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Standard Guide for
Quantitative Measures for Establishing Exoskeleton Functional Ergonomic Parameters and Test Metrics[1]

This standard is issued under the fixed designation F3518; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide provides quantitative measures for assessing one or more specific ergonomic parameters with respect to exoskeletons. Furthermore, this guide should be used in conjunction with Practice F3474, Guide F3519, and Standard Guide for The Application of Ergonomics to Prevent Injury During Exoskeleton Use[2].

1.2 This guide provides quantitative measures for the design, use, and construction of exoskeletons within the domains of industry, military, medical, first responders, and recreational.

1.2.1 Quantitative measures are a type of data that can be put into a numerical value. This type of measure allows statistical analysis to be performed on the data to yield an objective result.

1.3 *Units*—The values stated in SI units are to be regarded as the standard. No other units of measurement are included in this standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

F3474 Practice for Establishing Exoskeleton Functional Ergonomic Parameters and Test Metrics

F3519 Guide for Establishing a Reporting Structure for Exoskeleton Analysis

3. Terminology

3.1 *Definitions:*

3.1.1 *dynamometer, n*—instrument that measures the force output of grip strength.

3.1.2 *electromyography, n*—recording of the electrical activity of muscle tissue using electrodes to the skin or inserted into the muscle belly.

3.1.3 *heart rate, n*—speed with which the heart beats, measured in the number of contractions of the heart over the course of a minute.

3.1.4 *heart rate variability, n*—variation of the time between each heartbeat, specifically, the variation of the "R" to "R" intervals of the heartbeat QRS component.

3.1.5 *kinematics, n*—branch of mechanics concerned with the motion of objects without reference to the forces that cause the motion.

3.1.6 *motion capture, n*—process or technique of recording patterns of movement digitally.

3.1.7 *non-invasive, adj*—not requiring the introduction of instruments into the body.

3.1.8 *oscilloscope, n*—device for viewing oscillations, as of electrical voltage or current, by a display on the screen of a cathode ray tube.

4. Significance and Use

4.1 This guide provides a set of recommended quantitative measures which can be used to assess the task or human readiness, or both, of exoskeletons. All of the quantitative measures are used in ergonomic research to assist in objectively concluding the efficacy of an assessed metric.

4.2 Not every element of this guide may be applicable to all exoskeleton components or configurations. Nor are all the quantitative measures herein exhaustive. Selection of quantitative measures should be done based on the uncertainties surrounding the end use application of the exoskeleton. It is the

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[2] Unpublished ASTM standard under development.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

manufacturer's responsibility to determine which portions of this guide, and the corresponding measures, are applicable to their exoskeletons.

4.3 The ability to reproduce analysis between exoskeleton usage vs. non-exoskeleton usage is critical criteria in using a quantitative measures approach. A control method for reproducibility in a quantitative measures approach is a repeated measures design. A repeated measures design involves multiple measures of the same variable taken on the same end user, either under different conditions or over two or more time periods. The salient aspect of a repeated measures design is using the end user as the control.

5. Quantitative Measures

5.1 *Electromyography (EMG)*—EMG uses electrodes to measure the electrical activity of contracting skeletal muscles. There are several types of EMG depending on the type of electrodes used. Surface EMG (SEMG) traditionally uses surface electrodes for a non-invasive analysis of a muscle of interest. The muscle(s) of interest are those whose activations are anticipated to change due to use of the exoskeleton in comparison to the no-exoskeleton condition. (Activation of these muscles may be increased or decreased by the exoskeleton.) For example, the muscles of interest for an upper extremity exoskeleton include those involved in shoulder and upper arm movement. This assumes normally functioning muscles and does not account for neuromuscular degenerative pathologies (please seek a medical professional for appropriate implementation). Another type of electromyography is known as intramuscular electromyography. This is an invasive type of measurement because it uses fine-wire or needle electrodes that are inserted directly into the muscle. Because of its tiny surface area for recording electrical activity, intramuscular EMG allows for the assessment of individual motor units in the muscle of interest. Furthermore, fine-wire electrodes have a better signal-to-noise ratio than surface electrodes. However, fine-wire electrodes require special training and medical supervision to place the wires accurately and not damage the muscles during insertion and removal. For this reason, surface electrodes are recommended because of their non-invasive application.

