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The effect of ankle and hindfoot malalignment on foot mechanics in patients suffering from post-traumatic ankle osteoarthritis

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ABSTRACT

Background: Ankle and hindfoot malalignment is a common finding in patients suffering from post-traumatic ankle osteoarthritis. However, no studies have addressed the effect of concomitant foot deformities on intrinsic foot kinematics and kinetics. Therefore, the objective of this study was to investigate the effect of ankle and hindfoot malalignment on the kinematics and kinetics of multiple joints in the foot and ankle complex in patients suffering from post-traumatic ankle osteoarthritis.

Methods: Twenty-nine subjects with post-traumatic ankle osteoarthritis participated in this study. Standardized weight-bearing radiographs were obtained preoperatively to categorize patients as having cavus, planus or neutral ankle and hindfoot alignment, based on 4 X-ray measurements. All patients underwent standard gait assessment. A 4-segment foot model was used to estimate intrinsic foot joint kinematics and kinetics during gait. Statistical parametric mapping was used to compare foot kinematics and kinetics between groups.

Findings: There were 3 key findings regarding overall foot function in the 3 groups of post-traumatic ankle osteoarthritis: (i) altered frontal and transverse plane inter-segmental angles and moments of the Shank-Calcaneus and Calcaneus-Midfoot joints in the cavus compared to the planus group; (ii) in cavus OA group, Midfoot-Metatarsus joint abduction sought to compensate the varus inclination of the ankle joint; (iii) there were no significant differences in inter-segmental angles and moments between the planus and neutral OA groups.

Interpretation: Future studies should integrate assessment of concomitant foot and ankle deformities in post-traumatic ankle osteoarthritis, to provide additional insight into associated mechanical deficits and compensation mechanisms during gait.

Keywords: ankle osteoarthritis, malalignment, foot kinetics, kinematics, gait

1. Introduction

There is now a growing body of evidence for significant biomechanical impairment of the entire foot and lower limb in patients suffering from ankle osteoarthritis.^{1,28,34} Gait is asymmetric and characterized by decreased walking speed, stride length and ankle joint complex range of motion.³⁸ Patients also seem to adopt an analgesic walking strategy to prevent shear loading through the painful joint.³⁸ Changes in joint mechanics are not restricted to the painful ankle joint, but also affect hip mechanics, especially during the push-off phase of gait.^{8,34} Compensatory increases in hip flexion moment and in hip extension were reported in patients with ankle osteoarthritis, to cope with the decrease in plantarflexion moment resulting from reduced peak ankle plantar flexion during terminal stance.³⁷ 3D multi-segment kinematic foot models also revealed reduced range of motion in the intrinsic foot joints in patients suffering from ankle osteoarthritis compared to healthy reference data.^{19,27} However, further insight into the complex behavior of the foot and ankle during walking also requires analysis of power output.^{7,13,35,36} Recently developed 3D multi-segmental kinetic foot models were created to provide such estimations^{7,13,36} and were clinically interpreted in an accessible format through the use of the 3D angular relationships between joint moment and joint angular velocity vectors.⁷ These models are still only exploratory, but their importance should not be underestimated as they showed altered inter-segmental moments and power in the distal foot joints of the affected side in patients suffering from ankle osteoarthritis.^{13,35} However, published kinematic and kinetic studies tend to lack characterization of the ankle osteoarthritis,⁸ making the functional consequences difficult to determine without considering the morphological and structural changes associated with the ankle osteoarthritis.

End-stage ankle osteoarthritis rarely occurs in isolation, but more often presents concomitant ankle and hindfoot deformities.²⁴ As the ankle is a weight-bearing joint, the

intra-articular load distribution is not only influenced by the alignment of the tibiotalar joint itself but is also highly dependent on extra-articular mechanical forces related to the 3D orientation of the distal joints of the affected ankle.²⁰ However, these key factors and the corresponding changes in foot biomechanics have never been truly investigated. While the link is still unclear, the past literature stressed that, in order to systematically study foot and ankle pathology, objective measures of foot structure and intrinsic foot joint dynamics, sensitive to different foot morphotypes, are needed.^{6,25,31} Previous studies demonstrated that foot posture (e.g., cavus, planus) influences foot and lower limb muscle activity³¹ and joint kinematics⁵ and kinetics³⁶ during gait. For example, ankle and midfoot power generation in children with pes planovalgus was respectively 38% and 37% lower than in control subjects.³⁶ This means that functional consequences are difficult to determine without taking account of the morphological and structural changes associated with the ankle osteoarthritis.

