A Novel Device for Standardizing Marker Placement at the Calcaneus

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Background: The determination of anatomical reference frames in the rearfoot during three-dimensional multisegment foot modeling has been hindered by a variety of factors. One of these factors is related to the difficulty in palpating, or the absence of, anatomical landmarks. A novel device (the Calcaneal Marker Device) aimed at standardizing marker placement at the calcaneus was, therefore, developed and evaluated for its reliability.

Methods: Throughout a random repeated-measures design, the repeatability of calcaneal marker placement was evaluated for two techniques: manual placement and placement using the Calcaneal Marker Device. Translational changes after marker placement and the clinical effect on intersegment angle calculation were quantified.

Results: Intraobserver variability was greater in therapist 2 ($<$5.3 mm) compared with therapist 1 ($<$2.9 mm). Intraobserver variability was also found to be less than 1.6 mm throughout use of the device. Interobserver variability was found to be significantly higher for the position of markers placed manually (5.8 mm), whereas with the Calcaneal Marker Device, the variability remained lower ($<$1.3 mm). The effect on the computed intersegment angles followed a similar trend, with variability of 0.4° to 4.0° and 1.0° to 8.7° for CMD and manual placement, respectively.

Conclusions: These findings suggest that variations in marker placement are considerably reduced when the novel Calcaneal Marker Device is used, possibly toward the limits dictated by the fine motor skills of therapists and tissue artifacts. (J Am Podiatr Med Assoc 104(1): 43-49, 2014)

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The adequate analysis of foot and ankle kinematics is considered a critical element in understanding pathomechanically related lower-limb injuries.[1] Analyzing the complex behavior of this multisegmental structure has been a major challenge for many years; however, recent development of three-dimensional multisegment foot models (3DMFMs) can be considered an important evolution in podiatric medicine. Many such 3DMFMs have been published in the literature, each aimed at describing the complex kinematic behavior of the foot during ambulation.[2] Despite their value with respect to clinical decision making,[3,4] standardization is lacking, as reflected by the variety of anatomical marker sets that have been used. In fact, these markers are the basis for determining the anatomical reference frame of each segment.

A key segment in almost all 3DMFMs is the rearfoot because this segment is of utmost importance in many foot-related functional abnormalities.[5,6] Typically, determination of an anatomical reference frame for the talus and the calcaneus has been impeded owing to the intrinsic complexity of the tibiotalar and subtalar joints. Consequently, the rearfoot has often been considered as a rigid segment in these models; however, recent publications illustrate the ongoing will and creativity of certain researchers to develop and validate noninvasive marker protocols for distinguishing subtalar from tibiotalar kinematics.[7,8] Another factor that substantially hinders marker placement at the rearfoot and, therefore, the definition of adequate anatomical reference frame is the nature of the tissue underlying the skin, such as fat pad and tendons.[9,10] In addition, some anatomical landmarks are difficult to palpate, such as the tuberculum peroneum and the sustentaculum tali.[11] Finally, some anatomical landmarks may be very small (<5 mm) or even absent (eg, the tuberculum peroneum),[12,13] which further challenges the adequate determination of, for example, the "calcaneal" reference frame. As a consequence of all of these factors, the reliable representation of intersegment angles is affected, which further limits the clinical use of these 3DMFMs. To overcome some of the previously mentioned factors, a novel device was developed that aims to standardize marker placement at the calcaneus irrespective of anatomical landmarks. This article provides, in addition to a technical description of the novel device, the results of a reliability study performed to assess the clinical utility of the device.

Methods

Calcaneal Marker Device

The Calcaneal Marker Device (CMD) was designed to standardize marker placement at the medial and lateral borders of the calcaneus (Fig. 1). The CMD consisted of a horizontally oriented base plate that is held against the posterior aspect of the semi-weightbearing calcaneus. A vertically oriented plate was integrated into the middle of the base plate, allowing the device to accommodate different calcaneal lengths, and an oval hole allows visualization of the calcaneal midline. Two sliding arms were mounted to the base plate, allowing antero-

