Designation: F3578 – 22

Standard Test Method for Evaluating Exoskeleton Fall Risk due to Stumbling[1]

This standard is issued under the fixed designation F3578; 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 is to evaluate the extent to which an exoskeleton (see Section 3) improves, inhibits, or maintains (that is, does not affect) a user's ability to recover from a stumble perturbation.

1.1.2 Exoskeletons are designed to assist specific tasks and initially tested in controlled lab or controlled field settings. However, in the real world exoskeletons encounter less structured environments and situations (for example, hospital rooms, factory floors, construction sites). Even without exoskeletons people will stumble (that is, trip) or scuff their foot. It would be helpful to understand how wearing an exoskeleton affects a person's ability to recover from a stumble perturbation. Is one's ability to recover hampered, enhanced, or unaltered when using an exoskeleton? This test method specifies test setup, procedure, and recording to standardize testing exoskeleton user stumble recovery.

1.2 *Performing Location*—This test method shall be performed in a testing laboratory where the specified apparatus and environmental conditions are available and 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 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]

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

F3474 Practice for Establishing Exoskeleton Functional Ergonomic Parameters and Test Metrics

3. Terminology

3.1 General terminology for ASTM Committee F48 standards is listed in Terminology F3323. Terminology specific to this standard 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 *perturbation, n*—external disruption to body movement; in this standard, a perturbation specifically refers to a disruption to the lower limb trajectory during swing phase of gait due to an obstacle.

3.2.4 *scuff, n*—perturbation to the bottom of the foot during swing phase.

3.2.5 *stumble, n*—the act of tripping or losing balance as a result of a perturbation to the front of the foot/toe during swing phase.

4. Summary of Test Method

4.1 The task for this test method, exoskeleton user stumble recovery, is defined as the exoskeleton user stumbling during

[1] This test method is under the jurisdiction of ASTM Committee F48 on Exoskeletons and Exosuits and is the direct responsibility of Subcommittee F48.02 on Human Factors and Ergonomics.

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[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.

walking. This task is used to assess the extent to which an exoskeleton improves, inhibits, or maintains a person's ability to recover from a stumble. The task involves an exoskeleton user walking on a treadmill and experiencing a perturbation.

4.1.1 This test method can also be used to examine the response of the exoskeleton user to scuffs and other perturbation types, see 6.5.3.

4.2 The number of perturbations and conditions for each perturbation will be defined by the test requester prior to the test. The recommended apparatuses are described in Section 5. The test requester also selects the participants for the test, which should be representative of the expected user population of the exoskeleton to be tested.

4.3 The exoskeleton's capability is defined as the fall or recovery outcome of the task, as determined by the weight-bearing assistance provided by a force-instrumented overhead safety harness (see Section 6) and optionally the maximum trunk flexion after the perturbation as measured, for instance, by optical motion capture, a goniometer, or inertial measurement unit (IMU). These outcome metrics are evaluated by comparing the baseline case (that is, no exoskeleton) to the exoskeleton case to determine whether the exoskeleton improves, impedes, or maintains the exoskeleton user's performance (that is, fewer falls or less trunk flexion, or both, relative to baseline are improvements; more falls or more trunk flexion, or both, are impediments). The test requester can specify the number of perturbations, and as such, total falls out of total tests shall be recorded and used as the exoskeleton's fall risk, and can be compared to the user's fall risk in the baseline case, see 8.4.

4.3.1 All users are required to wear a harness to catch them after a fall to mitigate risk of injury. It is suggested that if the load cell measures >50 % bodyweight after a perturbation trial, even those including an apparent recovery, that trial should be recorded as a fall.

4.4 The exoskeleton user may undergo a familiarization period and practice walking on the treadmill with the sensory occlusion equipment (that is, dribble goggles to block the inferior visual field and wireless earbuds playing white noise along with noise cancelling headphones to block hearing, see Section 6) and harness prior to the test, see 9.8.8.

4.4.1 Practice is encouraged due to the potentially disorienting initial effects of the sensory occlusion equipment or discomfort associated with wearing a harness, or both. It is suggested that the exoskeleton user practice walking with and without the exoskeleton until they indicate they are comfortable walking continuously for 120 s or more. The practice time and protocol, as well as any prior experience by the user wearing the exoskeleton, should be described in the test report.

4.5 Additionally, acclimation to the perturbation protocol is recommended by allowing the user to experience at least one perturbation for both exoskeleton and baseline (no exoskeleton) cases to avoid inclusion of a potentially inconsistent first-time response in the data, see 9.8.8. The acclimation time and protocol, as well as any prior experience by the user with the test apparatus, should be included in the test report.

