Reliability of a Computer-aided Color-coded Video-based System for Clinical Assessment of the Foot

Heydar Sadeghi, PhD,[1] Mehrdad Anbarian, PhD,[2] Paul Allard, PhD,[3] Sebastien Hinse, MS,[4] Élodie Touchette, PhD,[5] and C.-H. Rivard, PhD (Orth)[6]

There is a need for a user-friendly system that can provide quick and reliable assessment of foot disorders. The study described in this report was undertaken to determine the inter-rater and intra-rater reliability of a computer-aided, color-coded, video-based system developed for the assessment of foot alignment in patients with and without pes cavus deformity. Initially, 15 pedal angles were repetitively measured 7 times on 6 color-coded images of both feet, in 20 healthy adults. From the 7 repetitive measurements, the intra-class correlation was calculated and analysis of variance was used to estimate the minimum number of trials that would be necessary to identify a statistically significant difference in the measurements. To determine intra-rater reliability, 5 examiners evaluated a single set of data taken from 10 subjects. Additionally, data were obtained for 20 subjects with pes cavus deformity. The average intra-class correlation coefficient (ICC) for the anglular measurements for 2 to 7 trials was 0.98 ± 0.06, while the intra-rater reliability was 0.90 ± 0.14. No statistically significant differences were observed between right and left foot angles in able-bodied subjects; whereas, in the pes cavus group, 8 different angular measurements were observed to be statistically significantly different. The results of this investigation indicate that a computer-aided, color-coded, video-based system can be used to make reliable measurements of postural alignment in patients with and without pes cavus. Level of Clinical Evidence: 5 (The Journal of Foot & Ankle Surgery 47(5):409–418, 2008)

Key words: biomechanics, color-coded video, correlation, foot, pes cavus, posture, reliability

Clinical evaluation usually involves visual examination of the patient to identify musculoskeletal deformities. Foot and ankle surgeons often rely on visual inspection in order to aid in the determination of the optimal intervention. Although visual inspection can be quick, simple, and cost-effective, the determination of the presence or absence of deformity based on gross visual observation is highly dependent on the observer's judgment and experience. To improve the quality of visual assessment, a wide variety of devices can be used; however, the application of many of these devices to the clinical setting can be limited due to technical complexity, operator training, lengthy data analyses, and high instrumentation costs (1–3). Although gross visual inspection of the foot is a qualitative examination (4), diagnostic radiographs, pressure-sensitive mats, and kinematic video equipment can be used to quantify anatomical misalignments and to aid in the determination of the most appropriate therapy. Diagnostic radiographic images, in particular, are commonly used to assess foot structure (5). Because of initial equipment costs, and because there is no safe dose of radiation exposure (which can be particularly problematic when extensive imaging of the axial skeleton is required), postural assessments based on radiographic analyses are not necessarily the ideal method for evaluating alignments in able-bodied individuals. Moreover, the precise meaning of some

Address correspondence to: Heydar Sadeghi, PhD, Human Movement Laboratory, Sainte-Justine Hospital, 3175 Côte Ste-Catherine, Montreal, Quebec, H3T 1C5, Canada. E-mail: sadeghih@yahoo.com

[1]Associate professor, biomechanist, Department of Kinesiology, Tarbiat Moallem University, Ministry of Sciences, Research and Technology, Tehran, Iran; Department of Medicine, Orthopaedic Surgery, University of Montreal, Montreal, Quebec, Canada; Research Center, Human Movement Laboratory, Sainte-Justine Hospital, Montreal, Quebec, Canada.

[2]Assistant professor, biomechanist, Department of Physical Education and Sport Sciences, Bu-Ali Sina University, Ministry of Sciences, Research and Technology, Hamadan, Iran.

[3]Associate professor, biomechanist, Department of Kinesiology, University of Montreal, Montreal, Quebec, Canada; Research Center, Human Movement Laboratory, Sainte-Justine Hospital, Montreal, Quebec, Canada.

[4]MSc in Kinesiology, Department of Kinesiology, University of Montreal, Montreal, Quebec, Canada; Human Movement Laboratory, Sainte-Justine Hospital, Montreal, Quebec, Canada.

[5]MSc in Kinesiology, Human Movement Laboratory, Sainte-Justine Hospital, Montreal, Quebec, Canada; Human Movement Laboratory, Sainte-Justine Hospital, Montreal, Quebec, Canada.

[6]Professor, Department of Medicine, Orthopaedic Surgery, University of Montreal, Montreal, Quebec, Canada; Department of Medicine, Orthopedic Surgery Department, Sainte-Justine Hospital, Montreal, Quebec, Canada.

This work was funded in part by the Natural Sciences and Engineering Research Council of Canada in collaboration with Cryos Technologies, Inc., Joliette, QC, Canada, who supplied some of the equipment used in this investigation.

1067-2516/08/4705-0006$34.00/0

doi:10.1053/j.jfas.2008.04.013

radiographic measurements, particularly in regard to subjective patient outcomes, can be difficult to determine.

Force plate systems can also be used to assess balance during static stance. In such systems, the force transducers are used to provide information about the excursion of the center of pressure, which is considered to be representative of sway or imbalance. These systems have been used to assess the influence of a lower limb orthosis on stability during stance in both able-bodied, nonathletic individuals (6) and in athletes with functional ankle instability (7). However, force-plate data are of limited use to clinicians without the additional information obtained from the use of video-recording equipment, radiography, clinical examination, or some other method of evaluation, since force transducers provide little information about the functional orientation and morphology of the feet. They do, however, provide practical information about the distribution of pedal weight-bearing force during static and dynamic stance, and overloaded areas of the foot can be readily identified (8). Although these systems have been used under conditions of dynamic load, such as during walking and running, their reliability in this regard has been questioned (9). Devices that measure pressure can be useful in the evaluation therapeutic interventions, but little is known about the orientation and segmental alignment of the foot as these variables relate to the assessment of foot pressure.

