



HAL
open science

Changes in ankle and foot kinematic after fixed-bearing total ankle replacement

Paul-André Deleu, Alexandre Naaim, Laurence Cheze, Raphaël Dumas, Bernhard Devos Bevernage, Ivan Birch, Jean-Luc Besse, Thibaut Leemrijse

► **To cite this version:**

Paul-André Deleu, Alexandre Naaim, Laurence Cheze, Raphaël Dumas, Bernhard Devos Bevernage, et al.. Changes in ankle and foot kinematic after fixed-bearing total ankle replacement. *Journal of Biomechanics*, 2022, 136, pp.111060. <10.1016/j.jbiomech.2022.111060>. <hal-03629153>

HAL Id: hal-03629153

<https://hal.science/hal-03629153v1>

Submitted on 4 Apr 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Journal Pre-proofs

Changes in ankle and foot kinematic after fixed-bearing total ankle replacement

Paul-André Deleu, Alexandre Naaim, Laurence Chèze, Raphaël Dumas, Bernard Devos Bevernage, Ivan Birch, Jean-Luc Besse, Thibaut Leemrijse

PII: S0021-9290(22)00114-2
DOI: <https://doi.org/10.1016/j.jbiomech.2022.111060>
Reference: BM 111060

To appear in: *Journal of Biomechanics*

Received Date: 25 October 2021
Revised Date: 14 February 2022
Accepted Date: 21 March 2022

Please cite this article as: P-A. Deleu, A. Naaim, L. Chèze, R. Dumas, B. Devos Bevernage, I. Birch, J-L. Besse, T. Leemrijse, Changes in ankle and foot kinematic after fixed-bearing total ankle replacement, *Journal of Biomechanics* (2022), doi: <https://doi.org/10.1016/j.jbiomech.2022.111060>

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2022 Published by Elsevier Ltd.



Changes in ankle and foot kinematic after fixed-bearing total ankle replacement

Paul-André Deleu, PhD^{a,b}, Alexandre Naaim, PhD^a, Laurence Chèze, PhD^a, Raphaël Dumas, PhD^a, Bernard Devos Bevernage, MD^{b,c}, Ivan Birch, PhD^d, Jean-Luc Besse, MD^{PhD a,e},
Thibaut Leemrijse, MD^{b,c}

^aUniv Lyon, Université Claude Bernard Lyon 1, Univ Gustave Eiffel, LBMC UMR_T9406, 43 Bd du 11 novembre 1918, F69622, Lyon, France

^bFoot & Ankle Institute, 5 Avenue Ariane, 1200 Brussels, Belgium

^cCHIREC Delta Hospital, 201 Boulevard du Triomphe, 1160 Brussels, Belgium

^dSheffield Teaching Hospitals NHS Foundation Trust, Woodhouse Clinic, 3 Skelton Lane, Sheffield S13 7LY, United Kingdom

^eHospices Civils de Lyon, Centre Hospitalier Lyon-Sud, Service de Chirurgie Orthopédique et Traumatologique, 69495 Pierre-Bénite Cédex, France

Paul-André Deleu (**Corresponding author**)

Foot & Ankle Institute

5 Avenue Ariane,

1200 Brussels, Belgium

Email : pa.deleu@gmail.com

Alexandre Naaim

Univ Lyon, Université Claude Bernard Lyon 1, Univ Gustave Eiffel,

IFSTTAR, LBMC UMR_T9406,

43 Bd du 11 novembre 1918,

F69622 Lyon (France)

Email : alexandre.naaim@univ-lyon1.fr

Laurence Chèze

Univ Lyon, Université Claude Bernard Lyon 1, Univ Gustave Eiffel,

IFSTTAR, LBMC UMR_T9406,

43 Bd du 11 novembre 1918,

F69622 Lyon (France)

Email : laurence.cheze@univ-lyon1.fr

Raphaël Dumas

Univ Lyon, Université Claude Bernard Lyon 1, Univ Gustave Eiffel,

IFSTTAR, LBMC UMR_T9406,

43 Bd du 11 novembre 1918,

F69622 Lyon (France)

Email : raphael.dumas@ifsttar.fr

Bernhard Devos Bevernage

Foot & Ankle Institute

5 Avenue Ariane,

1200 Brussels, Belgium

Email : bdevosb@hotmail.com

Ivan Birch

Sheffield Teaching Hospitals NHS Foundation Trust,

Woodhouse Clinic,

3 Skelton Lane,

Sheffield S13 7LY, United Kingdom

Email : ivanbirch@btinternet.com

Jean-Luc Besse

Hospices Civils de Lyon,

Centre Hospitalier Lyon-Sud,

Service de Chirurgie Orthopédique et Traumatologique,

69495 Pierre-Bénite Cédex, France

Email : jean-luc.besse@chu-lyon.fr

Thibaut Leemrijse

Foot & Ankle Institute

5 Avenue Ariane,

1200 Brussels, Belgium

Email : thibaut.leemrijse@gmail.com

Abstract

Ankle osteoarthritis is a chronic debilitating disease marked by cartilage breakdown, pain and significant biomechanical impairment of the entire lower limb. Total ankle replacement (TAR) has been encouraged during the last decade as it has the potential to maintain the existing pre-operative ankle range of motion and to protect the more distally located joints of the foot. Three-dimensional gait analysis using a multi-segment foot model can provide an objective analysis of TAR for the treatment of end-stage ankle osteoarthritis. Thirty-six patients suffering from post-traumatic end-stage ankle osteoarthritis were evaluated before and after TAR. A four-segment kinematic foot model was used to calculate intrinsic foot joint kinematics during gait. Spatio-temporal parameters were also assessed. Kinematic results were compared to a control group of asymptomatic subjects.

Differences in waveform patterns were mainly limited to dorsi-/plantarflexion inter-segment angles. At loading response, the Shank-Calcaneus plantarflexion angles as well as the Calcaneus-Midfoot dorsiflexion angle increased slightly in post-operative condition. During propulsion, an increase in Hallux-Metatarsus dorsiflexion angle was observed. Pain improved after surgery as supported by increased spatio-temporal parameters. While multi-segment foot and ankle kinematics were improved, they remained impaired compared to control values. This study confirms that TAR maintains the residual pre-operative range of motion after surgery from midstance to propulsion. Furthermore, the results suggest that the kinematic behavior of the foot joints distal to the affected ankle joint also improves post-operatively. The outcome of this study further emphasizes the clinical relevance of multi-segment foot modeling when assessing the outcome of TAR.

Keywords: Ankle, Osteoarthritis, Total ankle replacement, Foot kinematics, Fixed-bearing prosthesis

Words : 3473

CHANGES IN ANKLE AND FOOT KINEMATICS AFTER FIXED-BEARING TOTAL ANKLE REPLACEMENT

Abstract

Ankle osteoarthritis is a chronic debilitating disease marked by cartilage breakdown, pain and significant biomechanical impairment of the entire lower limb. Total ankle replacement (TAR) has been encouraged during the last decade as it has the potential to maintain the existing pre-operative ankle range of motion and to protect the more distally located joints of the foot. Three-dimensional gait analysis using a multi-segment foot model can provide an objective analysis of TAR for the treatment of end-stage ankle osteoarthritis. Thirty-six patients suffering from post-traumatic end-stage ankle osteoarthritis were evaluated before and after TAR. A four-segment kinematic foot model was used to calculate intrinsic foot joint kinematics during gait. Spatio-temporal parameters were also assessed. Kinematic results were compared to a control group of asymptomatic subjects.

