Article

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Combination of PedCAT Weightbearing CT With Pedography Assessment of the Relationship Between Anatomy-Based Foot Center and Force/Pressure-Based Center of Gravity

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Abstract

Background: A customized pedography sensor (Pliance; Novel, Munich, Germany) was inserted into a pedCAT (Curvebeam, Warrington, PA). The aim of this study was to analyze the relative position of the anatomical foot center (FC) and the pedographic center of gravity (COG). The hypothesis was that FC should be a good predictor of mediolateral position of COG but not longitudinal since hindfoot anatomy allows free anteroposterior movement but limited mediolateral movement.

Methods: In 90 patients (180 feet), a pedCAT scan with simultaneous pedography with full weightbearing in a standing position was performed. The morphology-based definition of the FC was performed with the pedCAT data following the Torque Ankle Lever Arm System (TALAS) algorithm. The force/pressure-based COG was defined with the pedography data using a software-based algorithm. The distance between FC and COG and the direction of a potential shift (distal-proximal, mediolateral) was measured and analyzed. COG motion during data acquisition was recorded and analyzed. Mean age of patients was 53.8 (range, 17-84) years, and 57 (63%) were female.

Results: The distance between FC and COG was 28.7 mm on average (range, 0-60). FC was distal to COG in 175 feet (97%; mean, 27.5 mm; range, –15 to 60) and lateral in 112 feet (62%; mean, 2.0 mm; range, –18 to 20).

Conclusions: There was a constant and major distal longitudinal shift of COG relative to FC and an inconstant minor mediolateral shift.

Clinical Relevance: The data might be taken into consideration for planning and follow-up in foot and ankle surgery.

Keywords: weightbearing CT, pedCAT, pedography, center of gravity (COG), foot center (FC)

PedCAT (Curvebeam, Warrington, MA) is a cone beam weightbearing computed tomography (WBCT) technology that allows 3-dimensional (3D) imaging with full weightbearing, which is not influenced by projection and/or foot orientation.[12] In the first published study, specific bone position (angle) measurements using pedCAT were compared with conventional weightbearing radiographs and conventional nonweightbearing computed tomography (CT).[12] The angles differed between radiographs, CT, and pedCAT, indicating that only pedCAT is able to detect the correct angles (ie, bone position).[12] In a subsequent study, the correlation between 3D bone position and pedobarographic measurements (ie, force and pressure [distribution]) has been investigated.[13] In that study, 3D bone position did not correlate with force and pressure distribution under the foot during simultaneous pedCAT scan and pedography.[13] Consequently, the bone positions measured with pedCAT did not allow conclusions about the force and pressure distribution in this static configuration.[13] Vice versa, pedography parameters did not allow conclusions about the 3D bone position.[13] One conclusion was that further investigations with a higher case number and different parameters should be carried out to further validate these surprising findings.[13]

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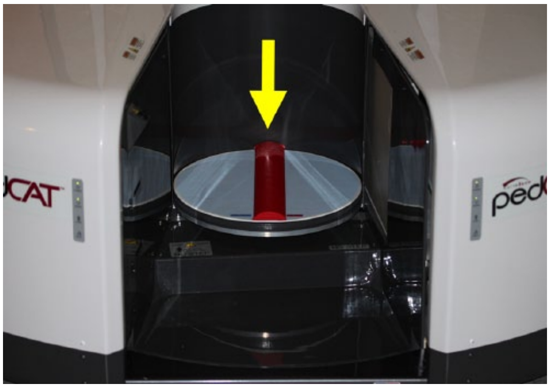

Figure 1. PedCAT with pedography sensor (arrow). An x-ray emitter and a flat-panel sensor on the opposite side are rotating horizontally around the feet. Resolution and contrast, which are the principal parameters for image quality, are comparable with modern conventional computed tomography.

Table 1. Registered Foot and Ankle Pathologies in 180 Feet in 90 Patients.[a]

Pathology	No.	%
Isolated hallux valgus	10	6
Complex forefoot deformity	24	13
Hallux rigidus	5	3
Flatfoot	18	10
Cavus foot	10	6
Other combined deformity	18	10
Ankle instability	20	11
Osteoarthritis without relevant deformity	23	13
None	52	29

[a]Complex forefoot deformity, hallux valgus plus lesser ray deformities. Hallux rigidus, only cases without deformity (ie, hallux valgus). Flatfoot, might include hindfoot valgus. Cavus foot, might include hindfoot varus. Ankle instability, only cases without relevant deformity such as hindfoot valgus/varus.

