Standard Test Method for Comparison of Rearfoot Motion Control Properties of Running Shoes[1]

This standard is issued under the fixed designation F 1833; 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.

INTRODUCTION

During a typical running step, the foot first makes contact with the ground on the rear lateral border of the shoe. At first contact between the foot and the ground, the foot is normally in a supinated or neutral position relative to the lower leg. During the first 50 to 150 ms of the period of ground contact, the foot rotates about the ankle and subtalar joints to a more pronated position. Pronation is a combination of eversion and abduction of the subtalar joint and dorsiflexion of the ankle joint.

Excessive pronation and possibly an excessive rate of pronation are believed to be risk factors in common overuse injuries among runners. Other risk factors include a runner's anatomical predisposition, (for example, joint alignment, bone curvature, joint laxity) previous injury history and training errors (for example, a sudden increase in the duration or intensity of training). Running shoes have been shown to influence pronation. Shoe design factors which have produced measurable effects on lower extremity motion under laboratory conditions include sole hardness, sole height and width, sole geometry and the presence or absence of orthotics and stabilizing devices.

1. Scope

1.1 This test method covers the measurement of certain angular motions of the lower extremity during running, specifically, the frontal plane projection of the pronation and supination of the lower leg relative to the foot ("rearfoot motion") and methods by which the effects of different running shoes on rearfoot motion may be compared.

1.2 As used in this test method, footwear may refer to running shoes, corrective shoe inserts (orthoses) or specific combinations of both. The effects of orthoses may vary from shoe to shoe. Therefore, comparisons involving orthoses shall be qualified by the specific style of shoes in which they are tested.

1.3 This test method is limited to the measurement of the two dimensional, frontal plane projection of the relative angular motion between the lower leg and the foot ("rearfoot motion"). It is not a direct measure of pronation or supination, which are three dimensional motions.

1.4 This test method is limited to running motions in which the heel makes first contact with the ground during each step.

1.5 This test method is applicable to measurements of rearfoot motion made while subjects run on a treadmill or while they run overground under controlled conditions.

1.6 The values stated in SI units are to be regarded as the standard. The inch-pound units given in parentheses are for information only.

1.7 *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 and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

F 539 Practice for the Fitting of Athletic Footwear[2]

F 869 Terminology Relating to Athletic Shoes and Biomechanics[2]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *ankle joint*—the joint between lower leg and foot formed by the articulations of the tibia and fibula with the talus.

3.1.2 *footstrike*—initial contact between the foot and the ground at the beginning of the stance phase.

3.1.3 *maximum rearfoot angle*—maximum value of the rearfoot angle recorded during the stance phase.

3.1.4 *peak angular velocity*—maximum rate of change of the rearfoot angle between footstrike and the occurrence of maximum rearfoot angle.

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[1] This test method is under the jurisdiction of ASTM Committee F-8 on Sports Equipment and Facilitiesand is the direct responsibility of Subcommittee F08.54on Athletic Footwear.

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[2] *Annual Book of ASTM Standards*, Vol 15.07.

3.1.5 *pronation*—three dimensional motion of the foot relative to the lower leg, combining eversion an abduction of the subtalar joint an dorsiflexion of the ankle joint.

3.1.6 *rearfoot angle*—the angle between the lower leg and the heel, viewed from the posterior aspect and projected in the frontal plane.

3.1.7 *rearfoot motion*—relative motion of the heel and lower leg during the stance phase.

3.1.8 *stance phase*—the period of a running step during which the foot is in contact with the ground.

3.1.9 *subtalar joint*—alternative name for the talocalcaneal joint.

3.1.10 *supination*—three dimensional motion of the the foot relative to the lower leg, combining inversion and adduction of the subtalar joint and plantar flexion of the ankle joint.

3.1.11 *talocalcaneal joint*—the joint formed by articulations between the talus and the calcaneus.

3.1.12 *time to maximum rearfoot angle*—elapsed time between footstrike and the occurrence of maximum rearfoot angle.