Differences in waveform patterns were mainly limited to dorsi-/plantarflexion inter-segment angles. At loading response, the Shank-Calcaneus plantarflexion angles as well as the Calcaneus-Midfoot dorsiflexion angle increased slightly in post-operative condition. During propulsion, an increase in Hallux-Metatarsus dorsiflexion angle was observed. Pain improved after surgery as supported by increased spatio-temporal parameters. While multi-segment foot and ankle kinematics were improved, they remained impaired compared to control values. This study confirms that TAR maintains the residual pre-operative range of motion after surgery from midstance to propulsion. Furthermore, the results suggest that the kinematic behavior of the foot joints distal to the affected ankle joint also improves post-operatively. The outcome of this study further emphasizes the clinical relevance of multi-segment foot modeling when assessing the outcome of TAR.

1. INTRODUCTION

A growing body of evidence has shown that patients suffering from ankle osteoarthritis have significant biomechanical impairment of the entire foot and lower limb (Deleu et al., 2021a; Queen, 2017). Their gait is characterized by a decreased step length, walking speed and mobility of the ankle joint complex when compared to a control group (Deleu et al., 2021a; Queen, 2017). Recently, 3D multi-segment kinematic foot models revealed compensatory strategies in the distal foot joints in patients suffering from ankle osteoarthritis compared to healthy reference data during walking (Deleu et al., 2021a; Khazzam et al., 2006). An inverted hindfoot position, in association with a more adducted position of the Calcaneus-Midfoot joint was found in patients suffering from end-stage post-traumatic ankle osteoarthritis which could be explained by co-contraction phenomena between the tibialis anterior and gastrocnemius muscle, both foot adductor and invertor muscles, in an attempt to keep the ankle joint stable from heel strike to midstance (Deleu et al., 2021a; von Tscharnner and Valderrabano, 2010). Once end-stage ankle osteoarthritis is no longer manageable through conservative treatment, surgical management has included ankle arthrodesis and total ankle replacement (TAR). While ankle arthrodesis has been recognized as being the “gold standard” intervention, TAR has been encouraged during the last decade as it has the potential to conserve pre-operative ankle range of motion (RoM) and to protect the neighbouring joints (Brodsky et al., 2011; Ingrosso et al., 2009). However, the latter effect has not yet been proven (Philippe et al., 2008).

A recent meta-analysis reporting the functional assessment of the ankle joint following a fixed-bearing prosthesis found moderate evidence of improved spatio-temporal parameters (i.e. mean 0.19m/s increase in walking speed) and ankle kinematics (i.e. mean 3 degrees dorsi-/plantarflexion RoM increase) compared to the pre-operative condition (Deleu et al., 2020a). However, these patients remained impaired in terms of gait compared to asymptomatic subjects (Deleu et al., 2020a, 2021b).

Unfortunately, gait analysis research has mainly focused on the affected ankle joint without monitoring potential compensatory mechanism in the distal foot joints during post-operative follow-ups (Deleu et al., 2020a; Fritz et al., 2021; Lullini et al., 2020). It is however of clinical interest to investigate the kinematic behavior of these intrinsic foot joints as they could provide an enhanced understanding of the compensatory strategies of the distal foot joints in patients suffering with end-stage ankle osteoarthritis after TAR. However, gait studies largely continue to implement a one-segment foot modeling approach to assess the effect of TAR (Deleu et al., 2020a; Lullini et al., 2020). Furthermore, the hypothesis testing of studies tend to be conducted on a relatively small number of summary metrics (e.g. RoM and peak values during specific sub-phases of the stance phase) (Choi et al., 2013; Deleu et al., 2020a; Queen et al., 2012; Segal et al., 2018; Usuelli et al., 2021). The use of these discrete values within time-continuous kinematic curves are computationally convenient, but it may ignore the majority of the data contained in the time continuous kinematic curves regarding the intrinsic foot joints distal to the ankle. With the use of one-dimensional statistical parametric mapping (SPM), the kinematic differences between pre- and post-operative conditions could be determined (Pataky, 2010). This is of interest for clinicians during their pathomechanical reasoning processes as SPM regards the whole time-series as the unit of observation. Furthermore, this methodological approach allows hypothesis testing at vector kinematic trajectory level to be conducted, with random field corrections simultaneously accounting for temporal correlation and vector covariance (Pataky et al., 2013).

The first aim of this study was to compare pre- and post-operative kinematics of the foot and ankle complex during gait in patients with end-stage ankle osteoarthritis treated with a TAR, and to compare the post-operative kinematics of the foot and ankle complex to a control group of asymptomatic subjects. It was hypothesized that patients with a fixed-bearing implant would maintain their pre-operative ankle inter-segment angle during the entire stance phase after

surgery (first hypothesis). The second aim of this study was to explore the changes in the intrinsic foot inter-segment angles distal to the affected ankle joint after surgery. The hypothesis was that the kinematic behavior of the adjacent and non-adjacent foot joints would be less impaired post-operatively, since pain-mediated motion patterns would be alleviated by TAR (second hypothesis). In addition, we further hypothesized that spatio-temporal parameters and multi-segment foot kinematics after TAR would be more in alignment with the values of the control group (third hypothesis).

2. METHODS

2.1. Participants

102 eligible patients suffering from end-stage ankle osteoarthritis (Takakura stage 3 – 4 (4 being complete obliteration of the joint space)) scheduled for primary TAR for pain relief between March 2017 and June 2020 were invited to participate in this prospective study. 36 consented to participate in the study (Table 1). This sample size provides 90% power and a p-value at 0.05 to detect a minimal clinical change between pre- and post-operative conditions for the ankle joint during the stance of the gait cycle. The hypothetical effect size for this analysis was estimated based on pilot results reported by Deleu et al. (2021) (Deleu et al., 2021b), which can be found in Supplementary material. The inclusion criteria were (1) diagnosis of post-traumatic end-stage ankle osteoarthritis with an indication for TAR, (2) being older than 18 years of age, (3) absence of systemic or neurological diseases, (4) capable to walk at least 100 meters with no aid and without rest. Exclusion criteria were (1) major lower limb orthopedic pathologies or surgeries and (2) any medical problem other than post-traumatic ankle osteoarthritis that could possibly affect gait. All patients were scheduled for TAR within two weeks of their preoperative data collection, and were tested again 1 year after surgery.

Patients included in this study received the CADENCE® prosthesis (Smith & Nephew, London, UK) which is a fixed-bearing implant.

A convenience sample of fifteen asymptomatic subjects (CTRL) (10 males and 5 females) participated in this study (Table 1) enabling the comparison of the postoperative data of patients after TAR to a control group. Exclusion criteria for the control subjects were any medical problems that could possibly affect normal gait. The local ethical committee approved the study (B200-2017-061) and all participants signed an informed consent form.