Center of gravity (COG) and foot center (FC) have been discussed to be important parameters for biomechanical assessment around the foot and ankle.[1,8] Consequently, these parameters were considered a basis for diagnostics and planning of corrective surgeries and/or joint replacement.[1,8] In particular, a semiautomatic system (Torque Ankle Lever Arm System [TALAS]; Curvebeam) designed to measure hindfoot alignment as a 3D biometric uses the anterior midline of the forefoot (which joins the FC with the midpoint between the first and the fifth metatarsal heads) as a landmark for hindfoot alignment.[8] The aim of this study was to analyze the difference between morphology or anatomy (bone/pedCAT)–based FC, calculated as the intersection of the median lines of the triangular-based pyramid model of the foot and force/pressure (pedography)–based COG. Motion of COG during the pedCAT/pedography scan should also be assessed as a potential source for bias. For this study, a customized pedography sensor (Pliance; Novel, Munich, Germany) was inserted into a pedCAT as described previously.[13] Our hypothesis was that the FC should be a good predictor of mediolateral position of the COG but not longitudinal position since the anatomy of the hindfoot allows free anteroposterior movement but limited mediolateral movement.

Methods

In a prospective, comparative, and consecutive study starting November 28, 2016, a total of 90 patients (180 feet) were included. A pedCAT scan with simultaneous pedography with full weightbearing in a standing position was performed (Figure 1). A customized pedography sensor (Pliance; Novel) was inserted into the pedCAT and connected to a PC with the standard software installed (Expert; Novel) (Figure 1).[13] Demographic data and underlying foot and ankle pathologies were registered.

The inclusion criteria were age ≥18 years, presentation at the local foot and ankle outpatient clinic, and having an indication for pedCAT. The indication for pedCAT was defined according to local practice as described previously.[12] These indications have recently evolved to include all patients presenting at our institution except initial postoperative follow-up radiographs without weightbearing. The exclusion criteria were age <18 years, no indication for pedCAT imaging, and participation in other studies. Approval from the local ethical committee was granted based on the indications as described above. Informed consent was obtained from all patients.

Mean age of patients was 53.8 (range, 17-84) years, and 57 (63%) were female. Height was 171 cm on average (range, 169-184 cm), weight was 71.4 kg (range, 43-108 kg), and body mass index (BMI) was 24.3 kg/m^2 (range, 15.6-34.8 kg/m^2). Table 1 shows the registered pathologies. Fifty-two patients (58%) had unilateral pathologies and 38 (42%) bilateral pathologies.

Image Acquisition—Foot Center

The patients walked into the device and were positioned in the bipedal standing position (Figure 1). Technically, an x-ray emitter and a flat-panel sensor on the opposite side were rotating horizontally around the feet. Resolution and contrast, which are the principal parameters for image quality, were comparable with modern conventional CT.[12] The acquisition time was 52 seconds. The morphology-based definition of the FC was performed with the pedCAT data following the TALAS algorithm (Figure 2a).[8] The software takes 4 bony landmarks into consideration (lowest point of