5.1.1 *SEMG Analysis*—The SEMG percentage of maximum voluntary isometric contraction (MVIC) analysis is evaluated using a peak amplitude analysis. The reason SEMG is assessed through a percentage of MVIC is because SEMG is purely a measure of muscle activity (measured in microvolts) without correlation to a force metric (**1**)[4]. Once data are acquired, descriptive statistics may be used to summarize the results.

5.1.2 *Percent MVIC*—Percent MVIC is conducted by capturing three to five maximum voluntary contractions trials for 6 s periods of a specific muscle of interest with external resistance applied (**1**). Averaging of the middle 2 s of each trial is performed against the total number of trials. Thus, for a 6 s period, seconds 1 and 2 and 5 and 6 are dropped (**1**). Seconds 3 and 4 would be averaged. The user will then perform the specific task based on the required evaluation. The MVICs are then averaged, bandpass filtered, and a root mean square (RMS) is calculated to result in a single number for each assessed muscle. This number is applied to the bandpass-filtered RMS value of the task evaluation results to conclude a percent MVIC of the user's muscle exertion.

5.1.2.1 *Percent MVIC Reference Posture*—The postures, positions, or movement patterns, or combinations thereof, adopted to perform percent MVIC should correlate to the task that the user will perform. For example, if a task requires a user to perform a pointing task and the muscle of interest is the anterior deltoid, then the percent MVIC should not use any resistance for the isometric contraction. Rather, the task should be performed by the user flexing their arm anteriorly without bending their elbow. For example, if the task requires lifting cans of paint from one table to another, and the muscle of interest is still the anterior deltoid, then the user should perform a resisted isometric contraction against an immovable object (such as a wall).

5.1.3 *Muscle Fatigue*—Muscle fatigue is assessed by transforming the EMG signal from the time domain to the frequency domain. This is commonly done using fast Fourier transform (FFT) of the bandpass-filtered RMS EMG measured during the task. Moving from the time to frequency domain allows the assessment of the onset of muscle fatigue based on changes in firing rates of different muscle fibers. The two predominant skeletal muscle fibers are Type I fibers, which are fatigue resistant, while Type II fibers are fast fatiguing. Frequency ranges from Type I and II fibers are 10 to 250 Hz. As a conceptual example, a frequency plot is a graph of frequency on the *x*-axis against power (or muscle activity) on the *y*-axis. Muscle fatigue occurs when the median value of the frequency plot shifts from a higher value to a lower value (Fig. 1). This shift is caused by an increase in the firing rate of Type I fibers with a simultaneous decrease in firing of Type II fibers. Muscle fatigue assessments should evaluate frequency change over time rather than an average frequency per job task.

5.1.4 *SEMG Utilization*—A SEMG user baseline task is measured with the exoskeleton doffed. Next, the task is repeated with the exoskeleton donned. MVIC and fatigue are subsequently analyzed and compared between the baseline and exoskeleton task executions. The effect of the exoskeleton should be assessed by comparative analysis between these conditions, and the results should show that the exoskeleton changes the level of muscle exertion in the desired direction from the baseline measurement. Appropriate sampling and statistical method should be considered. For example, an exoskeleton designed for industrial use to support the shoulders should reduce the level of muscle exertion. Alternatively, an exoskeleton designed for medical use to improve a patient's strength may increase the level of muscle exertion. Generally, this is to ensure that the patient can use the medical product safely and effectively for the intended use and use environment.

For further detail on SEMG, please review the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) project (**2**) and Cram and Criswell (**1**). SEMG research requires a high level of training and control to

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[4] The boldface numbers in parentheses refer to a list of references at the end of this standard.