Optical-electronic systems developed for gait analysis have also been used for the investigation of posture and balance (10–13). In order to use these systems, however, reflective markers positioned over anatomical landmarks and digitized so that their 3-dimensional (3-D) coordinates can be calculated before clinical information can be extracted. Although body alignment can be quantified with these systems, postural assessment is limited to the number and location of markers, and to the relationships between markers, and these variables do not necessarily identify all of the orientations and compensatory movements of the foot. Furthermore, these systems are rather expensive and require highly skilled operators, and tend to be reserved for use in research institutes.

Due in part to the technical factors and costs that limit the everyday clinical use of the aforementioned systems, most clinicians rely heavily on simple visual inspection to assess posture, foot alignment, and compensatory movements (4). Therefore, there is a need for systems that can quickly and accurately provide quantitative information pertaining to the alignment and orientation of the foot in the clinical setting, without the need for reflective markers and expensive measuring equipment (14). Such a system could provide the clinician with greater insight into the pathology at hand, and provide information that could lead to a more selective rehabilitation program, an improved orthosis, or a more appropriate surgical intervention. This study was undertaken to determine the reliability of the measurements taken with a commercially available computer-aided, video-based, color-coded postural alignment system. More precisely, we endeavored to establish the minimum number of trials required for a specific clinical evaluation, and to estimate the intra-tester reliability of these measurements, using the measurement system. To determine if the system could distinguish asymmetries between different feet, right and left foot angles were compared in able-bodied individuals having no known or symptomatic foot problems. Finally, to test the hypothesis that measurements taken with this postural measurement system could distinguish between 2 different foot conditions, results from subjects with pes cavus were compared to a group of healthy, able-bodied individuals.

Participants and Methods

A priori statistical power analysis (15) indicated that 2 groups of 20 participants would be required to identify a statistically significant difference, if such a difference existed, between the measurements obtained in this investigation ($\alpha = 0.05$, and $\beta = 0.80$). Inclusion criteria required that able-bodied volunteers comprised the control group, and patients with pes cavus comprised the comparison group. Although radiographic inspection was not required for inclusion, all of the participants in the investigation underwent clinical evaluation by an experienced foot and ankle surgeon who categorized the foot type and determined the group to which the participant would be assigned. To this end, the presence of a grossly elevated longitudinal pedal arch, marked plantar declination of the first metatarsal, and a palpably tight plantar fascia, as described by Turek (16), were used to characterize pes cavus deformity. The group of able-bodied (healthy) participants was recruited from the Department of Kinesiology of the University of Montreal, and consisted of the first 20 consecutive volunteers who responded to an invitation to participate in the research investigation. Criteria for exclusion from this group entailed the presence of signs or symptoms of pes cavus, or any other musculoskeletal or neurological disorder such as limb length inequity greater than 3 mm, scoliosis, back pain, hearing deficit, or visual impairment. Reliability testing was carried out using this group of participants. The comparison group consisted of 20 patients with grossly evident pes cavus, who were selected from a local private orthopedic clinical practice. In the second group, an orthopedic surgeon from a local private clinic selected 20 individuals who displayed grossly evident pes cavus, based on the criteria described above. All of the participants in both groups were informed about the rationale for and methodology of the study, verbally and in writing, before volunteering to participate in the human research protocol that had been approved by the University of Montreal Ethics Committee.

The computer-aided, color-coded, video-based postural measurement system, namely the Biovizion Medical Imaging System (Cryos Technologies Inc., Joliette, QC, Can-

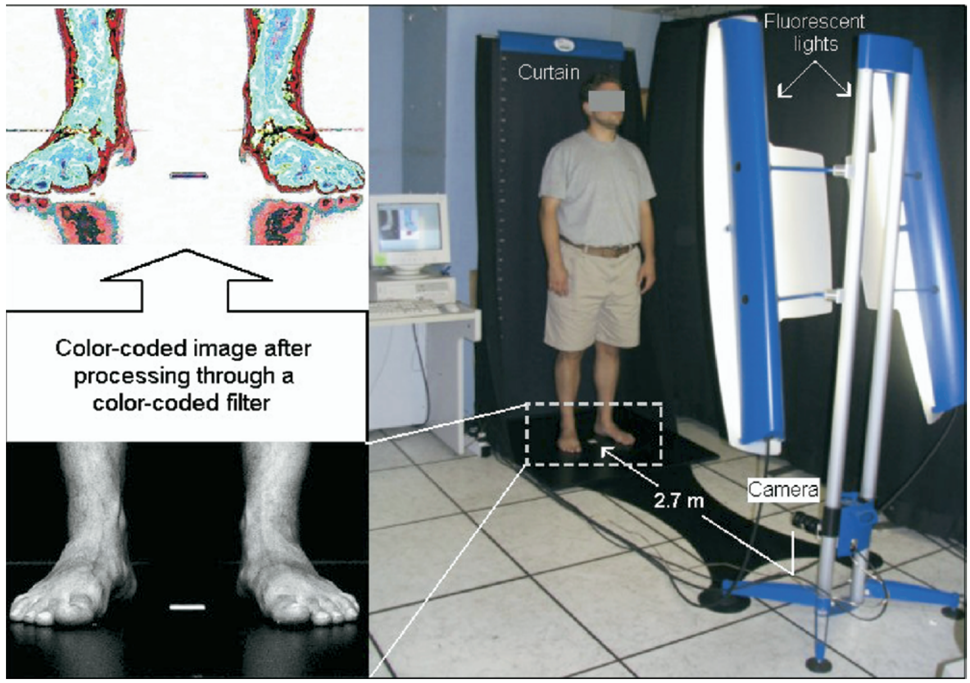


FIGURE 1 Color-coded video-based system illustrating the camera-based acquisition system.