The present study therefore aimed to investigate the interrelationship between osteoarticular foot deformities and changes in foot mechanics during gait in patients suffering from post-traumatic ankle osteoarthritis. A cohort of subjects suffering from end-stage post-traumatic ankle osteoarthritis was broken down into three deformity groups: neutral, planus and cavus. It is believed that ankle osteoarthritis may lead to altered mechanical load and maladaptive motion in foot joints other than the affected ankle joint. Therefore, our hypothesis was that the kinematic and kinetic curves of the intrinsic foot joints would differ between the three deformity groups, particularly in the transverse and frontal planes. Previous studies analyzing ankle osteoarthritis tested their hypotheses on a relatively small number of so-called summary metrics (e.g., peak values or range of motion values during sub-phases of the stance phase).^{19,35,38} These data-reduction techniques are computationally convenient, but may lead to opposing results or fragmented knowledge, impeding in-depth insight into compensation in the joints distal to the affected ankle joint.³² However, 1D statistical

parametric mapping (SPM), was able to unravel the kinematic and dynamic differences between the deformity groups. This is of interest for clinicians analyzing the pathomechanics of ankle osteoarthritis. Furthermore, as the deformity is 3-dimensional, affects several joints and impacts gait dynamics and energetics as a whole, all the inter-segmental kinematics, moments around the three joint axes and the power variables were analyzed for the Shank-Calcaneus, Calcaneus-Midfoot, Midfoot-Metatarsus, and 1st Metatarso-Phalangeal joints.

2. Methods

2.1. Participants

Twenty-nine subjects with end-stage post-traumatic ankle osteoarthritis (Takakura stage 3 to 4 (4 being complete obliteration of the joint space)) scheduled for primary total ankle replacement or ankle fusion between January 2017 and June 2019 participated in this study (Table 1). This study was approved by the local review board (B200-2017-061) and all participants signed an informed consent form. All patients suffered from end-stage post-traumatic ankle osteoarthritis secondary to ankle-related fracture (post-fracture) or to chronic ankle instability (post-sprain) (Table 1). Exclusion criteria were (1) age <18 years, (2) systemic or neurological disease, and (3) any medical problem other than post-traumatic ankle osteoarthritis liable to affect gait. Standardized weight-bearing radiographs of the foot and the ankle were obtained preoperatively to assess the concomitant foot and ankle deformities and categorize them in three deformity groups. Cavus type (hereafter referred as cavus OA) was defined as: varus position of the hindfoot and ankle joint complex, bony dorsum deformity of the midfoot characterized by dorsiflexion of the talus within the ankle, upward position of the metatarsals with respect to the ground, and high medial longitudinal arch (Figure 1 A,B,C). Planus type (hereafter referred as planus OA) was defined as: valgus position of the hindfoot and ankle joint complex, collapse deformity of the midfoot

characterized by a plantar flexion of the talus within the ankle, downward position of the metatarsals with respect to the ground, and low medial longitudinal arch (Figure 1 D,E,F). Subjects were allocated to the cavus or planus deformity group if they had 3 to 5 of these features with at least one deformity $\geq 10^\circ$. Neutral type ((hereafter referred as neutral OA) had no midfoot, hindfoot or ankle malalignment. Osteoarthritis severity was scored on the Canadian Orthopaedic Foot & Ankle Society (COFAS) classification system (Table 1)²⁴: Type 1, isolated ankle osteoarthritis; Type 2, ankle osteoarthritis associated with intra-articular ankle deformity or tight heel cord or both; Type 3, ankle osteoarthritis with deformity of the hindfoot, midfoot, tibia or forefoot; and Type 4, Type 1 to 3 with subtalar or calcaneocuboid or talonavicular osteoarthritis.²⁴