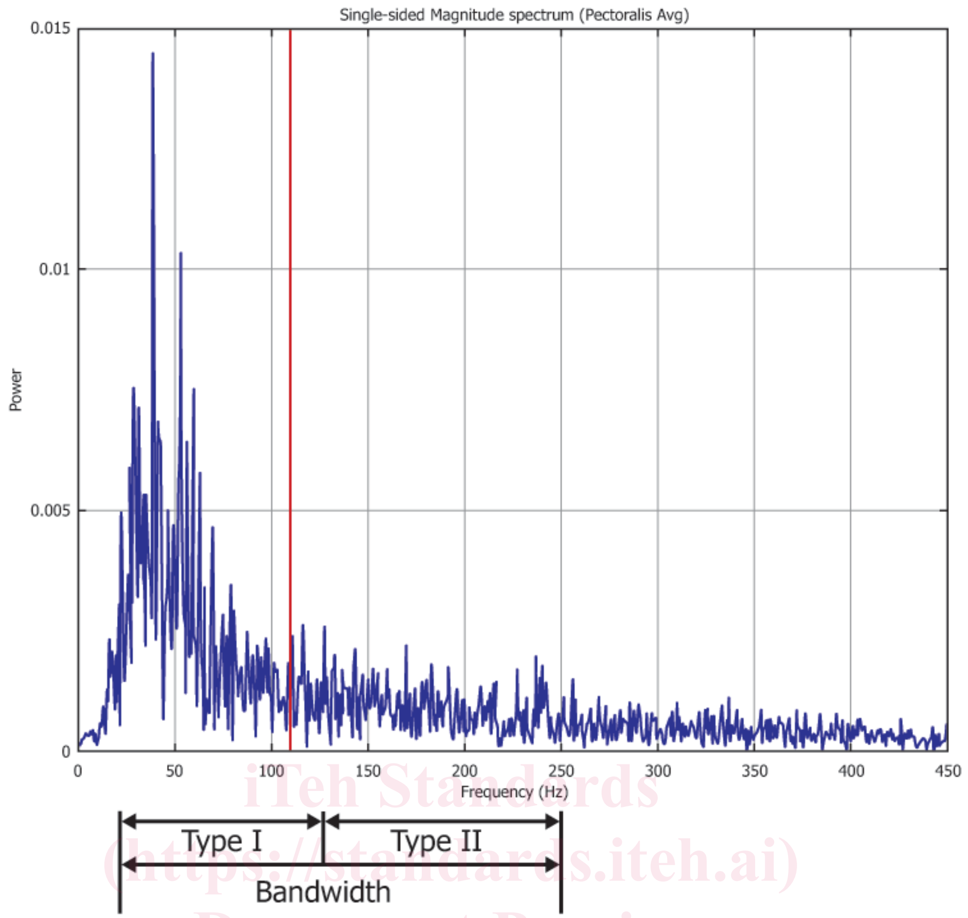

FIG. 1 Frequency Spectrum for Type I and Type II Fibers

ensure it is properly measured. Because exoskeletons may inhibit access to parts of the body where SEMG measurements may be desired, it is recommended that electrodes are placed on the subject with the exoskeleton on, or that the locations of the electrodes are identified with the exoskeleton on prior to performing baseline or exoskeleton condition data collection.

5.2 *Motion Capture*—Motion capture (MoCap) systems commonly use several infrared (IR) cameras and retroreflective markers. Therefore, MoCap systems tend to require a high level of training to ensure the required movement information with respect to the task is properly measured. The concept behind MoCap is the mathematical creation of a physical real-world space in a virtual environment. This is accomplished using a Cartesian coordinate system of x, y, and z where x is typically associated with anterior-posterior movement, y is typically associated with medial-lateral movement, and z is typically associated with vertical movements. To accomplish the prior, the use of a reference or ground plane is necessary to provide the proper orientation of the Cartesian coordinate system. Based on how the reference or ground plane is implemented, denotes the movement assignment associated with the coordinates. As a result, with the virtual world you are able to quantify various user angles (in degrees) of physical real-world movements. A basic MoCap system encompasses acquisition software, IR camera placement, IR camera calibration wand, setting the coordinate reference plane, user retroreflective marker placement, capture of task motion, and data-processing software.

