 12 Hz), it might be useful to define some index as the ratio of the height of the "tremor peak" to the height of the spectrum peak. This is essentially comparing the contribution of tremor to the overall contraction.

It might also prove enlightening to compare the absolute value of the peaks in the spectrum between normal subjects and those with neuromuscular disorders. In this

way it might be possible to obtain standard values for the normal population.

In conclusion, this study does show a difference in the sounds produced by healthy and diseased muscles. Further investigations could aid in understanding the mechanisms involved in sound production and may also provide information on the condition of the muscle. In any case, the study of muscle sounds is open to many directions of research.

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