3.1.13 *total rearfoot motion*—difference between the maximum rearfoot angle and touchdown angle.

3.1.14 *touchdown angle*—value of the rearfoot angle at the instant of contact between the foot and the ground during a running step.

4. Summary of Test Method

4.1 The rearfoot angle is defined by reference to markers placed on the lower leg and heel of the human subjects. While subjects run on a treadmill or overground the motion of the lower leg is recorded using a high-speed camera system positioned behind the subject and aligned with the subject's direction of motion. The time history of the rearfoot angle during the stance phase of running is determined by frame-by-frame analysis of the recorded motion. This process is repeated for each subject running in each of two or more footwear specimens. For each combination of subject and specimen, average values of maximum rearfoot angle, time to maximum rearfoot angle, total rearfoot motion and peak angular velocity are calculated. Analysis of variance is used to determine whether there are significant differences in rearfoot motion parameter between the specimens.

5. Significance and Use

5.1 This test method allows the rearfoot control properties of running shoes or corrective orthoses within shoes to be compared provided they are tested concurrently and under identical conditions.

5.2 Tests of this type are commonly used in the development and performance testing of running shoes and other in-shoe devices. Careful adherence to the requirements and recommendations of this test shall provide results which can be compared between different laboratories.

NOTE 1—The variance in rearfoot motion due to differences between shoes is generally smaller than the variance between subjects. Direct comparisons between shoes tested in different experiments is therefore not possible.

6. Apparatus

6.1 *Running Surface*:

6.1.1 *Treadmill*—A powered treadmill shall be used.

6.1.2 *Runway*—The runway used for overground running trials shall be a level surface with a minimum length of 15 m (50 ft).

6.2 *Means of Determining Running Speed*:

6.2.1 *A Calibrated Treadmill Speed Indicator*—For treadmill running, a calibrated means of determining the speed of the treadmill belt.

6.2.2 *Timing Apparatus*—For overground running, a timing apparatus shall be used to determine the elapsed time over a distance of 5 m (16 ft) with an accuracy of ±5 %. The average running speed, v, of the subject shall be determined by $v = s/t$ where s is the distance traversed and t is the elapsed time.

NOTE 2—An acceptable timing apparatus can be constructed using light beams, photocell detectors and an electronic timer. Two light beam/photocell detector units are positioned at head level and place 5 m (16ft) apart and on either side of test track on which rearfoot motion data will be recorded. The photocell circuit is connected to the electronic timer so that breaking of the first beam starts the timer. Breaking of the second beam stops the timer, which thus records the elapsed time.

6.3 *High Speed Camera System*—A cinephotographic or video camera or other optical system capable of tracking the motions of the lower leg at a minimum frame rate or sample rate of 200/s. If no derivatives are to be calculated, a minimum frame rate or sample rate of 100/s is permissible

NOTE 3—The minimum sample rate is based on the spectral composition of rearfoot motion at running speed of 3.8 ms^{-1}(8.5 mph). Tests conducted at higher running speeds may require higher minimum sample rates.

6.4 *Image Analysis Equipment*—Apparatus for determining the coordinates of markers on images from the high speed camera system, such as a digitizer, video processor or optical tracking system. The camera and image analysis equipment shall have a combined resolution such that the angle formed by leg and shoe specimen markers in a two dimensional plane normal to the axis of the camera can be determined with an error of less than ±0.5°.

NOTE 4—Greatest accuracy is achieved if the centroid of a marker is digitized. The use of large markers may decrease digitizing accuracy.

7. Specimens

7.1 *Acceptability*—The specimens may be any kind of footwear appropriate for use in or as a running shoe. The specimens shall be in the form of matched pairs (left and right).

7.1.1 *Shoes*—The specimens shall form matched pairs (left and right). All specimens shall be of the same size.

7.1.2 *Orthoses and In-Shoe Devices*—The specimens shall be in the form of matched pairs (left and right). All in-shoe device comparisons shall be made using devices in the same pair of shoes worn by the same subjects.

