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Foot & Ankle

Predictive Value of Manual Muscle Testing and Gait Analysis in Normal Ankles by Dynamic Electromyography

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ABSTRACT

Eight muscles about the ankle of seven normal subjects were assessed by electromyography (EMG) during manual muscle testing (MMT) and walking. Three strength levels (normal, fair, trace) and three gait velocities (free, fast, slow) were tested. The muscles studied included the gastrocnemius, soleus, posterior tibialis, flexor digitorum longus, flexor hallucis longus, anterior tibialis, extensor digitorum longus, and extensor hallucis longus. Relative intensity of muscle action was quantitated visually (using an eight-point scale based on amplitude and density of the signal). The data showed that EMG activity increased directly as more muscle force was required during the different manual muscle test levels and increased walking speeds. No MMT isolated activity to the specific muscle thought being tested. Instead, there always was a synergistic response. Both the gastrocnemius and soleus contributed significantly to plantarflexion regardless of knee position. The intensity of muscle action during walking related to the manual muscle test grades. Walking at the normal free velocity (meters/min) required fair (grade 3) muscle action. During slow gait the muscle functioned at a poor (grade 2) level. Fast walking necessitated muscle action midway between fair and normal, which was interpreted as good (grade 4).

Muscle function can be evaluated on qualitative and quantitative scales. Qualitative scales show presence and timing of muscular activity, while quantitative techniques measure intensity. Electromyography (EMG) is a means of measuring action potential of motor units in contracting muscle. Its main use has been on a qualitative rather than quantitative scale. Dynamic EMG has proven useful to evaluate abnormalities by identifying the configuration and timing of the muscle's electrical activity during gait in patients with spastic and neuromuscular disorders.[12,28] In addition to dynamic EMG, the timing of muscular activity during the gait cycle in normal and abnormal subjects has been evaluated by video, vector, and computer analysis.[4,12,14,21,30–32] Clinical decisions concerning surgical treatment are based on assumptions about the force balance, even though absolute values are not available. The ability and methods to meaningfully quantitate muscle action by dynamic EMG remain obscure. There is some controversy whether EMG can be quantitated. Inman et al.[20] felt that there was no quantitative relationship between EMG and tension if the muscle was changing in length. Their findings that short muscle lengths produce maximal signal while the longest lengths produce a reduced signal led them to this conclusion. However, the amount of variation in the shorter arcs of motion used for function was not evaluated. We feel that these changes in length are sufficiently small to allow meaningful quantification of muscular activity by dynamic EMG. This is particularly true during the stance phase when most activity is isometric or involves only 15° arc of motion at a relatively slow rate.

Prior attempts to interpret muscle force by EMG during submaximal exertion[11] and gait[10,14] use a scale of amplitude only or statistical regression analysis. Summation of action potentials involves an increase in density by greater signal frequency as well as an increase in amplitude. Computer analysis of raw EMG by integration, rectification, and other modalities exists.[3] These types of analysis require programming expertise, finances, computer equipment, and time. For more immediate quantitative interpretation of dynamic EMG by clinicians a visual analysis system would be valuable. Appropriate assessment of muscle action intensity should consider density as well as amplitude of the signal as both are modified by increased effort.

We feel that EMG can be used dynamically to quantify muscle action during gait as well as manual muscle testing (MMT). Muscle function can be measured in

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intensity by equipment such as Cybex and Orthotron (Lumex, Inc., Bayshore, N.Y.) isokinetically or Nautilus (Sports/Medical Industries, LeLand, Fla.) in a variable resistance isotonic exercise. The torque output of this equipment is commonly foot-pounds or newton-meters, and for functional interpretation and comparison, this must be normalized considering the subject's body weight or muscle size to accommodate anatomic differences. MMT provides a much more accessible means of evaluating muscle weakness, but this technique has been shown to lack specificity on the absolute force scale.[5] No direct measurement of muscle force during activity such as walking is possible (using the MMT, Cybex, Orthotron, or Nautilus testing methods). Dynamic EMG has this potential.

The ankle muscles were chosen for this study. The technique for testing muscles about the ankle is standardized, and comparison of force to normal reference ankles has been made.[5] The timing of activity and EMG of ankle muscles during gait has been well documented.[2,4,12,23,30–33] As the printed EMG record is the most readily available, that was the means for analysis of muscle action during MMT and gait.