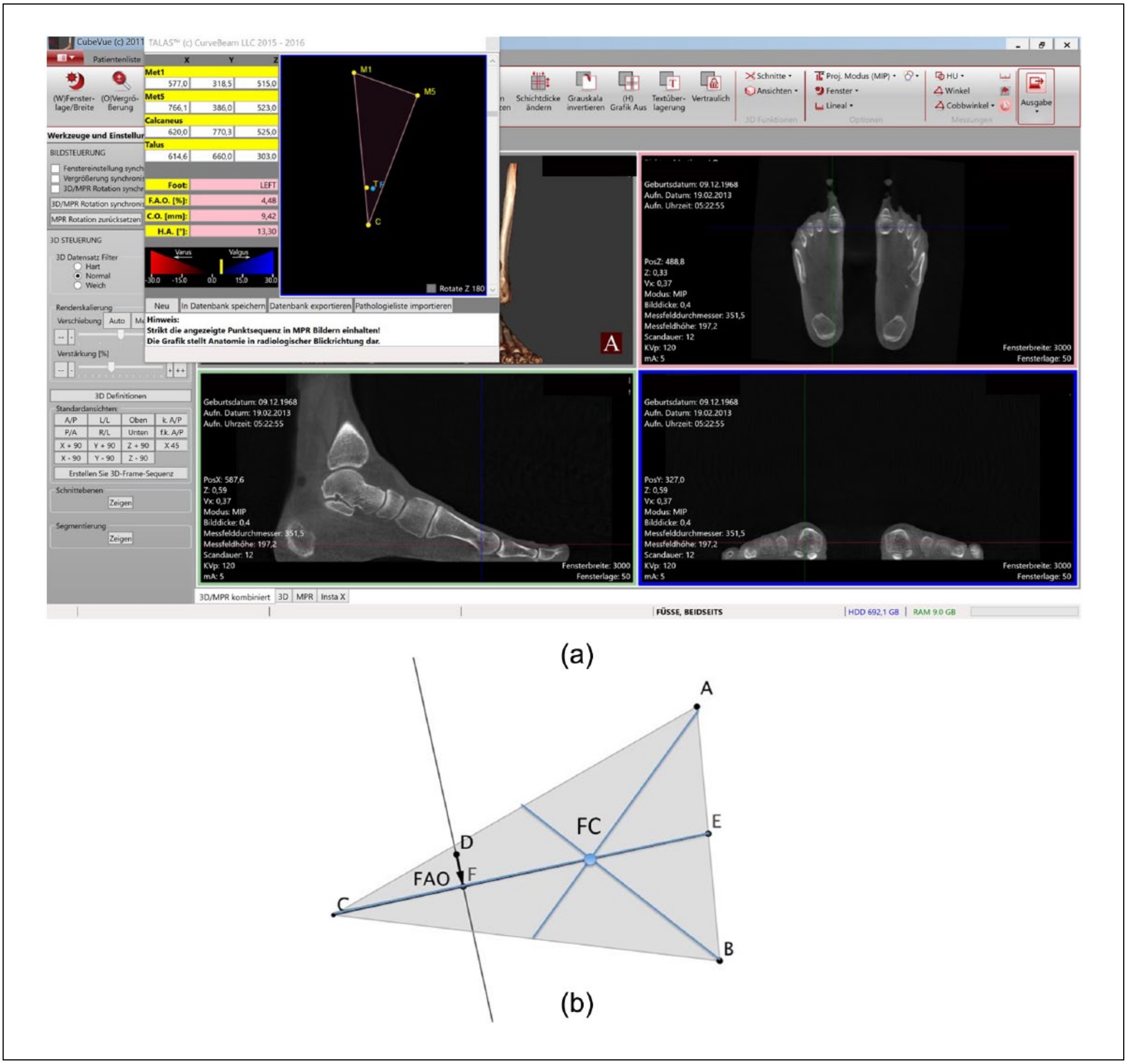

Figure 2. (a) The pedCAT software screen view with foot center (FC) definition with Torque Ankle Lever Arm System (TALAS) (top left), axial reformation (top right, red frame), parasagittal reformation (bottom left, green frame), and coronal reformation (bottom right, blue frame). The standard view is with a 1-mm slice thickness. For the definition of FC (F in image), the following landmarks are used: lowest point of posterior calcaneal process (C), center of talar dome/tibial plafond (T), lowest point of first metatarsal head (M1), and lowest point of fifth metatarsal head (M5). (b) The triangular-based pyramid model of the foot with foot ankle offset (where D is the projection of the center of the ankle, C the calcaneus weightbearing point, A the first metatarsal, and B the fifth metatarsal) and foot center (FC). E is the midpoint between M1 and M5.

posterior calcaneal process, center of ankle joint, lowest or weightbearing points of metatarsal heads 1 and 5). These landmarks are manually pointed out by the clinician using the MPR windows. This remains necessary as part of a semiautomatic process with the early version of the TALAS (Curvebeam) software used for this study. Future versions of this will include automatic detection of the landmarks. This defines a 3D volume as opposed to a 2-dimensional (2D) angle and allows for precise evaluation of hindfoot alignment, given as the foot ankle offset (FAO) (Figure 3b).[8] The software included a semiautomatic database (requiring manual input of the clinical record), which stores the 3D coordinates of the points, allowing further anonymous retrieval of the latter and secondary calculation of FC position.