ada), shown in Figure 1, was developed to provide rapid, quantitative information for assessment of foot pathology and postural compensations in the clinical environment. The system used in this investigation consisted of a 3-sided black imaging enclosure (1 m wide by 2 m high by 1 m in depth), upon which the patient undergoing evaluation stood. A digital camera was used to obtain a black-and-white image of a particular body part, namely the foot for the purposes of this investigation, and the digital information was collected and stored in a personal computer equipped with Biovision Software (Cryos Technologies, Joliette, QC, Canada). The height of the digital camera was adjustable from the substrate upward to the level of the pelvis, and a fiducial mark positioned on the wall of the 3-sided enclosure, facing the camera, was used to serve as a fixed basis for comparison and to facilitate alignment of the camera's optical axis. Moreover, the use of fluorescent lights to illuminate the feet ensured a uniformly lit (84 lux) and appropriately contrasted exposed body surface. There was also a floor marker over which the subject stood, in order to standardize the distance between the subject and the camera at 2.7 m. In an effort to avoid the influence of inadvertent study-induced alteration of the subject's foot posture, the individual stood freely without restraints such as straps or foot devices to induce a specific weight-bearing posture. After obtaining the image, a computer software algorithm was used to code the different gray levels of the image in order to enhance subsequent visual examination of the anatomical part and to facilitate clinical interpretation. For example, a specific part of the body can be visualized as a series of concentric ellipses of different colors. An aligned body posture can be quickly recognized by virtue of the symmetry in the surfaces of the ellipses and by the position of the color-coded projections, whereas an asymmetrical posture is characterized by distortions in the shape of the ellipses and in their color differences.

Postural assessment required that individuals stand over the floor marker on the 3-sided, black photometric stage, while facing the digital camera. The body parts to be studied had to be unshod and uncovered in order for the skin surface to be exposed to the camera. Although the posterior aspect of the trunk, portions of the pelvis, as well as the thighs and legs could be analyzed using this method, the focus of the current investigation, as previously stated, was confined to the feet only. Once the subject was in a full weight-bearing standing position, a specified number of digital images were obtained (Figure 2, A). Although the precise number of pictures obtained could vary with the needs of a particular investigation, for the purposes of the investigation described in this report, 6 digital images corresponding to 5 different views of the foot were obtained. Specifically, the 6 weight-bearing images included anterior and posterior views of the feet taken together, medial view of each foot, and finally a posterior view of each foot in plantarflexion. The last 2 views were original to this investigation, and were obtained in an effort to emphasize the relationship between the weight-bearing forefoot and the unloaded rearfoot that was free to make compensatory, weight-bearing adjustments. These 6 images formed a single dataset, or trial. Since the camera views and the portion of the foot under analysis varied, the subject had to reposition her/himself each time within the 3-sided analysis platform. This procedure took

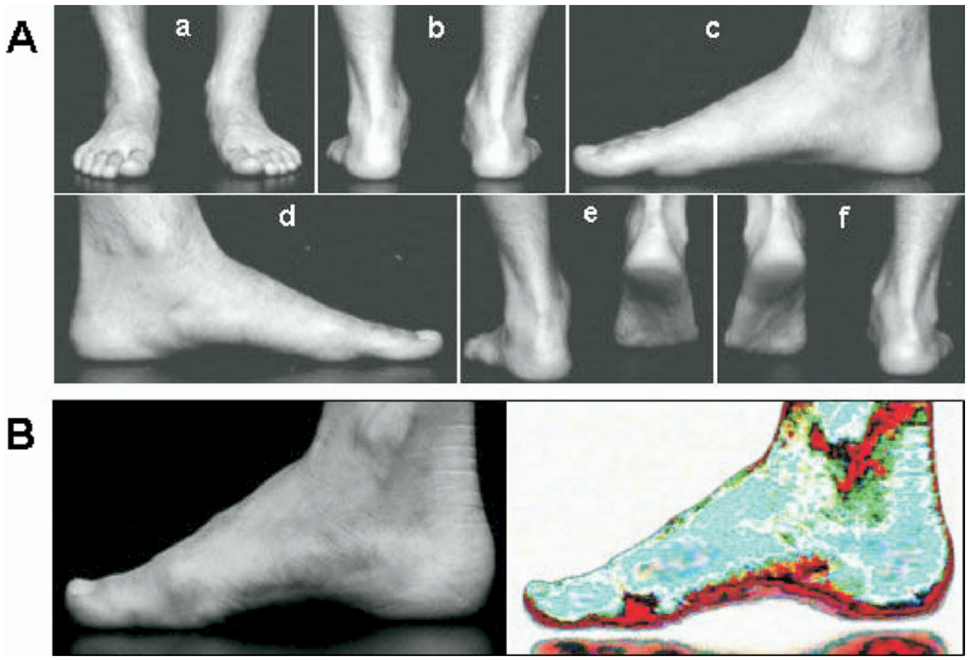


FIGURE 2 (*A*) A single trial of foot pictures taken from (a) anterior view of both feet, (b) posterior view of both feet, (c) medial view of the right foot, (d) medial view of the left foot, (e) plantar flexion of the right foot, and (f) plantar flexion of the left foot. (*B*) Digital picture of the medial view of the right foot and the color-coded picture of the same foot using a numerical filter.

less than 5 minutes, and each able-bodied subject was evaluated by the same person 7 times with a 1-minute resting period between each trial. Participants with pes cavus were assessed only once, since they were selected during the clinic sessions and because the reliability of the color-coded video-based photometric system had been determined during the first part of the study.

In regard to the analysis of the photographic, the gray tones on the numerical images represented the light reflected from the surface of the pedal skin. These gray levels were processed through a color-coded filter that associated a color with each level of gray. The purpose of the filter was to enhance the information present on the black and white image, by converting the reflected light to a series of concentric ellipses of different colors as shown in Figure 2, B, thereby depicting the geometry of the foot. The same color-coded filter was applied to all gray tone numerical images to standardize the color scheme. Since the colored contours emphasized body morphology, they facilitated angular measurements between body segments such as the heel and the midfoot. The general shape of the contours and their color-coded reflections were used to define the orientation of different body segments.