4.6 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, notifications of faults, and any safety concerns or physical discomfort. The user shall have the authority to request that the test be stopped at any point during the trial. However, it is the test supervisor's authority to judge the completeness of the repetition. If the testing is stopped before all specified trials are completed, the test is marked as incomplete.

4.7 The test requester has the authority to select the parameters that may affect the user for the task. The test requester 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. As such, variations to this test method are also described in this standard, including:

4.7.1 Leg swing percentage of perturbation;

4.7.2 Side experiencing perturbation (that is, right limb vs. left limb);

4.7.3 Obstacle weight and dimensions:

4.7.3.1 Changing the dimensions of the obstacle can allow the test to include scuffs and other perturbations, see 6.5.3.

4.7.4 Walking speed;

4.7.5 Environmental conditions including, for example, ground surfaces that are level or sloped or uneven/undulating; hard or soft; temperatures levels that are normal or extreme (Practice F3427); and

4.7.6 While carrying a load(s) (Practice F3443).

5. Significance and Use

5.1 There is strong evidence that exoskeletons can physically augment and assist users. They are typically designed and optimized with specific tasks in mind and initially tested in controlled lab or field settings. However, in the real world exoskeletons encounter less structured environments and situations (for example, hospital rooms, factory floors, construction sites, or even personal homes). In order to accelerate the adoption of exoskeletons in society, understanding their safety in the presence of perturbations is helpful. The testing results of the exoskeleton shall describe the extent to which the exoskeleton improves, inhibits, or maintains a user's ability to recover from stumbles, thus providing exoskeleton wearers and prescribers (for example, patients, clinicians, industry leaders, factory workers) with additional information about device performance and expectations.

5.2 The standard test apparatus and setup (see Section 6) is specified to be easily fabricated and implemented in gait or motion analysis laboratories. Variants of the apparatus, control algorithm, and test setup are acceptable to allow implementation in various lab settings with ranging experimental capabilities. The standard test setup and apparatus can also be used to support training and establish proficiency of exoskeleton users, as well as provide manufacturers with information about the performance of their exoskeleton(s) for tasks.

6. Apparatus

6.1 *Recommended Apparatus:*

6.1.1 A weighted obstacle must be introduced to the treadmill belt to induce the perturbation, in such a way that the exoskeleton user is unaware of the obstacle's approach (that is, low impulse and sound). This can be done more challengingly by hand, or through the use of an obstacle delivery apparatus, one suggested example of which is provided here.

6.1.2 The ramp consists of an acrylic track attached to an aluminum frame with adjustable, vibration-damping feet. The obstacle is held at a given point along the ramp via an electromagnet, which is held by a rod located by a pair of holes in the ramp (Fig. 1). The obstacle sits on the track via a set of flanged roller bearings mounted on shoulder bolts threaded into each corner (Fig. 1). The end of the ramp is parallel to the surface of the treadmill and overhangs the front edge to securely deposit the obstacle onto the treadmill (Fig. 2) without causing vibrations or an impact that would alert the participants to the impending perturbation. Bill of materials and instructions for building this ramp are freely available online.[3] Note that a large, padded bin is placed at the back end of the treadmill to catch the obstacle.

[3] S. T. King, M. E. Eveld, A. Martínez, K. E. Zelik, and M. Goldfarb, "A novel system for introducing precisely-controlled, unanticipated gait perturbations for the study of stumble recovery," *J. NeuroEngineering Rehabil.*, vol. 16, no. 1, p. 69, Jun. 2019, doi: 10.1186/s12984-019-0527-7.

6.2 *Optional Electronics and Algorithm:*

6.2.1 A predictive targeting algorithm can be used to elicit precisely timed perturbations during a given stride via computer assistance. This algorithm is freely available online.[3]

6.2.2 Force and moment data from an instrumented treadmill are required for the use of the algorithm.

6.2.3 Data is low-pass filtered to remove noise and clipped to prevent excessive voltage signals from damaging the microprocessor before it undergoes analog to digital conversion to be inputs for the algorithm which runs on a microprocessor.