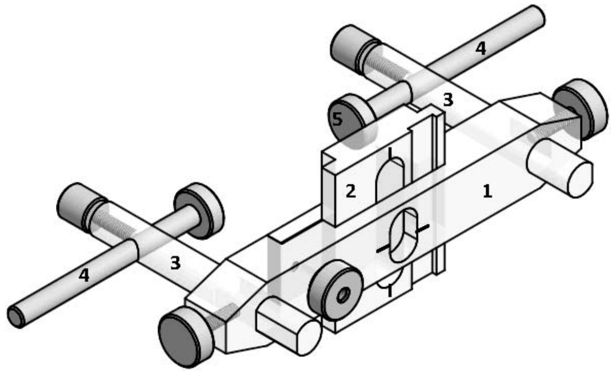

Figure 1. The Calcaneal Marker Device: base plate of the CMD (1), vertically oriented unit with oval hole (2), sliding arms allowing anteroposterior (3) and mediolateral (4) adaptation, and marker locator (5).

posterior movement of the marker locators. Movement of the marker locators in the mediolateral direction was facilitated by mounting the marker locators on sliding arms. Small lines were engraved in the arms to provide a metric scale (3-mm intervals). Anteroposterior positioning of the marker locator with respect to the base plate was standardized according to foot size (eg, European size 36–40, 3.0 cm; size 41–44, 3.3 cm; and size 45–48, 3.6 cm. It is recognized that the inclusion of only three anteroposterior positions is a limitation; however, it facilitates clinical use, and it is believed that errors associated with this standardization are small.

Participants

Eight healthy adults (mean $\pm$ SD age, 29.1 $\pm$ 6.3 years; mean body mass index [calculated as weight in kilograms divided by height in meters squared], 25.2) were recruited at the Clinical Motion Analysis Laboratory of the University Hospitals Leuven. Potential participants were excluded if they had a history of trauma of the foot and lower limbs or if they presented with a foot deformity (screened via standard clinical examination) or with a systemic or neurologic disorder. The Ethical Committee of the University Hospitals Leuven granted approval for the study, and informed consent was obtained from each participant.

Photogrammetric Equipment and 3DMFM

Marker three-dimensional (3-D) coordinates were acquired at 100 Hz using a 10 T-10 camera motion analysis system and Nexus motion capture software

(Vicon Motion Systems Ltd, Oxford Metrics, Oxford, England). The measurement error of the motion analysis system to reconstruct the 3-D position of stationary markers was less than 0.02 mm for all three planes. The 3DMFM protocol proposed by Leardini et al[6] was used to measure multisegment foot positions. This 3DMFM protocol measures multisegment foot positions of the shank and calcaneus, calcaneus and midfoot, midfoot and metatarsus, and calcaneus and metatarsus.

Protocol

Fifteen retroreflective markers (6 mm) were mounted on each foot and tibia over the anatomical landmarks of the 3DMFM (Table 1).[6] Participants were then seated in a chair and instructed to maintain a comfortable position during the whole test session to allow adequate data registration and interpretation (Fig. 2).

A repeated-measures design was used in which each participant had three calcaneal markers (sustentaculum tali, tuberculum peroneum, and posterior aspect calcaneus) attached a total of eight times. An additional marker on the posterior aspect of the calcaneus was used for creating the anatomical reference frame of the calcaneus in a static position. Marker attachment was performed by two therapists (t = 1,2), in two sessions (s = 1,2), using two distinct techniques (tech = 1,2). Therapist 1, a podiatric physician, had experience with 3DMFM marker placement and with the CMD, and therapist 2, a physiotherapist, had no experience with either technique. However, compared with the podiatric physician, the physiotherapist had much more clinical experience. Training of the physiotherapist was organized before initiation of the present study. This involved the placement of markers at the anatomical landmarks on several colleagues using both techniques. Each therapist was blinded to the marker placement of the other therapist, and the three calcaneal markers were removed after each session.

The first marker placement technique consisted of manually placing the sustentaculum tali, tuberculum peroneum, and posterior aspect calcaneus markers.

The second technique used the CMD. First, three midpoints were marked on the posterior aspect of the heel. A straight line was drawn joining the points, representing the frontal plane alignment of the calcaneus. Subsequently, a sliding caliper was held against the posterior aspect of the calcaneus to measure its width. This measurement was used to set the medial and lateral distance between the marker locators. The anteroposterior positioning of the marker locators was determined by the foot size of the participant. The CMD was then placed on the semiweightbearing calcaneus (Fig. 3). The correct alignment of the CMD in the frontal plane was achieved by superposing the engraved lines of the vertical plate with the bisection line on the posterior calcaneus. Adequate alignment in the sagittal plane was achieved by holding the vertical unit firmly against the posterior aspect of the calcaneus.

