EMG System Performance

By Motion Lab Systems, Inc.
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EMG Quality Assurance

Introduction

This document describes a series of simple tests that will verify that your EMG system is working correctly in a biomechanics, gait, or research environment. The discussions here provide the basic information necessary to demonstrate that your EMG system meets the requirements for the Commission for Motion Laboratory Accreditation, Inc. (CMLA) certification.

While the tests are specific to Motion Lab Systems MA300/400 systems, the tests described can apply to any EMG system used in a research, biomechanics or gait testing environment.

These tests assume that you have a Motion Lab Systems EMG system connected to an analog data collection (ADC) system and that you can visually monitor the all of the signals applied to the ADC. While many commercial motion capture systems offer an option to monitor any analog signals collected by the motion capture system, in general these Motion Capture analog monitoring systems are relatively low quality and may not provide the accuracy that a separate analog data collection system that is devoted to analog data, and not 3D data, offers.

The illustrations shown in these tests have been recorded using a DI-720 ADC sub-system (manufactured by Dataq Instruments) that provides accurate, real-time, live display and recording of up to 32 channels of high speed analog data.

If your motion capture ADC system does not provide an accurate real-time view of the data then you may need to record the signals described in the following tests and then inspect them post-collection, or purchase a separate ADC system that allows you to review the EMG signals in real-time to verify the system performance. For clinical and research use it is recommend that you always monitor the EMG signals in real-time as this enables you to verify that the motion capture system is being...
presented with accurate data to make good EMG recordings that contain clinically accurate EMG signals.

Common problems with viewing analog data with motion capture systems are that the analog data may be displayed at a low sample rate and “auto-scaled” to fill the display. Both of these “features” can make it very difficult to verify the accurate sampling of the analog data and can cause a loss of resolution in the displayed data, even if the data is being sampled at an adequate rate. Auto-scaling of the analog data display can make it difficult to determine the magnitude of the sampled data and frequently results in EMG data that is either distorted or has lost resolution because the ADC input range has been configured incorrectly.

Basic Functionality Tests

The tests described here are specific to the MA300 and MA400 systems but similar tests can be performed with any EMG system to verify basic operation.

To perform a basic MA300 or MA400 system functionality test, start with all pre-amplifiers, event switches, and any auxiliary connectors disconnected from the backpack unit (BPU), and then use the coaxial cable to connect the BPU to the desktop unit (DTU). Connect the DTU to the AC power and turn the AC power on, verify that the Power light is green on both the BPU and DTU. This indicates that both units have functioning power supplies and that the coaxial cable connecting the two units has continuity. This is a basic system test so if you are using the radio telemetry option with separate transmitters and receivers then disconnect them and perform these tests using a direct cable connection. Once you have verified the performance with a direct cable connection then only a simple test is required to confirm that the telemetry link is functioning.

With the DTU turned on and the green DTU power light illuminated, verify that the orange No Sig. and C.R.C lights on the DTU are both off. This indicates that the BPU and DTU are connected, and that the DTU is receiving error free data from the BPU. The BPU continuously streams data to the DTU regardless of whether any pre-amplifiers are connected to the BPU so these lights will always be off in normal, error free, operation. This also confirms that the coaxial cable is in good condition and that the BPU is generating a valid signal that is detected by the DTU.

The next step is to briefly disconnect the BPU from the DTU by uncoupling the coaxial cable from the BPU – as soon as the coaxial cable is disconnected from the BPU the orange No Sig. and C.R.C lights on the DTU should both turn on and will immediately turn off again when the cable to the BPU is reconnected. This confirms that the orange warning lights and error checking circuitry in the DTU are both functioning correctly. When the DTU is connected to the AC power and switched on with the BPU and DTU connected and functional, the green AC power light will always be on and both the orange No Sig. and C.R.C lights on the DTU should be off during normal error-free operation.

At this point we are confident that the Motion Lab Systems EMG system power supplies and internal circuits are functional. You can now connect the analog output of the EMG system to your ADC - the exact connections will vary with each ADC manufacturer - full pinout and connection details of your EMG system output signal assignment can be found in the EMG system User Guide. All Motion Lab Systems EMG systems are supplied with an analog output cable - this is available with either BNC or pin terminations and allows the user to test and measure the EMG signal output for fault-finding and performance verification.
Note that the analog output on the back of the DTU is electrically isolated from the subject connected backpack with an impedance of 10,000,000 ohms - this can be confirmed using a standard electrical multi-meter to measure the resistance between the coaxial connector on the rear of the DTU and the analog output connector casing directly below the coaxial connector. A full patient safety electrical isolation test may be performed by your biomedical electrical safety department according to their requirements and local regulations.

Federal and local regulations may require that all electrical equipment used in a clinical environment with human subjects is powered with hospital-grade AC line cords that verify the correct AC connections, and may prohibit the use of banana plug connectors with exposed metal surfaces for all electrical connections to a subject. All Motion Lab Systems backpacks use standard DIN 42802 touchproof connectors to comply with federal regulations and maintain patient safety.

Figure 2 - Medical leadwires connected to the subject should meet IEC/EN 60601-1 standards

Analog Data Collection Configuration

The tests described above have demonstrated that the EMG system powers up and that the DTU and BPU are connected and appear to be functioning, so the next step is to examine the analog signals generated by the EMG system.

Before you start to test the EMG system it is essential that the analog data collection system that you are using to record and or view the EMG system signals is set up correctly. The options controlling your analog data collection/sampling system will vary with each ADC or Motion Capture System manufacturer and it is best to check with the analog data collection system supplier for their recommendations to configure the ADC system to collect and store accurate EMG data. There are two basic factors that are very important for both accurate data collection and live EMG data monitoring.

Analog Range

The analog collection system that a Motion Lab Systems MA300 or MA400 EMG system is connected to should be configured to have an input range of ±5 Volts. This matches the output range of the MA300/MA400 EMG system which is ±5 Volts and therefore the ADC uses the full sampling measurement range to record the EMG signals. If the ADC input range is configured to be higher (typically ±10 Volts) then you will lose ADC resolution, reducing your EMG measurement resolution by 50%.
If the ADC range is lower (typically ±2.5 Volts or ±1.25 Volts) then it is very likely that the recorded EMG signal will be occasionally clipped and you will lose EMG signal information. The description of the ADC input range varies with different manufacturers systems, some ADC systems display a “gain” rather than an input range which means that you must check with your system supplier to verify the relationship between the ADC input range and the gain – typically the ADC range defaults to ±10 Volts with a gain of x1, setting the “gain” to x2 would then set the ADC range correctly to ±5 Volts. You may need to check with the ADC system manufacturer to verify the relationship between the gain and the ADC range in order to configure your ADC correctly. You can easily verify that the ADC range is correct by disconnecting the EMG pre-amplifiers from the EMG system BPU and setting each EMG channel gain to the maximum (gain setting #9 on the BPU). Then press the Test button on the BPU while monitoring the ADC signal.

The Test button on the EMG system BPU located to the right of the power light at the lower side of the BPU. The Test button is recessed; you will need a paper clip or small screwdriver to press the button. Note that the signal levels shown below are only valid when all the preamplifiers are disconnected from the BPU.

Pressing the BPU Test button, with the preamplifiers disconnected, applies a 78Hz sine-wave to all the EMG channels, at a level that generates a sine wave signal that will almost completely fill the ADC range when the BPU is set to maximum gain (each BPU channel gain switch set to #9) if the ADC input range is set correctly.

However if the ADC range is ±10 Volts then the Test signal will not fill the display and you will be losing signal resolution as shown above on the left. If the ADC range is less than ±5 Volts the test signal will be clipped causing the signal to be distorted as shown above on the right. When the ADC input range is set correctly then you will see the display in the center where a pure sine wave almost completely fills the available ADC range when the BPU Test button is pressed with the individual BPU channel gains set to #9.

### Analog Sampling Rate

In order to accurately record the EMG signal you must sample the analog data from the EMG system at a rate that is at least twice the bandwidth of the signal applied to
the ADC - this is called the *Nyquist Rate* and is the minimum sampling rate at which a signal can be recorded without introducing errors. For typical surface EMG recordings an ADC sample rate of 2000 samples per second per channel may be acceptable if you are confident that the signal does not contain any frequency content above 1 kHz. In general a sample rate of at least 5000 samples per second per channel is recommended to guarantee a clean, accurate, and alias-free EMG signal - this produces an analog data collection bandwidth of 2.5 kHz which, in combination with the default low-pass filters in the EMG system eliminates the possibility of signal alias errors in the recorded signal.