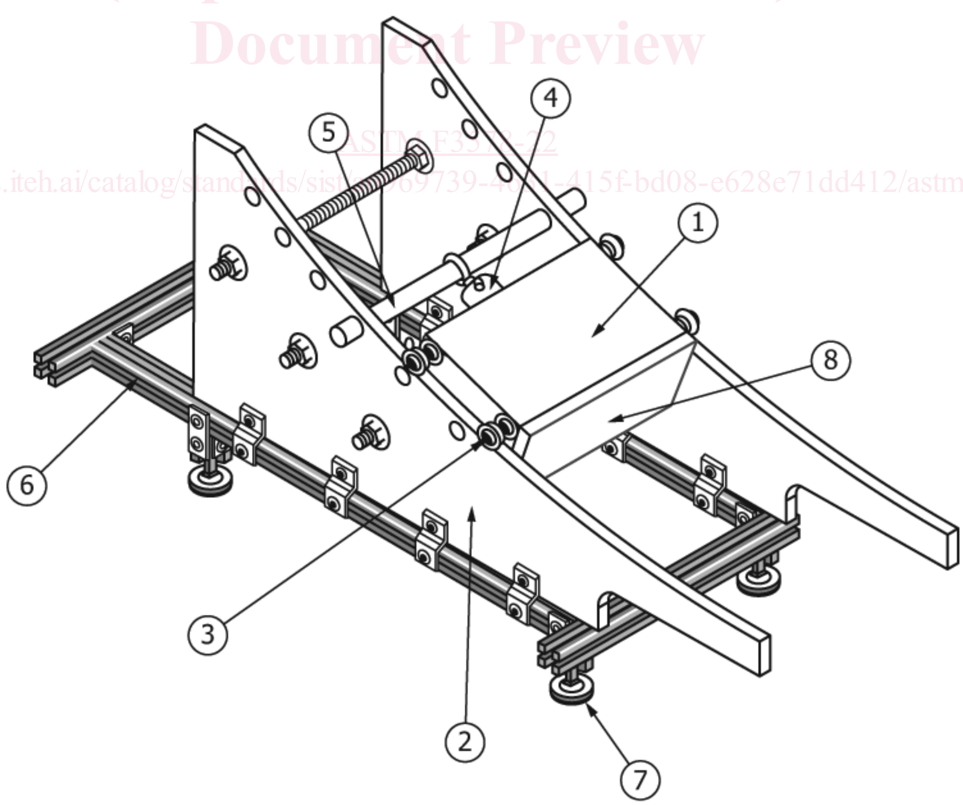
6.2.4 The algorithm uses the cyclic nature of gait, along with known time and position constants of the apparatus, to determine when the obstacle must be released to achieve a perturbation at a specific time. The algorithm computes key stride time metrics via gait event detection from the force and moment data inputs. Known apparatus time constants are preemptively inputted into the algorithm.

6.2.4.1 This algorithm requires a split-belt treadmill (that is, to collect force and moment data under each foot separately).

6.3 *Required Equipment:*

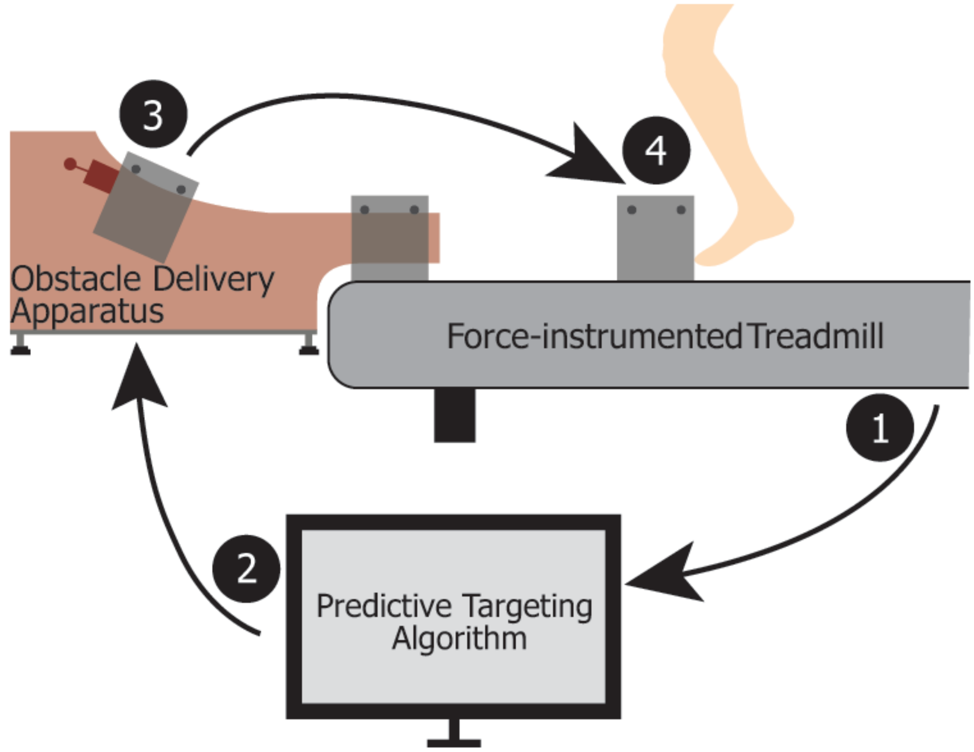
6.3.1 *Measurement Device*—A load cell in-line with the overhead harness will be provided to measure the bodyweight (force) assisted following the perturbation.