2.2. Fixed-bearing prosthesis

The Cadence prosthesis (Smith & Nephew, London, UK) is a new generation two-component, fixed-bearing, semi-constrained total ankle replacement system composed of a polyethylene meniscal insert attached to a bone-anchored tibial component (titanium alloy) and an anatomic shaped bone-anchored talar component (cobalt chrome alloy) (Figure 1) (Kooner et al., 2021; Rushing et al., 2021). The shape of prosthesis talar dome is characterized by two condylar surfaces (Terrill et al., 2015). The medial condyle of the talar dome has a smaller radius of curvature compared to the lateral condyle of the talar dome (Terrill et al., 2015). The bearing surface of polyethylene meniscal insert is shaped in a similar way to the talar dome in order to achieve a congruent fit between the two components (Terrill et al., 2015).

2.3. Data collection

The patients were asked to walk at a self-selected speed barefoot over a 10m walkway surrounded by an optoelectronic motion analysis system (Qualysis, Göteborg Sweden), composed of ten Miquis cameras, to track the trajectories of markers at a frequency of 200Hz. Sixteen 8mm retro-reflective markers were placed pre- and post-operatively by the same senior staff podiatrist with experience in three-dimensional multi-segment foot model protocol, on the

foot and shank of each patient in accordance with the requirements of the multi-segment Rizzoli foot model (Leardini et al., 2007). Participants performed five representative walking trials. All marker trajectories were computed by Qualysis Tracking Manager 2.16 (Qualysis, Göteborg Sweden).

2.4. Data analysis

Inter-segmental angles between the shank (Sha), calcaneus (Cal), midfoot (Mid), metatarsus (Met) and hallux (Hx) segments were calculated in accordance with the adapted Rizzoli multi-segment foot model developed by Deschamps et al. (2017) (IOR-4Segment-model 1) following ISB recommendations, where dorsi/plantarflexion is defined as rotation about the medial-lateral axis of the proximal segment, adduction/abduction about the superior-inferior axis of the distal segment, and inversion/eversion about an axis orthogonal to the first two axes (Figure 2) (Deleu et al., 2020b; Deschamps et al., 2017). The main difference between the original version of the multi-segment Rizzoli foot model and the adapted version developed by Deschamps et al. (2017) is the creation of a virtual cuboid marker, defined as being at 2/3 of the distal distance between the peroneal tubercle and the base of the fifth metatarsal (Deleu et al., 2020b; Deschamps et al., 2017). In the current study, the term joint describes the modelled biomechanical interaction between two adjacent segments. Motion of the calcaneus with respect to the shank, i.e. the ankle complex (hereafter referred as shank-calcaneus), the midfoot with respect to the calcaneus (hereafter referred as calcaneus-midfoot), the metatarsus with respect to the midfoot (hereafter referred as midfoot-metatarsus), and the hallux with respect to the metatarsus (hereafter referred as hallux-metatarsus) were calculated (Deleu et al., 2020b; Deschamps et al., 2017). An in-house written Matlab© program (Mathworks Inc., Natick, US) was used for inter-segment kinematics computations. The following outcome variables were investigated: pain score from the use of a Visual Analogue Scale (VAS),

walking speed, stride length, relative 3D inter-segmental angle of shank-calcaneus, calcaneus-midfoot, midfoot-metatarsus and hallux-metatarsus joints. All 1D data were time-normalized to 100% of the stance phase. As changes in walking speed after TAR and between control group and patients after TAR were expected (Deleu et al., 2020a; Ingrosso et al., 2009), piecewise linear length normalizations within the stance phase based on kinematically points of interest (i.e. heel strike, heel off and toe-off) were performed to remove temporal between- and within-stance phase misalignments (Helwig et al., 2011). Temporal alignment of gait data is required in order to make the point-by-point comparisons of inter-segmental trajectories biomechanically and clinically meaningful. This piecewise temporal alignment technique has been shown to outperform other commonly used alignment methods such as dynamic time warping in walking data (Helwig et al., 2011).

2.5. Statistical analysis

Shapiro-Wilk test was used to check data normality. Paired t-tests (significance threshold, $p < 0.05$) were conducted to compare spatiotemporal data and pain between pre- and post-operative conditions. Independent t-tests (significance threshold, $p < 0.05$) were conducted to compare demographic and spatio-temporal data between control group and TAR group.

Inter-segmental foot kinematics were compared using one-dimensional (1D) SPM (open source code; v.M.0.4.5; www.spm1d.org) (Friston et al., 1994; Pataky, 2010; Pataky et al., 2013). This statistical approach considers the whole 1D continuous vector trajectory that changes in time as the unit of observation, and time dependence is incorporated directly within the statistical testing. This method is based on the Random Field Theory which makes probabilistic conclusions based on the random behavior of the 1D observational unit (Pataky, 2010). This approach was validated for 1D data (Pataky et al., 2016). The statistical analyses were conducted in three stages. First, a paired Hotelling's T^2 (SPM{T2}) was performed to

assess the time varying three-component kinematic differences of the shank-calcaneus, calcaneus-midfoot, midfoot-metatarsus and hallux-metatarsus joints between pre- and post-operative conditions ($\alpha = 0.05$) (Figure 2). The principle was to find the critical T_2 value that smooth 1D multivariate Gaussian data would reach in alpha percent of an infinite number of experiments involving smooth 1D data. If the experimentally $SPM\{T_2\}$ trajectory crosses the critical value, the null hypothesis is rejected. Individual probability values were then calculated for each supra-threshold cluster that could have resulted from an equally smooth random process (Friston et al., 1994; Pataky, 2012; Pataky et al., 2013). Second, if significant differences were found, secondary post hoc analyses paired t-tests ($SPM\{t\}$) for each individual kinematic component (dorsi/plantarflexion, adduction/abduction, inversion/eversion) were performed.

Two sample Hotelling's T^2 tests were performed to assess the time varying three-component angles of the shank-calcaneus, calcaneus-midfoot, midfoot-metatarsus and hallux-metatarsus joints between groups (patients after TAR versus controls). By considering three-component angles (dorsi/plantarflexion, adduction/abduction, inversion/eversion waveforms), as well as collinearities between them are all modelled statistically. Where significant differences between respective groups were found, secondary post hoc analyses two-sample t-tests ($SPM\{t\}$) for each individual component (dorsi/plantarflexion, adduction/abduction, inversion/eversion) were performed.

3. RESULTS

3.1. *Spatiotemporal parameters and pain*

The spatiotemporal parameters showed a statistically significant increase in walking speed ($P < 0.001$) and stride length ($P = 0.001$) after surgery (Table 1). These improvements can be associated to pain relief ($P < 0.001$). No significant differences were found for age,

weight and height between the group of patients after TAR and the control group. However, the patients showed post surgery significantly shorter stride lengths ($P = 0.004$) and slower walking speeds than the control group ($P < 0.001$).

3.2. *Pre- versus post-operative condition*

The paired Hotelling's T^2 (SPM{T2}) showed significant differences between pre- and post-operative inter-segmental angles for the shank-calcaneus ($p = 0.047$; 6-9% of the stance phase), the calcaneus-midfoot ($P = 0.004$; 0-17% of the stance phase) and the hallux-metatarsus ($P = 0.036$; 90-96% of the stance phase) joints (Figure 3). No significant difference was shown for the midfoot-metatarsus joint. Post-hoc analyses paired t-tests (SPM{t}) for individual components of both conditions suggested that this difference was caused by an increase in plantarflexion during loading response (5-9% of the stance phase) together with an increased calcaneus-midfoot joint dorsiflexion (0-20.9% of the stance phase) in the post-operative condition (Figure 3). There was also shown to be an increase in hallux-metatarsus dorsiflexion during propulsion (89-98.5% of the stance phase) in the post-operative condition. No significant differences in inter-segment angles were observed during midstance.