Table 1. Foot Model Published by Leardini et al[6]

Anatomical Landmark	Label	Segment
Tibial tuberosity[a]	TT	Shank
Head fibula[a]	HF	Shank
Lateral malleolus[a]	LM	Shank
Medial malleoulus[a]	MM	Shank
Calcaneus posterior surface[b]	CA	Calcaneus
Peroneal tubercle[b]	PT	Calcaneus
Sustentaculum tali[b]	ST	Calcaneus
Navicular tuberosity[a]	TN	Midfoot
Base first metatarsal[a]	FMB	Metatarsus
Base fifth metatarsal[a]	VMB	Metatarsus
Base second metatarsal[a]	SMB	Metatarsus
Fifth metatarsal head[a]	VMH	Metatarsus
First metatarsal head[a]	FMH	Metatarsus
Second metatarsal head[a]	SMH	Metatarsus
Proximal phalanx hallux[a]	PM	Hallux

[a]Markers that remained on the foot during the whole test session.

[b]Markers placed throughout using the Calcaneal Marker Device.

Data Analysis

In the present study, planar variance of the three calcaneal markers (σ^2_D) occurring in both techniques was the result of two independent factors: the involuntary movement of the participant while seated in the chair (σ^2_M) and the marker placement error (σ^2_B): $\sigma^2_D = \sigma^2_M + \sigma^2_B$.

The involuntary movement of the participants while seated in the chair was quantified throughout each measurement performed by each of the two clinicians by calculating the displacements (x, y, and z) of the navicular tuberosity marker (Table 1). A "mean foot movement error" (x, y, and z) was subsequently calculated for each measurement, which served as a basis for further statistical analyses. The impact of this involuntary movement was also calculated with

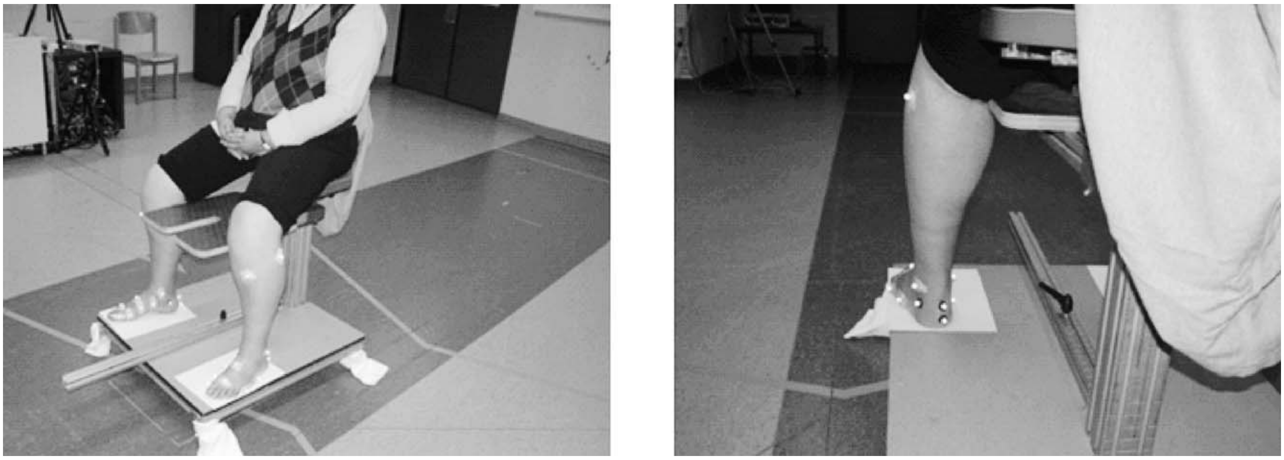

Figure 2. Seated position maintained by the participants throughout the complete test session. The orientation of the global reference frame was as follows: x-axis, pointing forward; y-axis, pointing to the left; and z-axis, pointing upward.