2.2. Radiographic assessment

Radiographic assessment comprised: (1) standardized anteroposterior ankle Méary view to measure the hindfoot deformity (γ angle: $<90^\circ$ = valgus; $>90^\circ$ = varus) and intra-articular ankle varus or valgus alignment (Tibia-Talus) (α angle: $<90^\circ$ = valgus; $>90^\circ$ = varus);^{24,30} (2) standardized weight-bearing lateral foot (and ankle) view to measure the midfoot deformity as the talus/1st metatarsal angle ($\geq 10^\circ$)²⁴ (β_1 angle: $\leq 170^\circ$ = bony dorsum deformity; $\geq 190^\circ$ = collapse deformity) and the medial longitudinal arch deformity as Djian-Annonier angle ($\geq 10^\circ$) (β_2 angle: $\leq 115^\circ$ = high arch; $\geq 130^\circ$ = low arch) (Figure 1).¹⁰

2.3. Data collection

In the measurement session, patients walked at self-selected speed over a 10m walkway in which an AMTI (Advanced Mechanical Technology, Inc., Watertown, MA, USA) with embedded force plate and Footscan® pressure plate (0.58 m x 0.42 m; 4,096 sensors, 2.8 sensors per cm^2 ; RsScan International, Paal, Belgium). The force plate was

custom-made to fit the dimensions of the pressure plate. This set-up provided continuous calibration of the pressure plate with respect to the force plate, using an RsScan® 3D box. Sixteen 8mm retro-reflective markers were placed on the foot and shank of each participant, according to the multi-segment Rizzoli foot model.²⁶ To record kinematic data during walking over the walkway, a passive optoelectronic motion analysis system (Qualysis, Göteborg Sweden) consisting of 8 Miquis cameras was used, sampling at 200 Hz. All marker trajectories were computed by Qualysis Tracking Manager 2.16 (Qualysis, Göteborg Sweden). Integration and synchronization of the 3 hardware devices used a Miquis Sync unit interface (Qualysis, Göteborg Sweden). Technical information about synchronization is provided in Supplementary Material. Data from the force and pressure plates were measured at a sampling rate of 200 Hz. Five representative trials were collected per participant. A trial was considered representative when the foot of interest made clear contact with the pressure plate without visual adjustment in step length or step frequency to aim at the pressure plate. Walking speed was required to be similar across all trials in a given recording session.

2.4.Data analysis

Inter-segment center definitions of the 4-segment foot model were based on an adapted version of Rizzoli's 3D multi-segment foot model, developed by Deschamps et al. (2017)(IOR-4Segment-model 1) (Figure 2).⁹ The main differences between IOR-4Segment-model 1⁹ and Rizzoli's foot model²⁶ consists in the creation of a virtual cuboid marker (FCub) at two-thirds of the distal distance between the peroneal tubercle (FPT) and the base of the fifth metatarsal (FMT), and in the definition of the Calcaneus-Midfoot joint center (ID). Inter-segment 3D rotations were computed according to Deschamps et al.'s IOR-4Segment-model 1 (2017), following ISB recommendations⁹, and were defined as follows: Shank-Calcaneus joint (midpoint between the malleoli markers, describing the shank-

calcaneus center), Calcaneus-Midfoot joint (midpoint between the cuboid (FCub) and the navicular bone (FNT), describing the calcaneus-midfoot center), Midfoot-Metatarsus joint (at the second metatarsal base (SMB), describing the midfoot-metatarsus center), and 1st Metatarso-Phalangeal joint (projection of 1st metatarsal head marker (FM1) vertically at mid distance to the ground, describing the metatarsus-hallux center).

