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Preoperative gait asymmetry in end-stage unilateral ankle osteoarthrosis patients

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ABSTRACT

Background: Gait asymmetries following unilateral ankle surgeries have been reported in published literature. Preoperative compensatory gait patterns are usually assumed to be the cause; however, this hypothesis is not backed by objective data. This study aims to assess gait symmetry in patients with unilateral ankle osteoarthrosis (AOA).
Method: 20 participants, including 10 controls and 10 AOA patients, were assessed using 3-D inertial sensors and pressure insoles. 46 gait parameters and foot sub-region relative motions were studied.
Results: Compared with the controls, significant differences were reported in 23 parameters on the affected side and 20 on the unaffected side. AOA bilateral comparison reported differences in 14 parameters, mostly in the toe region. Asymmetries were also found in forefoot relative motion.
Conclusion: Gait alterations are reported in AOA. One-third of measured parameters and forefoot relative motion reported marked gait asymmetries. Clarification of the origin of postoperative gait imbalances is likely to help clinicians optimize rehabilitation programs.

1. Introduction

Ankle osteoarthrosis (AOA) is a chronic progressive and degenerative disease, which affects the quality of life of the patients as a result of pain and progressing deformity. The most common cause of AOA is trauma [1–3]. The mental and physical impact of AOA is noted to be comparable to that of end-stage hip osteoarthrosis [4]. Surgical treatments to reduce pain and increase functional capacity are available for end-stage AOA. The most common surgical option is ankle arthrodesis (AA), which involves fusion of the tibiotalar joint. Total ankle replacement (TAR) is another common and viable option. Adaptive gait patterns are reported following both surgical options [5–7], as is common in other weight-bearing joints [8]. Notably, the qualitative subjective assessment for both surgical options has been shown to be comparable [9,10,5]. As a result, the postoperative adaptive patterns are assumed to be a residual effect of a patient's preoperative compensatory gait pattern rather than an outcome of the surgery itself, however, this hypothesis is not backed by objective evidence for end-stage AOA. Patients were reported to have an increased loading and an increased overall motion in the unoperated side to compensate for a loss of functionality in the operated side. In contrast, more recent studies carried out by the authors, utilizing a cutting-edge ambulatory gait assessment system and advanced analysis methodologies, have found TAR patient outcomes to be more comparable with controls than AA, particularly regarding gait symmetry [5,7]. It is therefore possible that AA may be objectively detrimental in this regard. A few studies have looked at gait alterations of patients with end-stage AOA in the past [11–14], however, bilateral gait was not assessed and only a minimal set of gait parameters were compared, due to technological limitations, leaving significant uncertainties. This study aims to objectively assess the bilateral gait mechanics of patients with end-stage AOA, utilizing the aforementioned ambulatory gait assessment system, which measures foot pressures as well as lower-limb momentum and inertia. The working hypothesis of the study is that patients with unilateral end-stage AOA exhibit significant bilateral gait alteration.

2. Methods

The study involved 20 participants, including 10 patients with end-stage AOA and 10 healthy age-matched controls. The patient group consisted of consecutive cases with isolated post-traumatic end-stage AOA – stages 3 and 4 in accordance with the Kellgren and Lawrence classification. Patients affected by other pathologies of the spine and/or lower extremities were excluded. Controls were

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Table 1
Demographics of AOA participants, mean (SD).

Demographics and clinical assessment	AOA (n = 10)	Control (n = 10)
Age	65.8 (8.9)	64.9 (9.1)
BMI	27.6 (3)	25.7 (5.5)
AOFAS-total	48 (18)†	100 (0)
AOFAS-pain	12 (10)†	40 (0)
AOFAS-function	31 (7)†	50 (0)
AOFAS-passive sagittal motion	4 (3)†	8 (0)
AOFAS-passive coronal motion	2 (2)†	6 (0)
FAAM-ADL	61 (19)†	100 (0)
EQ-5D	0.47 (0.3)†	1 (0)

† Significant difference ($p < 0.05$) compared with the controls.

volunteers with no prior history of lower limb or spinal injuries or pathologies. The clinical status and other relevant demographics of the AOA patients are provided in Table 1. All participants gave their informed consent, approved by the ethics commission of the University.

Clinical assessment included use of the American Orthopedic Foot and Ankle Society Score – hindfoot (AOFAS) [15], Foot and Ankle Ability Measure Score – activity of daily living section (FAAM) [16], and the general health specific score EQ-5D [17].