The first illustration below shows an EMG simulation test signal recorded with a sample rate of 1000 samples per second, while the second illustration shows the same test signal recorded at 100 samples per second – resulting in an aliased signal due to the low sample rate. Aliasing errors corrupt the recorded signal and result in subtly misleading data, presenting data that may appear to look like an EMG signal, but in reality bears very little relationship to the actual EMG data.

![Figure 4 - The Whisper EMG test signal sampled at 1000 samples/second.](image)

![Figure 5 - The same EMG test signal sampled at only 100 samples/second.](image)

Depending on the ADC specification, and controls available to you, you may have to perform the tests described above on each individual EMG channel. Most analog recording systems will use a common sample rate for all the analog channels but some systems may have individual channel gain settings (sometimes called “range”) on each of the individual analog channels. All analog channels must be set to record a signal range of ±5 Volts.

When setting the analog collection system sample rate, you must verify that each individual analog channel is sampled at a sufficiently high enough rate - some ADC manufacturers specify the individual sample rates per channel, while others specify a total throughput or sample rate for all of selected channels. If the ADC system sets a single sample rate as a throughput (i.e. the total number of samples times the total number of channels) then you may inadvertently set the rate too low.
For example a throughput sample rate of 4000 samples per second would be good for a single analog channel but would result in an individual channel sample rate of only 250Hz when sampling data from 16 analog channels (4000/16=250) resulting in an EMG bandwidth of only 125Hz (250/2=125) which is far too low and will result in aliasing generating errors in the recorded signal.

MA300-X systems have a fixed signal bandwidth of 1 kHz so a sample rate of at least 2000 samples per second per channel or higher is needed for accurate EMG data collection. Sampling at much lower rates may lead to analog aliasing artifacts in the recorded EMG signals.

MA400 systems include a variable low-pass filter in the Backpack that can be set to one of eight values from 350Hz to 2000Hz to limit the high frequency content of the EMG signals. A sample rate of at least 4000 samples per second per channel will work for any low-pass filter setting but if you are only recording surface EMG signals then it would be quite reasonable to set the low-pass filter to 500Hz and reduce the ADC sample rate to 1000 samples per second per channel.

The Nyquist frequency is half of the sampling rate of the ADC, sometimes called the folding frequency because any signal applied to the ADC at a higher frequency that the Nyquist frequency will be folded back to a lower frequency – for example if the ADC sample rate is 1000 samples per second then the Nyquist frequency is 500Hz and if the signal applied to the ADC contains a frequency of 600Hz then the ADC will record this as a 100Hz signal, an issue commonly called “analog aliasing.”

It is important to note that setting the ADC sampling rate to the Nyquist Rate is the only the minimum permissible sampling rate and the ideal sample rate for EMG data should always by higher than the Nyquist Rate.

EMG System Configuration

The next set of tests require that you can observe all of the analog output signals from the EMG system using your ADC - how you do this will vary depending on your hardware and/or data collection/recording system. Ideally you want to be able to view the output from all of the EMG system channels in real-time but if you cannot view, or monitor, all of the EMG signals in real-time then you will have to record the analog data from all of the channels during each of the following tests and visually examine the data before proceeding to the next test.

It is important to note that at this stage we are verifying the general operation, connection and configuration of the EMG system in conjunction with a third-party data collection system. Motion Lab Systems EMG systems are designed to be used with a wide variety of different analog data collection systems so the precise details of your configuration will almost certainly differ in some respects. Regardless of this, the general principles described here should work in most environments. Every attempt has been made to keep these tests simple to perform with a minimum of test equipment. The illustrations shown in these tests have been recorded using the MA720 (Dataq) ADC sub-system configured to display multiple analog channels simultaneously. The ability to monitor the full bandwidth of the live EMG signal is a great benefit and allows easy monitoring of the EMG data during subject data collections.

Verify the analog channels are connected

At this point we are testing only the BPU and DTU; the EMG pre-amplifiers should not be connected yet. While observing all of the analog signals, briefly turn the AC power to the DTU off, and then back on again - this will cause a power up transition to appear on all of the EMG channels as the DTU powers back up. This will appear...
as one or two series of spikes depending on the instant when the AC power is turned back on.

The power-on pulses that are recorded on each EMG channel should appear simultaneously and should have almost exactly the same amplitude. This test demonstrates that you are looking at the correct analog channels, connected to the ADC and that they are connected to the DTU with the ADC configured correctly to preview or record the correct channels. A subsequent test will verify that each of the individual EMG channels is connected to a specific ADC analog channel.

If you do not have the ability to visually monitor the live EMG signals then you may need to configure your data collection system to start recording analog data before performing the test as described above and then, once the test is completed, review the recorded results after the data collection using the motion capture or data collection system manufacturers review methods.

**Verify the ADC channel gain range**

Once you can confirmed that the ADC system is connected to the correct analog channels set all the gain controls on the BPU to the highest gain setting (#9) and, with all of the EMG pre-amplifiers disconnected from the BPU, observe the analog signals from the EMG system while pressing the Test button on the BPU. While the Test button is pressed, a 78Hz sine wave, equivalent to 156uV at skin surface, is applied to all of the EMG channels and will appear amplified to a high level on the DTU analog outs. The test signal is independently applied to each EMG input on the backpack so it is essential that the EMG pre-amplifiers are not connected during this
test as leaving a pre-amplifier connected could inject an external signal and will attenuate the test signal amplitude.

The result will be a sine wave appearing on each of the EMG system analog channels with an amplitude very close to ±5 Volts that almost completely fills the analog channel display if the ADC input range settings have been set correctly.

![Image of EMG System](image)

*Figure 7 - Pressing the BPU Test button fills the EMG channels when they are set to gain #9*

This test confirms the EMG signal path from the BPU inputs, through the DTU, to the data collection system ADC and shows that all of the analog channels on the ADC are functioning and set to the correct input range.

**Verify the analog channel offsets**

Now that we are confident that we are looking at the correct EMG channels and the ADC input range is correct, keeping the EMG pre-amplifiers disconnected, set all the gain controls on the BPU to the highest gain setting (#9), and the DTU high-pass filter (MA400 systems only) set to DC. Observe the analog signals on each EMG channel and check that the analog output from each analog channel connected to the DTU is within 100mV of 0 volts. This checks that the analog signals from the EMG system do not have any significant DC offsets. It is a simple test if you have a real-time display that displays the voltage level of each channel, otherwise you can measure each channel individually with a DC voltmeter and confirm that it has a value close to zero volts.
Verify the analog channel assignments

While keeping all the BPU gain controls set to maximum, connect an EMG pre-amplifier to the first EMG channel on the BPU and touch one of the pre-amplifier inputs with your finger. This will inject a high level of AC line noise (50 or 60Hz) into the first EMG channel on the BPU.

Verify that the ADC (and/or data collection system) you are using with your EMG system with, displays and records the AC line noise on the expected channel. This test confirms that each EMG output is connected to the correct ADC channel, and verifies that the applied signal only on the channel that the preamplifier is connected to and does not appear on any other channel.

Repeat this test for all EMG channels, using only a single pre-amplifier connected to the BPU at a time, to ensure that only one channel is active at a time. This confirms that each EMG channel is connected to a single analog channel. Document this configuration as it is important in research and clinical use to know exactly which muscle is associated with a specific analog channel.

In addition to identifying each individual analog channel, these tests have verified that, even at maximum gain, there is no cross-talk from one channel to another and that EMG data is only associated with a specific analog channel. Even a very large signal applied to one analog channel should not cause any disturbance on any other EMG channel.
Verify the EMG preamplifier functionality

Reset the gains on all the EMG channels to a lower value (2 or 3 normally) and test each of the pre-amplifiers, one at a time on the same channel, with the pre-amplifier connected to a muscle. An external ground electrode will be needed at this point. Surface pre-amplifiers can usually just be pressed against a muscle on the skin surface and adhesive silver/silver chloride (Ag/AgCl) gel electrode can be used for snap lead pre-amplifiers. Fine-wire pre-amplifiers can usually just have their metal connection posts pressed against the skin surface over a muscle site to obtain an EMG test signal. The abductor, adductor, flexor, and opponens pollicis group (your thumb texting muscles) are a convenient source of EMG for these tests.

This test has two phases; first you check for a flat baseline with no muscle activity (thumb relaxed) and then look for a clean EMG burst when the thumb is tensed. This test provides a quick verification of the performance and functionality of each pre-amplifier.

