Designation: F3523 – 21

Standard Test Method for Exoskeleton Use: Confined Space: Horizontal Movement[1]

This standard is issued under the fixed designation F3523; 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 *Purpose:*

1.1.1 The purpose of this test method, as a part of a suite of exoskeleton use test methods, is to quantitatively evaluate an exoskeleton's (see Terminology F3323) performance or safety of usage, or both, by the exoskeleton user (see 1.4) in confined spaces with horizontal user movement.

1.1.2 Exoskeletons shall possess a certain set of allowable exoskeleton user movement capabilities, including user-motion adaptability, to suit operations such as: industrial, military, response, medical, or recreational. Environments in these typical sectors often pose constraints to exoskeleton user movement to various degrees. Being able to pass-through or maneuver, or both, effectively in confined spaces is essential for exoskeleton deployment for a variety of tasks. This test method specifies apparatuses to standardize this confined space task for testing exoskeleton user movement along the horizontal axis.

1.1.3 Exoskeletons shall be able to handle many types of task and terrain complexities. The required movement capabilities include, for example: walking, running, crawling, climbing, traversing gaps, hurdles, stairs, slopes, various types of floor surfaces or terrains, and confined spaces. Standard test methods are required to evaluate whether or not exoskeletons meet these requirements.

1.1.4 ASTM Subcommittee F48.03 develops and maintains international standards for task performance and environmental considerations that include but are not limited to, standards for safety, quality, and efficiency. This subcommittee aims to develop standards for any exoskeleton application as exemplified as in 1.1.2. The F48.03 test suite consists of a set of test methods for evaluating exoskeleton capability requirements. This confined space: horizontal movement test method is a part of the test suite. The apparatuses associated with the test methods challenge specific exoskeleton capabilities in repeatable ways to facilitate comparison of different exoskeleton models or to facilitate application of exoskeleton capabilities to intended tasks.

1.1.5 The test methods quantify elemental exoskeleton use capabilities necessary for sector applications listed in 1.1.2 and perhaps others. As such, users of this test method should use either the entire suite or a subset based on their particular requirements. Users are also allowed to weight particular test methods or particular metrics within a test method differently based on their specific requirements. The testing results should collectively represent an exoskeleton's overall safety or performance, or both, as required for the task. These performance data can be used: to guide procurement specifications, for acceptance testing, and for training to use exoskeletons intended for specified applications.

NOTE 1—Additional test methods within the suite are anticipated to be developed to address additional exoskeleton capability requirements, including newly identified requirements, and even for new application domains.

1.2 *Performing Location*—This test method shall be performed in a testing laboratory or the field where the specified apparatus and environmental conditions are implemented.

1.3 *Units*—The values stated in SI units are to be regarded as the standard. The values given in parentheses are not precise mathematical conversions to inch-pound units. They are close approximate equivalents for the purpose of specifying material dimensions or quantities that are readily available to avoid excessive fabrication costs of test apparatuses while maintaining repeatability and reproducibility of the test method results. These values given in parentheses are provided for information only and are not considered 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*

[1] This test method is under the jurisdiction of ASTM Committee F48 on Exoskeletons and Exosuits and is the direct responsibility of Subcommittee F48.03 on Task Performance and Environmental Considerations.

Current edition approved Nov. 1, 2021. Published November 2021. DOI: 10.1520/F3523-21.

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:*[2]

D4276 Practice for Confined Area Entry

F3128 Specification for Poly(Vinyl Chloride) (PVC) Schedule 40 Drain, Waste, and Vent Pipe with a Cellular Core

F3323 Terminology for Exoskeletons and Exosuits

F3427 Practice for Documenting Environmental Conditions for Utilization with Exoskeleton Test Methods

F3443 Practice for Load Handling When Using an Exoskeleton

F3444/F3444M Practice for Training Exoskeleton Users

F3474 Practice for Establishing Exoskeleton Functional Ergonomic Parameters and Test Metrics

F3517 Practice for Movement Tests When Using an Exoskeleton

2.2 *Other Standards:*

ISO 13482 Robots and robotic devices — Safety requirements for personal care robots[3]

3. Terminology

3.1 General terminology for ASTM Committee F48 standards are listed in Terminology F3323. Terminology specific to this test method are shown in this section.

3.2 *Definitions:*

3.2.1 *apparatus, n*—a structure, object, test component, or artifact thereof, found or placed in an environment and used for a test.

3.2.2 *artifact, n*—a representative of real structure(s), object(s), or test component(s) and used for a test.