The specific objectives of this study were as follows: (1) to assess the potential of EMG to measure relative intensity of muscle action during MMT and walking at varying speeds; (2) to examine the specificity and accuracy of muscular action during MMT; and (3) to determine the functional grade of muscles necessary to walk at slow, normal, and fast speeds.

MATERIAL AND METHODS

Seven normal subjects (four men and three women) performed eight isometric manual muscle tests about the ankle and walked at varying speeds. Simultaneous EMG recordings were made with wire electrodes inserted into the following ankle muscles: gastrocnemius, soleus, posterior tibialis (PT), flexor digitorum longus (FDL), anterior tibialis (AT), extensor digitorum longus (EDL), extensor hallucis longus (EHL), and flexor hallucis longus (FHL). All data were obtained from the right lower extremity during one testing session. The subjects underwent gait analysis and MMT, which was done by an experienced registered physical therapist. EMG recordings were made during walking on a 10-meter runway of which the middle 6 meters were designated by photoelectric cells as the steady state data area. All runs were repeated twice at slow, normal, and fast velocities. Contact closing foot switches were used to differentiate the swing and stance portions of gait.[28]

Three levels of effort were assessed according to the muscle grading system of Daniels, Williams, and Worthingham (Table 1). The three grades were maximal resistance (normal), antigravity (fair), and palpable contraction (trace). Except for the gastrocnemius and soleus, all muscles were tested prone or sitting with knees flexed 90° to be antigravity for the fair grade. The gastrocnemius and soleus muscles were tested with the subject standing for the normal and fair grades. For a maximum effort, the gastrocnemius was tested with knees extended while the examiner pushed downward on the shoulders as the subject attempted heel raises. The soleus was tested at maximum grade similarly, except the knees were flexed 40° to 60°. Fair tests for gastrocnemius and soleus were done standing with heel raises performed against gravity with knees extended and flexed, respectively. The remainder of the six ankle muscles were tested with resistance supplied by the examiner's hand (J.G.) at the normal, fair, and trace levels.

TABLE 1
Muscle Grading Scale[4] (of Daniels, Williams, and Worthingham)

Grade	Letter	Definition
Normal	N	Complete range of motion against full resistance and gravity
Fair	F	Complete range of motion against gravity
Trace	T	Evidence of slight contraction by palpation, but no joint motion

Four muscle recordings were done simultaneously. The signals were amplified by a factor of 1,000 and transmitted by a four-channel telemetry system allowing for visual output on an oscilloscope and simultaneous recording on seven-channel analog tape.[28,29] The electrodes consisted of a pair of 50-μ, nylon-coated, nickel alloy wires with 2.5-mm barred tips.[4] Correctness of wire electrode placement was confirmed by visualizing the oscilloscope for adequacy of electrical signal and by observing ankle or foot action after electrical stimulation. From subsequent visicord paper displays, the data were interpreted visually by one investigator (M.L.I.).

An eight-point scale was devised to quantitate the EMG recordings. Equal importance was given to amplitude and density. The amplitude was measured in millimeters (mm) and assigned a number on the four-point scale. Amplitude of 1 mm was a 0.5 score, 2 mm was 1, and for each additional millimeter a 0.5 increase in score was given. Two sets of millimeters were assigned the same score: 4 mm and 5 mm was 2, and 7 mm and 8 mm was 3. Density also was assessed visually on a four-point scale in increments of 0.5 based on compactness of the EMG signal over the entire 2-sec recording of the MMT and through the period of maximal activity during gait. Zero on the density scale was no signal, two was 50%, and four indicated maximal activity as evidenced by darkening of the record. For the final rating, each muscle was given maximal value by adding the amplitude and density scores, and percentage was calculated by dividing this value by 8. Scoring for all data was repeated during three separate settings. As there were such minor discrepancies in either the amplitude or density when compared, the initial score was used. The data were normalized by the investigators similar to rectification and integration computer analysis.[3] To test the consistency of the scale, a second method of quantification was used to assess gait. A comparison of EMG signal at each of the three velocities of gait to the MMT data was made. For each muscle, maximal activity during the three gait velocities was compared to activity during MMT. This assessment was recorded as trace; less than, equal to, greater than fair; or normal muscle grade.