Gait assessment included a validated ambulatory gait assessment (AGA) system, consisting of pressure insoles (Pedar-X, Novel, Germany) and five inertial sensors with 3-D accelerometers and gyroscopes (Physilog, BioAGM, CH). Sensors were attached in accordance with a validated method [18]. A sensor is attached to the medial aspect of both tibias close to the ankle; one to the great tuberosity of the calcaneus; one between the base of the first and second metatarsals; and one on the dorsal aspect of the proximal phalanx of the first toe. Sensors are connected to two portable data acquisition systems (Physilog, BioAGM, CH) for freedom of movement. Participants walked along the 50-m hospital corridor twice. In the patient group, each foot was measured separately. Insoles as well as custom made sandals were available in four sizes. The setup, reliability, and accuracy of the applied gait assessment technology and assessment protocol have been validated [18,19].

Following functional calibration, see Ref. [20] for details, participants performed two 50 m walking trials for each foot. Trials were performed at their natural walking speed along the hospital corridor. The first and last three gait cycles of each trial were removed due to variations in the initiation and termination of walking. Based on the previously validated algorithms, 46 gait parameters were measured during each trial [18,19,21].

Spatiotemporal parameters assessed included stance in percentage of gait cycle time (%); cadence (steps/min); inner-stance events (loading, foot-flat and push-off (stance %)); stride length (m); speed (m/s); peak swing speed of shank (°/s); heel strike pitch angle (°); and toe off pitch angle (°). Intersegment range of motion (RoM) was assessed in the sagittal plane (dorsiflexion/plantarflexion) and coronal plane (inversion/eversion) for the following intersegments; toe, forefoot, hindfoot-shank and forefoot-shank [18]. Plantar pressure parameters were assessed at 10 anatomical sub-regions: hindfoot (lateral and medial); midfoot (lateral and medial); forefoot (lateral, central and medial); and toes (divided into third to fifth toe, second toe and first toe) [19]. The parameters assessed include total contact duration (Tc; stance %); maximum pressure (MaxP; kPa); and maximum force (MaxF; body weight %). Gait parameters were assessed for both the affected and unaffected sides of the AOA group and were compared with controls to quantify pathological variations as well as against each other to quantify gait symmetries.

To assess the relative motion between different foot segments, the continuous relative phase (CRP) was monitored between the hindfoot and shank, and the forefoot and shank. CRP takes into account and quantifies the relative range of motion and angular momentum of foot segments with respect to each other across the full extent of the gait cycle. CRP has been proven viable for movement coordination analysis [22] and has been shown by the authors to provide additional clinically relevant information missed by conventional analysis methods [7]. Notably, the amplitude of peaks in CRP curves can describe how fast and to what extent a joint or sub-region is being flexed or extended at various stages in the gait cycle. Bilateral asymmetries in CRP peaks are also strong indicators of compensatory gait patterns.

For statistical analysis, the one-way analysis of variance (ANOVA) is performed to compare the means among the groups. An unpaired Student's t-test is used to compare the two sides of the AOA group with the controls to quantify the significance of any differences. A paired Student's t-test is performed to compare the affected and unaffected sides in the AOA group to determine symmetries. Significance is defined for a p-value of 0.05.

3. Results

The spatiotemporal parameter results are displayed in Table 2. Compared with controls, both affected and unaffected sides showed reductions in loading duration, cadence, stride length, speed, peak swing speed of shank and toe-off pitch angle as well as an increase in foot-flat duration ($p < 0.05$). The affected side also showed a reduced heel-strike pitch angle ($p = 0.035$), while the unaffected side showed a longer stance period ($p = 0.01$) as well as a markedly reduced push-off angle ($p = 0.0004$). Bilateral comparison of the AOA group showed differences in stance and toe-off pitch angle ($p = 0.03$).

Kinematic results are shown in Table 3. The affected side showed reduced range of motion in all three intersegments in the sagittal plane and in the hindfoot-shank intersegment in the

Table 2
Spatiotemporal parameters of gait, mean (SD).

Spatiotemporal parameters	AOA affected side	AOA unaffected side	Control	ANOVA p-value
Cadence	96.9 (15.8)†	98.42 (14.9)†	115.9 (11.26)	0.005
Stance (GCT%)	58.6 (2.5)*	61.8 (3.86)†	58.2 (2.33)	0.0167
Loading (St%)	9.6 (3.05)†	9.1 (3.1)†	12.7 (3.5)	0.028
Foot-flat (St%)	61.39 (10.2)†	64.77 (7.23)†	51.76 (7.04)	0.002
Push-off (St%)	29.08 (9.29)	26.14 (4.8)†	35.5 (5.5)	0.009
Stride length (m)	0.99 (0.25)†	1.02 (0.26)†	1.26 (0.1)	0.0097
Speed (m/s)	0.83 (0.29)†	0.86 (0.29)†	1.23 (0.16)	0.0009
Peak swing speed (°/s)	289.16 (81.2)†	316.67 (69.1)†	400.2 (49.28)	0.001
Toe-off pitch angle (°)	55.2 (11.38)*,†	59.76 (10.67)†	70.29 (5.8)	0.002
Heel-strike pitch angle (°)	12.6 (5.79)†	16.5 (6.97)	21.31 (3.8)	0.08

GC%: gait cycle %, St%: stance time %.
†Significant difference ($p < 0.05$) compared with the controls.
*Significant difference ($p < 0.05$) between the affected and the unaffected sides of the AOA group.