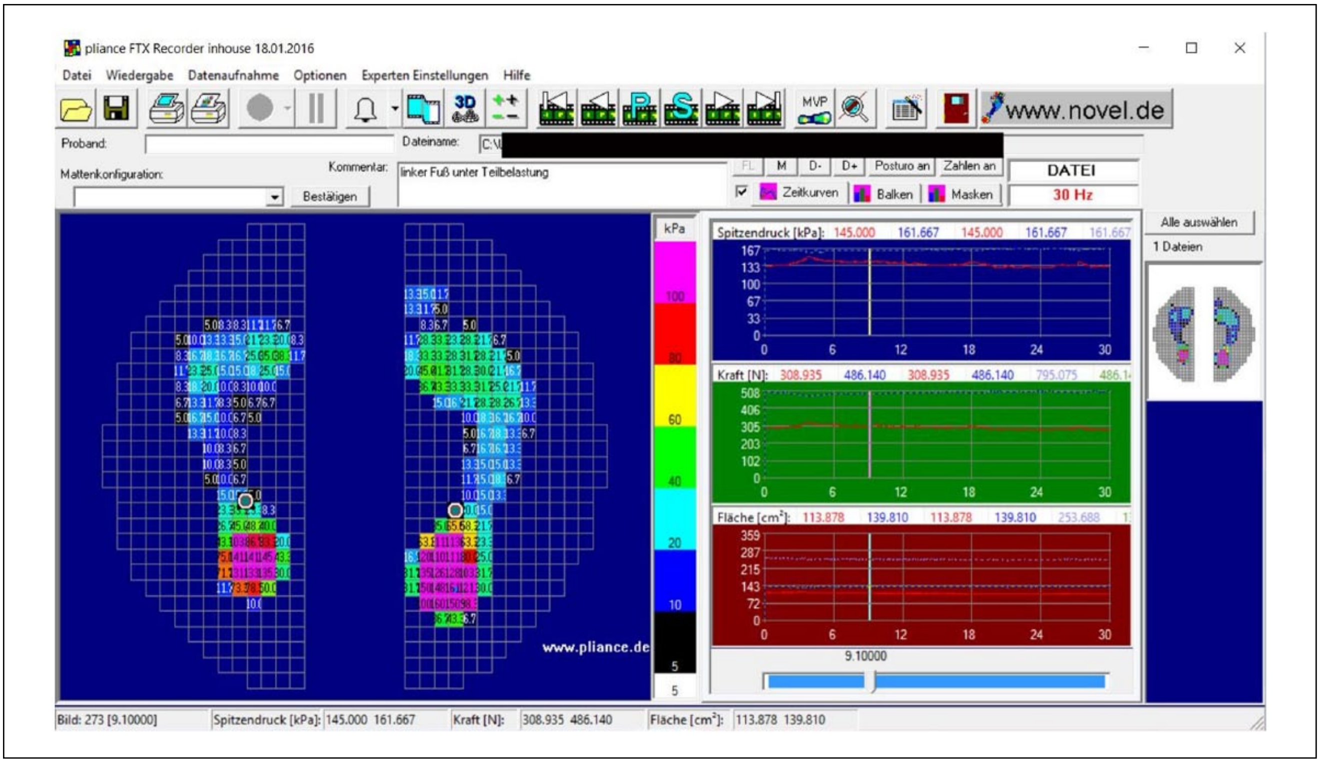

Figure 3. Pedography software screen view showing the center of gravity (COG) for each foot (circles).

Pedography—Center of Gravity

The data of the pedography sensor were gathered during the entire pedCAT scan (52 seconds). The force/pressure-based COG was defined with the pedography data using a software-based algorithm (Figure 3).[13] COG motion during data acquisition was recorded and analyzed.

Comparison Foot Center/Center of Gravity

The images with the FC (Figure 4a) and COG (Figure 4b) were semiautomatically superimposed (Figure 4c). The average position of COG during acquisition time was used for this superimposition. The distance between FC and COG (Figure 4c) and the direction of a potential shift (distal-proximal, mediolateral) was measured and analyzed. The pedographic images include a raster with 10 × 10-mm squares that correspond to the different sensor field with this exact geometric size (eg, Figure 4b,c). This raster was used as reference for the measurements.