RESULTS

The intensity of the EMG signal consistantly increased with muscular effort during both the manual muscle testing and walking at faster speeds (Table 2).

Manual Muscle Test Specificity

The difference between normal, fair, and trace MMT grades were statistically significant ($P < 0.001$) for all eight muscles tested as well as visibly distinct (Figs. 1–3). Grade fair for the small muscles averaged 47% of the grade normal effort. Higher values were found for both the gastrocnemius and soleus (66%). There was a recordable amount of activity at the trace level in most tests ranging from 4% to 19%.

None of the MMTs proved to be specific for the designated muscle. Flexing the knee to differentiate soleus and gastrocnemius action was ineffective. The soleus was equally active in both tests, and knee flexion reduced gastrocnemius activity only 15%. In addition, maximum testing for every muscle was accompanied by significant synergistic activity (average, 55% intensity) (Table 3). Even the antagonistic FHL muscle evidenced a 31% activity level when AT was tested at maximal effort.

Gait

While there was some variation in the subjects' chosen gait, all of the velocities and cadences exhibited a statistically significant ($P < 0.001$) difference comparing fast, free, and slow (Table 2). Their fast velocity averaged 116 meters/min, which was 137% of normal walking velocity. Free walking, averaging 80 meters/min, was 94% of normal velocity. During slow walking the subjects averaged 56 meters/min, a reduction to 67% of normal velocity.

The intensity of activity by EMG increased consistently in each muscle as the subjects walked faster. For the gastrocnemius and soleus the incremental difference was less but still significant compared to the other six muscles. The increase in absolute scores was statistically significant ($P < 0.005$) for the gastrocnemius and soleus. The differences of intensity at the three gait speeds among PT, FDL, AT, EDL, EHL, and FHL were more significant ($P < 0.001$).

Manual Muscle Testing Equivalent to Gait

The three manual muscle tests showed distinctly different EMG patterns (Figs. 1–3). While there were individual differences, comparisons between the EMG recorded at the varying gait velocities and the subjects muscle test grades confirmed increased intensity of muscle action at the faster walking speeds (Figs. 4 and 5). During fast walking the majority of the muscles (27) evidenced greater EMG activity than the fair muscle test value. Sixteen equaled fair and 12 were close to normal muscle grade. Only one was less than fair (Table 4). When the subjects walked at their normal free velocity, most muscle activity was equivalent to the fair grade (23), with equal numbers less than (15) and greater than (15) fair (Table 4). Visual comparison of electrical activity of the ankle muscles at the slow speeds demonstrated a corresponding reduction in intensity. During slow gait more muscle function was less

Fig. 1. EMG activity of AT during trace level MMT.

Fig. 2. EMG activity of AT during fair level MMT.

Fig. 3. EMG activity of AT during maximum level MMT.

TABLE 2
Comparison Velocity, % Normal, Cadence in Fast, Free, and Slow Gait

Gait speed	Velocity average (meters/min)	% Normal velocity	Cadence (steps/min)	Stride length
Fast	116	137	134	1.670
Free	80	94	110	1.483
Slow	56	67	91	1.235

TABLE 3
Muscle Action During Maximum MMTs[a]

MMT	Group I					Group II			
	Gastrocnemius	Soleus	PT	FDL		AT	EDL	EHL	FHL
Gastrocnemius	(86)	83	55	56	AT	(88)	90	75	31
Soleus	68	(75)	51	55	EDL	89	(98)	94	17
PT	44	43	(80)	80	EHL	63	76	(91)	1
FDL	33	24	48	(64)	FHL	36	43	13	(89)

[a] Numbers in parentheses refer to percent activity of specific muscle being tested; other numbers refer to percent activity of muscles not being tested but active when muscle on left tested.

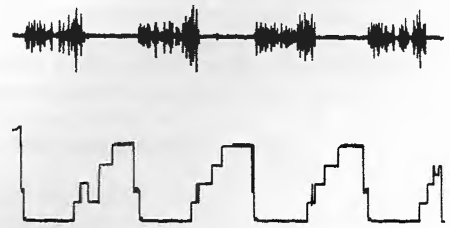

Fig. 4. EMG activity of AT during free (normal) walking.