7.2 *Number of Specimens*—Two or more specimens shall be compared in any trial. The maximum number of specimens that can be compared is limited by the number of subjects required to achieve acceptable statistical power.

7.3 *Number of Subjects*:

7.3.1 The number of subjects shall be a minimum of four times the number of specimens.

7.3.2 If specimens are to be presented to subjects in a balanced order, the number of subjects shall be a multiple of the number of shoes to be compared.

8. Conditioning of Specimens

8.1 Condition specimens by being used for a minimum of 8 km (5 miles) of running prior to testing.

NOTE 5—The cushioning and stability of running shoes change rapidly during the first few miles of use. These characteristics stabilize after approximately 5 miles (8 km) of running (3500 footfalls) and then change less over the next 250 miles (400 km) of wear.

9. Procedure

9.1 *Experimental Design*:

9.1.1 Conduct the test as an experiment with a repeated measures, within-subject design.

9.1.2 It is recommended that the order in which specimens are presented to each subject should be balanced, not randomized. A balanced order of presentation requires that the number of subjects must be a multiple of *n*! (*n* factorial) where *n* is the number of shoes to be tested. If it is not practicable to use a balanced order of presentation, use randomized order of presentation.

NOTE 6—The statistical power of the test may be improved if a balanced order is used.

9.2 *Subjects*:

9.2.1 *Humans Subjects/Ethics Committee Approval*—Obtain the approval of all administrative bodies having jurisdiction over the use of human subjects in the laboratory or institution where the test is to be performed before any part of the test is begun.

9.2.2 *Informed Consent*—Obtain the informed consent of all human subjects shall in compliance with the American College of Sports Medicine's "Policy Statement Regarding The Use Of Human Subjects and Informed Consent" **(1)** current at the time of the test.

9.2.3 *Shoe Size*—The running shoe size of choice for all test subjects shall be the same. Measure size for all subjects with a Brannock device and reported to the nearest half size (Practice F 539.)

NOTE 7—*Lower Extremity Evaluation*— In order to establish relationships between subtalar joint kinetics and the effects of different running shoes, it is recommended that the lower extremity of each subject be examined by a competent examiner in order to provide information on the sample population being studied. The evaluation should include a medical history of lower extremity injury, foot type, forefoot frontal plane alignment, rearfoot frontal plane alignment, tibial horizontal plane alignment, and range of motion of the subtalar joint. Determine the type of footstrike of the subject (rearfoot, midfoot, or forefoot striker) with a force measuring platform, a pressure distribution measuring platform or an in-shoe plantar pressure measuring device. (See Cavanagh and Lafortune **(2)**). The training habits of each subject, including training frequency, weekly training distance and training pace should also be noted.

9.2.4 *Treadmill Experience*—If the test is to be completed while subjects run on a treadmill, the subjects should be experienced treadmill runners. If the subjects are not experienced treadmill runners, a minimum of one 20 min period of treadmill acclimatization training should be held prior to data collection.

NOTE 8—During treadmill acclimatization training, start subject(s) at a slower pace and the speed gradually increased until the speed is slightly below or a the test speed. The duration and number of practice sessions depends on the comfort of the subject with treadmill running. Some indication of the degree of comfort with treadmill running are seen in hip flexion and stride length.

NOTE 9—Subjects should wear their own shoes (that is, not test specimens) during treadmill acclimatization training.

9.3 *Marker Placement*:

9.3.1 *Leg Markers*—Place markers on the rear of each subject's lower leg, at least 20 cm apart. Center lower marker on the Achilles tendon. Place the top marker below the gastronemius, and orient so that the transverse vertical plane projection of a line connecting the two markers is parallel to the transverse vertical plane projection of the axis of a lower leg (see Fig. 1).

NOTE 10—Clarke et al **(3)** describe the use of an apparatus for placing the markers in a repeatable manner. Specifically, a jig is used to find the geometric center of the knee joint. Markers are then centered on a line joining the knee joint center and the center of the Achilles tendon. The use of this test method is recommended.