5.2.1 *Retroreflective Marker Placement*—Critical to accurate measurement is the technique used to place retroreflective markers. Many systems will provide a MoCap suit of varying anthropometries to make marker adhesion fairly easy. These suits will commonly use a hook and loop method of marker adhesion. However, the intent of these retroreflective markers is to capture angles between user bony joint segments. So, it is necessary to apply the marker at the correct bony landmark, understanding the joint in question, and using a palpation technique to ensure the marker is placed on the appropriate bony landmark. Thus, the use of a MoCap suit requires a very snug fit to minimize the chances of suit movement from the bony landmark of interest while in use. Because of potential suit movement, many MoCap practitioners opt to not use MoCap suits and instead use double-sided tape adhered to the user's skin.

5.2.2 *MoCap Utilization*—A MoCap assessment consists of measuring the user performing the task of interest with the exoskeleton doffed. This provides a baseline for human movement with respect to that particular user. A user will then don the exoskeleton and perform the same task without any deviation from the baseline task. A comparison of donned and doffed exoskeleton metrics can be analyzed to assess if the exoskeleton restricts the user's range of motion or kinematics. Results should show that the exoskeleton maintains the user's range of motion. Exoskeletons may obstruct the cameras' view of the reflective markers, it is recommended that reflective markers are placed on the subject with the exoskeleton on, or that the locations of the reflective markers are identified with the exoskeleton on prior to performing baseline or exoskeleton condition data collection.

5.3 *Completion Time*—Completion time is a comparative measurement in the temporal domain to ascertain the duration of time required for a user to perform a specific task. A baseline measurement of a specific task is assessed without the exoskeleton. The same task is repeated, this time with the exoskeleton. Use of a time-measuring device is necessary with a resolution down to the second hash mark. A comparison of the execution times with and without the exoskeleton are analyzed to understand which method took longer. The results should show that the exoskeleton changes the completion time in the desired direction from the baseline measurement. For example, an exoskeleton designed for industrial use to support the shoulders should reduce or maintain completion time. Alternatively, an exoskeleton designed for medical use to improve a patient's strength or accuracy may increase the completion time.

5.4 *Pressure Mapping*—Pressure mapping is performed by instrumenting the exoskeleton user-interface areas or joint locations of an exoskeleton with thin film pressure sensors. Exoskeleton may place increased pressure on the user's soft and hard tissue, such as pinching or chafing. These pressure increases may occlude blood flow, reduce range of motion, and cause pain or discomfort, or both. Exoskeleton design should meet the intended anthropometric design range as specified by the Guide for Design for Population Accommodation.[2] As a result of the anthropometric design range, exoskeletons should be designed to mitigate added pressure to the user. In addition to pressure to the user at a perpendicular angle, there shall be a consideration for shear pressure as well. Shear pressure is typically at angles less than 90° and are analogous to a sliding pressure or force. An example of shear with respect to a donned exoskeleton occurs with a poor fit to the user. Therefore, when the user moves, the exoskeleton slides in the opposite direction of the user's initial movement (that is, Newton's Third Law of Motion). This sliding would typically be more of a micro slide over the course of completing a task. As a result, the micro sliding may aggregate to a serious cumulative effect to the user.

5.4.1 *Pressure-Mapping Measurements*—Thin film pressure-mapping sensors or pressure vests should be used. Particular focus should be placed at instrumenting the human-exoskeleton interface where the device comes in contact with the user's body, as previously mentioned. This is due to the potential for abrading or pinching of the user's skin, or both. Before measurements begin, the exoskeleton should be properly fitted to the user's body. To perform a pressure-mapping measurement, it is recommended that a trained practitioner in biomechanics or ergonomics, or both, perform the assessment and data analysis.

5.4.2 *Pressure Mapping Utilization*—Select a few tasks that are common and frequent for the measurement. The user should be instrumented and fitted with an exoskeleton. Thereafter, the exoskeleton should be donned and the task performed. In addition to the objective pressure sensor measurements, a user survey should be administered to capture nuanced information. Please see the Standard Guide and Model for Assessing Exoskeleton Use Intent for further details.[2] After data analysis, any deleterious pressure to the user should be mitigated.