3.3. *Control subjects versus patients after TAR*

The two sample Hotelling's T^2 (SPM{T2}) showed significant differences between the two groups for all the intrinsic foot joints (Figure 4). Post-hoc analyses two sample t-tests suggested that these differences were found mainly in the sagittal plane where the patient group after TAR had lesser plantarflexion in the shank-calcaneus (88.5-100% of the stance phase), calcaneus-midfoot (92-100% of the stance phase) and midfoot-metatarsus (80-97.5% of the stance phase) joints compared to the control group (Figure 4). Furthermore, it revealed that patients after TAR exhibited lesser hallux-metatarsus dorsiflexion during propulsion (83.5-94% of the stance phase) compared to the control group. Post-hoc analyses two sample t-tests for individual components of patients after TAR versus control group suggested that the

differences were also located in the frontal plane for shank-calcaneus joint and in the transverse plane for shank-calcaneus and calcaneus-midfoot joints: less shank-calcaneus eversion (7.5-15.5% of the stance phase) during loading response compared to control group, more abducted shank-calcaneus position (0-41%, 51-56% and 82.5-100% of the stance phase) during almost the entire stance phase compared to control group and less calcaneus-midfoot adduction (87-100% of the stance phase) during propulsion compared to control group (Figure 4).

4. DISCUSSION

This prospective study was designed to compare pre- and post-operative kinematics of the foot and ankle complex during gait of patients with end-stage ankle osteoarthritis treated with a TAR, as well as to compare the post-operative kinematics of the foot and ankle complex to a control group of asymptomatic subjects. Our first hypothesis was that patients with a fixed-bearing implant would maintain their preoperative ankle inter-segment angle after surgery during the entire stance phase. This was only partially confirmed by the results as the shank-calcaneus angle did not increase after surgery from midstance to pre-swing. These results corroborate the findings of earlier studies (Brodsky et al., 2021b, 2021a; Deleu et al., 2021b).

Contrary to expectations, an increased shank-calcaneus plantarflexion was found during loading response compared to pre-operative condition. Loading response is characterized by the abrupt transfer of body weight onto the forward limb using the calcaneus as a rocker that has just finished swinging forward. Therefore, the differences in shank-calcaneus plantarflexion might be explained by the fact that patients were no longer afraid to land properly on their ankle joint during walking. The significant increase in spatiotemporal variables seems to further corroborate these findings, as they provide a good indicator for a greater sense of stability and decreased joint pain while walking post-surgery (Deleu et al., 2021b; Queen et al., 2012).

The second hypothesis in this study was that the kinematic behavior of the adjacent and non-adjacent foot joints would be less impaired post-operatively, since pain-mediated motion patterns would be alleviated by TAR. The findings of this study revealed an interesting biomechanical phenomenon, in which patients demonstrated an increased calcaneus-midfoot joint dorsiflexion during loading response after surgery. This may also represent a good indicator of decreased joint pain as the calcaneus-midfoot joint controls the longitudinal arch deformation under load (Deleu et al., 2020b). It is of clinical interest to note that an increase in dorsiflexion between the hallux and the metatarsus during pre-swing was found after surgery, which may have originated from a pre-operative disuse or arthrogenic muscle inhibition (von Tscherner and Valderrabano, 2010). The shank-calcaneus and hallux-metatarsus joints undergo the largest ranges of motion around their medial-lateral axis, while moving together in opposite directions during preswing (Deleu et al., 2020b). Despite no statistical differences being found in shank-calcaneus plantarflexion during pre-swing, a trend to a post-operative increase in shank-calcaneus plantarflexion, associated with a significant increase in hallux-metatarsus dorsiflexion, can be seen from the results (Figure 3). Similar significant improvements in gait after TAR have been shown by Fritz et al. (2021) (Fritz et al., 2021). Although the kinematic behavior of the foot joints distal to the affected ankle joint appears to have improved post-operatively, the extent to which the changes in foot joint angles are attributable to pain relief and as opposed to the production of a more mechanically “functional” ankle, cannot be determined.

The last hypothesis was that spatio-temporal parameters and multi-segment foot kinematics after TAR would be more in alignment with the values of the control group (third hypothesis). However, the shank-calcaneus kinematics were not completely restored after surgery. Results demonstrated a significant reduction in shank-calcaneus plantarflexion during pre-swing and a more abducted position of the shank-calcaneus joint throughout almost the entire stance phase

compared to controls. These findings are consistent with Fritz et al. (2021) who reported the kinematic results in patients who underwent TAR with a two-component, fixed-bearing SALTO Talaris prosthesis using a multi-segment foot model compared to a control group (Fritz et al., 2021). It is, however, unclear if this more abducted position of the shank-calcaneus joint was related to sustained preoperative compensatory strategy arising from ankle osteoarthritis, alterations in ligamentous tension, anatomical variations or pre-operative disuse or arthrogenic muscle inhibition (Deleu et al., 2020a; Fritz et al., 2021; Queen, 2017; von Tscharner and Valderrabano, 2010).

The findings of this study should be considered in the context of three limitations. The first limitation is the short duration of follow-up (one year). Despite the improvement in the kinematic behavior of the ankle and intrinsic foot joints, it would be of clinical relevance to investigate if these improvements are maintained at intermediate and long-term follow-ups. Brodsky et al. (2021) reported a follow-up of almost 8 years after the implantation of a Scandinavian Total Ankle Replacement (STAR, Stryker, NJ, US) and found that their findings at long-term follow-up were consistent with their initial short-term findings (Brodsky et al., 2021a). The second limitation is the use of skin markers to estimate multi-segment foot kinematics. Soft-tissue artefact, reported as angular errors in the dorsi-/plantar-flexion, inversion/eversion and adduction/abduction angles, has been estimated to be as much as 2.45 degrees, 3.57 degrees and 4.28 degrees (Kessler et al., 2019). Although it should be noted that this artifact is likely to have affected both pre- and post-operative kinematics similarly, allowing for comparative analysis. Finally, since walking speed affects foot kinematics, caution should be exercised when interpreting the differences in joint RoM (Dubbeldam et al., 2010). Increase in walking speed affects mainly foot joint motion in the sagittal plane during pre-swing characterized by a decrease in RoM at lower walking speeds (Dubbeldam et al., 2010). It is however interesting to note that the increase in walking speed between pre- and

postoperative conditions had no impact on the intrinsic foot joints during pre-swing except for then metatarsus-hallux joint. However, clear differences in the sagittal plane during pre-swing were observed between postoperative patients and control subjects. As the differences in walking speed between the conditions and the groups were limited to 15 percent, one may presume that the observed kinematic differences are related to the intervention or to the pathologic condition. Therefore, future studies investigating foot joint kinematics should address this limitation by comparing post-operative subjects with speed-matched control subjects.

