The ratio of acoustic myography (AMG) amplitude to surface electromyography (EMG) amplitude is proposed as a measure of mechanical output compared with electrical activity of the contractile system. AMG to EMG ratios were measured from 16 children with muscle disease diagnosed by clinical criteria, EMG, and/or muscle biopsy. These were compared with the ratios from 11 normal volunteers spanning the same age range (7–16 years). AMG to EMG ratios were significantly ($P < 0.01$) different for the two populations. Using a linear discriminant function to define the normal range for AMG to EMG ratios yielded a sensitivity of 82% (13 of 16 abnormals diagnosed) and a specificity of 91% (10 of 11 normals). These findings suggest that surface recordings may provide significant diagnostic information in muscle disease. The accuracy may be improved further by using additional muscles (e.g., paraspinals) and evoked twitches.
Key words: pediatric muscle disease • muscle sounds • electromyography • muscular dystrophy

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ACOUSTIC AND SURFACE EMG DIAGNOSIS OF PEDIATRIC MUSCLE DISEASE

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Sounds emitted by muscles during contraction are an intrinsic component of the contractile mechanism. The sounds are produced by mechanical vibrations that occur at the resonant frequency of the muscle.[1–3,13] The resonant frequency of the muscle is determined by several parameters, including muscle mass, topology, and stiffness. The resonant frequency increases during a twitch since the muscle stiffness increases as more cross-bridges attach.[9,12]

Muscle sound recordings, known as acoustic myography or AMG,[6] are useful clinically in monitoring fatigue,[6] evaluating muscle contractile properties,[4] controlling a prosthetic device,[5] and monitoring force.[6–8,16] As an indicator of mechanical muscle activity, AMG can be combined with surface EMG to obtain a measure of the "efficiency" of electrical activity. DeVries[10] demonstrated that surface EMG amplitude to force ratios were lower in strong compared with weak individuals, suggesting a greater "efficiency of electrical activity" in the stronger persons. The results were extended to show an increase in the surface EMG amplitude to force ratio when muscles were fatigued.[11] The breakdown in electromechanical coupling that occurs with normal fatigue is reflected in a reduction of the ratio of AMG to EMG amplitudes.[6] The present study was performed to determine if the AMG/EMG ratio from normal muscle is significantly different from the AMG/EMG ratio from muscle in children with myopathy or muscular dystrophy.

METHODS

Forty-one subjects were tested, including 11 normal subjects. Volunteers were obtained by sending letters to all children with neuromuscular disease under the care of Dr. Hinton. Inclusion requirements included the following: (1) age more than 6 years, (2) mentally competent to understand instructions, (3) physically able to perform the required tasks, and (4) consent given by parents and

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child. Of the 30 patients, 6 had neuropathic disease and 8 were unable to lift a 1.0 kg weight, leaving 16 patient data sets for analysis. Consent was obtained in accordance with a protocol approved by the Western Ontario University Human Subjects Review Committee. Control subjects without historical or clinical evidence of neuromuscular disease were derived from an inpatient elective surgery population. Both the patient and the control groups ranged in age from 7 to 16 years. The patient diagnoses are shown in Table 1.