Inter-segmental forces (**F**) and moments (**M**) were computed in the inertial coordinate system by a bottom-up inverse dynamic method using a Newton-Euler recursive algorithm based on a homogeneous matrix formalism during the stance phase of gait.²⁹ Kinematic and force data were filtered using a low-pass zero-lag 4th order Butterworth filter, with 10 Hz cut-off frequency. Inertia and weight parameters of each foot segment were neglected, considering that inertia effects during stance are negligible compared to external forces.³⁵ The force plate data were distributed over each foot segment using a validated proportionality scheme.^{14,36} The subarea of each foot segment was estimated for each time frame by projecting the markers' position vertically on the sensor matrix of the pressure platform. The center of pressure (CoP) of each segment was calculated as the barycenter of all sensors allocated to the segment, based on the pressure values measured in each sensor. The resulting CoP of each estimated subarea was then used as the CoP for the corresponding foot segment in inverse dynamics calculations. The inter-segmental moments were expressed in the proximal segment coordinate system. For energetics, in supplement to the joint power, the 3D angle $\alpha_{M\omega}$ between the inter-segmental moment (**M**) and the inter-segmental angular velocity (ω) vectors was calculated as described by Dumas and Chèze (2008).¹² When the 3D angle $\alpha_{M\omega}$ is $<60^\circ$ or $>120^\circ$, the moment mainly drives the joint, with, respectively, propulsion or resistance; when it is between 60° and 120° , the moment mainly stabilizes the joint (additional information in Supplementary Material).¹² Inter-segmental kinematic and kinetic computations and extraction of discrete spatio-temporal variables (walking speed and stride

length) were performed using an in-house Matlab® program (The Mathworks Inc., Natick, MA, USA). Internal joint moments and powers were normalized by subject-mass and all 1D data were time-normalized to 100% of the stance phase. One-dimensional 3D inter-segmental kinematics, moments and power variables around the axes of the following inter-segmental joints were extracted to assess the differences between the three deformity groups: Shank-Calcaneus joint, Calcaneus-Midfoot joint, Midfoot-Metatarsus joint, and 1st Metatarso-Phalangeal joint.

2.5. Statistical analysis

First, the Shapiro-Wilk test was used to check data normality. One-way ANOVA and Kruskal-Wallis test were used to identify significant differences between groups for demographic, spatio-temporal and radiographic variables. For significant differences, Gabriel's post-hoc test or the Mann-Whitney-U test (adjusted P -value ($0.5/3=0.017$)) were used to indicate which groups were different. All statistical tests were conducted on SPSS software (version 25, IBM Corp, Chicago, USA).

One-dimensional statistical parametric mapping (SPM) was used to compare foot kinematics and kinetics between groups, using an open-source code (v.M.0.4.5; www.spm1d.org) in Matlab® (The Mathworks Inc., Natick, MA, USA).^{5,16} The main advantages of this methodological approach is that SPM regards the whole time-series as the unit of observation and that time-dependence is incorporated directly in statistical testing. 1D-SPM 1-way ANOVA over the normalized time series was used to confirm significant differences between groups. If statistical significance was reached, a post-hoc 1D-SPM 2-sample t-test (post-hoc P -value $0.05/3 = 0.017$) was used to determine between which groups the significant differences occurred. Conceptually, for example, an SPM post-hoc 2-sample t-test is similar to the calculation and interpretation of a scalar post-hoc 2-sample t-test at each

instant of time.

3. Results

3.1. Demographic, spatiotemporal and radiographic data

No inter-group differences were found for the demographic and spatio-temporal variables (Table 1). Significant differences were found between the cavus and planus OA groups for all radiographic parameters. The cavus OA group also showed significantly greater medial longitudinal arch deformation than the neutral OA group. Méary angle was significantly different on all between-groups comparisons.

3.2.SPM analysis

There were significant SPM{F} main effects between the three groups for all the intrinsic foot joints.

3.2.1. Planus OA versus neutral OA

Post-hoc comparisons showed no differences between planus and neutral OA groups for any foot inter-segmental angles or moments. However, 1D-analysis revealed that the planus OA group exhibited a greater Shank-Calcaneus power pattern ($p=0.016$; range: 93-94% of the stance phase) at end of stance phase than the neutral OA group.

3.2.2. Cavus OA versus neutral OA

The cavus OA group showed a more inverted angle of the Shank-Calcaneus joint ($p=0.017$, 0-6% & $p<0.001$, range: 10-72% of the stance phase) associated with a more abducted angle of the Midfoot-Metatarsus joint ($p<0.001$; range: 0-100% of the stance phase) than the neutral OA group during almost the entire stance phase. The 1st Metatarso-

Phalangeal joint showed greater dorsiflexion ($p=0.013$; range: 40-50% of the stance phase) in the cavus than in the neutral OA group during midstance. Post-hoc comparisons showed no differences in kinetics between these two groups.