6.3.1.1 It is suggested that if the load cell measures >50 % bodyweight after a perturbation trial, even those including an apparent recovery, that trial should be recorded as a fall.



A steel block *(1)* rests on an acrylic track *(2)* via flanged bearing stacks *(3)*. The block is held in place by an electromagnet *(4)*, whose position is determined by the height of the metal rod *(5)*. The track is mounted to an aluminum frame *(6)* with adjustable, vibration-damping feet *(7)*. Foam *(8)* is adhered to the front and bottom of the block to protect the exoskeleton user's toes and reduce the impulsive loading on the treadmill, respectively.[3]

FIG. 1 Obstacle Delivery Apparatus



The exoskeleton user walks on the instrumented treadmill. Ground reaction forces and moments are collected *(1)* and used to calculate the center of pressure under the foot, which is then used to detect gait events. These gait events are used to calculate the time at which the obstacle should be released using the predictive targeting algorithm *(2)*. At this time the electromagnet turns off *(3)* and releases the obstacle onto the treadmill such that a perturbation is introduced *(4)* at the desired percent of swing phase.[3]

FIG. 2 Schematic of the Stumble Perturbation System

6.3.2 *Safety Equipment,* including: a harness to prevent the exoskeleton user from falling onto the treadmill following a perturbation; and protective footwear to avoid direct impact of the obstacle to the exoskeleton user's toes.

6.3.3 *Testing Equipment,* including: dribble goggles to block the exoskeleton user's inferior visual field and prevent them from observing the approaching obstacle; wireless earbuds to play white noise and prevent the exoskeleton user from hearing the release of the obstacle; and passive, noise-cancelling, protective headphones to further prevent the exoskeleton user from hearing the release of the obstacle.

6.4 *Optional Equipment:*

6.4.1 *Safety Equipment*—For example: heart rate monitor, pulse oximeter, or any other safety equipment which the test requester deems necessary can be at the ready as needed.

6.4.2 *User Measurement Devices*—For example: motion capture system, goniometer, IMU, muscle activity sensors, heart rate monitors.

6.5 The test sponsor has the authority to customize the following in order to incorporate various test conditions:

6.5.1 *Swing Percentage of Perturbation*—Using the optional predictive algorithm or by manual release, the timing of the perturbation (that is, when in swing phase the perturbation occurs) can be controlled.

6.5.1.1 It is recommended that the perturbations be timed to occur in at least three points of swing phase: early, mid, and late. Prior studies[3-6] have found that individual responses differ depending on when in swing phase the perturbations occur.

6.5.2 *Side of Perturbation (that is, left vs. right limb)*—The apparatus shown in Fig. 1 can be reproduced in order to perform the perturbation on either limb of the exoskeleton user.

6.5.2.1 It is recommended that perturbations should be performed on both limbs in order to *(1)* prevent anticipation or *(2)* to account for potentially differing responses due to participant/exoskeleton asymmetries, or both. First, for healthy adults, limb dominance has not been shown to play a role in fall likelihood or recovery strategy selection, as it is primarily a reflexive response. Thus, for cases of healthy adults wearing a symmetrically weighted and controlled exoskeleton, which limb is tripped (that is, left versus right) should not influence fall outcomes. However, randomizing which limb is tripped has been recommended in order to prevent any anticipation from the participant of the nature of when/where the perturbation will occur. Second, if the exoskeleton is unilateral or

[4] A. M. Schillings, B. M. Van Wezel, and J. Duysens, "Mechanically induced stumbling during human treadmill walking," *J. Neurosci. Methods*, vol. 67, no. 1, pp. 11–17, Jul. 1996.

[5] J. J. Eng, D. A. Winter, and A. E. Patla, "Strategies for recovery from a trip in early and late swing during human walking," *Exp. Brain Res.*, vol. 102, no. 2, pp. 339–349, Dec. 1994, doi: 10.1007/BF00227520.

[6] C. Shirota, A. M. Simon, and T. A. Kuiken, "Trip recovery strategies following perturbations of variable duration," *J. Biomech.*, vol. 47, no. 11, pp. 2679–2684, Aug. 2014, doi: 10.1016/j.jbiomech.2014.05.009.

asymmetrical in weight or control, or if the individual has a mobility impairment that compromises coordination or strength unevenly, testing stumbles on both limbs would be recommended as outcomes could differ.