Data were recorded from the biceps brachii muscle during voluntary isometric contractions with the elbow flexed to 90°, the shoulder abducted to 90°, the forearm supinated, the hand open, and the subject lying supine in a comfortable position. The biceps brachii muscle was chosen because it is easily activated with good control, located where the microphone and EMG apparatus can be easily attached, and there are acoustic muscle data from biceps brachii in the literature for comparison. Subjects were tested with their arms strapped securely into the testing apparatus, leaving the elbow and forearm free to flex. The hand and wrist were attached to a pulley system of weights. Subjects were instructed to lift the weight by flexing the elbow and then hold the weight steady while the elbow was at 90°. Several separate levels of voluntary isometric contraction intensity were recorded from each subject by attaching various weights to the end of a pulley system. If subjects were unable to lift the 1.0 kg weight they were excluded from subsequent data analysis. Signals were recorded for 20 seconds with 40-second rest periods between each successive level. Sounds were recorded with a microphone (Model 21050A, Hewlett-Packard, Ltd, bandwidth of 0.1–1500 Hz) placed over the belly of the biceps brachii muscle. Force production was monitored with a force transducer (Model 208A03, PCB Piezotronics, Inc.), and surface electromyography signals were recorded (Model 14C11 amplifier, DISA). All three signals were recorded simultaneously on an FM tape recorder (Model R-61, TEAC, 0–800 Hz, ±3 dB). The signals were later digitized at a sampling rate of 3.3 kHz per channel with 12 bit resolution. Mean values, root mean squared (RMS) amplitudes, and least mean squared error linear regression coefficients were calculated digitally. RMS values are used rather than rectified, integrated values of EMG amplitudes because the RMS value is a measure of signal power, and the time integral of the RMS value is the energy of the signal. The rectified, integrated EMG signal amplitude is not easily related to a physical parameter such as energy or power; however, it does increase with increasing power. Lenman[14,15] used rectified integrated EMG while DeVries[10,11] used RMS values. Calculations of amplitudes were all performed without knowledge of which data sets were from patients and which were from control subjects.

Table 1. Diagnoses in the patient group.

Patient	Age	Sex	Clinical diagnosis	Muscle biopsy (age)	EMG (age)
1	16y10m	M	Duchenne muscular dystrophy	+ (3)	N/A
2	16y 4m	M	Duchenne muscular dystrophy	+ (5)	N/A
3	12y11m	M	Beckers dystrophy	+ (5)	N/A
4	12y 5m	F	Myotonic dystrophy	N/A	+ (7)
5	11y 5m	F	Mild myopathy	+* (11)	+
6	11y 0m	M	Duchenne muscular dystrophy	+ (5)	N/A
7	10y 9m	M	Duchenne muscular dystrophy	+ (3)	N/A
8	10y 7m	M	Duchenne muscular dystrophy	+ (5)	N/A
9	10y 3m	F	Dermatomyositis	N/A	+ (10)
10	10y 0m	M	Myotonic dystrophy	N/A	+ (3)
11	9y 6m	M	Duchenne muscular dystrophy	+ (8)	N/A
12	9y 3m	M	Duchenne muscular dystrophy	+ (5)	N/A
13	8y10m	M	Duchenne muscular dystrophy	N/A	N/A
14	8y 4m	M	Dermatomyositis	− (8)	+ (8)
15	7y 2m	M	Duchenne muscular dystrophy	+ (3½)	N/A
16	6y10m	F	Congenital myopathy	N/A	N/A

Note: Two patients (Nos. 13 and 16) did not have a biopsy or EMG recorded. Number 13 had a family history (brother with Duchenne Muscular Dystrophy) and a CK > 6000 in addition to clinical findings. Number 16 had significant, stable proximal weakness in arms and legs symetrically, without sensory changes. The family refused biopsy or EMG.
**Nonspecific myopathic changes.*

RESULTS

Figure 1 shows acoustic and surface EMG amplitudes as functions of force, up to 1.0 Kg, for both subject groups. There were no significant differences between the two groups for acoustic amplitudes at six of the seven force levels (Fig. 1A,B). The lack of significance is consistent with the concept that the acoustic signal reflects force output both in normal and diseased muscle. However, over the whole range of forces, the regression lines for acoustic data were different for two groups. The surface EMG signal amplitude was a significantly larger function of force for the patient group than for the control group. (Fig. 1C, D). The amplitudes of the patient group showed greater variability among individuals than the amplitudes of the control group; the variability is demonstrated by the larger error bars in Fig. 1C than in Fig. 1D.