3.2.3. Cavus OA versus planus OA

The main differences observed between the planus and cavus OA groups all concerned the frontal and transverse plane (Figure 3-4). The planus OA group showed a significantly more everted Shank-Calcaneus angle ($p<0.001$; range: 0-77% of the stance phase) associated with a more abducted Calcaneus-Midfoot angle ($p<0.001$; range: 0-94% of the stance phase) than the cavus OA group. The moment patterns revealed that the planus OA group exhibited larger Shank-Calcaneus inversion moment ($p<0.001$; range: 10-35% of the stance phase) than the cavus OA group (Figure 4). During propulsion, the cavus OA group showed larger Shank-Calcaneus abduction moment ($p<0.001$; range: 88-95% of the stance phase) than the planus OA group. However, no differences were observed for power or 3D α_{M10} angle patterns between the cavus and planus OA groups.

4. Discussion

To our knowledge, this was the first study to investigate the effect of ankle and hindfoot malalignment on the intrinsic foot mechanics in patients suffering from post-traumatic ankle osteoarthritis. Results showed that the cavus OA group presented a distinctive pattern of inter-segmental angles and moments compared to the neutral and planus OA groups. These differences shed light on a number of radiographic concepts which are currently used regarding the compensatory mechanism of the neighboring joints of the ankle, and in particular in the surgical management of intra- and extra-articular deformities in ankle osteoarthritis.

Concerning 3D inter-segmental rotations and actions, the most important differences were observed between the cavus and planus OA groups in the shank-calcaneus and Calcaneus-Midfoot joints during almost the entire stance phase. Our data seem to provide further evidence of the interrelationship between foot structure and alterations in foot mechanics. The cavus OA group showed a significantly greater inverted Shank-Calcaneus angle and a more adducted Calcaneus-Midfoot angle than the planus OA group. It is further believed that the etiology of these differences is mainly guided by the multiplanar orientation of the talus, guided in turn by the geometry of the subtalar joint.¹⁷ Radiographic and anatomical cadaver studies suggested that pes cavus feet have a high vertical subtalar joint axis associated with a talar head placed tightly within a subtalar joint geometry featuring a V-shaped groove, limiting subtalar joint motion.^{11,17} In contrast, the subtalar joint in pes planus feet seems to be characterized by a lower vertical axis associated with larger and relatively flat articular facets, allowing greater range of motion in the subtalar joint.^{2,17} This notion of talar head stability provided by the orientation of the axis and the subtalar joint geometry is further underpinned by the 3D α_{M0} angle of the Shank-Calcaneus and Calcaneus-Midfoot joints. Even though, with the numbers available, no significant difference could be demonstrated here, it could be observed from the 3D α_{M0} angle waveforms that both joints in the planus OA group adapted a more resistant configuration than in the cavus OA group (Figure 5). This could mean that the planus OA group has to counter higher external forces than the cavus OA group, to keep the foot from collapsing and to stabilize it during walking.

Another noteworthy finding in our study was the significant difference in inter-segmental angles between the cavus and the neutral OA groups. As expected, the cavus OA group showed a more inverted angle of the Shank-Calcaneus joint than the neutral OA group during a significant part of the stance phase. Similar shifts in Shank-Calcaneus kinematics were observed in previous studies highlighting differences in segmental foot kinematics

between rectus, planus and cavus feet.^{5,25} A study analyzing segmental foot kinematic differences between foot types reported a shift in forefoot kinematics toward adduction in cavus foot compared to a neutral group in a sample of asymptomatic healthy adults.²⁵ Therefore, considering the kinematic coupling between foot segments, it might be expected that cavus OA would exhibit greater Midfoot-Metatarsus joint adduction in association with the inverted position of the Shank-Calcaneus joint compared to neutral OA; in point of fact, however, a significantly more abducted position was found in the Midfoot-Metatarsus joint. This ‘twist’ in the osteo-articular geometry of foot may represent a compensatory mechanism to counter the varus inclination of the ankle joint and therefore to reduce the stress concentration located in the medial part of the joint. This kind of osteo-articular configuration of the hindfoot and ankle joint complex has often been referred as the “zig-zag” deformity, as the subtalar joint goes in the opposite direction to the tibiotalar deformity (Figure 1.F).^{16,21,23} Paradoxical shifts in load were reported by Knupp et al. (2011), with medial shifts in ankles with valgus deformity and lateral shifts in varus deformity.²²