Table 3
Intersegment range of motion at the sagittal and coronal planes, mean (SD).
*Significant difference ($p < 0.05$) between the affected and the unaffected sides in the AOA group.

Movement planes	Intersegments	AOA affected side	AOA unaffected side	Control	ANOVA p-value
Sagittal	Toe-forefoot	27.6 (9.17)*,†	32.46 (7.8)†	40.6 (4.3)	0.0008
	Hindfoot-shank	10.4 (3.9)*,†	14.5 (4.29)	15.0 (3.86)	0.026
	Forefoot-shank	15.9 (6.6)*,†	24.3 (5.79)	28.97 (6.29)	0.00015
Coronal	Toe-forefoot	10.1 (3.2)	11.5 (2.96)	12.7 (3.75)	0.21
	Hindfoot-shank	15.23 (6.9)	12.15 (3.79)	13.75 (2.9)	0.36
	Forefoot-shank	11.74 (3.87)*,†	16.5 (4.47)	16.9 (3.75)	0.01

†Significant difference ($p < 0.05$) compared with the controls.
*Significant difference ($p < 0.05$) between the affected and the unaffected sides in the AOA group.

coronal plane – this is when compared to both controls and bilaterally ($p < 0.05$). The unaffected side only reported a reduced range of motion compared with the controls in the toe-forefoot intersegment in the sagittal plane ($p = 0.005$).

Plantar pressure parameters, measurement in 10 sub-regions of the foot, are given in Table 4. The total contact duration showed significant reduction at the forefoot lateral, forefoot central, first, second and lateral toe sub-regions ($p < 0.05$) on both affected and unaffected sides when compared with the controls. In addition, the affected side also showed a reduced contact duration at the midfoot lateral region ($p = 0.013$) as well as marked reduction in maximum force at hindfoot medial, first and second toe sub-regions ($p < 0.0001$) and maximum pressure at hindfoot medial ($p = 0.005$) and first toe sub-region ($p = 0.001$). The unaffected side similarly reported a reduction in loading compared with the controls, due to a reduced maximum force at hindfoot lateral ($p = 0.003$), hindfoot medial and first toe sub-regions ($p = 0.006$) and the reduced maximum pressure at hindfoot medial and first toe sub-regions ($p < 0.05$). Notably, bilateral comparison showed a reduction in the total contact, maximum force and maximum pressure only in all toe sub-regions ($p < 0.05$) with the exception of the total contact duration at the lateral toes.

Foot segment relative motion, CRP, across 100% of the gait cycle is shown in Fig. 1. Notably, significant bilateral differences are

Table 4
Plantar pressure parameter of gait, mean (SD).