9.3.2 *Specimen Markers*—Place markers on the midline of the rear of each specimen, a minimum of 5 cm apart, such that the line joining the centroids of the two markers are perpendicular to the plane of the sole of the shoe (see Fig. 1).

9.4 *Standing Calibration*—In order to correct for differences in marker positioning between subjects, determine a calibration angle for each subject measuring the value of the rearfoot while the subject is standing in a neutral position. For the purposes of this test method, the neutral position is defined as standing with the medial edges of the shoe heels 5 cm (2 in) apart and the feet abducted 7°.

NOTE 11—When calculating rearfoot angles, subtract the calibration angle from the recorded data.

NOTE 12—Clarke et al **(3)** have described a simple jig for controlling the position of the feet while the calibration angle is recorded.

9.5 *Accommodation Period*—All subjects should have a warm-up period of approximately 2 min on the treadmill or 10 to 15 trials overground. The subjects should run at a speed less than test speed.

9.6 *Control of Running Speed*—Select a single running speed and use for all subjects and all specimens. Control the speed and hold constant with a tolerance of +5 % or less.

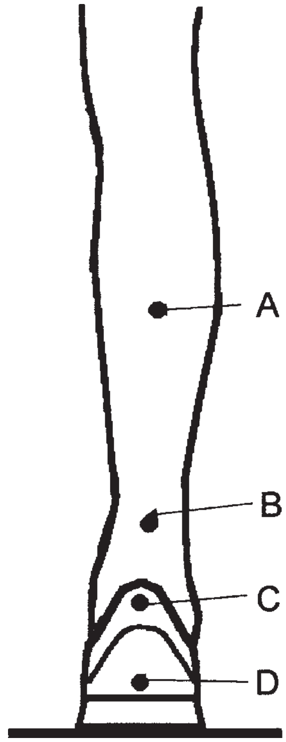
NOTE 13—In common practice, the selected running speed is 3.8 m s^{-1} (8.5 mph).

9.6.1 *Treadmill Running*—Set the running pace indicated by the calibrated treadmill speed indicator while the subject is running on it and hold constant.

NOTE 14—Speeds recorded while a treadmill is unloaded are not indicative of the loaded speed.

NOTE 15—Treadmill speed indicators are often inaccurate. The speed indicator must be carefully calibrated or an alternative tachometer used.

9.6.2 *Overground Running*—Use timing apparatus to determine the elapsed time over a known distance and hence to



NOTE 1—A: Lower leg marker centered on the Achilles tendon.

B: Top marker shall be placed below the belly of gastrocnemuis but at least 20 cm from Marker A. B is positioned so that the line connecting A and B is parallel to the axis of the lower leg.

C and D: Specimen markers placed on the rear of each specimen, a minimum of 5 cm apart, such that the line joining centroids of the two markers is perpendicular to the plane of the sole of the shoe.

FIG. 1 Posterior View of Lower Leg and Running Shoe Showing Location of Markers Defining Rearfoot Angle

determine the average speed of each subject during each trial. After each trial, calculate the average speed. Discard data from trials with average speeds deviating more than ±5 % from the selected running speed.

9.7 *Recording of Rearfoot Motion*—Use a high speed camera system to record the motion of the lower leg and foot during running.

9.7.1 *Position of Camera*—Position the camera behind the subject and aligned with the direction of running, in order to obtain a posterior view of the foot and leg. If a three dimensional camera system is used, process data as required to obtain the equivalent of a posterior view.

9.7.2 *Number of Steps*—For each subject-specimen combination, collect data for a minimum of five step cycles of the same leg. For overground running, this may be achieved by recording five running trails within the acceptable speed range.

9.8 *Data Processing*—For each subject-specimen combination, analyze a minimum of five steps.

9.8.1 *Digitizing*—For each step to be analyzed, use the image analysis equipment to determine the location of each marker in each frame of the motion recording. Begin analysis at least two frames before footstrike and no sooner than two frames after the heel has lost contact with the surface.

9.8.2 *Rearfoot Angles*:

9.8.2.1 For each frame, determine the rearfoot angle as the difference in the angular orientation of the line joining the centers of the two leg markers and the line joining the centers of the two specimen markers.