In all, 15 angles for each foot were measured on the 6 color-coded images of the same foot. Among these were some classic foot angle measurements, including the Meschan metatarsal break angle (17), an angle that is formed by the intersection of a line running between the most distal points on the first and second metatarsal heads, and a line running between the most distal points on the fifth and second metatarsal heads, in the transverse plane. The Meary-Tomeno axis (18), specifically the line bisecting the angle formed by the intersection of the lines tangential to the medial and lateral (in the transverse plane), and the superior and inferior (in the sagittal plane), cortices of the head of the talus, as they propagate distally to intersect at an apex centered in the first metatarsal head, was also measured. The purpose of the view of foot in weight-bearing plantarflexion was obtained in an effort to highlight the compensatory motion of the hindfoot in relation to the forefoot.

Data pertaining to all 20 able-bodied subjects were included in the estimation of the reliability of the color-coded video-based photometric system. The intra-class correlation coefficient (ICC) (18, 19) was calculated to estimate the reliability between 2 trials, then 3 trials, and up to a comparison of 7 trials. Because the ICC is a univariate statistical method that has the advantage of being sensitive to systematic changes in the mean scores from one set of observations to the next, analysis enabled us to partition the variances into the different component parts (20, 21). For each ICC, the 95% confidence interval was also calculated. Like the Pearson correlation coefficient, the value of the ICC varies from 0 to 1 and, as the ICC approaches 1 it is indicative of more reliability, whereas a value that approaches 0 is indicative of less reliability. Statistical differences between values for the right and left foot of each participant were determined using the paired Student t test. For all calculations, statistical significance was defined at the 5% level ($P \leq .05$), and the Bonferroni correction (22) was applied to minimize the likelihood of making a Type I error. Analysis of variance (ANOVA) was used to determine the statistical significance of differences between repeated (2 to 7 repetitions) ICC measurements, and significant differences were further evaluated using the Tukey post hoc test (23). To determine the variability between different evaluators, images from 10 of the above-noted 20 subjects participating in the first trial were given to each of 5 equally trained testers. The testers were all trained for 2 hours in an identical fashion by the same instructor, who did not take part in this reliability study and the training period lasted 2 hours. The digital images were randomly allocated to the 5 testers, who then measured the 15 angles of interest for each foot. ICCs were then used to determine intra-rater reliability, and ANOVA with the Bonferroni variance penalty was used to determine if statistically significant differences existed between these calculations and, once again, statistically significant differences were further subjected to Tukey's post hoc test.

Results

The group of able-bodied (healthy) participants consisted of 15 female and 5 male adults with a mean age of 24.6 ± 4.2 years, and a mean height and mass of 168.1 ± 9.4 cm and 60.7 ± 8.4 kg, respectively. The group of 20 pes cavus patients consisted of the same number of female and male volunteers as did the able-bodied group, although they were older (47.0 ± 15.3 years) and their mean height (164.4 ± 9.4 cm) and mass (67.2 ± 14.6 kg) were similar. The groups compared for age, weight and height differences using independent *t* tests (*P* values for age, weight, and height were .002, .442, and .780, respectively).

The mean values for the 15 angles measured on each foot of the 20 able-bodied subjects are depicted in Table 1. These values were taken from their first set of color-coded images (trial 1). There was no statistically significant difference between the right and left feet as determined by the paired *t* tests. Overall, the standard deviations associated with the angular measurements were relatively small, indicative of a high degree of precision, with the exception of the angle formed by the intersection of a line representing the weight bearing substrate and the vertical axis of the foot in both the frontal and sagittal views.

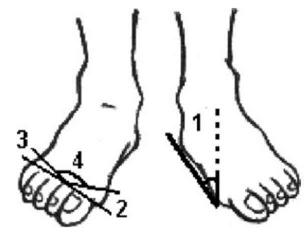
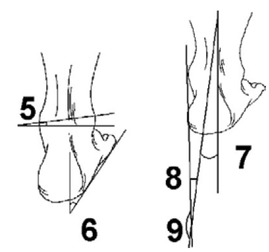
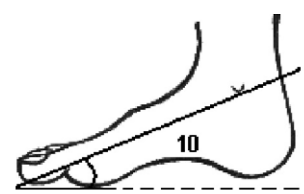
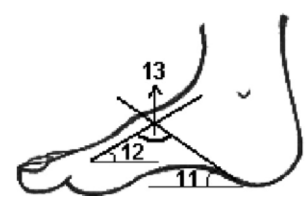
The mean inter-rater ICC values of all 15 angles, for the right and left feet separately, are shown in Table 2, and the mean and standard deviation for these measurements are depicted in Table 3. For each ICC, the 95% confidence interval fell within ± 2 standard deviations. For all of the angles measured, the photometric system showed a high degree of reliability, and this was particularly true for the medial sagittal and posterior frontal plane views. Angles taken from these views have been classically measured and frequently used in foot evaluation in a clinical setting. Figure 3 depicts the mean ICC values for the 30 angular variables measured on both feet in the able-bodied group. Results from just 2 trials, up to all 7 trials, are reported in Figure 3. The lowest individual ICC value was 0.72 for the axis defined by the line joining the first and second metatarsals and the horizontal substrate as measured on the anterior view of the left foot. Two angles displayed an ICC of 0.8, while all of the other angular measurements were greater than 0.9. Overall, the mean ICC value was 0.98 ± 0.06, and there was no statistically significant difference between the trials.

Figure 4 depicts the mean ICC values for the 5 raters using data obtained from the first trial in the able-bodied group. The lowest individual ICC value for the right foot was 0.56, and this was calculated for the angle made between the long axis of the first metatarsal and the horizontal substrate in the medial view. The lowest ICC value for the left foot was 0.55, and this was calculated for the axis defined by the line joining the first and second metatarsals and the horizontal substrate in the anterior frontal plane view. Twenty-six angles displayed an ICC above 0.9, and 2 were between 0.5 and 0.6, indicative of a poor correlation. The average intra-rater reliability was 0.90 ± 0.14 for both feet, and there was no statistically significant difference between the values obtained; and the medial view displayed the lowest ICC (0.79 ± 0.16) (Figure 4).