Figure 2 shows the relationship of surface EMG amplitude to acoustic amplitude for both groups. The patient group had higher ratios of surface EMG to acoustic amplitude than the control group. The nonparametric representation of acoustic and surface EMG data (Fig. 2) shows no overlap between the two groups and suggests that a good discriminant function can be obtained to distinguish between patients and controls. Using

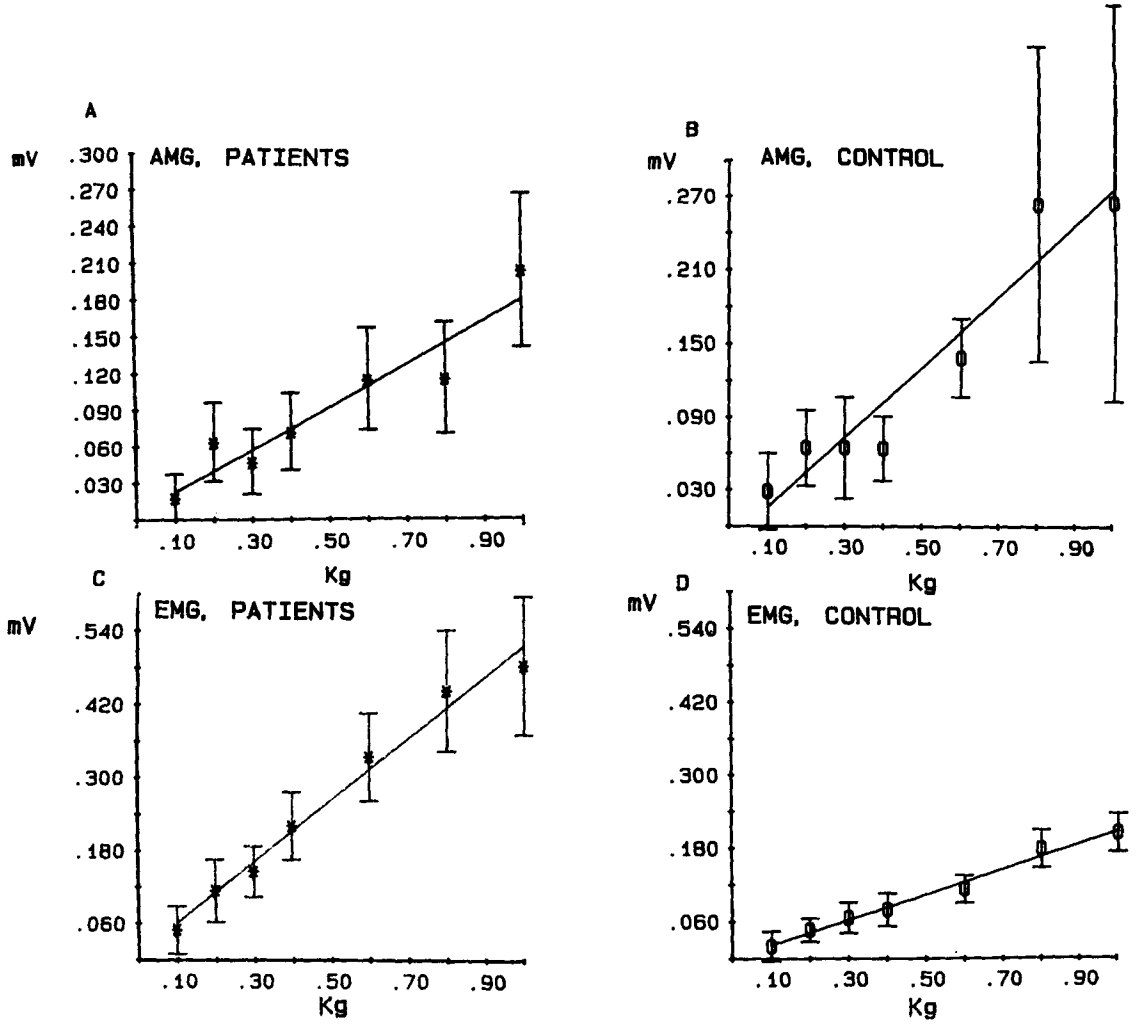

FIGURE 1. Acoustic and surface EMG data over the range of 0.1–1.0 kg mass lifted. (0) Data from the 11 controls; (*) data from the 16 patients. Error bars denote standard deviation. Solid lines represent least mean squared error linear regression. **(A)** Acoustic amplitude as a function of force in the patient group. Regression line slope is 0.17 ± 0.02. **(B)** Acoustic amplitude as a function of force in the control group. Regression line slope is 0.29 ± 0.03. Analysis of variance shows that the hypothesis that the regression lines in **A** and **B** have the same slopes is refuted with $P < 0.01$. **(C)** EMG amplitude as a function of force in the patient group. Regression line slope is 0.50 ± 0.02. **(D)** Surface EMG amplitude as a function of force in the control group. Regression line slope is 0.21 ± 0.01. Analysis of variance showed that the hypothesis that the regression lines in **C** and **D** have the same slopes is refuted with $P < 0.01$.