3.2.3 *confined space, n*—limited entry and egress.

3.2.4 *horizontal movement, v*—user moves on the horizontal plane.

3.2.5 *movement, v*—a particular instance or manner of user motion.

3.2.6 *test suite, n*—designed collection of test methods that are used, collectively, to evaluate an exoskeleton's safety and/or performance.

4. Summary of Test Method

4.1 The task for this test method, exoskeleton-user moving through a confined space with horizontal movement, is defined as the exoskeleton-user traversing from the START point specified by the test supervisor, and ending at the END point. A test repetition shall be (*1*) when the user passes completely through the confined space or (*2*) when the user passes completely through the confined space and then returns back to the START point after passing completely back through the confined space again, thus enabling continuous repetitions. Either 4.1 (*1*) or (*2*) shall be defined by the test requestor prior to the test. The specified path from the START point to the END point shall be defined by the test requestor prior to the test. The confined space: horizontal movement apparatuses are described in Section 5. See Fig. 1 for an illustration. Artifacts representing real apparatuses are described in Section 6.

4.2 The exoskeleton's capability is defined as the exoskeleton's ability to complete the confined space: horizontal movement task where the user is capable of passing through the set confined space and, if requested by the test requestor, can perform the task at the desired time to complete the test. Further, the test requestor can specify the statistical reliability and confidence levels of such a capability and thus dictate the number of successful task performance repetitions that are required. In such a case, the average time to complete the test shall be used as the exoskeleton user's capability.

4.3 The exoskeleton user is allowed to practice before the test.

4.4 Once the test begins, there shall be no verbal communication between the exoskeleton user and the test supervisor regarding the performance of a test repetition, other than instructions on when to start and notifications of faults and any safety related conditions. The user shall have the full responsibility to determine whether and when they have completed a repetition and notify the test supervisor accordingly. However, it is the test supervisor's authority to judge the completeness of the repetition.

NOTE 2—Practice within the test apparatus could help establish the applicability of the exoskeleton for the given test method. It allows the operator to gain familiarity with the standard apparatus and environmental conditions. It also helps the test supervisor to establish the initial apparatus setting for the test when applicable.

4.5 The test requestor has the authority to select the confined space opening for the traversing task. The test requestor also has the authority to select test methods that constitute the test event, to select one or more test site(s) at which the test methods are implemented, to determine the corresponding statistical reliability and confidence levels of the results for each of the test methods, and to establish the participation rules including the testing schedules and the test environmental conditions.

5. Significance and Use

5.1 Exoskeletons are being used in the industrial, military, response, medical, and recreational sectors to enhance safety and effectiveness of the user to perform tasks. Confined spaces exist in many of these areas, as shown in Fig. 1, requiring people to fit through small spaces and this is potentially even more difficult while wearing an exoskeleton. For example, in the automobile manufacturing industry, workers wearing exoskeletons are required to fit into a confined automobile door opening while carrying tools to attach components to the car body. In emergency response operations, exoskeletons are used to enhance the safety and effectiveness of emergency responders operating in hazardous and confined space environments

[2] 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.