When you have completed these tests you should be able to record excellent EMG signals. Please contact Motion Lab Systems if you have any questions, any problems completing these tests, or you are not happy in any way with the quality of the EMG data from your system. At this point, generally in less than an hour, you have completed a functional test of the EMG system and your analog data collection system. The only remaining EMG question is what gain settings are appropriate in day to day use. In general, each EMG channel gain should be set so that the EMG signal for the channel is visible but does not clip-clipping occurs when the gain is too high to reproduce the EMG signal. If in doubt, set the channel gain on the BPU to a lower setting. A gain setting between 2 and 4 will work for most situations, the higher gains are normally only needed for small, weak, or atrophied, muscles.

When you have completed these tests you have demonstrated that the system is working and you should be able to record excellent EMG signals. Additional tests that document the performance of the preamplifiers and the EMG system at a technical level are described in the next chapter. Please contact Motion Lab Systems if you have any questions, any problems completing these tests, or you are not happy in any way with the quality of the EMG data from your system.
System Measurements

Introduction

The previous tests demonstrate that the EMG system is functional and operational. If the tests have been completed successfully, you should be able to record EMG data, with the confidence that the EMG activity is being reliably recorded.

However, the tests described in the configuration chapter do not attempt to calibrate the EMG system. Calibration means that you have a record of a comparison of two measurement devices, one of known uncertainty (the EMG system) and one of known certainty (your measurement equipment). In the sense that the term calibration is legally used by the FDA, Motion Lab Systems EMG systems are not calibrated systems as the measurements performed by the system are not directly documented as traceable to the National Institute of Standards and Technology (NIST), formerly known as the National Bureau of Standards.

Technically, Motion Lab Systems EMG systems perform “observation and sampling” of the EMG signal but, since the precise amplitude of the EMG signal is dependent on a great number of external factors - notably electrode placement relative to the muscle and differing quantities of adipose tissue between subjects, there is no requirement, or advantage, to having the expense of a NIST traceable calibration record for your EMG system. Instead of maintaining NIST calibration records, the following instructions document procedures that a user can perform to have complete confidence that a Motion Lab Systems EMG system has an acceptable, and documented, degree of observational accuracy.

These described at a basic technical level, use a Model 220 Biomedical Function Generator (manufactured by Medi Cal Instruments, Inc. Lewis Center, OH) with a set of ECG snap lead to banana-plug adaptors, a Tektronix dual channel, digital oscilloscope (the TBS1052B includes many useful measurement functions) and optionally, an inexpensive Pulse Generator.

EMG System Gain Verification

Each EMG channel on an MA300/400 EMG system has ten gain settings - the tests described allow you to determine their accuracy by applying a known input voltage to the system and measuring the signal at the analog output. This is a simple calculation, Gain = V_{OUT}/V_{IN} although performing it for each gain setting on every EMG channel will be quite tedious. Verifying ten individual gain settings on sixteen EMG channels requires 160 individual measurements and calculations.

If you are testing an EMG system with a user adjustable low pass filter (Anti Alias Bandwidth switch on the BPU) then it should be set to the highest value (#0, i.e. 2kHz on the MA300/400 BPU). If you have a user adjustable high-pass (Artifact) filter, it should be set to the lowest value (25Hz) or disabled (DC) to avoid the filter interacting with the gain tests. The gain tests described are performed around 200Hz, a frequency that is least affected by any EMG system filtering.
Set the Model 220 Biomedical Function Generator to generate a 200Hz differential sine wave with a signal amplitude of 10mV, and connect the oscilloscope to the DTU analog output of the channel that you are testing. If necessary you can purchase a BNC connector analog output cable from Motion Lab Systems.

Use the Tektronix TBS1052B autoset function to configure the display range, manually adjusting the horizontal and vertical display scales if necessary. Use the Tektronix TBS1052B oscilloscope measurement functions to display the peak-to-peak output voltage and frequency as shown in the illustration above once a preamplifier is connected to the function generator.

Connect a pre-amplifier to the associated EMG channel on the BPU with the gain switch set to #0 and apply the differential Function Generator signal to the pre-amplifier inputs to obtain a clean sine-wave signal using the Function Generator with a set of snap lead to banana plug adaptors. Use the push button switches to select a
sine-wave signal and differential output mode – all Motion Lab Systems preamplifiers feature a differential input design so it is essential that the test signal applied to the preamplifiers is also differential for accurate test results.

Set the amplitude of the differential signal to 1.0 mV using the rotary amplitude switch. Select the 100-1K frequency range and set the frequency to 200Hz with the rotary control on the right side of the instrument.

If you are testing the MA420 or MA422 snap lead pre-amplifiers then these can be connected directly to the snap-lead adaptors, while MA411 pre-amplifiers will need to be manually held against the output terminals during the test. You will need to connect the Function Generator ground (black terminal) to the BPU ground (green touch-proof socket on the BPU) to the Function Generator ground (black terminal) to obtain a clean signal.

You can purchase a DIN touch-proof connector to banana plug lead from Motion Lab Systems if necessary.

Be careful not to touch the preamplifier inputs, or the signal generator contacts, when applying the signal to a preamplifier.

Figure 11 - A preamp can be held against the inputs to apply a differential EMG level signal.

Once the differential test signal is applied to the preamplifier and you have all the connections set to produce a clean sine wave on the oscilloscope, you can read the peak to peak voltage from the oscilloscope screen measurement – note that we are measuring the Peak to Peak signal voltage level for this test and all related measurements must use the same signal processing.

Record the EMG system gain switch setting, the signal voltage level generated by the Function Generator, and the Peak-Peak output voltage measured by the oscilloscope. Then select the next gain switch setting and, without adjusting the oscilloscope range, reduce the input voltage from the Medi Cal signal generator to obtain a clean sine wave signal without clipping or distortion. Repeat this procedure for each gain setting on the EMG system that you need to test, recording the voltages and switch settings each time.

Once every switch setting has been tested, the gain settings for each channel can be calculated - The numbers shown below are taken from one channel of a typical
MA400 EMG system with a differential, 200Hz sine wave generated by the MediCal signal generator applied to the inputs of a pre-amplifier (Vin), and the signal at the analog output connector of the EMG system (Vout) measured by a Tektronix TBS1052B digital oscilloscope. The gain calculation is Vout/Vin.

<table>
<thead>
<tr>
<th>Switch</th>
<th>Input V(Pk-Pk)</th>
<th>Output V(Pk-Pk)</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.010</td>
<td>4.72</td>
<td>476</td>
</tr>
<tr>
<td>1</td>
<td>0.003</td>
<td>6.52</td>
<td>2173</td>
</tr>
<tr>
<td>2</td>
<td>0.001</td>
<td>4.32</td>
<td>4240</td>
</tr>
<tr>
<td>3</td>
<td>0.001</td>
<td>5.96</td>
<td>5960</td>
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<tr>
<td>4</td>
<td>0.001</td>
<td>7.52</td>
<td>7520</td>
</tr>
<tr>
<td>5</td>
<td>0.0008</td>
<td>7.08</td>
<td>8850</td>
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<tr>
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<td>0.0005</td>
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<td>12080</td>
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<td>6.92</td>
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<td>7.08</td>
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<tr>
<td>9</td>
<td>0.0003</td>
<td>5.88</td>
<td>19600</td>
</tr>
</tbody>
</table>

The individual gains can be verified by a simple output/input=gain calculation.

These numbers indicate that the system is performing correctly but do not exactly match the numbers printed on the front of the BPU. This is normal, and is a result of a number of factors that interact to cause a difference between the expected numbers and the measured results.

The two principle factors affecting these results are that the gain of the pre-amplifier and the gain of the EMG system both have tolerances. A 20x gain pre-amplifier has an accuracy tolerance of ±2% which means that the gain of the pre-amplifier will be between 19.6 and 20.4 - this is only a very small amount but this difference is amplified by the gain of the EMG system (BPU and DTU), thus for gain setting #4 (8000) the actual gain will be between 7840 and 8160 if the EMG system had a gain of exactly 400. However the EMG system gain has a ±5% tolerance and therefore can be between 380 and 420 yielding a potential total gain range from 7440 to 8568.

These calculations assume that the Function Generator creating the signal, and the Oscilloscope measuring the signal, are both generating, and measuring, perfectly accurately but these instruments also have measurement tolerances (typically an additional ±2%) which can further affect the measured numbers particularly since the signal levels being measured are very low. In addition external noise sources (AC power line noise), the frequency, and the signal type used to perform the test, will also affect the numbers.

The lesson is that absolute gain accuracy is very difficult to achieve, and even harder to verify. However the measured results of this test confirm that the EMG system is performing as expected - in this case, each gain setting from 0 to 9 produces a higher measured gain that is within the anticipated system tolerance for each setting. You can repeat these measurements for each EMG channel if desired.
Pre-amplifier Common Mode Performance

The Model 220 Biomedical Function Generator can generate both differential signals where the output appears between the two red banana connectors, and common reference signals where the output appears simultaneously on the two red connectors with reference to the common black (ground) connector. This second mode (non-differential) allows us to evaluate the common mode rejection ratio (CMRR) of the pre-amplifiers used by the EMG system using the same experimental conditions that have generated the gain figures above.