The positioning of the 1st Metatarso-Phalangeal joint was also found to be significantly different, as the cavus OA group showed less hallux plantar flexion with respect to the forefoot than the neutral OA group. This reduced plantar flexion of the 1st Metatarso-Phalangeal joint may reduce loading underneath the hallux during the stance phase. This finding is supported by comparable studies analyzing kinematic and plantar pressure measurements between normal, planus and cavus feet.^{3,4}

The majority of the significant differences were found in the cavus group versus both the neutral and planus groups. In contrast, no significant differences in inter-segmental angles or moments were observed between the planus and neutral groups. This suggests that the present results may be attributed to these two pathologic groups adopting a similar walking pattern to avoid pain in their arthritic ankle. Inspection of between-group comparisons found

that the cavus OA group had significantly greater radiographic deformities than the neutral and planus OA groups. Only one variable differed significantly between the planus and neutral OA groups. This could mean that the difference in malalignment of the ankle and hindfoot between these two groups was not sufficiently great to be detected dynamically during gait.

The findings of this study should be considered in the context of two limitations. First, our classification of multi-joint, multi-planar foot deformities was based on 2D plain weight-bearing radiographs. Assessment of submalleolar deformity is challenging, due to the limited imaging modalities. New-generation weight-bearing CT scans may be a valuable tool to better represent the 3D orientation of the hindfoot and ankle malalignment in ankle osteoarthritis. Moreover, partitioning of the total ground reaction forces acting on the calcaneus segment was based on an estimation method (proportionality scheme) which combined pressure and force plate data together with marker placement data. Even though this proportionality scheme was validated, the reported ankle inter-segmental moments and powers should be regarded as estimates. A second limitation was the use of skin markers to estimate joint centers and segment kinematics. Soft-tissue artefacts have been reported to be as much as 3-4 mm on the surface of the foot.¹⁸ The impact of these errors on the estimation of the moments and powers is currently difficult to estimate.

5. CONCLUSION

Three key findings in overall foot function were observed between three groups of post-traumatic ankle osteoarthritis: (i) altered frontal and transverse plane inter-segmental angles and moments of the Shank-Calcaneus and Calcaneus-Midfoot joints in the cavus OA group compared to the planus OA group; (ii) the cavus ankle group, Midfoot-Metatarsus joint abduction tried to reduce the varus inclination of the ankle joint; and (iii) there were no

significant differences in inter-segmental angles or moments between the planus OA group and the neutral OA group. These findings indicate that malalignment of the hindfoot and the ankle as revealed by radiographic assessment does indeed influence foot mechanics during gait in patients suffering from post-traumatic ankle osteoarthritis.

CONTRIBUTIONS

PAD and TL were responsible for the conception and design of the research, reviewing articles, analyzing data, interpreting the results, writing and drafting the manuscript, and approving the final version of the manuscript. AN and LC were responsible for conception and design of the review, reviewing articles, drafting, critically appraising and revising the manuscript for intellectual content. JLB, RD, LG and BDB were responsible for the conception and design of the review, drafting, critically appraising and revising the manuscript for intellectual content. All authors read and approved the final version of the manuscript.

COMPETING INTEREST STATEMENT

The authors do not have any significant conflicts of interest relevant to this manuscript.

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FIGURE LEGENDS

Table 1: Demographic, spatio-temporal and radiographic data for the three patient groups: post-traumatic ankle osteoarthritis associated with planus foot deformity (Planus OA), with cavus foot deformity (Cavus OA), and without foot deformity (Neutral OA). Abbreviations: COFAS: Canadian Orthopaedic Foot & Ankle Society classification system for ankle osteoarthritis; MLA: medial longitudinal arch; SD: standard deviation; BMI: body mass index; N/A: not applicable; N.S.: not significant. Statistics: Depending on the distribution of the demographic and spatio-temporal data, 1-way ANOVA (normal distribution)^a or Kruskal-Wallis test (non-normal distribution)^b was used to assess statistical differences for each variable between the three groups. ^c χ^2 Extended Chi-square test ; *Gabriel's post-hoc test (adjusted P -value 0.3/3=0.017); ** post-hoc Mann-Whitney U test (adjusted P -value 0.3/3=0.017).