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

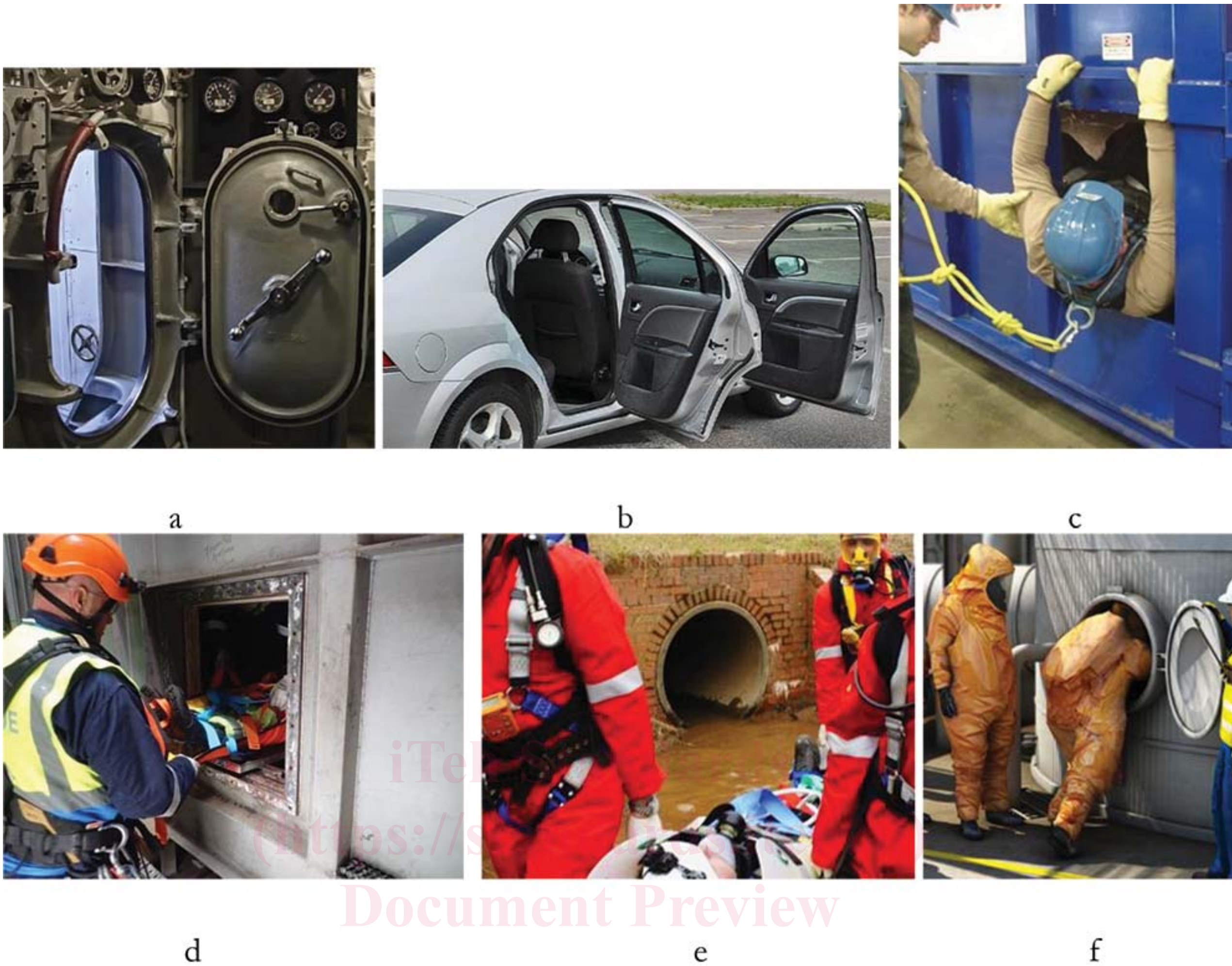


FIG. 1 Examples of Confined Spaces for People Moving Horizontally to Pass Through in Various Sectors, including: (a) Military, (b) Automotive Manufacturing, (c) Industrial Safety, (d and e) Rescue, (f) Chemical Manufacturing

for search and rescue of victims. The testing results of exoskeletons shall describe, in a statistically significant way, how reliably the exoskeleton is able to support tasks within the specified types of environments, confinements, and terrains, and thus provide sufficiently high levels of confidence to determine the applicability of the exoskeleton.

5.2 This test method addresses exoskeleton safety and performance requirements expressed by emergency responders, military, manufacturing, or other organizations requesting this test. The safety and performance data captured within this test method are indicative of the test exoskeleton's and the exoskeleton user's (see 9.6.6) capabilities. The safety and performance data from these tests are essential to guiding the procurement and deployment decisions of exoskeleton purchasers and users.

5.3 A standard artifact is specified to be easily fabricated. This facilitates evaluation by exoskeleton developers, manufacturers, and users, and to provide replication of confined space: horizontal movement tests across the exoskeleton sectors. The artifact can also be used to support training (see Practice F3444/F3444M) and to establish proficiency of exoskeleton users, as well as provide manufacturers with information about the minimum confined space that is feasible for their exoskeleton(s) with user.

5.4 Although the test method was developed for the sectors listed in 5.1, it may be applicable to other operational domains.

6. Apparatus

6.1 The actual confined space apparatus, as exemplified in Fig. 1, may be used for this test. In the event that the actual confined space apparatus is not available or the test is to be exactly replicated by others, or both, artifacts representing the apparatus as described in 6.2 and 6.3 shall be used. Two types of artifacts are described: (*1*) load-bearing, confined space: horizontal movement artifact and (*2*) movement-detection, confined space: horizontal movement artifact.