Foot segments		AOA affected side	AOA unaffected side	Control	ANOVA p-value
Hindfoot lateral	Tc	56.07 (16.98)	61.4 (22.8)	49.79 (8.67)	0.28
	Max F	22.37 (9.65)	17.78 (6.66)†	30.07 (10.07)	0.01
	Max P	82.92 (21.9)	74.98 (26.7)	98.3 (35.78)	0.1
Hindfoot medial	Tc	58.26 (17.1)	66.79 (16.8)	62.5 (18.5)	0.5
	Max F	27.76 (5.9)†	27.2 (12.89)†	41.6 (8.9)	0.0016
	Max P	97.05 (21.5)†	99.25 (44.5)†	136.75 (34.41)	0.0018
Midfoot lateral	Tc	59.55 (12.44)†	60.37 (20.77)	43.59 (14.7)	0.03
	Max F	12.49 (7.9)	11.42 (9.5)	9.86 (5.6)	0.7
	Max P	30.59 (13.05)	34.65 (24.27)	25.64 (14.4)	0.7
Midfoot medial	Tc	40.09 (17.4)	35.17 (12.66)	27.19 (8.5)	0.08
	Max F	5.06 (2.5)	3.38 (2.5)	4.3 (2.8)	0.37
	Max P	16.37 (6.04)	12.89 (6.59)	13.25 (5.64)	0.37
Forefoot lateral	Tc	87.83 (4.8)†	89.27 (4.87)†	78.22 (14.5)	0.02
	Max F	28.66 (12.93)	22.68 (11.5)	32.26 (9.5)	0.15
	Max P	116.97 (41.13)	93.2 (44.47)	101.47 (35.27)	0.9
Forefoot central	Tc	84.7 (5.76)†	85.42 (11.5)†	70.44 (13.4)	0.004
	Max F	26.28 (7.9)	20.05 (11.65)	28.66 (6.9)	0.08
	Max P	148.99 (42.35)	109.12 (59.33)	129.73 (29.86)	0.15
Forefoot medial	Tc	63.09 (12.3)	65.23 (16.08)	59.02 (16.68)	0.62
	Max F	14.12 (7.57)	14.48 (9.08)	17.54 (7.94)	0.5
	Max P	73.52 (36.89)	75.30 (39.54)	71.74 (26.28)	0.9
Lateral toes	Tc	30.76 (14.29)†	29.39 (9.9)†	18.99 (6.32)	0.02
	Max F	2.32 (2.05)*	4.24 (1.86)	4.52 (3.16)	0.1
	Max P	14.75 (5.92)*	21.27 (6.76)	18.1 (6.11)	0.08
Second toe	Tc	23.17 (12.6)*,†	37.67 (6.82)†	30.99 (6.81)	0.0048
	Max F	2.14 (1.49)*,†	5.86 (2.47)	6.05 (2.63)	0.0006
	Max P	26.84 (14)*	46.19 (16.97)	38.49 (11.94)	0.018
First toe	Tc	20.33 (11.38)*,†	48.74 (9.65)†	36.05 (10.54)	0.00001
	Max F	4.39 (4.46)*,†	8.59 (2)†	15.38 (6.86)	0.0001
	Max P	37.21 (29.71)*,†	55.28 (13.98)†	80.12 (24.48)	0.0008

Tc: total contact duration, MaxF: maximum force, MaxP: maximum pressure.
† Significant difference ($p < 0.05$) compared with the controls.
* Significant difference ($p < 0.05$) between the affected and the unaffected sides in the AOA group.

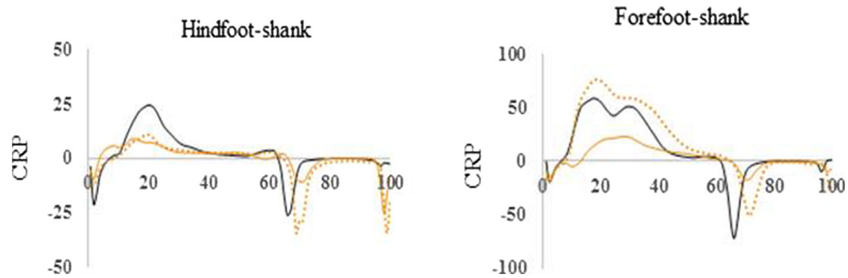

Fig. 1. Continuous relative phase (CRP) curves representing coordination pattern at hindfoot-shank and forefoot-shank intersegments in the sagittal plane. The black line represents controls, bold line represents the affected side of the AOA group and the dotted line represents the unaffected side of the AOA group.

recorded. There is a marked reduction in relative motion between the hindfoot and shank throughout the stance phase for both the affected and unaffected sides ($p < 0.0001$). There is also a reduction in toe-off peak amplitude ($p < 0.0001$), but only for the affected side. A similar reduction in relative motion throughout the stance phase and toe-off peak is shown between the forefoot and shank of the affected side ($p < 0.0001$), however, the unaffected side remains comparable with the control group throughout the stance phase. The patient group also exhibits a marked delay in the toe-off peak for both hindfoot and forefoot with respect to the control group.

4. Discussion

This study aims to determine the role of preoperative unilateral end-stage AOA gait asymmetries in commonly reported postoperative compensatory gait patterns. The study investigated spatiotemporal, kinematic and plantar pressure parameters of gait, as well as the relative motion of hindfoot and forefoot with respect to the shank. AOA patients were compared with an age-matched control groups and were assessed for bilateral gait asymmetries. The cumulative measured outcomes of all 46 gait parameters agrees with existing literature, showing that patients with unilateral end-stage AOA walk with an altered gait pattern. Furthermore, both the relative motion analysis and one-third of the assessed gait parameters reported bilateral alterations, suggesting compensatory actions are being adopted by the unaffected side.