Table 1 depicts the angular values for the right and left feet of able-bodied individuals having no known or symptomatic foot problems. The Student *t* test for dependent samples did not reveal any significant differences between the measurements obtained by the photometric system for the right and left feet. The angular measurements for the able-bodied subjects and those individuals with pes cavus are depicted in Table 3. These are the pooled values for the measurements obtained for the right and left feet. Except for the angle sustained between the medial base of the foot in reference to the vertical measured in the frontal view, the standard deviations for the pes cavus group were generally higher than those obtained for the able-bodied feet. Statistical differences were observed in 8 angles taken in the anterior, posterior, medial, and plantarflexion camera views (Table 3). In the medial view, the angle sustained by the first metatarsal and the horizontal was statistically 1.2° higher in the group of individuals with pes cavus. The angle between the axis of the first metatarsal and the calcaneus, representing the medial arch, was also less pronounced by 9°, indicating a statistically significantly accentuated arch.

Significant statistical differences were also observed for 4 other angular measurements taken in the anterior and posterior views. These included the horizontal base of the foot, in the medial view, in reference to the vertical, in the anterior view, which decreased from 28.6° (± 30.3) to 12.5° (± 8.2); the horizontal base of the foot, in the lateral view, in reference to the vertical, in the posterior view, which decreased 39° (± 24.1) from a value of 60.6° (± 26.9); as well as the internal malleolus-heel, with respect to the vertical, in the posterior view, which was 7.1° (± 4.3) compared to 16.5° (± 6.8) in the able-bodied group. In the pes cavus group, moreover, the angle of the lesser toes, as measured in the anterior view, was 16.5° (± 6.8), and this

TABLE 1 Means and standard deviations of the 15 angles measured on the anterior, posterior, medial, and plantar flexion views for the right and left feet of able-bodied subjects

Views	Angles	Mean (SD) Right	Mean (SD) Left	*P*	Images
Anterior					
1	Line following the medial base of the foot in reference to the vertical axis	31.5 (33.9)	25.7 (26.7)	NS	
2	Tangent of first to second MTP joints in reference to the horizontal axis	5.4 (1.4)	6.7 (0.8)	NS	
3	Tangent of second to fifth MTP joints in reference to the horizontal axis	7.3 (4.6)	6.9 (4.1)	NS	
4	Meschan angle is formed by angles B and C	168.7 (6.9)	165.7 (4.4)	NS	
Posterior					
5	Line joining the external and internal malleoli in reference to the horizontal axis	13.8 (3.7)	12.0 (3.9)	NS	
6	Line following the lateral base of the foot in reference to the vertical axis	64.2 (17.0)	57.1 (34.3)	NS	
7	Axis bisecting the Achilles tendon (inferior leg) in reference to the vertical axis	5.2 (3.6)	3.0 (3.4)	NS	
8	Axis bisecting the Achilles tendon in reference to the line joining the medial malleolus and the medial border of the heel	16.1 (6.0)	17.4 (5.8)	NS	
9	Pronation angle is formed by the angular measurement between C and D	159.5 (3.5)	164.3 (8.1)	NS	
Medial					
10	Axis bisecting the first metatarsal bone and the talus in reference to the horizontal axis (Meary-Tomeno line)	24.7 (1.5)	24.5 (1.5)	NS	
11	Axis of the inferior-posterior point of the calcaneus and inferior point of the talo-navicular joint in reference to the horizontal axis	35.6 (2.2)	34.7 (3.0)	NS	
12	Axis of the internal sesamoid and inferior point of the talo-navicular joint in reference to the horizontal axis	12.1 (3.1)	12.0 (2.2)	NS	
13	Djian-Annonier angle is formed by angles B and C	132.3 (5.0)	133.3 (4.3)	NS	
Plantar flexion					
14	Axis following the medial border of the heel in reference to the vertical axis	25.1 (7.0)	22.5 (6.8)	NS	
15	Axis following the bases of the second and fifth MTP joints in reference to the horizontal axis	15.4 (5.2)	18.9 (5.7)	NS	

MTP, metatarsophalangeal; NS, not significant.

was more than twice that observed in the able-bodied group (7.1°± 4.3). This difference was indicative of compensatory pronation of the forefoot, and this led to an 11° reduction in the Meschan angle. The purpose of the view of foot in plantaflexion weight-bearing position (flex foot view) was to highlight the relative motion or compensation of the heel

TABLE 2 Mean inter-rater intra-class correlation coefficients (ICCs) for all 15 angles measured for the right and left feet, separately

Views	Angles	ICC values	
		Right foot	Left foot
Anterior			
1	Line following the medial base of the foot in reference to the vertical axis	1.00	1.00
2	Tangent of first to second MTP joints in reference to the horizontal axis	0.74	0.82
3	Tangent of second to fifth MTP joints in reference to the horizontal axis	0.80	0.90
4	Meschan angle is formed by angles B and C	0.86	0.72
Posterior			
5	Line joining the external and internal malleoli in reference to the horizontal axis	0.95	0.92
6	Line following the lateral base of the foot in reference to the vertical axis	0.98	0.99
7	Axis bisecting the Achilles tendon (inferior leg) in reference to the vertical axis	0.83	0.94
8	Axis bisecting the Achilles tendon in reference to the line joining the medial malleolus and the medial border of the heel	0.99	0.99
9	Pronation angle is formed by the angular measurement between C and D	0.93	0.93
Medial			
10	Axis bisecting the first metatarsal bone and the talus in reference to the horizontal axis (Meary-Tomeno line)	0.97	0.91
11	Axis of the inferior-posterior point of the calcaneus and inferior point of the talo-navicular joint in reference to the horizontal axis	0.86	0.95
12	Axis of the internal sesamoid and inferior point of the talo-navicular joint in reference to the horizontal axis	0.90	0.81
13	Djian-Annonier angle is formed by angles B and C	0.92	0.93
Plantar flexion			
14	Axis following the medial border of the heel in reference to the vertical axis	0.99	0.96
15	Axis following the bases of the second and fifth MTP joints in reference to the horizontal axis	0.96	0.97