6.2 *Load-Bearing, Confined Space: Horizontal Movement Artifact:*

6.2.1 Where load from the exoskeleton user, exoskeleton, and other equipment is to be applied to the apparatus (for example, the user leans on the structure or contact from equipment on the apparatus occurs), the load-bearing, confined-space: horizontal movement artifact should be designed and constructed as exemplified in Fig. 2 and detailed in

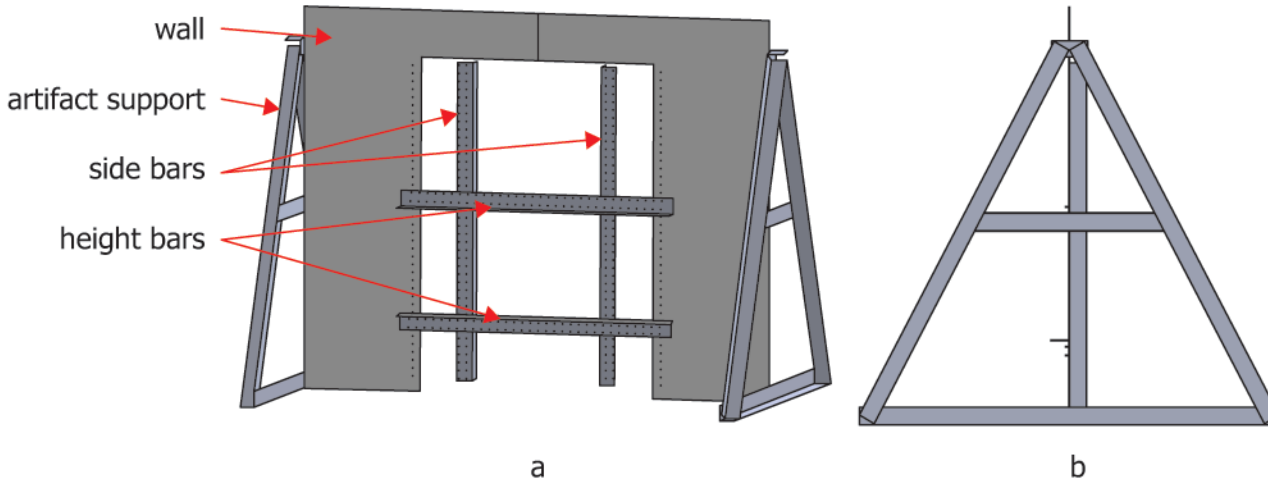


FIG. 2 Full Load-Bearing Load-Confined Space: Horizontal Movement Artifact (a) Isometric View, (b) End View

Appendix X1, and used for confined space testing. Note that the artifact should be engineered as a safe structure. The artifact wall is made from 13 mm thick steel sheet. (Note: Lighter weight materials, such as aluminum, may also be used so long as they can withstand applied forces.) Adjustable vertical bars and height bars are made from 6.4 mm thick by 102 mm steel angles and include 9.5 mm dia. holes spaced at 51 mm. Legs are also made from the same steel angles and welded or bolted into triangular shapes and to the wall as shown in Fig. 2. The full structure as shown weighs approximately 575 kg (1266 lb), providing sufficient artifact fixturing in place, although with portability.

6.2.2 The artifact may also be anchored to the floor to further resist movement.

6.2.3 Where available and appropriate, an alternative to using legs (that is, triangular frames or triangular side panels) is to attach the artifact wall directly to a super-structure (for example, masonry wall with rollup door opening) that is structurally capable of supporting the artifact, user, exoskeleton, equipment, etc. Leg and mounting alternatives shall be noted on the test report.

6.2.4 Padding or other materials may be added to the artifact to limit risk of user injury during tests. All such additions shall be noted on the test report.

6.2.5 Additional vertical or height bar confinement angle, or both, c-channel, or other forms may be added to the confinement framing. All such additions shall be noted on the test report.