5. CONCLUSION

Patients with a fixed-bearing implant seem to maintain their ankle angles from midstance to pre-swing during gait after surgery. The outcome of this study further showed that changes in foot inter-segment angles after TAR are not restricted to the affected ankle joint, but seem also to affect the neighbouring foot joints. While multi-segment foot kinematics improved, they were not restored to control values. The findings of this study further emphasize the clinical relevance of multi-segment foot modeling when assessing the outcome of TAR.

COMPETING INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ACKNOWLEDGEMENTS

This study was funded in part by a clinical research Grant (BDB 2017/12) of the Belgische Vereniging voor Orthopedie en Traumatologie (BVOT). Sponsor had no involvement in this article.

FIGURE LEGENDS

Table 1: Demographic data of patients suffering from end-stage ankle osteoarthritis (Abbreviations: BMI: body mass index; SD: standard deviation; N/A: not applicable; pre-op: pre-operative; post-op: post-operative; CTRL: control)

Figure 1 : (A) preoperative and (C) postoperative standardized anteroposterior weight-bearing radiographs of the Cadence prosthesis; (B) preoperative and (D) postoperative Standardized neutral weightbearing lateral foot (and ankle) radiographs of the Cadence prosthesis.

Figure 2: Inter-segment center definitions were defined according to an adapted version of Rizzoli foot model (Leardini et al. 2007) developed by Deschamps et al. (2017) (IOR-4Segment-model 1). Markers name: 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); first, second and fifth metatarsal base (FMB, SMB, FMT); first, second and fifth metatarsal head (FM1, FM2, FM5); PD6: distal dorso-medial aspect of the head of the proximal phalanx of the hallux; hallux-metatarsus joint center (FM1); midfoot-metatarsus center (SMB); calcaneus-midfoot center (ID).

Figure 3: Inter-segment angle waveforms representation with +/- 1 standard deviation cloud for the intrinsic foot joints between pre- and post-operative conditions during the stance phase of gait: Sha-Cal: shank-calcaneus; calcaneus-midfoot; midfoot-metatarsus; hallux-metatarsus: Pre-operative condition in red and post-operative condition in blue; DF: dorsiflexion ; PF: plantarflexion; Add: Adduction ; Abd :Abduction ; Inv: Inversion ; Ev: Eversion. The first column shows the graphical results of the paired Hotelling's T^2 (SPM{T2}) performed to assess the time varying three-component kinematic angle differences for each intrinsic foot joint between pre- and post-operative conditions ($\alpha = 0.05$). Statistical between conditions (pre- versus postoperative) differences according to the post-hoc analyses paired t-tests

(SPM_t) for individual components of both conditions for individual component of the foot inter-segment angles are presented underneath each figure as a red color box.

Figure 4: Between group comparison (post-operative data versus control data) inter-segment angle waveforms representation with +/- 1 standard deviation cloud for the intrinsic foot joints during the stance phase of gait: Sha-Cal: shank-calcaneus; calcaneus-midfoot; midfoot-metatarsus; hallux-metatarsus: Pre-operative condition in red and post-operative condition in blue; DF: dorsiflexion ; PF: plantarflexion; Add: Adduction ; Abd :Abduction ; Inv: Inversion ; Ev: Eversion. The first column shows the graphical results of the two-sample Hotelling's T² (SPM_{T2}) performed to assess the time varying three-component kinematic angle differences for each intrinsic foot joint between the two groups (post-operative data versus control data) ($\alpha = 0.05$). Statistical between-group differences according to the post-hoc analyses two sample t-tests (SPM_t) for individual component of the foot inter-segment angles are presented underneath each figure as a red color box.

Supplementary material: A priori power analysis results

REFERENCES

- Brodsky, J.W., Jaffe, D., Pao, A., Vier, D., Taniguchi, A., Daoud, Y., Coleman, S., Scott, D.J., 2021a. Long-term Functional Results of Total Ankle Arthroplasty in Stiff Ankles. *Foot Ankle Int.* 42, 527–535. <https://doi.org/10.1177/1071100720977847>
- Brodsky, J.W., Polo, F.E., Coleman, S.C., Bruck, N., 2011. Changes in Gait Following the Scandinavian Total Ankle Replacement. *J. Bone Jt. Surg.* 93, 1890–1896. <https://doi.org/10.2106/JBJS.J.00347>
- Brodsky, J.W., Scott, D.J., Ford, S., Coleman, S., Daoud, Y., 2021b. Functional Outcomes of Total Ankle Arthroplasty at a Mean Follow-up of 7.6 Years. *J. Bone Jt. Surg.* 103, 477–482. <https://doi.org/10.2106/JBJS.20.00659>
- Choi, J.H., Coleman, S.C., Tenenbaum, S., Polo, F.E., Brodsky, J.W., 2013. Prospective study of the effect on gait of a two-component total ankle replacement. *Foot Ankle Int.* 34, 1472–1478. <https://doi.org/10.1177/1071100713494378>
- Deleu, P.A., Besse, J.L., Naaim, A., Leemrijse, T., Birch, I., Devos Bevernage, B., Chèze, L., 2020a. Change in gait biomechanics after total ankle replacement and ankle arthrodesis: a systematic review and meta-analysis. *Clin. Biomech.* 73, 213–225. <https://doi.org/10.1016/j.clinbiomech.2020.01.015>
- Deleu, P.A., Chèze, L., Dumas, R., Besse, J.L., Leemrijse, T., Devos Bevernage, B., Birch, I., Naaim, A., 2020b. Intrinsic foot joints adapt a stabilized-resistive configuration during the stance phase. *J. Foot Ankle Res.* 13, 1–12. <https://doi.org/10.1186/s13047-020-0381-7>
- Deleu, P.A., Leemrijse, T., Chèze, L., Naaim, A., Dumas, R., Devos Bevernage, B., Birch, I., Besse, J.L., 2021a. Post-sprain versus post-fracture post-traumatic ankle osteoarthritis: Impact on foot and ankle kinematics and kinetics. *Gait Posture* 86, 278–286. <https://doi.org/10.1016/j.gaitpost.2021.03.029>
- Deleu, P.A., Naaim, A., Leemrijse, T., Dumas, R., Devos Bevernage, B., Besse, J.L., Crevoisier, X., Chèze, L., 2021b. Impact of foot modeling on the quantification of the effect of total ankle replacement: A pilot study. *Gait Posture* 84, 308–314. <https://doi.org/10.1016/j.gaitpost.2020.12.027>
- Deschamps, K., Eerdeken, M., Desmet, D., Matricali, G.A., Wuite, S., Staes, F., 2017. Estimation of foot joint kinetics in three and four segment foot models using an existing proportionality scheme: Application in paediatric barefoot walking. *J. Biomech.* 61, 168–175. <https://doi.org/10.1016/j.jbiomech.2017.07.017>