MTP, metatarsophalangeal.

in relation to the forefoot. In the able-bodied group, the plantarflexion weight-bearing frontal plane view of the foot, from the posterior aspect, showed a $17.1° \pm 5.7°$ angle between the axis of the hindfoot and that of the forefoot, representative of hindfoot pronation relative to the forefoot. This angle was statistically significantly increased by 5.2° in the pes cavus group ($22.3° \pm 11.2°$), indicative of increased but persistent hindfoot pronation relative to the forefoot.

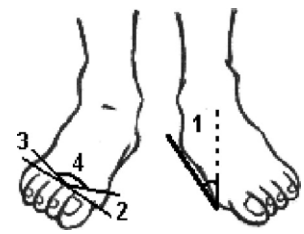
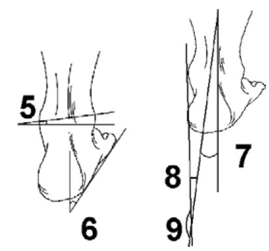
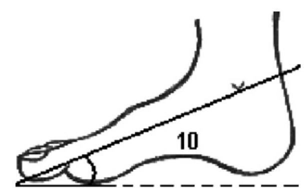
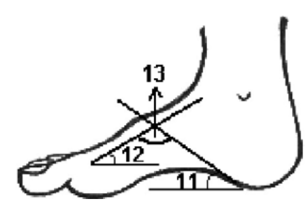
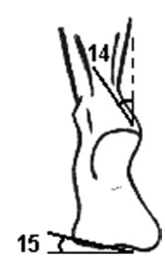
Discussion

Using the computer-aided, color-coded, video-based photometric system described in this investigation, pedal morphology was immediately recognizable. The system provided detailed quantitative information that was useful in the clinical evaluation of pedal morphology. Pedal angular measurements used to define foot structure in different planes of the foot, were used to distinguish pes cavus from non-cavus feet. Similarly, the photometric system could be used to identify other pedal misalignments, such as pes planus, hallux valgus, hammertoes, and other defined deformities.

Although ankle ranges of motion are readily available in the anatomical and surgical literature (24, 25), there is considerably less scientific information describing the angular excursions and normal alignments of pedal structures other than the ankle, subtalar, and metatarsophalangeal joints. Although radiography can provide useful insight into pedal skeletal alignment, it is often limited to diagnostic purposes and it is seldom used in overall postural assessment. The color-coded, video-based, photometric system could be considered an alternative to visual clinical foot assessment, and an adjunct to the standard radiographic examination. In order for this to become popular, however, standard foot photometric angular measurements still need to be defined and the video-based system validated. Though limited to 20 able-bodied subjects, the data in Table 1 provide a basis for future comparison with pathological foot conditions.

The first objective of this study was to determine the number of trials required for a clinical evaluation. Intra-trial reliability is essential in evaluating the effects of an intervention on postural and foot assessment. ICC values were used to illustrate whether measurement errors or natural physiological differences between individuals caused the variations. Based on this working assumption, ICC values higher than 0.8 were considered as excellent (26). For example, the retest reliability of forceplate measures for assessing steadiness in stance varied between 0.31 and 0.85 (27). In this study, the average ICC value for 2 to 7 trials was 0.98. The average ICC value did not increase significantly with additional trials and no statistically significant

TABLE 3 Means and standard deviations of the 15 angles measured on the anterior, posterior, medial, and plantar flexion views for the able-bodied individuals and subjects with cavus feet

Views	Angles	Mean (SD)		*P*	Images
		Able-bodied	Pes Cavus		
Anterior					
1	Line following the medial base of the foot in reference to the vertical axis	28.6 (30.3)	12.5 (8.2)	0.020	
2	Tangent of first to second MTP joints in reference to the horizontal axis	6.0 (1.3)	7.3 (6.2)	NS	
3	Tangent of second to fifth MTP joints in reference to the horizontal axis	7.1 (4.3)	16.5 (6.8)	0.000	
4	Meschan angle is formed by angles B and C	167.2 (5.9)	156.2 (9.1)	0.000	
Posterior					
5	Line joining the external and internal malleoli in reference to the horizontal axis	12.2 (3.9)	15.8 (5.3)	NS	
6	Line following the lateral base of the foot in reference to the vertical axis	60.6 (26.9)	39.2 (24.1)	0.005	
7	Axis bisecting the Achilles tendon (inferior leg) in reference to the vertical axis	4.1 (3.6)	3 (3.1)	NS	
8	Axis bisecting the Achilles tendon in reference to the line joining the medial malleolus and the medial border of the heel	16.8 (5.6)	17 (6.4)	NS	
9	Pronation angle is formed by the angular measurement between C and D	162.0 (6.6)	162.2 (7.8)	NS	
Medial					
10	Axis bisecting the first metatarsal bone and the talus in reference to the horizontal axis (Meary-Tomeno line)	26.4 (1.4)	27.6 (3.6)	0.000	
11	Axis of the inferior-posterior point of the calcaneus and inferior point of the talo-navicular joint in reference to the horizontal axis	12.1 (2.6)	12 (3.1)	NS	
12	Axis of the internal sesamoid and inferior point of the talo-navicular joint in reference to the horizontal axis	35.1 (2.6)	39.3 (4.3)	0.000	
13	Djian-Annonier angle is formed by angles B and C	132.8 (4.6)	128.7 (5.6)	0.007	
Plantar flexion					
14	Axis following the medial border of the heel in reference to the vertical axis	23.8 (6.9)	21.1 (6.2)	NS	
15	Axis following the bases of the second and fifth MTP joints in reference to the horizontal axis	17.1 (5.7)	22.3 (11.2)	0.014	

MTP, metatarsophalangeal; NS, not significant.

difference was noted between the sets of trials. This implies that a single set of images is sufficient and there is no statistical advantage in making additional evaluations to improve the overall reliability of the measurements.