5.5 *3D Volumetric Changes*—Assessments of 3D volume are accomplished through the use of a 3D scanner and software application designed to extract such measurements. Relevant volume changes include those of specific body parts as a subject moves and bends, which may need to be accommodated within soft or rigid aspects of an exoskeleton. Failure to account for the full volumetric change of a body within an exoskeleton with rigid parts may result in reduced mobility, discomfort, pain, or injury as discussed in 5.4. Additionally, the total volume occupied by a subject with and without an exoskeleton may be calculated in order to account for any additional space needed in the work environment where the exoskeleton will be used, or any area a subject wearing the exoskeleton may be expected to move through.

5.5.1 *3D Volumetric Changes Measurements*—Any of several high accuracy whole body 3D scanners with short imaging time (<20 s) may be used to collect 3D scan images of subjects. Likewise, there are multiple software applications which extract measurements from 3D scans (linear, circumferential, surface area, and volumetric) though they often return disparate results and so some care should be taken in selecting the appropriate scanner and software for each application. When collecting a 3D scan, the subject should be scanned outside of the exoskeleton, holding a neutral position and then scanned again while holding a position that maximizes the volume and splay of specific body parts (for example, sitting, squatting, bending, flexing) which may be of interest in the design or assessment of a given exoskeleton. It is also possible to investigate volumetric changes throughout a movement, though this requires the use of a specialized temporal 3D scanner. Collection of 3D scans for the purpose of quantifying encumbrance should be accomplished through scans of subjects with the exoskeleton both donned and doffed, holding the same position during both scans. Many simple linear and circumferential dimensions of change may also be collected via anthropometer or scientific measuring tape by trained professionals.

5.5.2 *3D Volumetric Changes Utilization*—Measurements are extracted from 3D scans via appropriate software. The comparison between measurements taken while the subject was relaxed and measurements while they were flexing, for example, would show the range of dimensions which must be accommodated within the design of an exoskeleton. This is especially important for exoskeletons which must fit snugly, but which should not apply undue pressure. Analysis of the encumbered 3D scans may be accomplished through extracted measurements at specific points of interest. Additionally, an overlay of one scan on top of the other to illustrate the exact points and extent of encumbrance may be performed. Such overlaid scans are also valuable in highlighting stand-off of an exoskeleton from the surface of the body, to include locations where this may be excessive as well as where they may be potentially restrictive or discomforting.

5.6 *Near IR Spectroscopy (NIRS)*—NIRS is a continuous, non-invasive, real-time technique for quantifying the level of oxygenation in blood vessels in vivo using wavelengths of near-infrared light spectrum (780 to 2500 nm). NIRS measures the amount of oxygen in the hemoglobin of red blood cells. Since contracting muscles uses oxygen, measuring levels of oxygenation in muscles during a physical task provides data on localized muscle activity and muscle fatigue (**3**). In certain circumstances, fatigue assessments with NIRS would be performed in conjunction with SEMG.

5.6.1 *NIRS Measurements*—NIRS assessment consists of measuring the user performing the task of interest without the exoskeleton. This provides a baseline for human muscle activation with respect to that particular user. A user will then don the exoskeleton and perform the same task without any deviation from baseline. A comparison of conditions with and without the exoskeleton can be analyzed to assess if there is an increase in blood flow to the muscle group of interest. One common NIRS metric is the tissue oxygenation index (TOI). TOI reflects local metabolic and hemodynamic changes in the prime muscles and is calculated as a ratio of oxygenated hemoglobin to total hemoglobin in the muscle tissue (**4**). NIRS assessments need to be consistent, precise, and localized to the doffed and donned measurement sites.