Statistics

The statistical analysis was performed with Microsoft Excel 2016 (Microsoft, Redmond, WA) and SPSS 24.0 (SPSS, Inc, an IBM Company, Chicago, IL). The data (distances/shift between FC and COG) were successfully tested for normal distribution with a Shapiro-Wilk test. A bilateral paired *t* test was used to compare data from the left with the right foot. One-way analysis of variance (ANOVA) with potential post hoc Scheffe test was used for data comparison between different pathologies. Pearson test (2-sided) was used for correlation of BMI with measured data (distances/shift between FC and COG). Correlation was defined as significant when $P < .05$ and, when significant, then sufficient when $r > 0.5$ or $r < -0.5$.

Results

Maximum COG motion during the 68 seconds of the pedography scan was 1.2 mm on average (range, 0-4.8 mm). Table 2 shows measurements of position differences of COG and FC. The distance between FC and COG was 28.7 mm on average (range, 0-60 mm). FC was distal to COG in 175 feet (97%; mean, 27.5 mm; range, –15 to 60) and lateral in 112 feet (52%; mean, 2.0 mm; range, –18 to 20). No distal or proximal shift of FC occurred in 4 feet (2%) and proximal shift in 1 (1%). No lateral or medial shift of FC occurred in 35 feet (19%) and medial shift in 33 (18%). The variation was high, as shown by high standard deviations. No difference between the right and left side occurred (*t* test, each $P \geq .5$). No difference between pathology groups occurred (1-way ANOVA, distance FC/COG, $P = .62$; mediolateral shift, $P = .48$; distal-proximal shift, $P = .53$, post hoc test not applicable). No significant correlation with BMI occurred (Pearson, distance FC/COG, $P = .36$;