9.8.2.2 *Angle Convention*—The convention for reporting rearfoot angles is shown in Fig. 2. Define the rearfoot angle as a negative (-) value when the foot is pronated and as a positive (+) value when the joint is supinated. A neutral rearfoot angle is defined as zero (0) degrees (see Fig. 2).

9.8.2.3 *Subtraction of Calibration Angle*—Adjust each value of the rearfoot angle recorded by subtracting the calibration angle recorded for the same subject/specimen combination.

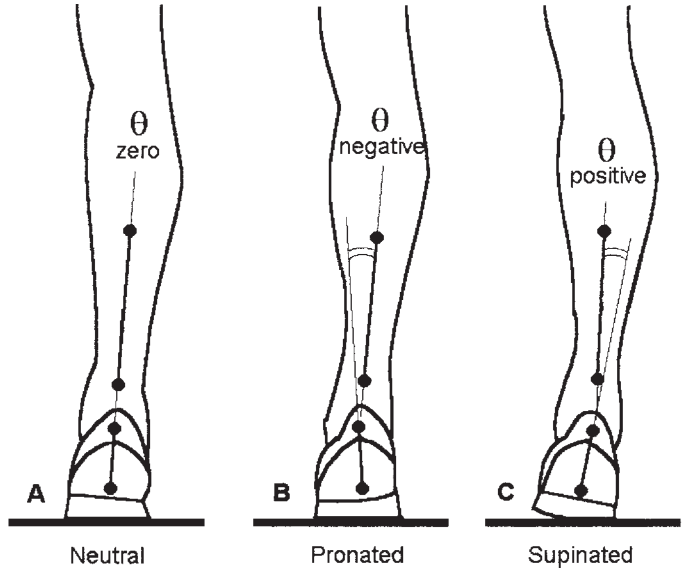
9.8.2.4 *Time History*—For each step analyzed, collate the rearfoot angles calculated for each frame to create a rearfoot angle-time history for that trial.

9.8.3 *Filtering/Smoothing*—Smooth the rearfoot angle-time curve by applying a filter with an equivalent cutoff frequency in the range 15 to 20 Hz.

NOTE 16—Depending on the type of filter used, it may be necessary to digitize extra frames at the beginning and end of each trial.

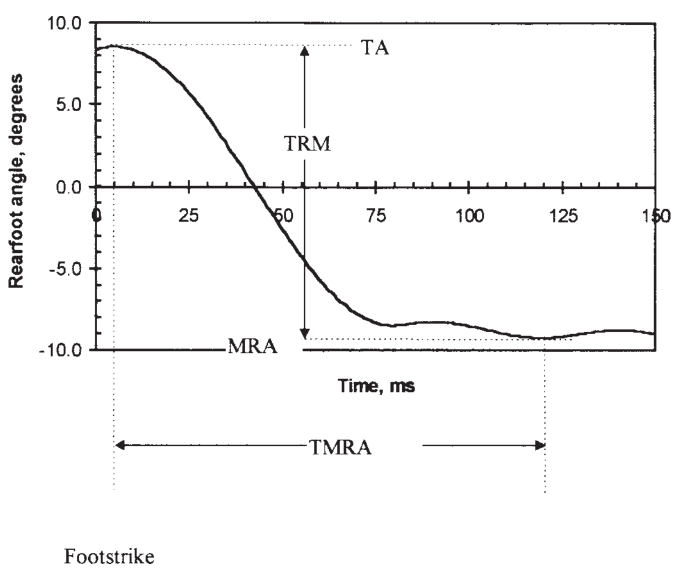
9.8.4 *Differentiation*—Determine the first time derivative of each rearfoot angle-time history using a finite difference method or other appropriate numerical differentiation technique (see also 6.3).

9.9 *Typical Curves*—Fig. 3 shows a typical rearfoot angle-time history and Fig. 4 its first time derivative. The typical



NOTE 1—A negative rearfoot angle indicates a pronated position (B). A positive value of the rearfoot angle is used to indicate a supinated position (C). A rearfoot angle of zero indicates that the foot is in the neutral position (A).