- Dubbeldam, R., Buurke, J.H., Simons, C., Groothuis-Oudshoorn, C.G.M., Baan, H., Nene, A.V., Hermens, H.J., 2010. The effects of walking speed on forefoot, hindfoot and ankle joint motion. *Clin. Biomech.* 25, 796–801.
<https://doi.org/10.1016/j.clinbiomech.2010.06.007>
- Friston, K.J., Holmes, A.P., Worsley, K.J., Poline, J.-P., Frith, C.D., Frackowiak, R.S.J., 1994. Statistical parametric maps in functional imaging: A general linear approach. *Hum. Brain Mapp.* 2, 189–210. <https://doi.org/10.1002/hbm.460020402>
- Fritz, J.M., Canseco, K., Konop, K.A., Kruger, K.M., Tarima, S., Long, J.T., Law, B.C., Kraus, J.C., King, D.M., Harris, G.F., 2021. Multi-segment foot kinematics during gait following ankle arthroplasty. *J. Orthop. Res. Off. Publ. Orthop. Res. Soc.*
<https://doi.org/10.1002/jor.25062>
- Helwig, N.E., Hong, S., Hsiao-Wecksler, E.T., Polk, J.D., 2011. Methods to temporally align gait cycle data. *J. Biomech.* 44, 561–566.
<https://doi.org/10.1016/j.jbiomech.2010.09.015>
- Inghosso, S., Benedetti, M.G., Leardini, A., Casanelli, S., Sforza, T., Giannini, S., 2009. GAIT analysis in patients operated with a novel total ankle prosthesis. *Gait Posture* 30, 132–137. <https://doi.org/10.1016/j.gaitpost.2009.03.012>
- Kessler, S.E., Rainbow, M.J., Lichtwark, G.A., Cresswell, A.G., D’Andrea, S.E., Konow, N., Kelly, L.A., 2019. A Direct Comparison of Biplanar Videoradiography and Optical Motion Capture for Foot and Ankle Kinematics. *Front. Bioeng. Biotechnol.* 7, 1–10.
<https://doi.org/10.3389/fbioe.2019.00199>
- Khazzam, M., Long, J.T., Marks, R.M., Harris, G.F., 2006. Preoperative gait characterization of patients with ankle arthrosis. *Gait Posture* 24, 85–93.
<https://doi.org/10.1016/j.gaitpost.2005.07.006>
- Kooner, S., Kayum, S., Pinsker, E.B., Al Khalifa, A., Khan, R.M., Halai, M., Daniels, T.R., 2021. Two-Year Outcomes After Total Ankle Replacement With a Novel Fixed-Bearing Implant. *Foot Ankle Int.* 42, 1002–1010. <https://doi.org/10.1177/10711007211005781>
- Leardini, A., Benedetti, M.G., Berti, L., Bettinelli, D., Nativio, R., Giannini, S., 2007. Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. *Gait Posture* 25, 453–462. <https://doi.org/10.1016/j.gaitpost.2006.05.017>
- Lullini, G., Caravaggi, P., Leardini, A., Ortolani, M., Mazzotti, A., Giannini, S., Berti, L., 2020. Retrospective comparison between a two- and three-component ankle arthroplasty: clinical and functional evaluation via gait analysis. *Clin. Biomech.* 80, 105180. <https://doi.org/10.1016/j.clinbiomech.2020.105180>

- Pataky, T.C., 2012. One-dimensional statistical parametric mapping in Python. *Comput. Methods Biomech. Biomed. Engin.* 15, 295–301.
<https://doi.org/10.1080/10255842.2010.527837>
- Pataky, T.C., 2010. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J. Biomech.* 43, 1976–1982.
<https://doi.org/10.1016/j.jbiomech.2010.03.008>
- Pataky, T.C., Robinson, M.A., Vanrenterghem, J., 2013. Vector field statistical analysis of kinematic and force trajectories. *J. Biomech.* 46, 2394–2401.
<https://doi.org/10.1016/j.jbiomech.2013.07.031>
- Pataky, T.C., Vanrenterghem, J., Robinson, M.A., 2016. The probability of false positives in zero-dimensional analyses of one-dimensional kinematic, force and EMG trajectories. *J. Biomech.* 49, 1468–1476. <https://doi.org/10.1016/j.jbiomech.2016.03.032>
- Philippe, P., Paul, C., Mark, M., Jean-Noel, C., Delphine, P., Thierry, J., 2008. Ankle Replacement versus Arthrodesis: A Comparative Gait Analysis Study. *Foot Ankle Int.* 29, 3–9. <https://doi.org/10.3113/FAI.2008.0003>
- Queen, R., 2017. Directing clinical care using lower extremity biomechanics in patients with ankle osteoarthritis and ankle arthroplasty. *J. Orthop. Res.* 35, 2345–2355.
<https://doi.org/10.1002/jor.23609>
- Queen, R.M., De Biassio, J.C., Butler, R.J., DeOrto, J.K., Easley, M.E., Nunley, J.A., 2012. Changes in pain, function, and gait mechanics two years following total ankle arthroplasty performed with two modern fixed-bearing prostheses. *Foot Ankle Int.* 33, 535–542. <https://doi.org/10.3113/FAI.2012.0535>
- Rushing, C.J., Law, R., Hyer, C.F., 2021. Early Experience With the CADENCE Total Ankle Prosthesis. *J. Foot Ankle Surg.* 60, 67–73. <https://doi.org/10.1053/j.jfas.2020.08.023>
- Segal, A.D., Cyr, K.M., Stender, C.J., Whittaker, E.C., Hahn, M.E., Orendurff, M.S., Ledoux, W.R., Sangeorzan, B.J., 2018. A three-year prospective comparative gait study between patients with ankle arthrodesis and arthroplasty. *Clin. Biomech.* 54, 42–53.
<https://doi.org/10.1016/j.clinbiomech.2018.02.018>
- Terrill, L., Shawn, R., Daniels, T.R., Hyer, C.F., Parekh, S.G., Pedowitz, D.I., 2015. TOTAL ANKLE REPLACEMENT PROSTHESIS. *WO 2015/175560 A1*.
- Uselli, F.G., Indino, C., Leardini, A., Manzi, L., Ortolani, M., Caravaggi, P., 2021. Range of motion of foot joints following total ankle replacement and subtalar fusion. *Foot Ankle Surg.* 27, 150–155. <https://doi.org/10.1016/j.fas.2020.03.015>
- von Tscherner, V., Valderrabano, V., 2010. Classification of multi muscle activation patterns

of osteoarthritis patients during level walking. *J. Electromyogr. Kinesiol.* 20, 676–683.

<https://doi.org/10.1016/j.jelekin.2009.11.005>

Journal Pre-proofs

FIGURE LEGENDS

Table 1: Demographic data of patients suffering from end-stage ankle osteoarthritis (Abbreviations: BMI: body mass index; SD: standard deviation; N/A: not applicable; pre-op: pre-operative; post-op: post-operative; CTRL: control)

Figure 1 : (A) preoperative and (C) postoperative standardized anteroposterior weight-bearing radiographs of the Cadence prosthesis; (B) preoperative and (D) postoperative Standardized neutral weightbearing lateral foot (and ankle) radiographs of the Cadence prosthesis.

Figure 2: Inter-segment center definitions were defined according to an adapted version of Rizzoli foot model (Leardini et al. 2007) developed by Deschamps et al. (2017) (IOR-4Segment-model 1). Markers name: 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); first, second and fifth metatarsal base (FMB, SMB, FMT); first, second and fifth metatarsal head (FM1, FM2, FM5); PD6: distal dorso-medial aspect of the head of the proximal phalanx of the hallux; hallux-metatarsus joint center (FM1); midfoot-metatarsus center (SMB); calcaneus-midfoot center (ID).