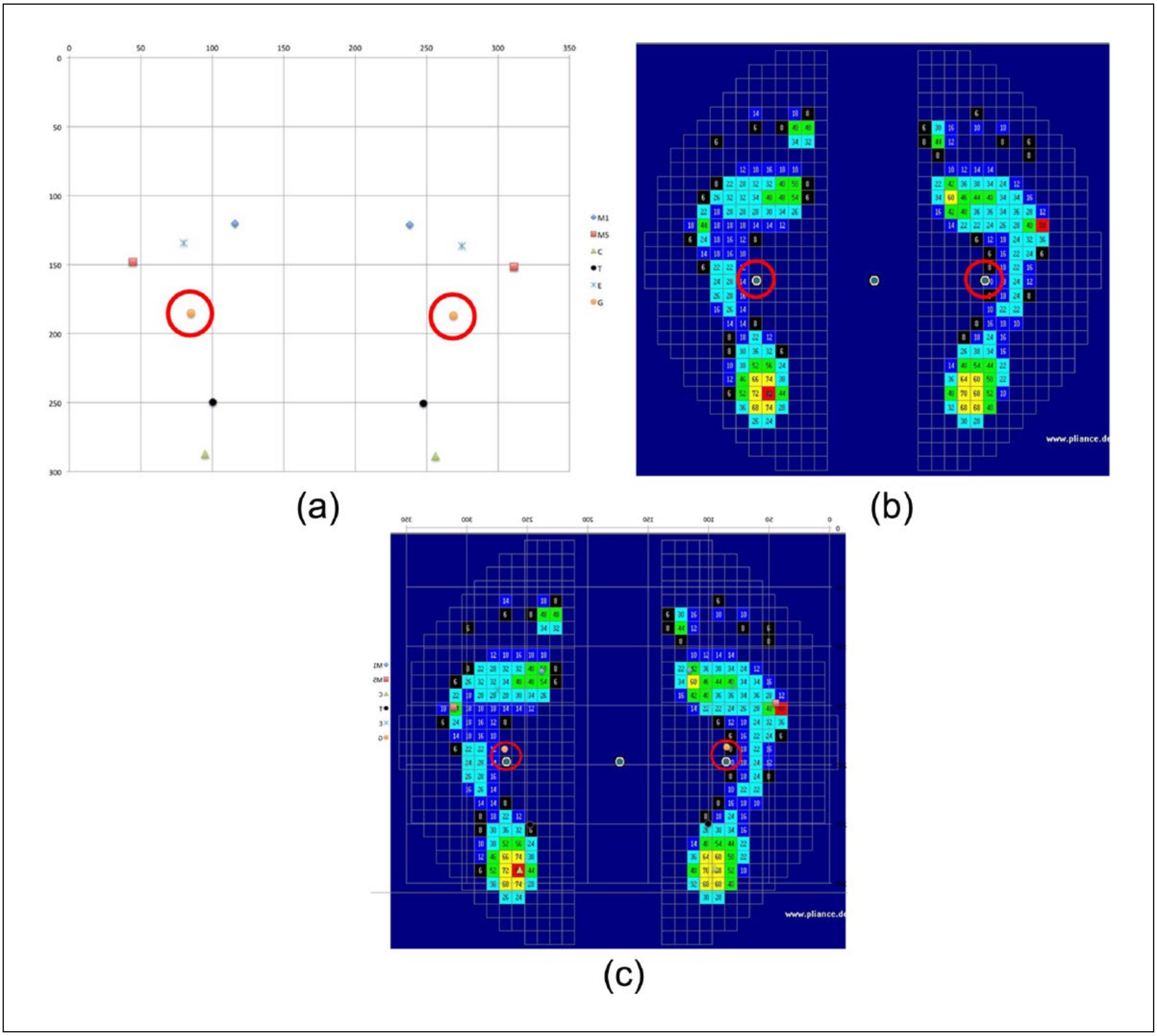

Figure 4. (a) An exported image from Torque Ankle Lever Arm System (TALAS) with foot center (FC) of both feet (yellow points in red circles, labeled with G). The right foot is displayed on the left side. For the definition of FC, the following landmarks are used: lowest point of posterior calcaneal process (C, green triangles), center of talar dome/tibial plafond (T, black point), lowest point of first metatarsal head (M1, blue rhombus), and lowest point of fifth metatarsal head (M5, red square). (b) An exported image from the pedography software with the center of gravity (COG) (white/blue points in red circles) of each foot. The right foot is displayed on the right side. The squares have a size of 10 × 10 mm. The numbers in some squares show the measured pressure (kPa), and the different colors are coding different pressure values. (c) The superimposition of the TALAS and pedography images (a and b). FC (red points) and COG (white/blue points) are both surrounded by a red circle. The TALAS image was horizontally mirrored for superimposition of the same foot side. The right foot is displayed on the right side for the TALAS and pedography image.

mediolateral shift, $P = .91$; distal-proximal shift, $P = .20$, r value irrelevant due to missing significance).

Discussion

This is the first study analyzing the correlation between the positions of the force/pressure-based COG and the anatomy/morphology-based FC.

Center of Gravity

COG is an important biomechanical parameter.[2,4,14,15,18] It is principally a function of force, related to body weight: COG force (N) = body weight (kg) × g (acceleration of gravity). COG is typically related to the entire body, which is the typical case during unipedal stand or the stance phase during gait.[2,4,14,15,18] During bipedal stand, each foot can be

Table 2. Measurements of Position Differences of Center of Gravity (COG) and Foot Center (FC).[a]

Parameter	Right (n = 90), mm	Left (n = 90), mm	Bilateral (n = 180), mm	*t* Test Right/Left, *P* Value
Distal-proximal				
Mean	27.3	27.8	27.5	.8
Standard deviation	13.3	13.4	13.3	
Minimum	0	−15	−15	
Maximum	60	60	60	
Mediolateral				
Mean	1.8	2.2	2.0	.5
Standard deviation	4.9	4.5	4.7	
Minimum	−18	−11	−18	
Maximum	10	20	20	
Distance				
Mean	28.1	29.0	28.7	.7
Standard deviation	13.4	12.8	12.9	
Minimum	−16	0	0	
Maximum	60	60	60	

[a]Parameter distal-proximal, distance in exact distal to proximal direction between COG and FC. Positive value means that COG is proximal to FC and negative value that COG is distal to FC. Parameter medial-lateral, distance in exact medial to lateral direction between COG and FC. Positive value means that COG is medial to FC and negative value that COG is lateral to FC. Parameter distance, distance between COG and FC. Negative value not possible; value "0" means no distance between COG and FC.

considered for a COG. It correlates with axes of the entire leg, tibia (lower leg), and hindfoot axis. It is influenced by deformities of the leg (varus/valgus/antecurvation/recurvation) and/or foot (hindfoot valgus/valgus, flatfoot, etc).[16] It changes its position in relation to the foot during the stance phase of gait. COG has an influence on forces/torques/moments, for example, in the ankle with or without replacement. COG is adequately defined with software-based analysis of pedography data.[3] It can be considered that strictly from the point of view of physics, if we do not take into account the actions of the muscles and the soft tissues, the COG of the whole body has to be situated vertically above the mathematical center of gravity of the weightbearing surface of the foot.[7] However, in reality, the actions of the muscles and soft tissues will have an influence on the position of COG. In this case, what should be observed is that this action maintains the COG laterally, but the longitudinal position should be more variable since the anteroposterior axis corresponds to the main degree of freedom of the ankle joint.