5.6.2 *Concurrent EMG NIRs Assessment*—Both EMG and NIRS sensors require placement at the muscle belly to obtain best estimates of electrical activity or blood flow, respectively, from the two techniques. As such, multimodal muscle assessments using EMG and NIRS may result in compromising probe locations as it can be particularly challenging to obtain oxygenation from the same muscle fiber bundle as electrical signals, without contamination from adjacent muscles. Thus it is essential that the priority for the type of assessment, NIRS or EMG, be determined a-priori to ensure that the primary assessment captures desired (and high quality) muscular signal. For larger muscles, such as quadriceps or biceps, multimodal EMG and NIRS assessments are more favorable than the smaller muscles of the forearm.

5.7 *Energy Consumption (Metabolic Rate)*—Energy consumption is an objective measure of the rate of energy expenditure a user expends to perform work. This is typically measured in kilocalories per minute. A kilocalorie is the energy required to raise the temperature of 1 kg of water by 1°C (this can also be measured in joules). The corresponding values are specific to an individual user based on the specific task being performed. This is due to the anatomical and physiological differences among users, and the values are typically a normalized percentage of energy expenditure. Many parameters are considered in performing an energy expenditure analysis: heart rate, age, body weight in kilograms, height in meters, and volume of oxygen and carbon dioxide inhalation and expiration or VO_2 and VCO_2. As a result, energy consumption analysis is primarily performed in a laboratory environment.

5.7.1 *Volume of Oxygen*—Volume of oxygen refers to the amount of oxygen a user consumes. This marker predicts cardiorespiratory fitness and energy consumption. Cardiorespiratory fitness measures the muscle's use of oxygen for aerobic activities and the heart's ability to pump blood to the muscles to perform the aerobic activity.

5.7.2 *Volume of Carbon Dioxide*—Volume of carbon dioxide refers to the amount of carbon dioxide a user produces.

5.7.3 *Energy Consumption Utilization (Metabolic Rate)*—Energy consumption can be measured with heart rate monitoring sensors and a face mask for volume of oxygen and carbon dioxide. A resting measurement in the posture (for example, standing) that the exoskeleton will be used should be taken with a user not wearing the exoskeleton to subtract from baseline, and exoskeleton measurements to calculate percent change. A baseline measurement of one user is then performed with the exoskeleton doffed, followed by a measurement of the same activity with the exoskeleton. The resting measurement is then subtracted from both the baseline and exoskeleton measurements to calculate a percentage change and this measurement is compared with the exoskeleton donned values of the same user. The combination of heart rate and volume of oxygen and carbon dioxide is an excellent predictor of energy consumption. The desired outcome is a change in energy consumption in the desired direction. For example, an exoskeleton for industrial use should reduce or maintain energy consumption compared to the baseline value. It may be desired that an exoskeleton for medical use increase or decrease energy consumption depending on the plan of care and the goals of treatment. Accurately measuring the resting, doffed, and donned energy consumption is critical for comparison.

5.8 *Strength Assessment*—Strength assessments are traditionally performed using a dynamometer and force plates.

5.8.1 *Dynamometers*—Dynamometers can assess grip strength, strength of an individual appendage, or whole-body strength. The significance of a dynamometer is the ability to isolate an individual muscle group for strength assessment. This is accomplished through isokinetic movements or isometric contractions of the muscle group of interest. Dynamometers assess the amount of resistance applied by the muscle to not allow over or under contraction. This averts the potential for injury and allows the user to gauge their strength potential.

5.8.2 *Force Plate*—Force plates measure reaction forces based on applied forces (Newton's Third Law of Motion). These force measurements encompass the upper, lower, or whole body, or combinations thereof. The significance of a force plate is that based on Newton's Third Law, whatever force is applied by the user's muscles has an equal and opposing reactive force. Typically, this is through the ground in what is referred to as ground reaction forces. Traditionally, force plates are used in gait laboratories to analyze force changes while walking. Force plates can be stand-alone or integrated into a treadmill (single or split belt), handrails, stairs, screens, and so forth.

5.8.3 *Strength Assessment Utilization*—Strength assessment consists of measuring the user performing the task of interest with the exoskeleton doffed. This provides a baseline for human muscle activation with respect to that particular user. Assessing in such a manner provides intuition on low-, medium-, and high-muscle activations of a user. These values