The CMRR of an EMG pre-amplifier describes the ability of the pre-amplifier to reject signals that appear simultaneously on both amplifier inputs. Typically in EMG recordings this is a measure of the pre-amplifiers ability to reject AC line signals and is defined as the ratio of the powers of the differential pre-amplifier gain ($A_d$) to the common-mode gain ($A_{cm}$), measured in decibels:

$$CMRR = 20 \log_{10}\left(\frac{A_d}{A_{cm}}\right) \text{dB}$$

Since we are only measuring the CMRR of the pre-amplifier, the EMG system gain is not a factor in the calculations. We can perform this test at a single BPU EMG channel gain setting as we have already measured the gain with a differential signal applied (a gain of 504 with a 10mV input at #0 in the previous section). Applying a differential 10mV, 200Hz sine wave to the pre-amplifier inputs and verify the output signal level - in this example 5.04V out yields a system gain with a differential signal ($A_d$) of 504.

Press the Model 220 Function Generator DIFF / COMM switch IN to generate a common mode output, thus applying a 10mV sine wave signal to both pre-amplifier inputs simultaneously with reference to the ground to measure the common mode gain. If the pre-amplifier is functional then it will have a very low common mode gain and you will see a flat line - no output. Increase the voltage of the sine wave applied to the pre-amplifier to ±10Vpp by releasing the V / mV switch on the Function Generator and use the oscilloscope measurement function to measure the size of the resulting output voltage. This should be a small voltage, in this example 280mV yielding a common mode gain ($A_{cm}$) of 0.028, allowing an estimation of the Common Mode Rejection Ratio:

$$CMRR = 20 \log_{10}\left(\frac{504}{0.028}\right) = 20 \log_{10}(18000) = 85\text{dB}$$

This is an acceptable result and indicates that the pre-amplifier is functional but you will notice that the CMRR result is somewhat lower than you might expect given the specified pre-amplifier CMRR of 100dB. This discrepancy is a result of imperfect test conditions.

Measuring the real CMRR of a device requires that you eliminate all external noise from the gain tests and this is not possible under normal bench conditions. As a result, the 280mV common mode output voltage measurement will not be a pure 200Hz sine wave, there will usually be a small AC line voltage component in the measured voltage in addition to the 200Hz applied to the pre-amplifier, causing the common mode gain to appear be higher than it actually is, and thus lowering the CMRR. Once again, this illustrates the difficulty of making perfect measurements in an imperfect world.
EMG System Noise Level

Measuring the background noise level of an EMG system channel is relatively simple, connect a preamplifier to the channel under investigation, set the channel gain to a minimum (#0) and adjust the Model 220 Function Generator output to apply a 200Hz sine wave to the preamplifier at a level that generates a full scale sine wave – typically a 10V peak to peak (±5V) output level which will be displayed at 2V per division on the oscilloscope. Then turn the power off to the Function Generator – the sine wave signal will disappear and the oscilloscope will display a flat line. Now reduce the oscilloscope vertical scale until the flat line becomes noisy – typically with an oscilloscope setting of 50mV per division. The average noise level can be measured by the oscilloscope “Mean” measurement setting.

EMG System Frequency Response

Measuring the frequency response of an EMG system has three purposes, to determine the low frequency cutoff, the high frequency cutoff, and to verify that the EMG channel frequency response is reasonably flat between these two frequencies. A frequency response is normally described as a low frequency -3dB, and a high frequency -3dB. This means that the EMG system will pass signals at the same gain between these two frequencies with the -3dB point indicating that a signal at this frequency will be attenuated by 50%, with the attenuation increasing as the test signal passes the quoted frequencies.

This is a relatively simple test to perform, set the Model 220 Function Generator to generate a sine wave at 200Hz with a peak to peak amplitude of 10mV, set the EMG channel gain to #0, and monitor the EMG channel output with the oscilloscope. Connect a pre-amplifier and use the Tektronix TBS1052B autoset function to configure the display range. This sets the “mid-band” level which we will use to determine the -3dB points (the frequency at which the observed sine-wave signal is only 50% of the observed amplitude at mid-band.

The MA300-X EMG system bandwidth is fixed at 10-1000Hz so you can skip to the next paragraph if you are testing an MA300-X system. MA300 and MA400 systems have a user adjustable Low Pass filter on the BPU and, in addition, MA400 systems include a user adjustable High Pass filter (optional on the MA300). If you are working with one of these systems set the BPU Low Pass filter switch (Anti Alias Bandwidth) set to #0 for a maximum bandwidth of 2000Hz to start this test. Set the High Pass filter to “DC” (off) or 20Hz if you have an older DTU filter.

You can now vary the sine-wave signal frequency using the Function Generator rotary FREQUENCY adjustment, selecting high and lower frequency ranges with the push button range controls while observing the signal amplitude with the oscilloscope. Use the Function Generator controls to lower the sine-wave frequency until the amplitude drops by 50% - you may adjust the oscilloscope horizontal scale (sweep speed) but do not touch the autoset or channel gain controls. The frequency at which the amplitude is 50% of the mid-band level is the -3dB value for the low end of the frequency response.

Now use the same controls to increase the sine-wave frequency, observing the amplitude return to the mid-band level and then, as you continue to increase the sine-wave frequency, it drops to 50% of the mid-band level - this is the -3dB point for the upper end of the frequency response. Once you have noted the upper -3dB point, continue increasing the sine wave signal frequency until the signal disappears (the oscilloscope display is flat). The signal should rapidly decrease once the -3dB point is passed and should never increase. If the signal amplitude were to suddenly
increase as the applied frequency increases after the upper -3dB point then it would indicate that signal aliasing is occurring.

You can repeat these measurements for each EMG channel, and each Low Pass and High Pass filter setting if these options are available. Since there are a total of 10,240 combinations of these setting on a 16 channel EMG system (16 channels, 8 LP settings, 8 HP settings and 10 gain settings) you may find it effective to simply measure a single channel one gain value and then visually confirm the other combinations as necessary.

### EMG System Transient Performance

Measurements of the frequency response of an EMG system provide a basic assessment of the system performance but the frequency response test is performed with a pure sine wave signal, and EMG signals do not resemble a sine wave. A typical EMG contraction consists of a stream of pulses of electrical activity from the motor neurons and the muscle fibers that are activated during a muscle contraction. These pulses do not resemble a sine wave and have complex frequency content.

A comprehensive measurement of the EMG system transient performance requires a pulse generator that can produce a stream of short pulses but we can make a basic evaluation of the EMG system transient signal performance by using the Model 220 Biomedical Function Generator to apply a square-wave signal to the EMG pre-amplifier instead of a sine-wave. Use the same settings (200Hz, 10mV) as we used for the first gain test, select a square-wave signal and you should see a waveform resembling the illustration here recorded from an MA420 pre-amplifier on an MA400 with the high pass filter set to DC (disabled) and the BPU low pass filter set to 2,000Hz.

![Figure 12 - MA400 + MA420 preamplifier (10-2000Hz) square wave response.](image)

You can evaluate the transient performance of the EMG system by looking at the oscillation (ringing) in the signal after each fast vertical transition and, if your BPU has a variable low pass filter (not available on the MA300-X systems) you can observe the changes in the system performance as you reduce the low-pass filter frequency.

The illustration above shows the results that you can expect from an MA400 and MA420 preamplifiers with a full bandwidth of 10-2000Hz. The MA300-X system
System Measurements

System Verification EMG System Performance

The system with the same MA420 preamplifier has a fixed bandwidth of 10-1000Hz resulting in the waveform shown below. The minor changes observed in both vertical and horizontal slopes of the applied square wave are a result of the lower bandwidth of the MA300-X system.

![Figure 13 - MA300-X + MA420 preamplifier (10-1000Hz) square wave response.](image)

The final illustration below shows the same 200Hz square wave after it has passed through an MA400 with the EMG bandwidth low-pass filter set to the lowest setting of 350Hz, matching the bandwidth of many low quality EMG systems. The 200Hz square wave applied to the preamplifier has essentially lost all of the harmonic components leaving only a pure sine-wave that does not resemble the square wave applied to the EMG system inputs.