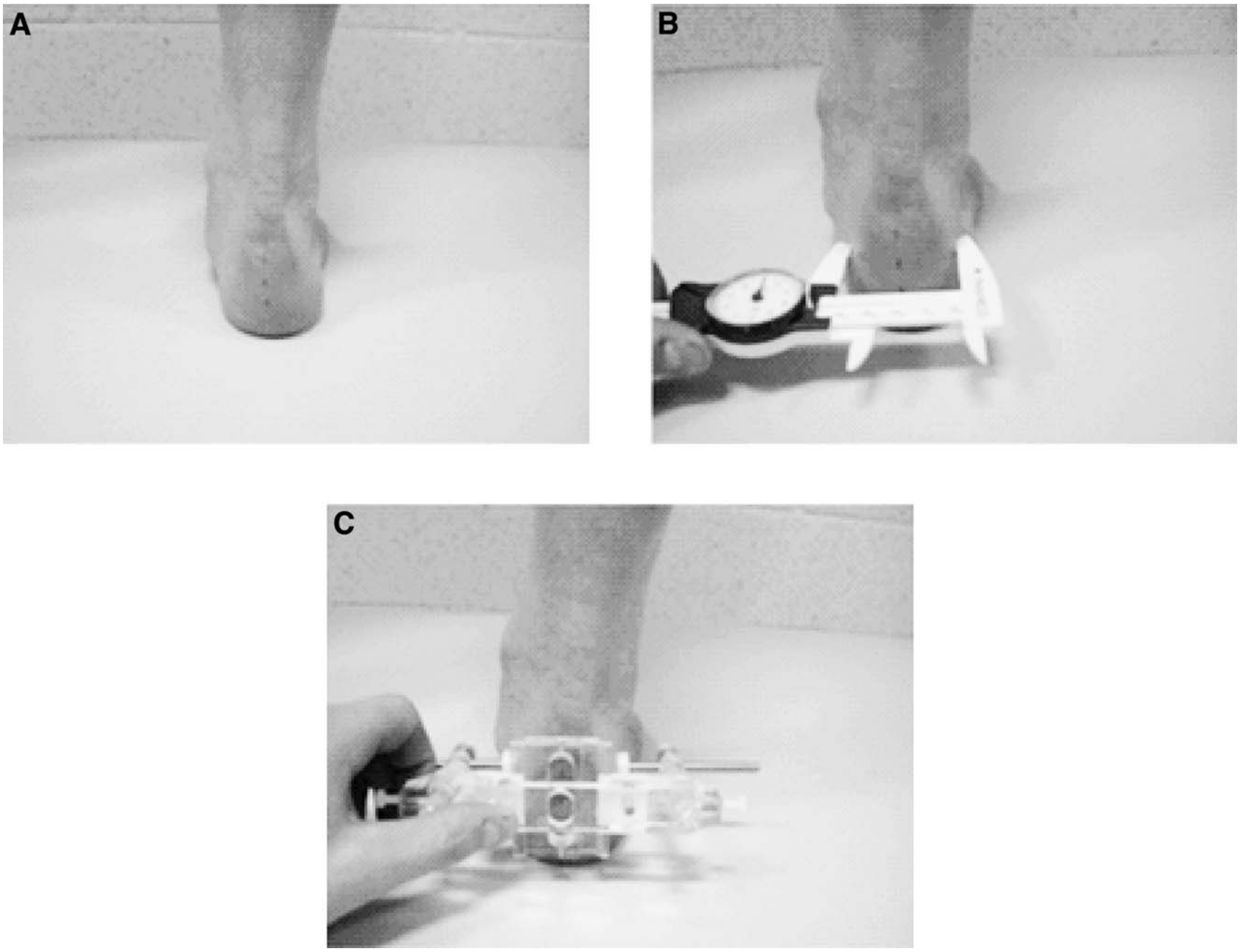

Figure 3. A, Determination of three midpoints on the calcaneus to represent frontal plane alignment of the calcaneus. B, Measurement of heel width using a caliper. C, Positioning of the device on the calcaneus.

respect to the static 3-D angles of the foot model, and, in analogy, a "mean foot angle movement error" (x, y, and z) was determined for each measurement by considering the 3-D intersegment angle between the midfoot and the metatarsal. The latter angle was chosen because it is the only 3-D intersegment angle that does not necessitate the anatomical reference frame of the calcaneus.

The intraobserver and interobserver marker placement variability and the interobserver intersegment angle variability were estimated using variance calculations (Table 2).

Results

Changes in the navicular marker positions and the midfoot-metatarsal angle were less than 1.3 mm and less than 0.96°, respectively, except for three measurement sessions. In these three cases, both participants moved considerably (>5.5 mm). The marker placement data and the intersegment angles from these measurement sessions were excluded from the statistical analysis. In general, manual marker placement was found to be performed with greater variability by therapist 2 (<5.3 mm) compared with therapist 1 (<2.9 mm). Intraobserver variability was found to be less than 1.6 mm throughout use of the CMD (Table 3).