FIG. 2 Posterior View of the Right Foot and Lower Leg Showing the Rearfoot Angle, θ, Defined as the Angle Between the Transverse Vertical Plane Projection of the Line Formed by the Leg Markers and the Transverse Vertical Plane Projection of the Line Formed by the Specimen Markers



NOTE 1—The following parameters are indicated: touchdown angle (TA); maximum rearfoot angle (MP); time to maximum rearfoot (TMP) and total rearfoot motion (TRM).

FIG. 3 Typical Time History of the Rearfoot Angle During a Running Step

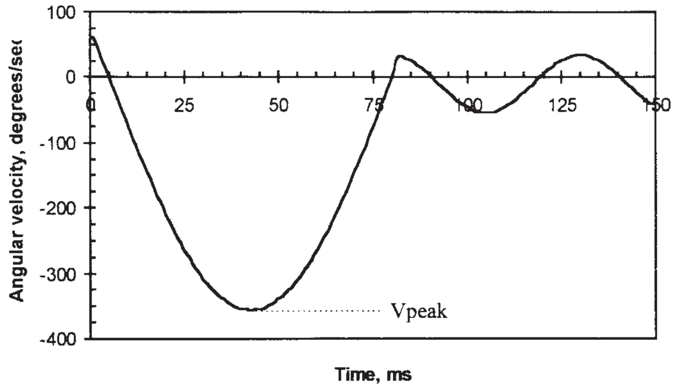
normal pattern is characterized by between 5 and 10° of supination at footstrike. During the first 30 to 50 ms after footstrike, the foot pronates and the rearfoot angle increases to between 5 and 15°. Normal but atypical patterns include those in which the foot remains supinated throughout the step and those in which the foot is pronated at initial contact.

9.10 *Rearfoot Motion Parameters*—Determine the following parameters by inspection of each rearfoot angle-time history and its first derivative.

9.10.1 *Touchdown Angle*—The value of the rearfoot angle at the instant of contact between the foot and the ground during a running step, TA in Fig. 3.

9.10.2 *Maximum Rearfoot Angle*—Maximum value of the rearfoot angle recorded during the stance phase, MRA in Fig. 3.

9.10.3 *Time to Maximum Rearfoot Angle*—Elapsed time between footstrike and the occurrence of maximum rearfoot angle, TMRA in Fig. 3.



NOTE 1—The peak angular velocity (Vpeak) is indicated.

FIG. 4 First Derivative of the Rearfoot Angle Time History Shown in Fig. 3

9.10.4 *Total Rearfoot Motion*—Difference between the maximum rearfoot angle and touchdown angle, TRM in Fig. 3.

9.10.5 *Peak Angular Velocity*—Maximum rate of change of the rearfoot angle footstrike and the occurrence of maximum rearfoot angle, Vpeak in Fig. 4.

9.10.6 *Averaging*—For each subject-specimen combination, the values of each parameter from the analyzed steps shall be average to obtain a mean score.

10. Statistical Analysis

10.1 *Analysis of Variance*—For each calculated rearfoot motion parameter, use one-way analysis of variance for correlated means to test the null hypothesis that there are no significant differences between the mean scores recorded for each footwear condition (see Appendix X1).

10.2 *Post-Hoc Analysis*—In the event that analysis of variance results in a significant *F*-ratio and rejection of the null hypothesis, a Tukey test or other appropriate post-hoc analysis may be used to test for the presence of differences between pairs of footwear conditions.

11. Report

11.1 Report the following information:

11.1.1 *Specimens*—A description of the specimens tested.

11.1.2 *Environment*—A description of the physical environment in which trials were conducted.

11.1.3 *Equipment*—A description of the equipment used to collect data including descriptions and specifications of the running surface the means of determining running speed, the high speed camera system and image analysis equipment. If a treadmill is use, report the type of treadmill, including it's surface characteristic, power, bed length, bed width, stiffness and friction characteristics. If overground running is used, report the surface type, length, stiffness and friction characteristics.