Figure 3: Inter-segment angle waveforms representation with +/- 1 standard deviation cloud for the intrinsic foot joints between pre- and post-operative conditions during the stance phase of gait: Sha-Cal: shank-calcaneus; calcaneus-midfoot; midfoot-metatarsus; hallux-metatarsus: Pre-operative condition in red and post-operative condition in blue; DF: dorsiflexion ; PF: plantarflexion; Add: Adduction ; Abd :Abduction ; Inv: Inversion ; Ev: Eversion. The first column shows the graphical results of the paired Hotelling's T^2 (SPM{T2}) performed to assess the time varying three-component kinematic angle differences for each intrinsic foot joint between pre- and post-operative conditions ($\alpha = 0.05$). Statistical between conditions (pre- versus postoperative) differences according to the post-hoc analyses paired t-tests

(SPM_t) for individual components of both conditions for individual component of the foot inter-segment angles are presented underneath each figure as a red color box.

Figure 4: Between group comparison (post-operative data versus control data) inter-segment angle waveforms representation with +/- 1 standard deviation cloud for the intrinsic foot joints during the stance phase of gait: Sha-Cal: shank-calcaneus; calcaneus-midfoot; midfoot-metatarsus; hallux-metatarsus: Pre-operative condition in red and post-operative condition in blue; DF: dorsiflexion ; PF: plantarflexion; Add: Adduction ; Abd :Abduction ; Inv: Inversion ; Ev: Eversion. The first column shows the graphical results of the two-sample Hotelling's T² (SPM_{T2}) performed to assess the time varying three-component kinematic angle differences for each intrinsic foot joint between the two groups (post-operative data versus control data) ($\alpha = 0.05$). Statistical between-group differences according to the post-hoc analyses two sample t-tests (SPM_t) for individual component of the foot inter-segment angles are presented underneath each figure as a red color box.

Supplementary material: A priori power analysis results

Fig. 1.



Journal

Fig. 2.

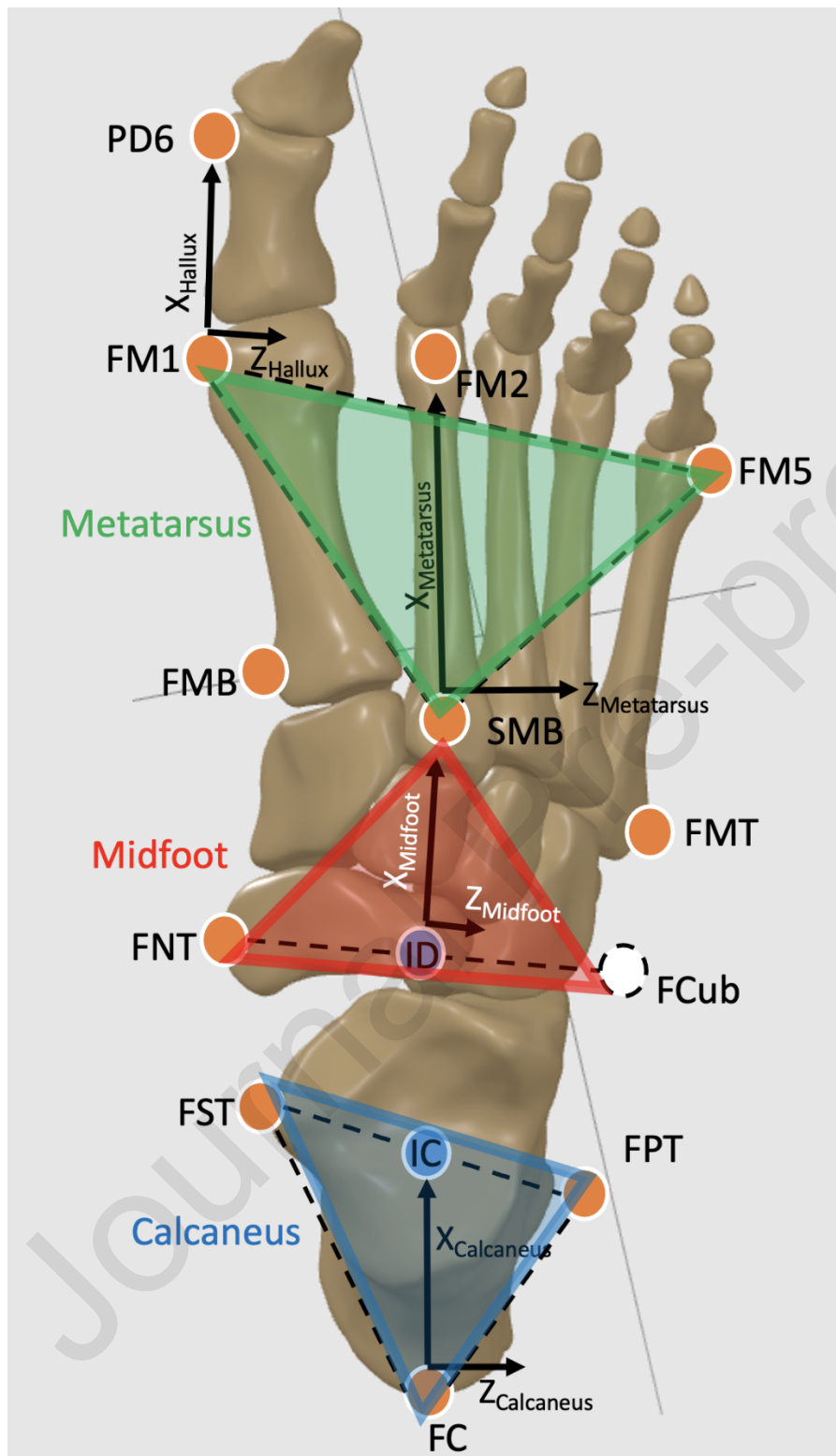


Fig. 3.