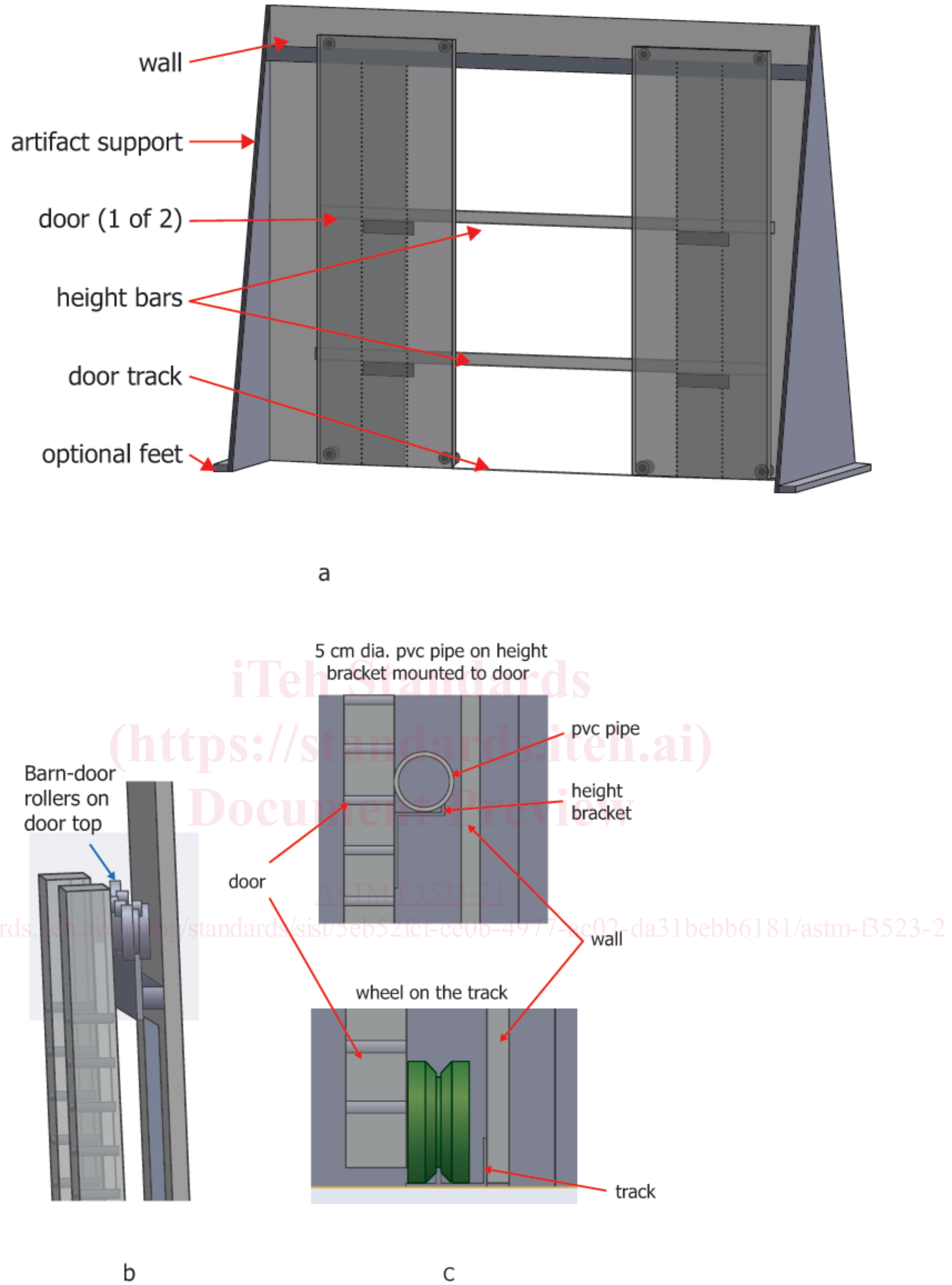
6.2.6 The artifact can be used as a structure for supporting confined-space openings or spaces that represent actual confined-spaces. All such additions shall be noted on the test report.

6.3 *Movement-Detection, Confined Space: Horizontal Movement Artifact:*

6.3.1 Where user-associated contact detection (for example, user, exoskeleton, equipment) is to be measured, for example in combustion hazard areas, training, or smallest access, the movement-detection, confined space: horizontal movement artifact (see Fig. 3) may be constructed and used for tests. Contact with the artifact from the exoskeleton user, exoskeleton, and any other equipment (for example, personal protective equipment, test measurement equipment) which causes artifact component movement shall be detected by visual detection or sensors. A maximum of 4 kg-m impact load, as determined from PVC pipe bend (see Specification F3128), can be applied to the artifact height bars. Other height bar materials, such as wood 2 by 4 nominal size bars, for example Sitka spruce with a modulus of elasticity of 10.34 GPa (1.5 Mpsi), may replace PVC pipe height bars, although medium-density fiberboard (MDF) door construction materials limit vertical height bar loading.