Differences in testers were expected to influence the results (28). Five testers were similarly trained and each evaluator measured angles from color-coded images from 10 selected able-bodied subjects. The intra-rater reliability

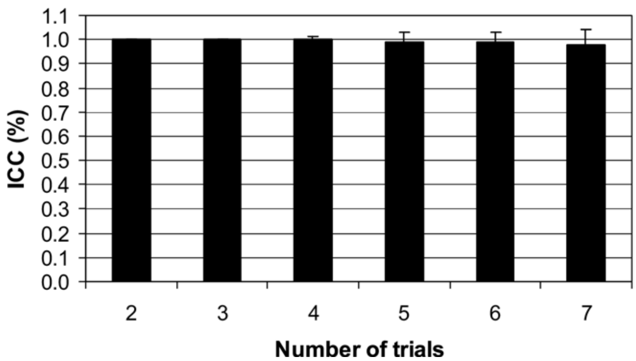


FIGURE 3 Intra-trials class correlation values of the angles measured on both feet of 15 able-bodied subjects for the first 2 trials up to all 7 trials.

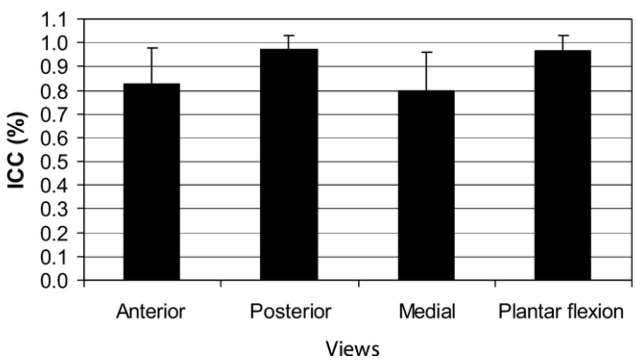


FIGURE 4 Intra-rater class correlation values for the foot in anterior, posterior, medial, and plantarflexion views, based on 10 sets of 6 images taken from 10 able-bodied subjects.

was good to excellent with the exception of 2 angles that showed poor reliability. The 2 angular measurements were associated with different camera views, and we feel that their reliability could be improved by defining more precisely how these angles should be measured. The intra-rater reliability was generally similar to the intra-trial reliability that indicated the stability of the measurements when different raters evaluated the same patient.

Subjects with a cavus foot attitude were evaluated and results were compared to a group of individuals having no symptomatic foot problems, in order to test the hypothesis that measurements taken with the photometric system could be distinguished between the 2 groups. Out of the 15 angular measurements, 8 of them were statistically significantly different. These were obtained from all camera views with the exception of the lateral side of the foot. Generally these angles could be associated with pes cavus deformity, as described by Turek (16). Namely, the arch was more accentuated by about 9° as a result of a drop of about 5° in the sagittal plane alignment of the first metatarsal as observed in the medial view. In the anterior view, the lesser toe was pronated to approximately 16.5° ± 6.8° compared to the 7.1° ± 4.3° alignment observed in able-bodied subjects, resulting in a more pronounced Mescham angle (lesser toes relative to the hallux, or metatarsal break angle) of 156.2° ± 9.1° compared to 167.2° ± 5.9°. The posterior view did not show a statistically significant difference in rearfoot pronation, when considering the changes that occur in the cavus foot as described in Turek (16).

A new finding was identified in this investigation, namely a more normally aligned foot orientation observed from the projected view of shank with respect to the base of the foot. Three angles measured in the anterior and posterior views were statistically significantly smaller in the pes cavus group, when compared to the able-bodied group. We postulate that the leg was laterally displaced over the foot as the latter assumes a supinated attitude in association with pes cavus.

The advantages of the photometric system used in this investigation are its simplicity and the fact that minimal skill is required to use it properly. The data and the images collected with the system are also available immediately for clinical use, and can be downloaded to a computer for storage or analysis. The images, moreover, can be used for comparison with normative datasets, or used for pre-surgical planning and post-surgical monitoring. In essence, the photometric system is a useful alternative to the standard visual examination and goniometry. Still further, since each subject acted as his or her own control in regard to comparison of the left and right feet, the effect of gender or the presence of asymptomatic foot ailments such as rearfoot valgus probably had little or no influence on the results. It is also important to note that, during the photometric examination, the individual stood freely without restraints such as straps or foot devices to induce a specific weight-bearing posture. For example, a floor template to standardize the orientation of the feet as well as the distance between the heels was not used, since such methodology could have inadvertently reduced or exaggerated the foot's true configuration. Although such methods could be useful in the assessment of able-bodied individuals, we felt that use of a floor template would have been detrimental to any clinical evaluation where foot position and orientation could mask important clinical information such as the extent of tibial rotation, hyperpronation, or other biomechanical measurements.

Although the reliability was found to be relatively high in able-bodied individuals, and the potential of the color-coded video-based system was illustrated in assessing individuals with pes cavus, the photometric system described in this report remains to be compared to a non–video-based system in order to truly appreciate its clinical usefulness. It is not likely that comparison with other motion analysis systems would be of much use, since the technology and limitations are similar to the color-coded system described in this report. Radiography, if clinically justified, would probably be the most worthwhile system for comparison. Another limitation of this investigation is related to the fact that the participants in this investigation were assigned to the able-bodied or pes cavus groups by means of clinical examination, and this could have imparted some degree of selection bias in that the classification of the participants may have been different had radiographic measurements been used, or if another experienced clinician had made the determinations. Yet another limitation of this photometric system is the number of trials that need to be collected in order to determine the reliability of a meaurement.