Spatiotemporal analysis shows end-stage AOA patients to have significant differences across the majority of parameters, when compared with the controls. This is in agreement with previous preoperative AOA analyses [12,13]. Most notably, a reduced cadence, speed, peak swing speed, toe-off pitch angle is recorded, indictive of a restricted range of motion and/or a deliberate reduction of overall loading to reduce pain. Furthermore, bilateral gait alterations are presented by means of an increased in both stance phase duration and toe-off pitch angle in the unaffected side, indictive of an adopted limp.

Kinematic analysis reports a reduced hindfoot, forefoot and toe range of motion of the affected side in the sagittal plane when compared to controls. This is in agreement with previous studies [12,13]. Further asymmetries were recorded in the coronal plane, at the forefoot with respect to the control group. Reduced toe-forefoot RoM on the affected side led to reduced toe-off pitch angle and to reduced and delayed toe loading on the affected side compared to the unaffected side causing the major asymmetry in the gait pattern of patients with AOA.

Plantar pressure results showed significant reductions in force and pressure of the hindfoot-medial of both the affected and unaffected sides. Furthermore, significant increase in forefoot contact duration of both the affected and unaffected sides were recorded, which corresponds with the measured increase in stance phase duration. Most notably, however, is the significant asymmetries recorded in the force, pressure and contact duration at the toe sub-regions.

Foot-segment relative motion, continuous relative phase, is also assessed. Looking at the stance-phase, the hindfoot CRP curve shows a marked reduction in peak amplitudes for both affected and unaffected sides. This is indictive of joint stiffness and/or apprehensive slower movements, which corresponds well with significant reductions in hindfoot force and pressure. In contrast, the forefoot CRP curve presents similar reductions in the stance-phase peak for the affected side, but the unaffected side is more comparable if not greater than the controls. This marked asymmetry, taking into account the reduction in hindfoot CRP, is indicative of a gait pattern in which the unaffected sides in underutilising the hindfoot range of motion, plausible slightly dorsiflexed at all times, in favour of more activation and loading in the forefoot to compensate for the overall reduced functionality in the affected side – again, corresponding well with measured increases in forefoot contact duration.

Overall, our results suggest that a bilateral compensatory gait pattern is adopted in patients with end-stage AOA. In particular, an increase in stance phase duration, forefoot contact duration and toe-region loading and motion in the unaffected side to compensate for a general reduction in functionality of the affected side. This aligns with authors' previous postoperative studies, wherein significant toe-region RoM and loading asymmetries ($p < 0.05$) were recorded and stance phase durations are seen to remain increased on the unoperated side ($p < 0.05$) [5]. Notably, toe-region loading asymmetries are less present in TAR patients than in those who underwent AA, with both affected and unaffected sides being more comparable to controls. This study therefore supports the existing hypothesis that post-operative gait asymmetries are likely due to an adopted preoperative compensatory gait pattern. Furthermore, taking into account the authors' previous studies, one could conclude that TAR patients find it easier to overcome previous compensatory habits as a result of the tibiotablar joint not being fused. Gait outcome of patients following TAR and AA suggest that may be the preoperative adopted gait pattern is reversible. Authors suggest that if the patient is made aware about this adopted gait pattern and trained accordingly before the surgery, this could lead to faster rehabilitation and could help improve the prognosis in terms of gait symmetry.

The main strength of this study is the use of a cutting-edge ambulatory gait assessment system, which allows patients to walk naturally during gait assessment, having no gait lab restrictions and having every step recorded in the process. Furthermore, a detailed 46 gait parameters assessment was performed along with the relative motion between the hindfoot and shank and forefoot and shank. The assessment of the whole foot as well as bilateral comparisons, instead of just the affected joint on the affected side, is shown to provide the clinically relevant information needed to improve patient prognosis. This study is also the first to compare both the affected and unaffected sides in patients with end-stage AOA with the controls. One limitation of this study is the small population size. Nonetheless, results present accepted levels of significance. Another limitation is the absence of longitudinal evaluation including the same patients before and after surgery in order to observe the evolution of the pathologic gait parameters.

In conclusion, patients with end-stage unilateral AOA presented an altered gait pattern when compared with the controls. Furthermore, bilateral gait alterations are reported in the AOA group, particularly in the range of motion in the sagittal plane, the use and activation of the toe-region and the relative motion of the forefoot. The results suggest that a preoperative compensatory gait pattern is therefore likely a significant contributing factor to postoperative asymmetries, supporting the existing hypothesis. Note that other factors such as pain, apprehension, prolonged immobilisation and naturalisation to the postoperative changes must still be taken into account. Rehabilitation programs designed with this study's conclusions in mind could prove more effective and potentially shorten rehabilitation times.

Author contribution

Both authors were equally involved in this work.

Conflict of interest

None.

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