Interobserver variability was found to be significantly higher for the position of markers placed manually, for all three markers and planes, except for the posterior aspect calcaneus marker (x-plane). Throughout use of the CMD, the variability remained less than 1.3 mm. The effect on the intersegment angles followed a similar trend, with variability of 1.0° to 8.7° and 0.4° to 4.0° for manual and CMD placement, respectively.

Discussion

The results of this study demonstrate that use of the CMD improved the consistency of marker placement

Table 2. Notations and Calculations Needed to Determine Intraobserver and Interobserver Marker Placement Variability and Interobserver 3-D Intersegment Angle Variability

Description	Notation
The variance for all measurements for a given participant (p), a given marker (m), a given coordinate (c) (x, y, or z), a given therapist (t), a given technique (tech), and a given number of sessions (s). Subindices can be left out. If, eg, the measurements of all participants are used, the corresponding subindex (p) is left out.	σ^2 (p,m,c,t,tech,s)
Variance of the marker placement with respect to the anatomy	σ^2_B
Variance of the involuntary motion of a participant while seated in a chair. This is independent of the therapist.	σ^2_M
Variance of the marker position measurement	σ^2_D
Computing σ^2_B	$\sigma^2_B = \sigma^2_D - \sigma^2_M$
Computing σ^2_B (p=1;m=CA;c=x;t=1;tech=1),(intra), the intraobserver variance of the marker placement for a participant 1, marker CA, coordinate x, therapist 1, with technique 1 for both sessions	σ^2_D (p=1;m=CA;c=x;t=1;tech=1) – σ^2_M (p=1;m=NAV;c=x)
Computing σ^2_B (p=1;m=CA;c=x;tech=1)(inter), the interobserver variance of the marker placement for a participant 1, marker CA, coordinate x, with technique 1 for both sessions and both therapists	σ^2_D (p=1;m=CA;c=x;tech=1) – σ^2_M (p=1;m=NAV;c=x)
Interobserver variability for 3-D intersegment angles was determined for a given participant (p), a given foot model joint and joint direction (c), a given therapist (t), a given technique (tech), and a given number of sessions (s). σ^2_B (p=1;a=Sha-Cal;y=add/abd;tech=1)(interangles)	σ^2_D (p=1;a=Sha-Cal;y=add/abd;tech=1)

Note: Arithmetic mean and standard deviation was calculated for the small cohort, and the *t* test was used to determine significant differences between techniques.

Abbreviations: add/abd, adduction/abduction; CA, posterior aspect calcaneus; NAV, navicular bone; Sha-Cal, shank and calcaneus; 3-D, three-dimensional.

Table 3. Marker Placement Variability Associated With Both Techniques

Intraobserver Variability

Marker: Plane	Manual Placement $\sigma^2_{B\ (intra)}$ Therapist 1	Manual Placement $\sigma^2_{B\ (intra)}$ Therapist 2	Manual Placement *P* Value	Device $\sigma^2_{B\ (intra)}$ Therapist 1	Device $\sigma^2_{B\ (intra)}$ Therapist 2	Device *P* Value
CA:X	0.5 ± 0.5	0.4 ± 0.3	NS	0.6 ± 0.4	0.7 ± 0.6	NS
CA:Y	0.9 ± 0.9	0.8 ± 0.9	NS	1.0 ± 1.2	1.0 ± 0.7	NS
CA:Z	0.9 ± 0.8	1.3 ± 0.9	NS	0.8 ± 0.9	0.9 ± 0.9	NS
PT:X	1.4 ± 2.0	5.3 ± 3.7	<.001[a]	0.5 ± 0.5	1.4 ± 2.8	NS
PT:Y	0.8 ± 0.9	2.4 ± 2.1	.018[a]	0.6 ± 1.0	1.3 ± 2.5	NS
PT:Z	1.0 ± 1.0	1.3 ± 0.9	NS	1.2 ± 0.8	1.6 ± 1.9	NS
ST:X	2.9 ± 2.5	2.6 ± 2.5	NS	0.7 ± 0.7	0.6 ± 0.4	NS
ST:Y	0.7 ± 0.8	0.8 ± 0.8	NS	0.7 ± 0.9	0.8 ± 0.9	NS
ST:Z	1.5 ± 1.0	1.2 ± 1.2	NS	1.0 ± 1.2	1.4 ± 0.9	NS

Note: Data regarding marker placement (mm) and inter-segment angle (degrees) are given as mean ± SD for the complete cohort. Global reference frame: x-axis, pointing forward; y-axis, pointing lateral; and z-axis, pointing upward.