6.5.3 *Obstacle Dimensions and Mass*—The obstacle can be machined to be any desired weight/size, assuming the flanged roller bearings can be mounted properly. This allows for the modification of the perturbation scenario and profile (that is, a lighter obstacle can simulate tripping on an empty box or a small object, while a heavier obstacle can simulate tripping on a brick or a curb. A longer obstacle may require both feet to cross the obstacle to recover, while a shorter one only requires one. Different shapes allow for different perturbation profiles as well, as a triangular or trapezoidal obstacle allows for a scuff rather than a stumble). The nominal size and weight obstacle used in prior publications are 20 cm by 12.5 cm by 7.5 cm (8.125 in. by 5 in. by 3 in.) and 16 kg (35 lb).[3]

6.5.4 *Walking Speed*—The initial height of the center of mass of the obstacle determines the horizontal velocity at exit, and thus the ramp includes multiple starting points for the obstacle (that is, multiple initial heights) in order to approximate a range of treadmill belt speeds. The starting height can additionally be fine-tuned via a threaded interface between the electromagnet and the rod to more precisely match a given belt speed.

6.5.4.1 It is suggested that at a minimum the exoskeleton be tested at the walking speed of its intended use.

6.5.5 Environmental conditions including, for example, ground surfaces that are level or sloped or uneven/undulating, hard or soft; temperatures levels that are normal or extreme (Practice F3427).

6.5.6 While carrying a load(s) (Practice F3443).

7. Hazards

7.1 While human safety standards are to be established and maintained by the test requester to fit their specific needs, some minimum elements of safety equipment must be met.

7.1.1 An overhead harness must be used to prevent the exoskeleton user from making contact with the treadmill during a fall.

7.1.2 Shoes with a protective toe (for example, steel-toed shoes), which shunt force to the ankle, should be worn to avoid pain associated with stubbing the toe on the obstacle.

7.1.3 Foam padding on obstacle can additionally provide protection for the exoskeleton user's feet while contacting the obstacle.

8. Calibration and Standardization

8.1 The exoskeleton configuration as tested shall be described in detail on the test form, including all subsystems and components and their respective features and functionalities, including version or iteration details as applicable. The configuration shall be subjected to all planned perturbation trials. Any variation in the configuration, or failure to complete all trials, shall cause the resulting exoskeleton variant to be retested across all trials to provide a consistent and comprehensive representation of the performance.

8.2 Once the test supervisor begins the first trial, 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 requester. Battery changes/charging shall be noted on the test report. Unless otherwise stated by the requester, during the test the exoskeleton shall not be allowed any human physical intervention, including adjustment, maintenance, or repair. Any such actions shall be considered a fault condition and the test should be restarted from the beginning.

8.4 The metric for this test method is number of falls (that is, harness assist) as determined by the load-instrumented harness. Additionally, the maximum trunk flexion angle during the recovery, as measured by motion capture, a goniometer, or an IMU can be used as a recovery performance index, providing insight on the overall difficulty of the recovery even if it did not result in a fall. These two metrics are to be compared across the two test cases (that is, no exoskeleton versus exoskeleton) to determine the impact the exoskeleton has on the exoskeleton user's performance. These results shall also be included on the test form. Any anomalous events will also be recorded on the test form including unintended stumbles or scuffs, as well as deviations from typical gait behavior. These metrics apply for both the baseline (no exoskeleton) and the exoskeleton cases.

8.4.1 It is suggested that if the load cell measures >50 % bodyweight after a perturbation trial, even those including an apparent recovery, that trial should be recorded as a fall.

8.5 The test requester has the authority to specify any and all environmental variables. All environmental settings shall be documented using Practice F3427.

8.6 The test requester has the authority to specify the number of repetitions for each type of perturbation trial (swing phase of perturbation, side perturbed, etc.). Considerations for user fatigue, abilities, exoskeleton capabilities, and other characteristics that may impact the tests shall be considered. Extending the duration of the test (for example, allowing larger breaks or rest time between perturbation trials) may also be included in the overall test confidence and shall be noted on the test report.

9. Protocol/Procedure

9.1 The test requester should consult the appropriate ethics committee and obtain approval if required before proceeding with this standard.

9.2 The test requester requests a test, including all test parameters (for example, test apparatus, environment, exoskeleton configuration, testing order, etc.) to be recorded and documented.

9.3 The environmental conditions of the space where the test will be performed shall be documented using Practice F3427 allowing test repeatability.