Fig. 5. EMG activity of AT during fast walking.

than fair (24) than equaled this effort level (18), with only three registering functional level fell between fair and normal, thus approaching good manual muscle test level (69%). Normal free walking velocity required a fair effort (58%), while a slow pace approximated grade poor (43%). During the fast and free speed of walking, the dorsi and plantar flexor muscle groups responded similarly. With a slow pace, however, the pretibial muscles remained at the fair level, while the plantar flexors functioned less than fair. A difference between gastrocnemius and soleus activity also was evident. The soleus persisted at the vigorous heel rise level for both fast and free walking, whereas the gastrocnemius was less than fair for both free and slow gait.

TABLE 4
MMT Equivalent of Gait

	Trace	Fair−	Fair	Fair+	Normal
Fast gait					
Gastrocnemius		1	4	1	1
Soleus			4	1	2
PT			1	3	3
FHL				5	2
FDL			1	3	3
AT			3	4	
EDL			1	6	
EHL			2	4	1
Total		1	16	27	12
Free gait					
Gastrocnemius		5	1	1	
Soleus		2	4	1	
PT		2	4	1	
FHL			1	6	
FDL		4			3
AT		2	2	3	
EDL			6	1	
EHL			5	2	
Total		15	23	15	3
Slow gait					
Gastrocnemius		5	1		
Soleus		5	1		
PT		5	1		
FHL		2	2	2	
FDL	1	1	3	1	
AT		2	4		
EDL		2	4		
EHL		2	4		
Total	1	24	20	3	

DISCUSSION

Other investigators have performed similar studies.[1,6–9,13,15,16–19,22,24–27] This study is unique because it has provided a more objective perception of manual muscle tests, visual interpretation of dynamic EMG, and the level of muscle function during walking.

All of the manual muscle tests proved only semiselective. While each procedure (except the soleus test) elicited the strongest reaction from the designated muscle, none excluded significant activity by other muscles. To the contrary, most of the available synergists participated at a fair (grade 3) level. Thus, interpretations of manual strength testing must be supplemented by observation of muscle tissue contractions and palpation of tendon tension to different muscles under pathological conditions.

According to the visual quantitation scoring used in this study, fair (grade 3) strength for the gastrocnemius and soleus equaled 66% of maximum. This finding is considerably greater than the 35% value Beasley reported. Several factors contributed to this discrepancy. Beasley used a force sensor to directly determine the strength represented by the manual muscle tests. Also, his levels of weakness were the maximum capability of persons with residual paresis from poliomyelitis, and these were compared to the maximum strength of a group of unimpaired persons. All the data were adjusted for subject differences in weight and height. In our study normal subjects were asked to produce fair and trace efforts. Presumably, this would avoid intersubject bias. Review of the video recordings, however, revealed that in their fair efforts these normal persons moved more briskly than a polio patient would and stretched to assure the full range had been completed. Hence, their muscular exertion was a vigorous fair, more likely equally a fair plus grade.

A second problem was the difficulty of determining maximum ankle plantar flexor strength by manual testing. Beasley's quantitation found the manual grade of normal (grade 5) represented only 80% of true normal. The clinical tests used to differentiate fair and normal triceps surae performance rely on repetition of the same task. One complete heel rise earns a fair grade. Ten successful repetitions is called normal strength. For EMG comparison it was necessary that we have a single value. This was obtained by giving maximal manual resistance against the subject's heel rise effort. The results suggest that maximum capability was not challenged.

The relative intensity of calf muscle activity identified during walking (68% maximum) is consistent with the levels reported by Dubo et al.[14] who also used visual grading of their EMG records. To simplify the interpretation their data were electronically integrated to provide a linear display of the EMG. Intensity of action was judged by amplitude. They found peak activity for both the gastrocsoleus and anterior tibialis muscles to approximate 70% of maximum. These values are inconsistent with energy cost thresholds. Muscular effort of this magnitude represents strenuous activity which could be sustained for just a very few minutes rather than being the customary "tireless" walking pattern. This implies that momentary peaks of recorded EMG are more representative of the fibers in immediate proximity of the electrodes than general muscle action. Thus, the data need to be averaged over pertinent time intervals, consistent with rates at which muscles change their force.

By relating the quantitated EMG values for the gait data to those obtained with the manual muscle test, the numerical confusion was circumvented. By this technique the peak intensity of muscle action during free walking was found to approximate the vigorous fair (grade 3) effort of normal persons utilizing low energy costs.

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