In conclusion, the color-coded information obtained with the photometric imaging system described in this report can be used to quantitatively assess segmental pedal alignment. The system's reliability varied from good to excellent, indicating that it could be a useful clinical tool for collecting valid information related to body posture and foot alignment. Although no asymmetry was observed between right and left foot angles in able-bodied subjects, the main characteristics of the subjects with a pes cavus deformity were identified and were found to be statistically significantly different from subjects having no known foot problems.

Acknowledgments

The authors thank Manon S. Allard and Pierre Tombal who collected and processed some of the data.

References

1. Cappozzo A, Cappello A, Della Croce U, Pensalfini F. Surface marker cluster design criteria for the 3D bone movement reconstruction. IEEE Trans Biomed Eng 44:1165–1174, 1997.
2. Della Croce U, Cappozo A. A spot check for estimating sterophotogrammetric errors. Med Biol Eng Comp 38:260–266, 2000.
3. Conforto S, Schmid M, Camomilla V, D'Alessio T, Cappozzo A. Hemodynamics as a possible internal mechanical disturbance to balance. Gait Posture 14:28–35, 2001.
4. Morag E, Cavanagh PR. Structural and functional predictors of regional peak pressures under the foot during walking. J Biomech 32:359–370, 1999.
5. Lamm BM, Mendicino RW, Catanzariti AR, Hillstrom HJ. Static rearfoot alignment: a comparison of clinical and radiographic measures. J Am Podiatric Mel Assoc 95(1):26–33, 2005.
6. Calmels P, Escafit M, Domenach M, Minaire P. Posturographic evaluation of the proprioceptive effect of ankle orthoses in healthy volunteers. Int Disab Stud 13:42–45, 1991.
7. Baier M, Hopf T. Ankle orthoses effect on single-limb balance in athletes with functional ankle instability. Arch Phys Med Rehab 79: 939–944, 1997.
8. Bryant A, Singer K, Tinley P. Comparison of the reliability of plantar pressure measurements using the two-step and mid-gait methods of data collection. Foot Ankle Int 20:646–650, 1999.
9. Randolph AL, Nelson M, Akkapeddi S, Levin A, Alexandrescu R. Reliability of measurements of pressures applied on the foot during walking by a computer insole sensor system. Arch Phys Med Rehabil 81:573–578, 2000.
10. Allard P, Lachance R, Aissaoui R, Duhaime M. Simultaneous bilateral 3-D gait analysis. Hum Mov Sci 15:327–346, 1996.
11. Sadeghi H, Allard P, Duhaime M. Contributions of lower limb muscle power in gait of people without impairments. Phys Ther 80:1188–1196, 2000.
12. Sadeghi H, Allard P, Prince F, Labelle H. Gait symmetry and limb dominance in able-bodied gait: a review. Gait Posture 12:34–45, 2000.
13. Winter DA, Patla AE, Prince F, Ishac M, Cielo-Perczak K. Stiffness control of balance in quiet standing. J Neurophysiol 80:1211–1221, 1998.
14. Song J, Hillstrom HJ, Secord D, Levitt J. Foot type biomechanics: comparison of planus and rectus foot types. J Am Podiatric Med Assoc l 86(1):16–23, 1996.
15. Cohen J, ed. *Statistical Power Analysis for the Behavioral Sciences*, ed 2, pp 36–37, Lawrence Erlbaum Associates, Hillsdale, NJ, 1988.
16. Turek SL. *Orthopaedics Principles and their Applications*, p 2066, JB Lippincott Co., Toronto, 1977.
17. Micael J, Shereff MD. Radiographic analysis of the foot and ankle. In: *Disorders of the Foot & Ankle: Medical and Surgical Management*, ed 2, vol. 1, pp 91–108, edited by MH Jahss, WB Saunders, Inc., Philadelphia, 1991.
18. Shrout PE, Fleiss JL. Intraclass correlation: uses in assessing rater reliability. Psychol Bull 86:420–428, 1979.
19. Baumgartner TA. Norm-referenced measurement: reliability. In: *Measurement Concepts in Physical Education and Exercise Science*, pp 45–72, edited by MJ Safrit, TM Wood, Human Kinetic Publisher, Champaign, IL, 1989.
20. Low JL. The reliability of joint measurement. Physiotherapy 62:227–229, 1976.
21. Stratford P, Agostino V, Brazeau C, Gowttzke BA. Reliability of joint angle measurement: a discussion of methodology issues. Physiotherapy Canada 36(1):5–9, 1984.
22. Holland BS, Copenhaver M. Improved Bonferroni-type multiple testing procedures. Psychol Bull 104:145–149, 1988.
23. Tukey JW. Some thoughts on clinical trials, especially problems of multiplicity. Science 198(4318):679–684, 1977.
24. American Academy of Orthopaedic Surgeons. *Joint Motion: Method of Measuring and Recording*, p 87, The British Orthopaedic Association, E&S Livingstone, Ltd., Edinburgh and London, 1966.
25. Oberg T, Karsznia A, Oberg K. Joint angle parameters in gait: reference data for normal subjects, 10–79 years of age. J Rehabil Res Dev 31:169–178, 1994.
26. Williams DS, McClay IS. Measurements used to characterize the foot and medial longitudinal arch: reliability and validity. Phys Ther 80(9): 864–81, 2000.
27. Goldie PA, Bac TM, Evans OM. Force platform measures for evaluating postural control: reliability and validity. Arch Phys Med Rehabil 70:510–517, 1989.
28. Berg KE, Latin RW. Measurement and data collection concepts. In: *Essentials of Research Methods in Health, Physical Education, Exercise Science, and Recreation*, ed 2, pp 161–171, edited by KE Berg, RW Latin, Lippincott Williams & Wilkins, Philadelphia, PA, 2004.