Abbreviations: Add/Abd, adduction/abduction; CA, posterior aspect calcaneus; Cal-Met, calcaneus and metatarsus; Cal-Mid, calcaneus and midfoot; Do/PF, dorsiflexion/plantarflexion; Inv/Eve, inversion/eversion; MLA, medial longitudinal arch; NS, not significant; PT, tuberculum peroneum; Sha-Cal, shank and calcaneus; ST, sustentaculum tali.

[a]Statistically significant at $\alpha = 0.05$ (paired *t* test).

at the medial and lateral aspects of the calcaneus. This finding is believed to be of clinical interest because orientation of the calcaneus is of utmost importance in many foot-related functional abnormalities,[6] and it is for this reason that other authors have also put efforts into the development of a foot-related device.[14,15] Simon and coworkers[14] developed the "heel alignment device" to standardize marker placement at the calcaneus. The CMD differs from that proposed by Simon et al[14] in that the relationship with the long axis of the foot is not considered. It was not considered in this study on the basis of clinical observations by the investigators that in many foot abnormalities, the transverse plane orientation of the calcaneus does not coincide with the long axis of the foot. Moreover, we believe, contrary to Simon and coworkers, that marker placement should be undertaken in a weightbearing or semiweightbearing situation because it allows better interpretation of the overall alignment of the rearfoot,[14] being in a corrected or uncorrected position.[16]

Use of the CMD also makes placement of the calcaneal markers independent of anatomical landmarks, a considerable advantage when landmarks are indistinct or absent.[12,13] We, therefore, believe that other 3DMFMs could benefit from this novel device (eg, the Oxford Foot Model developed by Carson et al[5]). Ideally, the latter should be tested in a validation study of the novel device that would focus on analyzing reliability in people with foot deformities.

It should be emphasized that adequate training of clinicians undertaking marker placement is of primary importance. Although this has been demonstrated for manual marker placement, it is of equal importance when a device is used to facilitate marker placement. In addition, note that in the present study, the device was used in a semiweightbearing situation. This position was adopted because we believe that the participants would be in a more comfortable position to maintain their foot position throughout each measurement session.

Conclusions

The CMD is an inexpensive tool for standardizing skin-mounted marker placement at the calcaneus. These findings suggest that variance in marker placement is considerably reduced when the novel device is used, possibly toward the limits dictated by the motor skills of therapists.

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Conflict of Interest: None reported.

Table 3. extended

Interobserver Variability

$\sigma^2_{B\ (inter)}$ Manual Placement	Device	*P* Value	Intersegment Angle	$\sigma^2_{B\ (inter\ angles)}$ Manual Placement	Device	*P* Value
0.4 ± 0.3	0.6 ± 0.5	NS	Sha-Cal Do/PF	1.9 ± 1.6	0.7 ± 0.5	.007[a]
1.2 ± 0.8	1.1 ± 0.9	NS	Sha-Cal Add/Abd	1.0 ± 0.2	0.4 ± 0.1	.009[a]
1.4 ± 0.7	1.0 ± 0.8	NS	Sha-Cal Inv/Eve	2.0 ± 1.7	0.5 ± 0.8	.002[a]
5.8 ± 2.8	1.3 ± 1.8	<.001[a]	Cal-Mid Do/PF	4.2 ± 3.0	2.9 ± 2.1	NS
1.9 ± 1.0	1.1 ± 1.9	NS	Cal-Mid Add/Abd	3.4 ± 2.1	1.9 ± 1.1	.023[a]
2.7 ± 1.6	1.2 ± 1.3	.036[a]	Cal-Mid Inv/Eve	2.1 ± 0.9	1.5 ± 0.6	NS
4.4 ± 3.2	0.8 ± 0.7	<.001[a]	Cal-Met Do/PF	4.2 ± 1.7	2.2 ± 1.9	.024[a]
0.9 ± 0.8	0.6 ± 0.9	.049[a]	Cal-Met Add/Abd	3.0 ± 1.7	1.9 ± 0.9	NS
3.5 ± 2.3	1.2 ± 0.9	.001[a]	Cal-Met Inv/Eve	3.9 ± 1.6	1.5 ± 0.9	.045[a]
			MLA	8.7 ± 7.1	4.0 ± 3.3	.031[a]

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