6.3.2 This test artifact, as modeled in Fig. 3, detailed in Appendix X1, and shown as actual in Appendix X2, includes a flat plywood wall measuring 3.0 m wide by 2.4 m high by 2 cm thick and supported in a vertical position by attaching a 2.4 m high by 1.2 m wide by 2 cm thick isosceles triangle plywood artifact support. Optional feet materials, as shown in Fig. 3, may also be fastened to the support bottom to allow floor mounting or weights to be added to hold down the artifact. Materials for the wall are 2 cm nominal plywood, plastic, or similar. The wall includes a 1.5 m wide by 2.1 m high centered opening measured from the floor.

6.3.3 A barn-door style rail, shown in Fig. 3(b), is mounted along the upper edge of the wall cutout and supports a right and a left MDF door, each measuring 61 cm wide by 2.3 m high by 5 cm thick with two 6.4 cm diameter grooved barn-door rail wheels at the top and two 10 cm diameter by 2.5 cm thick wheels at the bottom. The doors roll within a track mounted to the bottom of the wall and support the door weight. It is ideal to use lightweight, for example, hollow-core wooden door materials. The right door includes a series of horizontally aligned and paired 0.95 cm diameter holes spaced at 25 cm side-to-side for attachment of an aluminum angle height bar support. The hole series is spaced 13 cm from the left door edge and spaced 5 cm from the door bottom to the door top. Fig. 3(a) shows the door holes through semi-transparent doors (that is, only to show hole and height bar support detail). The left door holes are mirrored from the right door, that is, are spaced beginning at 13 cm from the right edge. Door wheel details are shown in Fig. 3(c).



NOTE 1—Doors are shown as translucent to show hole and other details.

FIG. 3 Movement-Detection, Confined Space: Horizontal Movement Artifact (a) Full Artifact, (b) End View of Barn-door Support Design, and (c) End Views of Height Bar and Door Wheel Details

6.3.4 Height bars ideally made of nominal 7.6 cm diameter plastic tubing (for example, schedule 40 PVC pipe) by 2.3 m long rest on the left and right height bar supports as detailed in Fig. 3(c). Plastic tubing pipe includes rounded edges where exoskeleton user contact hazards are minimized. Alternatively, the height bars can be made of 2 by 4 nominal wood. Wooden 2 by 4 height bars are less ideal than PVC pipe due to additional hazards of user head, limb, etc. contact with wood height bars, and minimized movement detection from applied force.

6.3.5 The open space defined by the left and right doors and the upper and lower height bars, if included, is considered the confined space: horizontal. Doors are intended to be on wheels so that they will move if the exoskeleton user applies minimal force to the door. Similarly, the height bars are intended to be lightweight to detect their movement upon contact by the exoskeleton user. In the event that contact is allowed between the exoskeleton user and the artifact, the doors may be clamped to the wall and the height bars made of heavier materials, as described in 6.3, or may also be clamped to the doors.