Figure 1: (A,C,D,F) Standardized anteroposterior ankle Méary radiographic view to measure the hindfoot deformity. Hindfoot axis with respect to the ground (γ angle: valgus ≤ 80 degrees; varus ≥ 95 degrees) and the intra-articular ankle varus or valgus alignment (position of the talus with respect to the axis of the tibia: $\leq 80^\circ$ valgus; $\geq 100^\circ$ varus);^{12,19} (B,E) Standardized weight-bearing lateral foot (and ankle) radiographic view to measure the midfoot deformity as the talar/1st metatarsal angle ($\beta 1$ angle: $\leq 170^\circ$ high arch (cavus); $\geq 190^\circ$ low arch (planus)) and medial longitudinal arch deformation as the Djian-Annonier angle ($\beta 2$ angle: $\leq 115^\circ$ high arch (cavus); $\geq 130^\circ$ low arch (planus)). Fig 1 A,B,C are foot and ankle deformities associated with the planus OA group; D,E,F, associated with the cavus OA group. Fig. F shows the “zig-zag” deformity, as the subtalar joint goes in the opposite direction (valgus) of the tibiotalar deformity (varus).

Figure 2: Inter-segment centers were defined according to an adapted version of Rizzoli's foot model (Leardini et al. 2007) developed by Deschamps et al. (2017) (IOR-4Segment-model 1). Marker names: upper ridge of the posterior surface of the calcaneus (FC); peroneal tubercle (FPT); sustentaculum tali (FST); virtual cuboid marker (FCub), tuberosity of the navicular bone (FNT); 1st, 2nd and 5th metatarsal base (FMB, SMB, FMT); 1st, 2nd and 5th metatarsal head (FM1, FM2, FM5); PD6: distal dorso-medial aspect of the head of the proximal phalanx of the hallux; 1st metatarso-phalangeal center (FM1); midfoot-metatarsus center (SMB); calcaneus-midfoot center (ID)

Figure 3: Kinematic waveform representation with ± 1 standard deviation cloud for the intrinsic foot joints: Sha-Cal: Shank-Calcaneus; Cal-Mid: Calcaneus-Midfoot; Mid-Met: Midfoot-Metatarsus; 1st Metatarso-Pha: 1st Metatarso-Phalangeal joint. Cavus OA group (blue), Neutral OA group (green) and Planus OA (purple); DF: dorsiflexion; PF: plantar flexion; Add: Adduction; Abd: Abduction; Inv: Inversion; Ev: Eversion.

Figure 4: Kinetic between-group comparison of inter-segmental Shank-Calcaneus moments (Mx & My) during the stance phase of gait. Cavus OA group (blue), Neutral OA group (green) and Planus OA group (purple); Sha-Cal: Shank-Calcaneus; **A-C, G-I:** Mean kinetic trajectories with their respective standard deviation clouds. **D-F, J-L:** SPM results: SPM{t} curve is the trajectory of the post-hoc 2-sample t-test. Conceptually, an SPM post-hoc 2-sample t-test is similar to the calculation and interpretation of a scalar post-hoc 2-sample t-test at each instant of time. Where the SPM{t} curve exceeds the critical threshold (red dotted line in graphs D-F & J-L) at one or multiple time nodes, this area is shaded in gray and a

significant difference is present between the corresponding moment curves in the graph above.

Figure 5: Kinetic between-group comparison of 3D angle $\alpha_{M\omega}$ of the Shank-Calcaneus (Sha-Cal) and Calcaneus-Midfoot (Cal-Mid) joints during the stance phase. Cavus OA group (blue), Neutral OA group (green) and Planus OA group (purple); Sha-Cal: Shank-Calcaneus; When the 3D angle $\alpha_{M\omega}$ is $<60^\circ$ or $>120^\circ$, the moment mainly drives the joint, with, respectively, propulsion (**P**) or resistance (**R**). When the 3D angle $\alpha_{M\omega}$ is between 60° and 120° , the moment mainly stabilizes the joint (**S**); **A-C, G-I**: Mean kinetic trajectories with their respective standard deviation clouds. **D-F, J-L**: SPM results: SPM{t} is the trajectory of the post-hoc 2-sample t-test. Conceptually, an SPM post-hoc 2-sample t-test is similar to the calculation and interpretation of a scalar post-hoc 2-sample t-test at each instant of time. Where the SPM{t} curve exceeds the critical threshold (red dotted line in graphs D-F & J-L) at one or multiple time nodes, this area is shaded in gray and a significant difference is present between the corresponding 3D angle $\alpha_{M\omega}$ curves in the graph above.