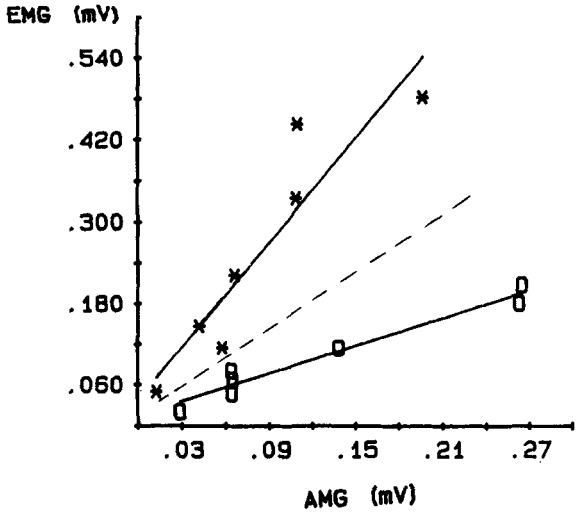

FIGURE 2. AMG amplitude as a function of EMG amplitude, average values for each group are shown for masses from 0.1 to 1.0 kg. (0) Controls; (*) patients. Solid lines are linear least mean squared error regression lines. The slope for the control group regression line is 0.68 ± 0.05; the patient group regression line slope is 2.6 ± 0.4. Analysis of variance shows that the hypothesis that these slopes are the same is refuted with $P < 0.01$. The dashed line represents the discriminant function used to classify each individual data set as normal or abnormal. The slope of the discriminant line is 1.4.

the linear discriminant function shown as a dashed line in Fig. 2 to define a normal range yields the diagnostic accuracy shown in Table 2. Of the 16 patients, 13 were diagnosed and 2 were in the normal range. Of the 11 controls, 10 were in the normal range and 1 was abnormal. These values imply a sensitivity of 81% and a specificity of 91%.

Table 2. Diagnostic accuracy.

	EMG/AMG ratio	
Diagnostic group	Normal	Abnormal
Control	10	1
Patient	3	13

Note: Fischer's exact test yields P = 0.0003 that these results are due to chance.

DISCUSSION

The combination of surface EMG and acoustic signals provides a measurement of electromechanical coupling in muscle. In diseased muscle, the "electromechanical efficiency" is reduced, probably due to atrophic fibers that generate electrical activity with little mechanical contribution. The increase in surface EMG amplitude as a function of force in myopathic weakness has been reported previously.[14] In our study, reduced efficiency is reflected by increased ratios of surface EMG to acoustic signals as well as increased EMG/force ratios.

The use of acoustic signals allows data to be obtained when force measurements are unavailable. For example, paraspinal muscles are frequently involved early in myopathies, but accurate force measurements are hard to obtain from paraspinal muscles. Acoustic signals are easy to obtain from paraspinal muscle groups.[16] Eliminating the need for a force transducer apparatus opens the possibility of ambulatory recordings as well as providing much faster data aquisition when several muscles are to be sampled.

In the normal subjects at low levels of force, the acoustic signal was matched by a quadratic function better than a linear function. The quadratic behavior at low force levels and linear behavior at moderate force levels is consistent with previous reports.[6,16] The explanation may lie in the size principle and contractile properties of muscle—smaller, earlier-recruited motor units develop fused tetanus at lower firing frequencies than larger, later-recruited motor units. Since muscle fibers that are exerting a fused tetanic contraction do not emit muscle sound during the plateau, a nonlinear component is introduced by motor units that fuse at different firing frequencies. This effect can be used to an advantage—the silence of muscle fibers during tetanic plateaus offers the opportunity to listen to late-recruited motor units selectively, an opportunity without an analog in electromyography.

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