11.1.4 *Protocol*—The number of subjects, selected running speed and the number trials performed by each subject in each specimen.

11.1.5 *Variables*—Grand mean values and standard deviations for each specimen of the following parameters: touchdown angle (TA); maximum rearfoot angle (MP); time to maximum rearfoot (TMP), total rearfoot motion (TRM) and , if derivatives were calculated, peak angular velocity (Vpeak).

11.1.6 *Statistical Analysis*—Results of the analysis of variance, including a table of variances, degrees of freedom, F-ratios and probability scores. If a post hoc analysis is used to determine the statistical significance of differences between the mean scores of any pair of specimens, the method of analysis and results shall be reported.

12. Precision and Bias

12.1 A testing program is in progress for the purpose of determining repeatability and reproducibility.

13. Keywords

13.1 orthoses; pronation; rearfoot motion; running shoe; stability

APPENDIX

(Nonmandatory Information)

X1. EXAMPLE STATISTICAL ANALYSIS

X1.1 In order to determine the statistical significance of differences between shoes tested using this method, a one way analysis of variance for correlated mean is used to test the null hypothesis that there are no significant differences between the mean scores recorded for each footwear condition. The following example shows the calculation of an analysis of variance for an experiment in which twelve subjects were used to compare three different shoes. The example data are for maximum rearfoot angle (MP). The same method can be applied to the rearfoot motion parameters

X1.2 The data for this example are summarized in Table X1.1. For each subject and footwear condition there is a score for maximum rearfoot angle derived from the analysis of rearfoot motion.

X1.2.1 The number of conditions, $Nc = 3$,

X1.2.2 The number of subjects, $Ns = 12$, and

X1.2.3 The total number of samples $N = Nc.Ns = 36$

X1.3 The analysis of this data proceeds as follows:

X1.3.1 Calculate the sums and sums of squares for each row (subject) and column (footwear condition) and add them to the table (see Table X1.2).

X1.3.2 Calculate the grand total (GT):

$$GT = \{\Sigma x\}^2 / N \tag{X1.1}$$

where:

Σx = the total of all the raw scores.

In this example, $GT = (541.5)^2/36 = 8145.1$.

X1.3.3 Calculate the Total sum of squares (SS_{total}):

TABLE X1.1 Example Raw Data

	Footwear Condition		
Subject	A	B	C
1	16.4	16.9	17.6
2	12.5	12.4	13.7
3	15.0	14.7	16.6
4	17.6	18.0	20.1
5	6.7	5.7	5.5
6	14.5	15.0	15.7
7	15.0	14.1	14.5
8	9.1	9.8	11.2
9	13.1	14.0	16.1
10	14.5	15.4	17.7
11	21.6	20.7	22.0
12	19.2	18.8	20.1

TABLE X1.2 Data Table with Sums and Sums of Squares

	Footwear Condition			
Subject	A	B	C	Sum
1	16.4	16.9	17.6	50.9
2	12.5	12.4	13.7	38.6
3	15.0	14.7	16.6	46.2
4	17.6	18.0	20.1	55.7
5	6.7	5.7	5.5	17.9
6	14.5	15.0	15.7	45.2
7	15.0	14.1	14.5	43.6
8	9.1	9.8	11.2	30.1
9	13.1	14.0	16.1	43.3
10	14.5	15.4	17.7	47.5
11	21.6	20.7	22.0	64.3
12	19.2	18.8	20.1	58.1
Sum	175.2	175.5	190.8	541.5
Sum of Squares	2740.0	2748.2	3247.5	8735.6

$$SS_{total} = \Sigma x^2 - GT \tag{X1.2}$$

where:

Σx^2 = the sum of squares of all the raw scores.