![Figure 14 - A 200Hz square wave filtered at 350Hz results in a sine wave.](image)

**Signal Latency**

Any electrical component, that is not a straight piece of wire with zero resistance, will affect the flow of information. In the tests above we have documented the changes in the signal amplitude and the frequency performance of the signal as it
passes through the EMG system being tested. As the EMG signal flows through the electronic components in the system there will inevitably be some delay of the signal - this is primarily due to the limits placed by the high frequency performance of the system. An electrical signal cannot go faster than the speed of light and the presence of any capacitance in the transmission line will slow the signal down while sampling an analog signal, converting it to digital values and then back to analog values also takes additional time. Any of these methods may be built into an EMG system to provide electrical isolation of the subject from the electrical equipment used in the lab and all of these factors will result in a degree of signal latency.

Knowing the length of this delay (the signal latency) allows you to synchronize the data from your EMG system with other data sources such as 3D motion and Forces and Moments recorded at the same time as the EMG activity.

Measuring signal latency requires a pulse generator that can generate a 1ms pulse at 20ms intervals - we can use a short 20ms interval because Motion Lab Systems EMG system have a very low latency but if you are performing this test on other manufacturers systems you many need to generate the pulse at much greater intervals to be confident that your signal latency measurements are correct. This test cannot be performed with a square wave or sine wave generator because the repetitive waveforms prevent clear observation of the latency.

The illustration above shows the pulse generator output on the upper trace, a 1ms pulse which is simultaneously applied (via an attenuator) to the EMG system pre-amplifier inputs. The EMG system analog output is displayed on the lower trace of the oscilloscope. This has a grid at 1ms intervals allowing easy measurement of the system latency, the length of time between the pulse being applied to the input and the pulse appearing at the output. The delay from the start of the upper pulse to the start of the lower pulse is about 1.2ms while the delay from the peak of the first pulse to the peak of the output pulse is 2ms. The first measurement (start of input signal to start of output signal) is the inherent system latency - this is a constant delay, while the second measurement - the delay from the top of the input pulse to the top of the output pulse - is determined by the bandwidth of the EMG system.

The bandwidth of an MA300-X system is fixed at 10-1000Hz resulting in a constant signal latency that does not change. However EMG systems with a variable low pass filter (MA400 etc.) will have different degrees of signal latency depending on the low pass filter settings. The relationship between the EMG system latency and the
EMG system bandwidth can be explored with the experimental conditions described above. The Tektronix TBS1052B digital oscilloscope includes a number of useful features that are very useful when making these measurements.

In the illustration shown below, the ability to measure the time between two cursors has been used to display the maximum latency of an MA400 system with the low pass filter set to 350Hz. The difference in time between the first cursor placed on the leading edge of the input pulse on the upper trace and the second cursor placed on the peak of the second trace (the analog output of the DTU) displays the maximum signal latency at 350Hz which is 5.68ms.

![Image](image.png)

Figure 16 - Filtering the input signal results in both temporal and waveform changes.

**Pulse Response**

In addition to measuring the system latency, applying a small pulse to the input of the EMG system allows you to evaluate the quality of the filters in the signal path by looking at the difference between the input signal and the output signal. Besides the delay caused by the latency, the most significant difference between the two signals is the amount of ringing that appears in the output signal after it has passed through the internal electronics and signal processing within the EMG system.

Ringing is the normally small oscillations that are seen in the output signal at the base and peak of the pulse, some degree of ringing is inevitable in any filter system and is caused by varying amounts of inductance and capacitance in the filter circuitry. The rapid changes in the signal applied to the EMG system input causes these components to resonate at their characteristic frequency domain, determined by the filter used and creates the ringing effect in the signal. This ringing needs to be minimal if you are planning any analysis of the frequency content of the EMG signal as its presence will add considerable distortion to the spectral content of the EMG signal.

The pulse response of the system at normal EMG signal levels is affected by the bandwidth of the system - the greater the bandwidth of the system permits a better EMG signal level pulse response resulting in a much more accurate and cleaner EMG signal while the filter design quality also affects the results. In some cases, applying just a single pulse to the EMG system input can generate a stream of gradually decreasing pulses.
Figure 17 - Radio-telemetry data transmission can result in significant signal latency.

The example shown above was recorded from a third-party manufacturers radio-telemetry EMG system using the same 1ms pulse signal source as the signal latency test earlier and is used here to demonstrate a poor EMG system pulse response. This EMG system has a significant signal latency - the time between the input pulse (upper trace) and the output pulse (lower trace) is almost 20ms, but the most significant feature is that a single pulse applied to the EMG system input, results in an output pulse that “rings” with a train of slowly diminishing oscillations appearing after the pulse appears in the EMG system output. Clearly this system does not have a real-time signal output and the ringing in the system output results in significant differences between the EMG signal at the subject’s skin surface and the EMG signal presented by the system for subsequent analysis.
The Whisper EMG Simulator

The Whisper EMG Simulator was designed and built by Roessingh Research and Development in Enschede, Netherlands in 1998 and distributed and supported in the United States by Motion Lab Systems. The Whisper generates a simulated EMG signal with a series of calibration pulses at typical surface EMG levels and applies a 40Hz common mode signal to the output. These features make it very useful for a quick EMG performance test.

Figure 18 - The Whisper EMG Simulator.

The original product included a software application that performed a series of tests that evaluated the recorded Whisper signal and reported the results but the application is no longer supported. It was written to run on Windows XP but cannot be installed and run on Windows Vista or any later versions of the Microsoft Windows operating system. Tests performed with the Whisper application were relatively complex and required multiple EMG signal recordings – since the Whisper application is no longer supported, it will not be used in the following descriptions.

However, when used simply as an EMG signal generator, the Whisper remains a very useful device that allows anyone to quickly apply a repeatable series of EMG performance tests to any EMG system. This chapter documents the use of the Whisper as a physical EMG signal test source.

A quick functional test of EMG equipment is based on the idea that faulty EMG systems and accurate, functional, EMG systems will produce different EMG signals when a known, reproducible EMG signal is applied to each system. A visual inspection of an EMG system's response to a standardized EMG signal is therefore a good way to quickly verify the performance of an EMG instrument or an EMG data collection system by observing the standardized test signal generated by the Whisper.
after it has passed through the EMG instrumentation under test and comparing the resulting signal with the signal that was applied to the EMG system inputs.

If you have an original Whisper unit (they are no longer manufactured by Roessingh Research and Development), you may need to replace the four AA batteries in the battery compartment. Once the batteries have been replaced, turn the power switch on and check that the switch LED changes color when the START switch is pressed. Contact Motion Lab Systems if your Whisper unit is not working or you are experiencing any problems.

Start by examining the unit and becoming familiar with the layout of the front panel connections and controls, from the left to right you find:

- EMG Ground (Signal Reference)
- EMG Signal Output
- Differential Mode Signal On/Off Switch
- Common Mode Signal On/Off Switch
- Start Button
- Power On/Off Switch
- LED indicator: Simulator On/Off/Active

A common problem with older Whisper units is internal battery holder corrosion.

The Whisper is powered by 4 AA cells located in the battery compartment in rear of the Whisper. The battery holder can be removed by pressing the two clips on the battery holder together in the direction shown by the arrows. When you insert the four AA batteries pay attention to the polarity of the batteries to ensure that they are inserted correctly.

Once the battery pack is inserted into the back of the Whisper you are ready to generate EMG signals. The Whisper can be checked by turning on the POWER switch at the right side of the front of the unit. The power switch LED will glow green if the batteries have been inserted correctly. If the LED does not light up then check that the batteries are inserted correctly and that the battery pack has been firmly inserted into the Whisper.

Another common problem with older units is the START switch may not work reliably.

If the batteries are inserted into the Whisper correctly, and the power switch LED lights when the POWER switch is turned on, you can test that the unit is functioning by pressing the START button, located to the left of the POWER switch. The LED will change from green to orange-red as the Whisper starts to generate an EMG test sequence and then return to green after 20 seconds. The Whisper is now operational.

The differential simulated EMG signal generated by the Whisper is available from the two pin LEMO socket, adjacent to the EMG ground connector. Motion Lab Systems has developed and makes available an easy to use preamplifier interface with three standard banana jacks and snap-connector interfaces with a standard touch-proof ground connector cable that can connect directly to the DIN standard ground connector on all Motion Lab Systems backpacks.
This interface is completely shielded in a metal housing and connects directly to the Whisper LEMO interface allowing a standard surface preamplifier to be held against the interface while simultaneously touching the ground connector or metal casing to ensure that very little external AC line interference is applied – something that caused numerous problems with the original interface supplied with the Whisper. By using three standard jack sockets with banana plug snap adaptors, the Whisper can easily connect to any surface preamplifier or snap lead preamplifier. Fine wire preamplifier can also be easily held against the interface making it very easy to test individual preamplifiers and verify their performance to both detect an EMG level signal and reject AC line interference.