Foot Center

FC is based principally on a "function" of the morphology of the foot and mainly the bone shape and position.[10,17] It corresponds to the mathematical center of a simple, triangular-based pyramid model of the foot (Figure 2b). As COG, it is principally an important biomechanical parameter.[8] It is influenced by deformities of the foot (hindfoot valgus/valgus, flatfoot, etc).[16] In contrast to COG, FC is not influenced by deformities of the leg above the ankle (varus/valgus/antecurvation/recurvation) and does not change during the gait stance phase.[10] Similar to COG, FC has an influence on forces/torques/moments, for example, in the ankle with or without total joint replacement. FC is adequately defined with a semiautomatic software (TALAS; Curvebeam) based on pedCAT data[8] and a mathematical algorithm. TALAS was designed to provide computerized, semiautomatic, and automatic 3D biometrics of the foot and ankle.[8]

As outlined above, both COG and FC are potentially important parameters for foot morphology and especially biomechanics. Both have been investigated but not together in one investigation as far as we know.[2-4,8,10,14,15,17,18] The technical possibilities have not been present before 2016, the combination of pedCAT and pedography being first established in 2014, and TALAS was developed in 2016.[8,13] One would expect that COG and FC are not completely congruent because they are a function of different parameters (force/morphology). As expected, there was a spatial difference between FC and COG. This "expected" finding was quantified with this study (Table 2). The shift between COG and FC in the investigated 180 feet was relevant in the longitudinal axis (FC was 27.5 mm distal to COG) and relatively minor in the mediolateral axis (average shift of 2 mm) with a high variability, which probably accounts for individual variations of the rest position among patients. FC was distal to COG in 175 feet (97%) and lateral in 112 feet (52%; mean, 2.0 mm; range, –18 to 20). No difference between right and left side occurred. The interpretation of these data is difficult, and no comparable data have been reported in the literature so far.

COG is the more biomechanical parameter and is located proximally in almost all investigated feet and medially in the majority of the feet in relation to FC, representing the more morphology-based parameter. This finding is just a fact, but what does this mean? We formulated the following explanation: mediolateral shift is symmetrical, indicating simple oscillations of the mean rest position across our population, which has a 50/50 chance of being measured lateral or medial, while the anterior shift is explained by a spontaneous anterior shift at rest to balance posterior chain muscular balancing mediated by the Achilles tendon. Our practical interpretation and recommendation is that these data and findings stand alone to date as additional research and clinical parameters for foot and ankle. The data could be a basis for prediction of COG based on FC without additional pedography.

With respect to the potential upcoming rise of weightbearing CT as the new standard for foot and ankle imaging beyond the recent/current golden standard conventional radiographs, these findings confirm the relationship between the TALAS algorithm and the physics of gravity as described by Newton. In this model, the foot is considered its own reference in which weight (force) is repeatedly applied on the center of the ankle joint, and ground reaction force from the calcaneus weightbearing point on strike, moving anteriorly throughout to the gait to the center of gravity of the forefoot (approximated by the midpoint between M1 and M5), along a straight line. This line has previously been found to be concurrent with experimental findings in the literature and was called the gravitational line (GL).[2,7,11]

According to the TALAS theory, to maintain a standing posture, the COG has to remain not over the FC but over the GL during gait and in a static posture, with any other configuration meaning that the body is falling over to one side. In normally aligned feet, this means that the center of the ankle joint has to be also over the GL. In fact, as confirmed by a previous clinically validated study, it is slightly medial in a static position to accommodate the fact that the ankle joint is solidly contained by the medial collateral ligaments and the lateral malleolus, which acts as a lateral strut.[8] So, although the pedCAT imaging is static and the FAO a static measurement of hindfoot alignment, this study confirms that it provides relevant information on the biomechanical structure of the foot and ankle, which directly influences its dynamic behavior.