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	Planus OA (n=8 ankles)			Cavus OA (n=10 ankles)			Neutral OA (n=12 ankles)			ANOVA Kruskal- (H)
	Mean	SD	Min-Max	Mean	SD	Min-Max	Mean	SD	Min-Max	F / H
Age (years)	63.50	11.32	38-74	61.44	7.4	51-73	59.17	7.3	46-68	2.848 (H)
Height (m)	1.71	0.12	1.48-1.87	1.73	0.08	1.65-1.90	1.73	0.1	1.57-1.90	0.171 (F)
Weight (kg)	84.63	11.00	69-99	79.56	12.34	65-100	85.5	16.43	59-111	0.511 (F)
BMI	29.12	3.79	24.3-33.78	26.5	4.21	22.04-34.60	28.41	4.32	21.38-34.60	0.940 (F)
Walking Speed (m/s)	0.88	0.21	0.61-1.27	0.98	0.17	0.73-1.22	0.95	0.17	0.65-1.27	0.693 (F)
Stride Length (% Height)	0.63	0.07	0.56-0.75	0.65	0.06	0.58-0.74	0.66	0.08	0.45-0.75	0.424 (F)
Meary (degrees)	79.6	2.86	75-84	91.4	4.0	85-99	85.5	2.84	81-90	28.513 (F)
MLA (degrees)	126.4	10.41	108-141	110.6	4.52	104-115	118.9	4.66	111-126	14.967 (H)
TALOMI (degrees)	187.5	11.07	174-202	172.4	6.54	162-185	178.4	5.07	170-186	11.513 (F)
TibiaTalus (degrees)	83.6	7.07	72-93	97.2	7.5	90-109	89.5	3.9	82-93	12.610 (H)
Ankle OA subtype (N)	Post-fracture N=5		Post-sprain N=3	Post-fracture N=3		Post-sprain N=7	Post-fracture N=8		Post-sprain N=4	χ^2 (2, N=30) = 0.19
COFAS	Type 1	1		Type 1	2		Type 1	8		
	Type 2	2		Type 2	3		Type 2	0		
	Type 3	5		Type 3	4		Type 3	2		
	Type 4	0		Type 4	1		Type 4	2		

Table 1: Demographic, spatio-temporal and radiographic data for the three patient groups: post-traumatic ankle osteoarthritis associated with planus foot deformity (Planus OA), with cavus foot deformity (Cavus OA), and without foot deformity (Neutral OA). Abbreviations: COFAS: Canadian Orthopaedic Foot & Ankle Society classification system for ankle osteoarthritis; MLA: medial longitudinal arch; SD: standard deviation; BMI: body mass index; N/A: not applicable; N.S.: not significant. Statistics: Depending on the distribution of the demographic and spatio-temporal data, 1-way ANOVA (normal distribution)^a or Kruskal-Wallis test (non-normal distribution)^b were used to assess statistical differences for each variable between the three groups. ^c χ^2 Extended Chi-square test; *Gabriel's post-hoc test (adjusted *P*-value 0.3/3=0.017); ** post-hoc Mann-Whitney U test (adjusted *P*-value 0.3/3=0.017).

HIGHLIGHTS

- Malalignment in ankle osteoarthritis does affect foot mechanics during gait
- Frontal and transverse plane kinetics should be assessed in ankle osteoarthritis
- Calcaneus-Midfoot and Midfoot-Metatarsus joints are affected by malalignment in ankle osteoarthritis
- Cavus osteoarthritic group compensate ankle varus deformity through Midfoot-Metatarsus joint

Figure 1

Figure 2

Figure 3

Sha-Cal Mx Inv(+) Ev(-)

Sha-Cal My Add(+) Abd(-)

Figure 4

Sha-Cal Alpha

Cal-Mid Alpha

Figure 5