Figure 19 - Just hold the pre-amplifier against the connectors to apply the Whisper signal.

Figure 20 - A Whisper with the new interface and ground cable ready to use.
Whisper Testing

Set both the DIF. MODE (Differential Mode Signal) and COM. MODE (Common Mode Signal) switches in the ON position to generate a differential EMG signal with a common mode component.

Now the Whisper is ready for use - you can switch on the Whisper using the POWER switch on the right side of the front panel. The LED above the switch should light up green. At this point the Whisper is ready to generate a signal at surface EMG levels when you press the start button.

The Whisper will start generating an EMG test sequence as soon as you push the START button, located to the left of the POWER switch. You will need to start your EMG recording system at the same time as you press the Whisper START button. If your EMG system includes High Pass and Low Pass filters then either disable them or set them to perform the least amount of filtering of the EMG signal.

Connect the ground cable to the Whisper ground jack, adjacent to the EMG signal output, and either hold the preamplifier directly against the red and black connectors while simultaneously touching the metal case to avoid injecting any external AC line interference. Take care not to touch the preamplifier EMG inputs as you hold a surface or fine-wire preamplifier against the connections. Turn the Whisper on, verify that the power LED is green, then start your EMG data collection recording system and press the START button on the Whisper to initiate the test. The LED above the Whisper power switch will turn orange / red and your EMG recording instrument will record a standard EMG test signal from the Whisper for the next twenty two seconds. At the end of the EMG test sequence the Whisper LED turns green again and you can stop your recording device and store your data.

Figure 21 - The Whisper signal consists of 5 pulses followed by 15 seconds of simulated EMG.

Once you have completed an EMG test recording you can view the recorded EMG data using your normal methods. If your EMG instrumentation records raw EMG then your recording should look like the signal that is shown above.

The basic idea of an equipment test is that a standardized EMG test signal will be applied to the EMG instrumentation on a regular basis. The output of the EMG instrumentation will be recorded and test parameter values will be calculated from the recorded signal in order to obtain a record of the performance of the EMG instrumentation and recording system.

By comparing the test results from a Whisper test with the results of earlier tests it is possible to check that the EMG system and EMG recording channels for any signs of degradation. A faulty EMG system will produce a different EMG record from a functioning EMG system when both systems are presented with a standard EMG test signal such as generated by the Whisper.
The test signal generated by the Whisper is stored as digital values within the Whisper so that every test performed will generate exactly an identical EMG signal for each test depending on the front panel switch settings. The output signal consists of two components – these are:

- A differential mode component (the EMG signal).
- A common mode component (AC interference).

The differential component consists of five, positive, leading pulses that are followed by the digitized EMG signal. The common mode component consists of a 40 Hz sine wave. Each of the two components can be generated and applied to the EMG output signal independently via the two DIF. and COM. mode switches on the front of the Whisper.

Both signals are generated as soon as the START button is pushed and released to allow the Whisper to produce a range of test signals under control of the user. The ability to combine and separate the differential and common mode components of the EMG test signal is invaluable in fault finding and testing EMG systems and components.

**The standard EMG test signal**

The standard Whisper test signal consists of a simulated differential mode EMG signal with a 40Hz AC sine wave common mode component optionally superimposed on the EMG signal. This allows a number of different EMG instrumentation parameters to be observed in a single test sequence.

**The differential mode component**

The differential mode signal consists of five leading pulses, followed by fifteen seconds of standard EMG generated from a signal stored in the Whisper EPROM's. The pulses are spaced 1 second apart. The duration of each pulse is one millisecond, with a pulse amplitude of 500 μV. There is one second between the release of the START button and the first pulse and one second between the fifth leading pulse and the simulated EMG signal. The simulated EMG signal is fifteen seconds long. The Whisper stops one second after the stored EMG signal has finished. The illustration below shows a sample of the differential mode simulated EMG signal, while the illustration above the entire fifteen-second sequence.

*Figure 22 - The simulated EMG signal generated by the Whisper from a digital recording.*

The differential mode EMG signal, that is stored within each Whisper, is a simulated signal so that it has a precise amplitude, and known frequency components. This avoids the problems inherent in recording a long, continuous burst of EMG from a human subject which will normally contain both motion artifact and varying degrees of AC power line interference. In a paper published in 1981, *Frequency parameters*
of the myoelectric signal as a measure of muscle conduction velocity (IEEE Trans. Biomed. Eng. Vol. 28, p. 515-523), Stulen, F.B. and De Luca, C.J. proposed that a stationary EMG signal simulation can be obtained by band-pass filtering a white noise random sequence. The fifteen seconds of EMG, stored in the Whisper were obtained by low-pass filtering and then high-pass filtering fifteen seconds of white noise. The low-pass filter was a 2nd order, 80 Hz filter and the high-pass filter was a 1st order, 40 Hz filter. The digital filter used a 1024 Hz sample rate.

As a result, the Whisper EMG signal is simply a simulation and does not replicate the dynamics of a real-life EMG signal but, since it is digitized and stored identically in every Whisper Unit with a series of precise test pulses and an optional common mode component, it is a very useful test source that allows users to verify and compare basic EMG system performance. While the original software application supplied with the Whisper no longer runs on modern computers, the analog signal generated by the Whisper can be applied to any EMG system and a simple visual observation of the signals after they have passed through the EMG system is all that is needed for anyone to demonstrate that their EMG system is functional.

The common mode component

The common mode signal generated by the Whisper consists of three parts. During the first six seconds, the common mode signal remains 0.0 Volt. As soon as the differential mode signal starts to output the stored EMG signal, the common mode signal becomes a sinusoidal signal with an amplitude of 1.00 Volt at a frequency of 40 Hz. This common mode signal remains present for fifteen seconds and then returns to 0.0 Volt during the last second of each simulation. The common mode signal frequency is fixed at 40Hz to allow the original Whisper software to distinguish between AC line interference (either 50Hz or 60Hz) and the Whisper common mode signal.

By applying the common mode signal to the differential EMG signal, the resulting signal applied to the EMG system inputs makes it very easy to observe any weakness or failure in the EMG preamplifier common mode rejection performance. Good common mode performance means that the applied common mode signal is almost completely eliminated while the EMG signal is unaffected.

EMG signal specifications

The standard test signal generated by the Whisper to test the performance of your EMG recording instrumentation has the following characteristics:

<table>
<thead>
<tr>
<th>Test parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMG signal RMS Value</td>
<td>200</td>
<td>μV</td>
</tr>
<tr>
<td>EMG signal Mean Value</td>
<td>0.1</td>
<td>μV</td>
</tr>
<tr>
<td>EMG signal bandwidth</td>
<td>10 to 250 -6 dB</td>
<td>Hz</td>
</tr>
<tr>
<td>Leading Pulse Width</td>
<td>1</td>
<td>ms</td>
</tr>
<tr>
<td>Leading Pulse Amplitude</td>
<td>500</td>
<td>μV</td>
</tr>
<tr>
<td>Individual pulse interval</td>
<td>1.0</td>
<td>seconds</td>
</tr>
<tr>
<td>Common Mode Amplitude</td>
<td>1.0</td>
<td>Volt</td>
</tr>
</tbody>
</table>
The EMG signal RMS Value indicates the Root Mean Square amplitude of the fifteen seconds of digitized EMG signal while the EMG signal Mean Value is the mean value of the 15 seconds of digitized EMG signal indicating that the EMG signal contains both positive and negative components about the baseline.

The simulated Whisper EMG signal, digitized and stored in the Whisper to generate identical signals for every test was originally generated by processing white noise and has a relatively low fixed bandwidth.

The Leading Pulse Width and Amplitude refer to the five leading pulses that are generated at the start of the EMG signal sequence. The Individual pulse interval is the time between each of the five successive pulses that precede the EMG test signal.

The Common Mode Amplitude is the amplitude of the common mode sine wave that can be optionally applied to the simulated EMG signal to test the ability of the EMG system to reject common modes signals – typically caused by AC line interference. The Common Mode Frequency is the frequency of the common mode sine wave test signal which is set at 40Hz to avoid confusion with 50Hz or 60Hz AC interference.

## EMG System Testing

The Whisper EMG Simulator generates a precise and repeatable, differential, simulated EMG signal that accurately reproduces the conditions and voltage levels common to normal biological EMG data collection each time. As a result, a simple visual observation of the signal generated by an EMG system when the Whisper EMG Simulator signal is applied to the EMG system inputs is all that is needed to confirm that the EMG system is operating accurately and functionally.