One can formulate the hypothesis that if a more precise approximation of the forefoot center of gravity can be integrated in the TALAS software and the data merged with dynamic pedography, an even closer correlation may be found in the future. Upcoming studies might also investigate different foot and ankle pathologies (ie, FC/COG and potential spatial differences). We investigated the potential influence of the underlying pathology on the measurements. An influence of different deformities, for example, was expected. However, different pathologies did not show different measurements (ie, was not statistically significant either and the number of pathologies was too low to make any determination). Different sides did not show different measurements. Taking into consideration missing pathology-related and side-to-side parameter differences, patients with unilateral vs bilateral pathologies did not show different measurements. Also, a correlation between BMI and the measurements did not occur.

Limitations

The main shortcoming of the study is the semiautomatic superimposition of the different images with the FC from the pedCAT/TALAS system and the COG from the pedography system. It would be desirable that the superimposition is fully automatic based on markers that are visible in both data sets (pedCAT and pedography). Also, the FC definition using data from the TALAS software is also semiautomatic, since the landmarks (lowest point of posterior calcaneal process, center and summit of talar dome, lowest point of metatarsal heads 1 and 5) are recorded freehand by the user. Even though this method has demonstrated excellent inter- and intraobserver reliability (0.99 and 0.97, respectively), a fully automatic software-based definition of the landmarks and consequently FC would be desirable, less time-consuming, and probably even more reproducible than the current version, which still relies on human intervention.[8] Pedography to date is a dynamic method used for the detection and analysis of the entire stance phase during gait and not only for standing position (ie, static pedography). We measured a static state of the foot, and we are aware that this is not directly related to the dynamic mechanics of the foot.[11,13] We did not design the introduced method to mimic dynamic pedography.[11,13] It has been previously shown and was discussed above that static pedography also allows assessment of the biomechanics of the foot.[5,6,11] Another possible shortcoming could have been relevant motion of COG during the 68 seconds of the data acquisition caused by the patient's motion. Our measurements show that the COG did move 1.2 mm on average with a maximum of 4.8 mm, which was considered not relevant. However, individual variations of the rest position between patients (patients settling down more anteriorly or more posteriorly or inclining more to one side than the other) may explain the observed variations. We did not investigate difference in pressure loading the left vs right foot in this study. An earlier study dealing with pedography in bipedal stand showed no pressure differences between the left and right foot.[11]

Radiation Dose

The radiation dose of the pedCAT was not investigated in this study. However, it remains a concern to provide the best and least invasive methods of investigation for our patients.[12,13] Recently, the dose of foot/ankle radiographs, CT, and pedCAT was measured and analyzed using a foot and ankle phantom.[9] The dose for adults for 3 radiographs from 1 foot (dorsoplantar + lateral + oblique) was 0.7 μSv, the dose for a bilateral pedCAT scan was 4.3 μSv, and the dose for conventional CT of 1 foot/ankle was 25 μSv.[9] This means that a bilateral pedCAT scan has a comparable dose as 18 unilateral radiographs of the foot and 17% of an unilateral CT of the foot and ankle.[9] This study also measured the dose of an unilateral pedCAT scan, which was 1.4 μSv, comparable to 6 unilateral radiographs of the foot and 5.6% of an unilateral CT of the foot and ankle.[9] This radiation dose is somewhat relative because virtual radiography can be created from the pedCAT data.[12]

In conclusion, despite the COG not relevantly moving during a combined pedCAT/pedography scan in the investigated 180 feet, there was an anterior/distal translation of COG relative to the FC. This expected finding was quantified with this study. FC was 27.5 mm distal and 2 mm lateral relative to FC on average with a high variability. The data could be a basis for prediction of COG based on FC without additional pedography. It also validates the use of TALAS as a relevant and informative hindfoot alignment measure in relation to the forces in the foot and ankle, at least from a static standpoint. Definition of COG might be taken into consideration for planning and follow-up for corrections/fusion around the hindfoot and for total ankle replacement, implying that it would be useful to systematically associate pedCAT imaging and pedography, or try to merge data from dynamic pedography with pedCAT images. Upcoming studies might also investigate different foot and ankle pathologies (ie, FC/COG and potential spatial difference). Future studies should also evaluate which parameter should be analyzed for preoperative planning and for postoperative control.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Martinus Richter, MD, PhD, reports shares from Curvebeam outside the submitted work. Francois Lintz, MD, PhD, reports personal fees and other from Curvebeam outside the submitted work.

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