In this example, SS_{total}=8735.6 - 8145.1 = 590.5

X1.3.4 Calculate the between trials sum of squares (SS_{trials}):

$$SS_{trials} = \{(\Sigma x_1)^2 + (\Sigma x_2)^2 \ldots + (\Sigma x_{Nc})^2\}/Ns - GT \tag{X1.3}$$

where:

$(\Sigma x_i)^2$ = the square of the sum of all the scores for the i th footwear condition.

In this example, $SS_{trials} = \{(175.2)^2 + (175.5)^2 + (190.8)^2\}/3 - 8145.1 = 13.2$.

X1.3.5 Calculate the between subjects sum of squares ($SS_{subjects}$):

$$SS_{subjects} = \{(\Sigma x_A)^2 + (\Sigma x_B)^2 \ldots + (\Sigma x_{Ns})^2\}/Nc - GT \tag{X1.4}$$

where:

$(\Sigma x_j)^2$ = the square of the sum of all the scores for the j th subject.

In this example, $SS_{subjects} = \{(50.9)^2 + (38.6)^2 + (46.2)^2 + (55.7)^2 + (17.9)^2 + (45.2)^2 + (43.6)^2 + (30.1)^2 + (43.3)^2 + (47.5)^2 + (64.3)^2 + (58.1)^2\}/12 - 8145.1 = 566.9$.

X1.3.6 Calculate the interaction sum of squares ($SS_{interaction}$):

$$SS_{interaction} = SS_{total} - SS_{subjects} - SS_{trials} \tag{X1.5}$$

X1.3.7 Calculate the degrees of freedom associated with each sum of squares:

$$DF_{total} = N - 1$$

$$DF_{trials} = Nc - 1$$

$$DF_{subjects} = Ns - 1$$

$$DF_{interaction} = (Ns - 1)(Nc - 1) \quad \text{(X1.6)}$$

In this example:

$$DF_{total} = 35$$

$$DF_{trials} = 2$$

$$DF_{subjects} = 11$$

$$DF_{interaction} = 22$$

X1.3.8 Create a table of variances using the model shown in Table X1.3. For each source of variation, the variance is calculated and entered into the table.

$$V_{trials} = SS_{trials} / DF_{trials}$$

$$V_{subjects} = SS_{subjects} / DF_{subjects}$$

$$V_{interaction} = SS_{interaction} / DF_{interaction}$$

TABLE X1.3 Layout of Table of Variances

Source of Variation	Sum of Squares	Degrees of Freedom	Estimated Variance	F
Between Trials	SS_{trials}	DF_{trials}	V_{trials}	F_{trials}
Between Subjects	$SS_{subjects}$	$DF_{subjects}$	$V_{subjects}$	$F_{subjects}$
Interaction	$SS_{interaction}$	$DF_{interaction}$	$V_{interaction}$	. . .
Total	SS_{trials}	DF_{trials}	V_{trials}	

X1.3.8.1 The F values for the two main factors of interest are calculated as follows:

$$F_{trials} = V_{trials} / V_{interaction}$$

$$F_{subjects} = V_{subjects} / V_{interaction}$$

The table of variances for the data used in this example are shown in Table X1.4.

X1.3.9 The significance of each F value can be determined by referring to standard statistical tables. In this example, significant F value with 22 degrees of freedom for the lesser variance and 2 degrees of freedom for the greater variance are 3.443 at a probability level of 0.05 and 5.72 at a probability level of 0.01. Since the observed F value of 13.9 between trials exceeds the critical F value of 5.72 at the 0.01 probability level, there is a less than 1 % probability that the observed differences between the mean scores of each footwear condition are due to chance. The null hypothesis that there are no significant differences between the footwear conditions is therefore rejected.

X1.3.9.1 In instances where more than two footwear conditions are used and significant differences are detected, a post-hoc analysis (for example, a Tukey test) may be used to identify which footwear conditions are the source of the significant differences.

TABLE X1.4 Example Table of Variances

Source of Variation	Sum of Squares	Degrees of Freedom	Estimated Variance	F
Between Trials	13.2	2	6.59	13.9
Between Subjects	566.9	11	51.54	108.6
Interaction	10.4	22	0.47	. . .
Total	590.5	35	16.87	

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