Whisper EMG testing is quick and easy to perform when you can observe the EMG signal in real-time allowing immediate observation of the applied signal. This is the recommended method. If you cannot monitor the real-time signal generated by the EMG system when the Whisper signal is applied to the preamplifier inputs then you will need to record each test and then immediately examine the recording to determine the results of each test.
To generate the EMG test signal for easy visual testing, the Differential Mode switch (DIF. MODE) and the Common Mode Signal (COM. MODE) switches should both be set ON. When the Whisper unit is turned on and the START switch pressed then the Whisper will generate a twenty second test signal that consists of five individual one millisecond pulses, each one second apart, followed by fifteen seconds of a simulated EMG signal that includes a significant common mode component.

![Switches](image)

This test signal sequence was originally designed by Roessingh Research and Development, to be applied to an EMG system to allow the operator to verify the system performance by recording the signal after it had passed through the EMG system and performing a complex software analysis of the recorded signal, comparing it directly to the known sequence of data that the Whisper generates each time that the Whisper Start button is pressed, and documenting any variations between the applied signal and the results generated by the EMG system.

While the Roessingh Research and Development software generated scientifically significant results, it required a complex series of four separate recordings for each test. The tests each generated a unique signal for twenty seconds and had to be conducted in a well-defined signal environment with no external interference of any kind – a situation that is relatively easy to create in a research environment, but very difficult to maintain in the average gait or biomechanics laboratory. This often resulted in individual EMG system evaluations that required several hours to collect and interpret the results before any assessment of the system performance could be generated.

The original Whisper signal evaluation software was written in LabVIEW for the early versions of the Microsoft Windows operating system and no longer runs on any current versions of the Windows operating system since Windows XP, but the unique and versatile signal generated by the Whisper can still be applied to an EMG system and visually observed to confirm the EMG system functionality.

**The Five Calibration Pulses**

The first five seconds of the differential Whisper test signal comprises of five individual pulses at one second intervals. Each pulse has an amplitude of 500 μV, a width of 1ms and a baseline inter-pulse interval.

Observing the effect that the EMG system has on the applied pulse, allows anyone to make an estimation of the EMG system bandwidth and the internal performance of EMG system signal processing that affects the EMG signal. The rapid rise and fall of the pulse leading and trailing edges contain high frequency signal components while the changing DC levels as the pulse returns to the baseline a low frequency applies a low frequency signal component. In addition, observing the inter-pulse interval baseline between successive pulses provides a clear indication of any background noise or instability in the system.
The pulse applied to the EMG system has a distinct shape that contains several important components that will be modified by the internal processing in the signal electronics of the EMG system. As can be seen in the recording shown above, the pulse consists of a very rapid rise to the 500µV amplitude that is maintained as at a constant level of one millisecond. After one millisecond the pulse level immediately returns to the original baseline level which is then maintained until the next pulse one second later.

The rapid rise and fall of the input signal means that it contains very high frequency components which may be altered by the EMG system, indicating how the system responds to high frequencies. The flat top of the pulse and the stable baseline after the pulse returns to the original level indicate the response of the system to low frequency signals.

The signal shown above is the output of an MA300 EMG system with signal bandwidth from 5Hz to 2 kHz (-3dB). The slightly slower rise time of the initial
The changes to the original pulse shape are a result of multiple factors and the illustration above shows the relatively minor changes to the input pulse signal which are easy to see in this simple visual environment. Detailed and scientifically valid measurements would require significant analysis of the signal but once you understand that the pulse response of a system can reveal the general functioning of the device then it is easy to apply the Whisper test signal to any EMG system and quickly obtain a firm understanding of its bandwidth and internal signal processing.

The two signals above illustrate that a pulse applied to the EMG system is being accurately detected and reproduced. EMG motor unit recruitment is the activation of the multiple series of individual motor units during an increasing voluntary muscle contraction, where each individual motor unit generates a pulse. These multiple pulses are detected as the EMG signal so the response of the system to a single pulse provides a lot of information about the quality of the observed EMG signal generated at the output of the system.

The EMG system output pulse shown above is a reasonably accurate representation of the pulse applied to the EMG system inputs. The reasonably high performance of the EMG system has only cause a slight change to the rise and fall times of the pulse. The signal below is significantly different as a result of the EMG system high frequency response being limited to 500 Hz instead of 2 kHz. The reduced bandwidth has slowed the rise and fall times of the pulse and introduced a small amount of oscillation (less than 20% of the pulse height) after the pulse returns to the baseline. This is a typical distortion that is introduced by filtering an analog signal.

In the example below, the Whisper calibration pulse has been applied to a third-party EMG system with a similar frequency response but resulting in an additional 75% signal overshoot as the pulse returns to the baseline together with a significantly longer period of baseline instability that appears to have generated additional low frequency noise. This is typically a side effect of intense filtering that introduces additional signal artifacts into the filtered signal. In the example shown the high-
pass filter, designed to remove low frequency artifact from the EMG signal, has affected the high frequency components of the EMG signal.

Figure 26 - The Whisper pulse from a system with a 20Hz to 450 Hz 80db/decade bandwidth.

Extensive low-pass filter is built into many radio-telemetry EMG systems to ensure that additional high frequency signals do not cause EMG signal aliasing, a common problem with many early radio telemetry EMG systems. As a result some EMG systems may cause additional signal distortion. The illustration below shows the output of a third-party radio-telemetry system with a 5 Hz to 500 Hz bandwidth. The signal shows significant ringing when the one millisecond Whisper test pulse is applied but the signal remains oscillating about the baseline. This suggests that the low frequency performance is good but the additional high frequency ringing suggest that the low-pass filtering is causing significant addition signal components.

Figure 27 - The Whisper pulse from a radio telemetry system with a 5Hz to 500Hz bandwidth.

**Pulse Performance**

The signals illustrated in this section from various manufacturers EMG systems tested with a Whisper EMG simulator are all acceptable – the variations between the
calibration pulse signals essentially simply document the differences in the specified performances and reveal the quality of the internal design and signal filtering.

These differences are generally only significant if the EMG system is used for research or scientific signal analysis, areas of study that normally require higher quality data than the signals needed to simply determine if a muscle is active or not.

In addition to the pulse performance, all of the signals demonstrate a generally flat baseline between the pulses suggesting that the system have relatively good baseline noise performance. The illustration below shows the signal from a third-party EMG system with adequate performance although the baseline displays continuous low level noise that might be considered clinically significant low level muscle activity when the EMG signals is processed and analyzed but since the documentation for the EMG system that created this noisy baseline states that it is “a biofeedback device and is not intended for measurement, treatment or diagnosis of any clinical application” you cannot complain about the poor performance.

![Figure 28 - A Whisper test signal indicating poor performance with excessive baseline noise.](image)

The noisy baseline signal above can be compared to the signal generated by a higher performance Motion Lab Systems MA300 system shown below. Both signals were generated from the same Whisper test signal but display some noticeable differences. The MA300 baseline between the pulse and the start of the EMG signal is quieter and would not suggest that there might be any additional muscle signals present in real life use.

![Figure 29 - The Whisper test signal indicating good performance with minimal baseline noise.](image)

In addition the EMG signal above is more detailed as a result of the higher frequency bandwidth performance of the MA300 – you can see some components of the EMG signal above that do not appear in the third-party system output as the lower bandwidth of that system has eliminated parts of the EMG signal spectrum resulting in a low of resolution of the recorded EMG signal.
The Simulated EMG Signal

Once the five calibration pulses are complete, the Whisper test signal transforms to generating a differential simulated EMG signal with a common mode component. If the EMG system is functional then the common mode component will not affect the differential test signal and the observed simulated EMG signal will represent a typical EMG recording with an amplitude that appears to slightly exceed the preceding five pulses as shown below. This allows the user to confirm that the EMG system is rejecting common mode signals (typically produced by AC power line interference) and functioning correctly.

Figure 30 - A twenty second Whisper test signal indicating good Common Mode performance.

If the signal in EMG channel under test appears to swamp the observed EMG signal, generating a significantly larger signal than the five preceding pulses, then it is likely that the EMG system input is not rejecting the common mode signal. The five preceding calibration pulse indicate the start of the test and the common mode test signal is applied when the simulated EMG signal is generated in both the Whisper DIF MODE and COM MODE switches are on. This sequence allows the user to verify that the common mode signal is being applied to the EMG input.

Figure 31 - A twenty second Whisper test signal indicating bad Common Mode performance.