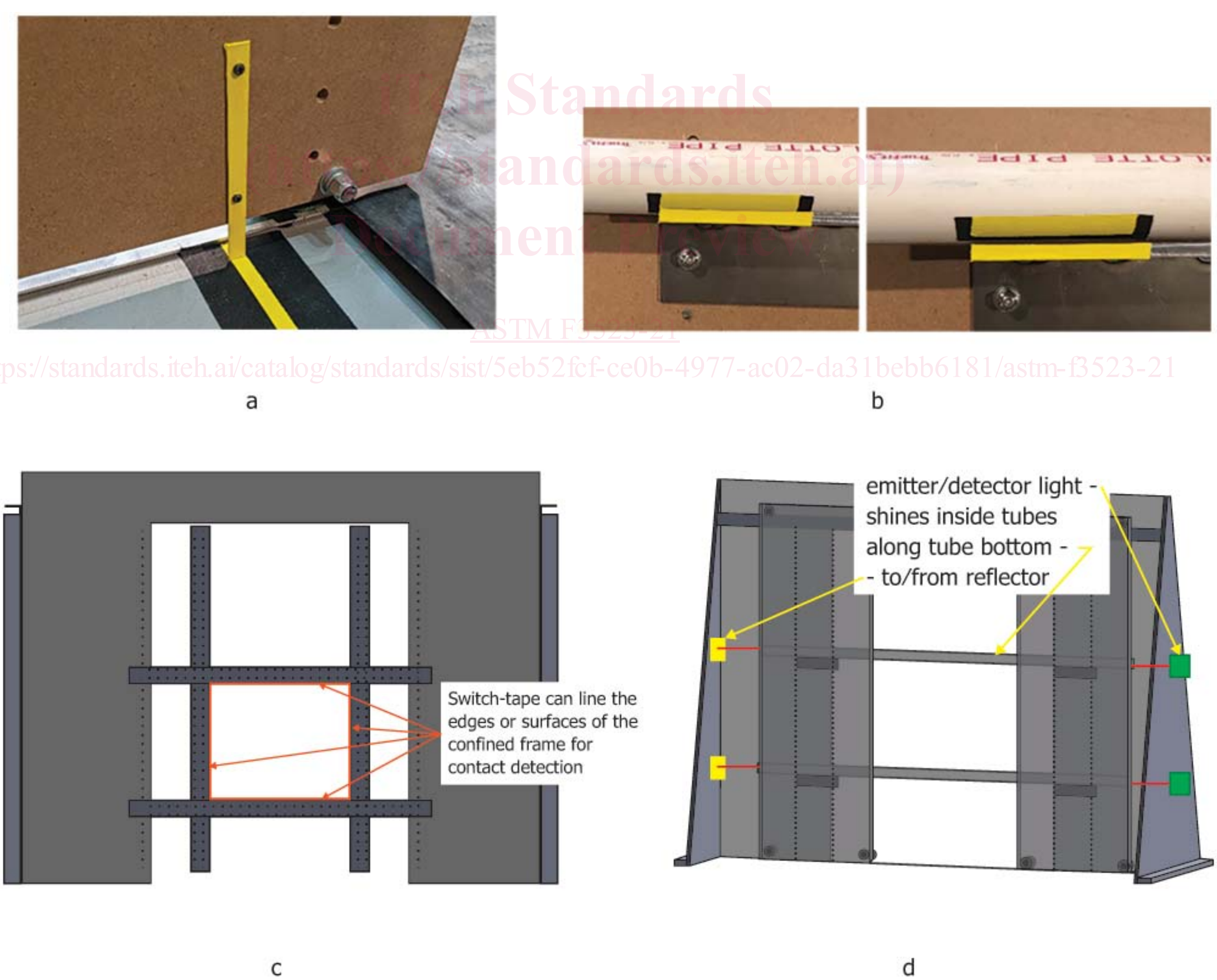
NOTE 3—In Fig. 3(a), the lower bar placement can define the confined space pass-through as below or above the lower bar, dependent upon the requested test.

6.3.6 The test supervisor or test technician is intended to monitor the apparatus (that is, real or artifact) during the test to detect any unintentional movement of the apparatus, especially when using the movement-detection artifact. Fig. 4(a) shows a door-movement method with a thin bar closely mounted above, without contact, and a tape line of the same width. Once the door moves, the thin bar will move away from the aligned tape. Alternative detection methods may also or instead be used, such as tape switches (see Fig. 4(b)), emitters/detectors (see Fig. 4(c)), optical tracking systems, cameras, or other similar electronic methods. Fig. 4 shows examples of electronic detection methods for artifact contact or movement, or both. Electronic or other detection methods may be applied to either artifact or the real apparatus.

6.3.7 Various test conditions, such as apparatus surface types and conditions, or environmental conditions, for example, wetness and floor friction level, and temperature, shall be facilitated as the test requestor requires. The apparatus condition shall be recorded on the test report and the environmental condition shall be recorded as defined in Practice F3427.

6.4 The confined space: horizontal movement artifacts, either movement-detection or load-bearing, can be modified as needed to mimic closer to the actual confined space or task, or both. Example modifications are provided in 6.4.2 and 6.4.3. All modifications to the apparatus (real or artifact) shall be detailed on the test report such that exact replication can occur.

6.4.1 If curved confinements exist within the pass-through area, they are either (*1*) for example, formed using 3D printed materials from computer aided design models or cutout from wood, plastic, metal, or other materials and attached to the



(a) Door-movement detection bar above floor tape, (b) height bar-movement detection with tape, (c) switch tape for contact detection in the opening, and (d) emitter/detector for horizontal bar movement detection.

FIG. 4 Examples of Detection Methods

confinement pass-through area (see example in Fig. 5), or (*2*) attaching straight bar(s) defining the chord between two curve points and attached to the artifact. Note that (*2*) may provide a slightly smaller confined space pass-through than in (*1*) or using the real apparatus.

6.4.2 *Artifact Modification Example 1 – Automobile Door*—This artifact modification mimics an automobile door opening measuring 91 cm wide by 122 cm high with the opening bottom being 40 cm above the floor (see Fig. 6(a)). The further confinement of a windshield-limiting space is also included in the artifact. An angled bar matching the windshield angle is also hinged to the upper height bar and rests on an additional height bar support as shown in Fig. 6(b). Further confinement can also be added to the artifact and documented on the test report if additional opening complexities exist. For example, curved areas or a raised floor as appropriate to mimic the real application.