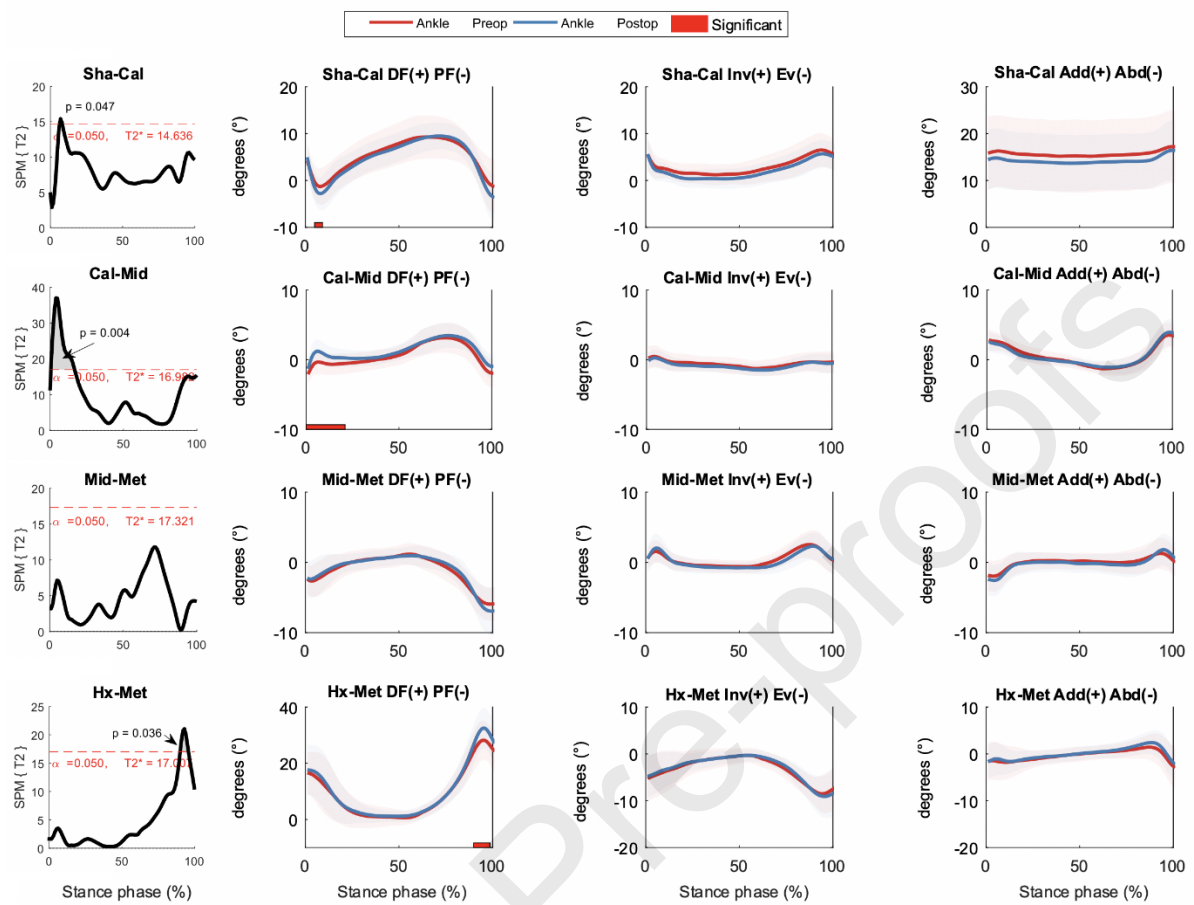


Fig. 4.

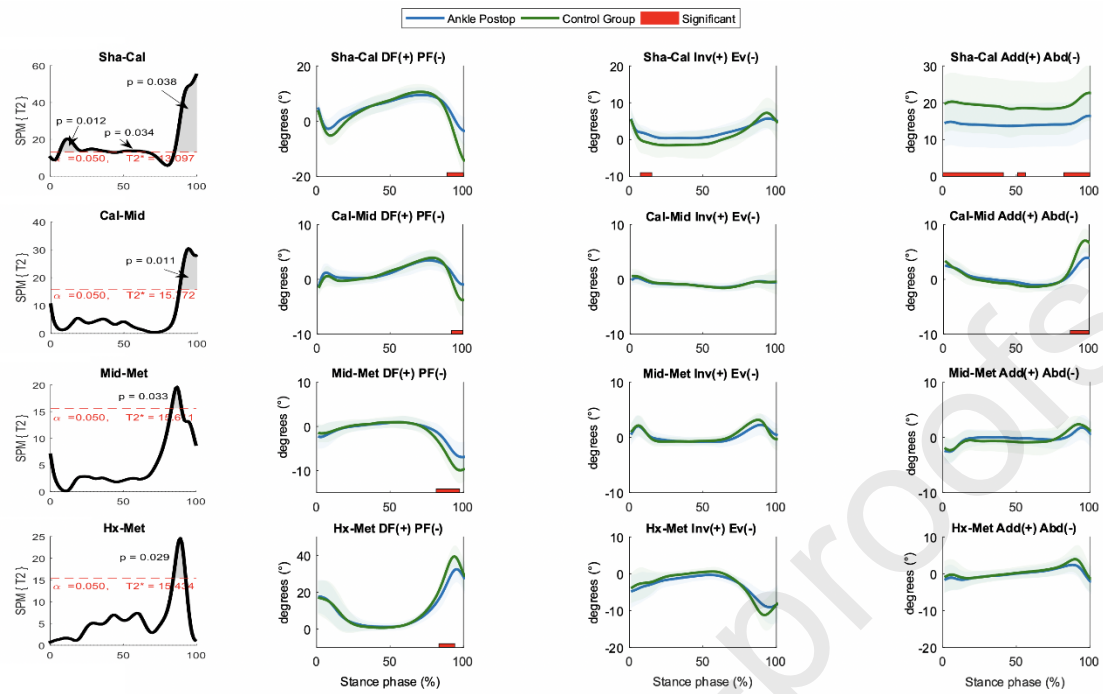


Table 1 : Demographic data of patients suffering from end-stage ankle osteoarthritis (Abbreviations: BMI: body mass index; SD: standard deviation; N/A: not applicable; pre-op: pre-operative; post-op: post-operative; CTRL : control)

	Pre-operative condition (N=36)		Post-operative condition (N=36)		Control group (N=15)	
	Mean	SD	Mean	SD	Mean	SD
Age (years)	59.9	11.34	60.31	11.35	57.8	9.17
Height (m)	1.70	0.08	1.70	0.08	1.73	0.08
Weight (kg)	81.64	12.22	81.05	11.82	76.69	16.34
BMI (kg/m ²)	28.2	4.03	27.99	3.91	25.47	4.19
Male:Female	17 : 19		17 : 19		10 : 5	
Pain (VAS)	8.02	0.22	1.09	1.22	0	0
Walking speed (m/s)	0.93	0.17	1.06	0.17	1.22	0.12
Stride length (% Height)	0.66	0.06	0.70	0.07	0.77	0.05

Supplementary material: A priori power analysis results

G*Power (Version 3.1.9.6) was used to perform an a priori power analysis for a dependent groups t test comparing pre- and post-operative conditions in patients suffering from end-stage ankle osteoarthritis. The main characteristic for ankle osteoarthritis is the alteration of the sagittal plane ankle mechanics. Therefore, the hypothetical effect size for this analysis was estimated based on the following discrete zero-dimensional sagittal plane variables extracted from the pilot results reported by Deleu et al. (2021)* for the range of motion of the ankle joint for 5 gait sub-phases: stance phase, loading response, midstance, terminal stance and pre-swing.

Sagittal ankle joint range of motion variables	Mean Pre-op to Post-op difference	Pooled Standard Deviation	Effect size (δ)	Power	Alpha	Tails	N
Range of motion during stance phase	3.2	5.68°	0.563	0.900	0.05	Two-tailed	36
						One-tailed	29
Range of motion during loading response	2.5°	3.43°	0.728	0.900	0.05	Two-tailed	21
						One-tailed	18
Range of motion during midstance	2.4°	4.40°	0.707	0.900	0.05	Two-tailed	18
						One-tailed	14
Range of motion during terminal stance	0.2°	0.90°	0.222	0.900	0.05	Two-tailed	216
						One-tailed	176
Range of motion during preswing	3.6°	5.70°	0.632	0.900	0.05	Two-tailed	29
						One-tailed	23

*Deleu, P.A., Naaim, A., Leemrijse, T., Dumas, R., Devos Bevernage, B., Besse, J.L., Crevoisier, X., Chèze, L., 2021. Impact of foot modeling on the quantification of the effect of total ankle replacement: A pilot study. *Gait Posture* 84, 308–314.
<https://doi.org/10.1016/j.gaitpost.2020.12.027>