When a bad common mode signal is seen a quick test can be performed to confirm the common mode performance by turning the DIF MODE switch off while the test is running which will remove the differential simulated EMG signal, leaving only the common mode component applied to the EMG input allowing a visual determination of the common mode performance. This will normally show some small amount of common mode signal but always much lower amplitude that the EMG test signal.
The Quick Whisper Test

The preceding discussions and illustrations document the extensive details of the performance of an EMG system that the Whisper Test Signal can reveal. These discussions are provided to attempt to explain, in detail, how the Whisper test signal works. But for day to day testing all that is needed is to setup your EMG system so that you can visually monitor the individual EMG channel output signals and then apply the Whisper Test Signal, generated with both differential (DIF.MODE switch ON) and common mode (COM.MODE switch ON) components to each EMG channel and check the following points:

1. Do you see five calibration pulses?
2. Is the baseline flat and noise free between each of the pulses?
3. Does the simulated EMG signal look like EMG and appear to be about the same amplitude as the calibration pulses?

If the answer to each of the three questions is yes, then you can be confident that your EMG system is functional.

If the five calibration pulses appear to be distorted, or don't appear at all, then check the sampling frequency of the data collection system and any frequency bandwidth settings on the EMG system.

If the baseline is not flat and noise free for specific individual EMG channels then the preamplifier used by the channel may be defective. If all the channels display a problem then check the EMG system ground cable between the Whisper and the EMG system.

If most of the preamplifiers work but some do not, then return the defective preamplifiers to Motion Lab Systems for repair.
Data Collection System synchronization

A typical biomechanics 3D data collection environment records data from multiple sources when evaluating human motion, typically 3D marker motion, force plates, and EMG etc., so it is essential to verify both the temporal and physical relationships between all of the data. Accurate temporal synchronization of the EMG and limb motion data is very significant when evaluating the electrical signals generated by the muscle activity in a limb with the physical motion of the limb to determine the limb functionality.

The example below shows an EMG recording from a radio-telemetry system with a significant temporal delay, causing the EMG activity to appear to be prolonged and occurring slightly later than the expected normal EMG activity bar shown below the pulse. Under certain circumstances this might be considered clinically significant.

![Figure 32 - A delayed EMG signal showing muscle activity and expected normal activity.](image)

You can verify the overall system integration of your EMG system in a typical 3D motion capture laboratory environment with a simple test by applying a single stimulus to the entire data collection system. The test described here is intended to easily demonstrate that the 3D motion data collection environment is functioning correctly and provides some basic timing data about the EMG system in combination with the force plates and 3D system that will allow you to verify that all the data recorded by the system is accurately synchronized. You may want to perform this test whenever any hardware or software components (e.g. a new data collection software release or the installation of a new EMG, or force plate system) of the 3D data collection environment are changed or updated.

Connect a small (one or two inch diameter) loudspeaker to one of the EMG system pre-amplifiers, set the EMG channel gain to a minimum (#0) and place loudspeaker on the force plate - this will generate a small signal of a few millivolts (a typical EMG level) that the pre-amplifier can detect when the force plate is tapped.
generating a common signal that can be detected by both the force plate and the EMG system.

Figure 33 - Using an EMG preamplifier to detect an impact on a force plate.

Now drop a golf ball onto the force plate surface and the EMG system will detect the impulse that the loudspeaker produces when the golf ball lands on the force plate and, as the golf ball strikes the force plate, the force plate will record the impact at the same time.

If your 3D motion capture system uses retro-reflective markers you can cover the golf ball with reflective tape so that the golf ball motion can be recorded - if your 3D system uses active markers, then you may want to replace the golf ball with another object that can support an active marker.

To document the potential system latency, all you have to do is perform a 3D system data collection while recording EMG data from the EMG system input connected to the loudspeaker, force data from the plate that the EMG sensor is resting on, and 3D marker motion data collection, preferably at the highest frame rate supported by the 3D system, while dropping the reflective golf ball, or motion sensor, a short distance onto the force plate. When it strikes the force plate you will see a pulse on the EMG channel generated by the loudspeaker and a small pulse on the force plate z-axis channel, while observing that the recorded object vertical trajectory will instantly change as it strikes the plate, generating a single signal in all three sensors.

You can now use the 3D system data that you have recorded to measure the degree of signal latency of the entire 3D data collection environment and demonstrate that motion, forces, and EMG data are all being accurately recorded for analysis. It is recommended that the raw, unmodified 3D data files generated by this test are stored so that the system performance can be verified over time and a record of the system performance is maintained.

An example of this test is shown using the Mokka application to open a C3D file in Figure 34 which displays the marker trajectory in the 3D environment on the left as the ball strikes the force plate with the marker Z axis motion at the top on the right.
side, above the force plate Z axis response, and the EMG sensor signal. This graphically illustrates a single frame of latency for both the force plate and analog EMG signals – since the 3D frame rate for this test was 250 frames per second it illustrates a system latency of approximately 4ms affecting both the force and analog EMG data.

In each case, the latency in both the force and EMG data can have different sources since each signal is generated independently. Both the force plate and EMG sensors generate analog signals that are normally filtered as part of the data processing before digitization – low pass analog filtering normally generates a delay, the magnitude depending on the degree of filtering.

![Graph showing latency](image)

Figure 34 - Marker trajectory, force plate response, and EMG signal displayed using Mokka.

Note that some manufacturers EMG preamplifiers feature a built-in accelerometer and if you are testing one of these systems then you should record both the impact signal generated by the loudspeaker and applied to the EMG preamplifier inputs, as well as the integrated accelerometer signal to verify the synchronization of all of the sensors in the system.

Once this test has been performed, if the motion and data capture system provides any method of compensating for timing delays then it may be possible to adjust the data collection parameters to remove the measured latency from the recorded data by changing the data collection parameters. The test can then be repeated to verify that the data collection is perfectly synchronized.

The advantage of performing this test is that it verifies the data synchronization by measurements. Traditionally, most 3D data collection environments assume that the data is synchronized without performing any tests to verify the performance. A manufacturer might state that their system latency is 27ms but, while that may be accurate for the manufacturers system, it is not a measurement of the latency for the data collection system environment.

For example, while EMG system latency is often discussed, force plates are always assume to have zero latency – while this may be correct for the force plate sensor, the data from the sensor is often filtered which can add latency to the sampled data as can be seen in the data shown above.
Normal Muscle Activity timing

Various software applications from Motion Lab Systems, Inc. include MUSCLE.INI, an ASCII text file that contains normal EMG activity timings digitized from a number of different publications:


[COMBINED LOWER LIMB] – The default comprehensive ensemble list of EMG activity timings and standard muscle names updated from timing data in the [Normal EMG], [Normal Adult EMG] and [OrthoTrack 4.1] sections.

[NORMAL ADULT EMG] – EMG activity timings digitized from graphs widely distributed, and in common usage, in the United States Physical Therapy community in the 1980-90s. These graphs, together with normal angular and force data, were prepared by John L. Hagy, Roger A. Mann M.D., and Cecil W. Keller at the Shriners Hospital for Crippled Children, San Francisco in 1973, and are based on fine-wire studies of ten adult subjects.


[ORTHOTRACK 4.1] – EMG activity timings and muscle names supplied by the Motion Analysis Corporation with their Clinical OrthoTrack application in the 1990’s. These timings were generated at Alfred I. duPont Hospital for Children in Wilmington, Delaware from a surface EMG study of approximately 100 normal children ranging from 5-17 years old.

[VICON CLINICAL MANAGER] – The first release the Vicon Clinical Manager (VCM), was installed in the United States at Indiana University in April, 1992 and did not include any normal EMG activity timing data. VCM was modified during the installation by Dr. Julian Morris, PhD., to display EMG normal timing information with 5% resolution based on a conversation with the customer, Dr. Richard Linseth, M.D. This EMG activity timing information was added to the default VCM distribution as a DST formatted ASCII file called EMGBAR.GCD and distributed by Oxford Metrics, Ltd., with subsequent VCM installations.

[POLYGON] – This timing information is distributed with the Vicon Motion Systems (formerly Oxford Metrics Ltd) Polygon reporting and presentation tool. This section uses the same muscle name abbreviations as VCM data but has slightly different EMG activity timing and 2% resolution – this data is probably derived from the original VCM timing and contains similar anomalous Extensor Digitorum Longus and Iliopsoas timing seen in the Vicon Clinical Manager section.

[1 YEAR OLD] ... [7 YEAR OLD] – Seven sections containing EMG muscle activity timings for children by age, digitized from graphs published in The Development of Mature Walking (1988) by David Sutherland, Richard Olshen, Edmund Biden and Marilynn Wyatt based on data from up to 30 subjects aged 1 to 7 years old.

Note that the numbers within the MUSCLE.INI file can be modified by users but that reinstalling the application will overwrite any changes, restoring the original files.
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