6.4.3 *Artifact Modification Example 2 – Aircraft Aisle*—This artifact modification mimics an aircraft aisle (see Fig. 7(a)) opening measuring 41 cm wide by 213 cm high above the floor (see Fig. 7(b)). Wooden panels, measuring 109 cm high, that is, similar to aircraft seat heights, rest on the floor and are attached to the left and right doors to define the 41 cm opening for 2.4 m or more. Additional floor support or bracing can also be added to the panels for panel stability. Additional panels can be added to increase aisle length, and additional contours, for example, seat armrests, can be also added.

7. Hazards

7.1 Examples of hazards for confined space: horizontal movement tasks when using exoskeletons include: being stuck in tight spaces, catching the exoskeleton or body part on the opening causing pinches, burns, strains, pressures, and collisions dependent upon the exoskeleton, the test environment, and the apparatus (for example, the test structure). Refer to Practice D4276 which covers recognized procedures necessary to protect the health and safety of workers required to enter confined spaces. Refer to the References section **(1-4)**[4] in order to characterize biomechanical stressors. Note that although these references address typical risks and mitigation procedures, they may not address safety issues for an exoskeleton user.

7.2 Safety standards providing risks and mitigation procedures for hazards when using an exoskeleton are developed or being developed, including:

7.2.1 ISO 13482;

7.2.2 Test Method for Measuring Exoskeleton Ease of Use, Usefulness, and Use Intent;[5]

7.2.3 Guide for General Guidelines to Risk Management of Exoskeletons;[5]

7.2.4 Guide for Management of Internal and of External Sources of Risk.[5]

8. Calibration and Standardization

8.1 The exoskeleton configuration as tested shall be described in detail on the test report, including all subsystems and components and their respective features and functionalities, including version or iterations details as applicable. The configuration shall be subjected to all the appropriate tests within the suite of exoskeleton test methods. Any variation in the configuration shall cause the resulting exoskeleton variant to be re-tested across all the test suites to provide a consistent and comprehensive representation of the performance. Upon publication and to ensure standardized documentation, a future Practice for Documenting Exoskeleton Configuration[5] shall be used to record the exoskeleton configuration. Additional information describing the exoskeleton, exoskeleton user, and the exoskeleton fit to the user should also be documented.

8.2 Once an exoskeleton user begins a test, by starting to execute the task as specified in 4.1, the exoskeleton shall be used to perform the task for the specified number of repetitions through completion, without changing the exoskeleton or apparatus.

8.3 A battery may be changed or charged between repetitions, provided that other configurations remain unaltered and if allowed by the test requestor. Unless otherwise stated by the requestor, during the test the exoskeleton shall not be allowed to have the energy/power source replenished nor shall

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

[5] Standard under development.

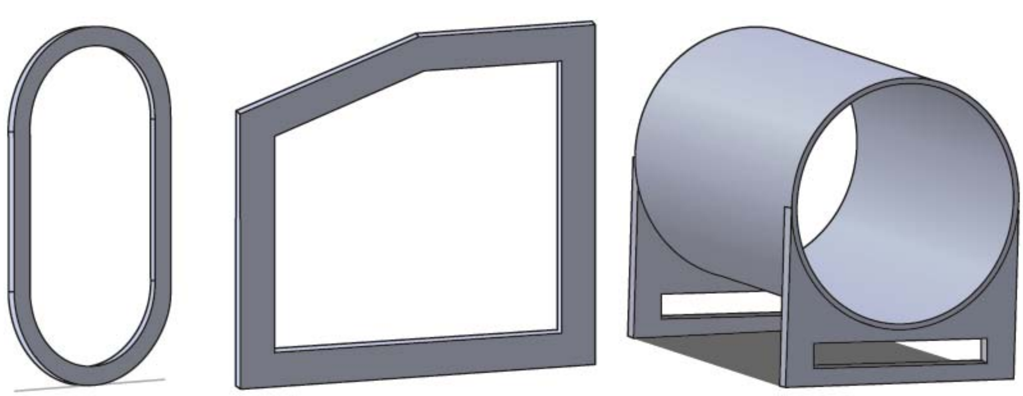


FIG. 5 Example Confined-Space Attachments to Artifact to Represent Close Approximation to Real Pass-through Openings and Spaces