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# Decreased Mechanical Work Demand in the Chopart Joint After Total Ankle Replacement

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# Foot & Ankle International

## DECREASED MECHANICAL WORK DEMAND IN THE CHOPART JOINT AFTER TOTAL ANKLE REPLACEMENT

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Manuscript ID	FAI-22-0143.R1
Manuscript Type:	(Original) Clinical Research Article
Keywords:	Biomechanics, Gait Studies, Arthritis
STRUCTURED ABSTRACT (Limit 300 words) Background, Methods, Results & Conclusion:	<p>Background: The success of total ankle replacement (TAR) must be based on restoring reasonable mechanical balance with anatomical structures that can produce mechanical joint work through elastic (e.g., tendons, fascia) or viscoelastic (e.g., heel pad) mechanisms, or by active muscle contractions. Yet, quantifying the work distribution across the affected joint and the neighbouring foot joints after TAR is lacking. Therefore, the objective of this study was to investigate if there is a change in the joint work distribution across the Ankle, Chopart, Lisfranc and Metatarso-phalangeal joints during level walking before and after patients undergo TAR.</p> <p>Methods: Fifteen patients with end-stage ankle osteoarthritis scheduled for primary TAR for pain relief were recruited and peer-matched with a sample of 15 control subjects. All patients underwent a 3D gait analysis before and after surgery, during which a kinetic multisegment foot model was used to quantify inter-segmental joint work.</p> <p>Results: The contribution of the ankle joint (<math>P = .007</math>) to the total foot and ankle positive work increased significantly after TAR. In contrast, a significant decrease in the contribution to the total foot and ankle joint positive work (<math>P &lt; .001</math>) were found at the Chopart joint after TAR. The foot joints combined produced a significant increase in a net mechanical work from + 0.01 J/kg before surgery to + 0.05 J/kg after TAR (<math>P = .006</math>).</p> <p>Conclusions: The findings of this study corroborate the theoretical rationale that TAR reduces significantly the compensatory strategy in the Chopart joint in patients suffering from end-stage ankle osteoarthritis after TAR. However, the findings also showed that the contribution of the ankle joint of patients after TAR to the total foot and ankle joint positive work remained impaired compared to the control group.</p>

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1     **DECREASED MECHANICAL WORK DEMAND IN THE CHOPART JOINT**  
2                             **AFTER TOTAL ANKLE REPLACEMENT**

3     **ABSTRACT**

4     **Background:** The success of total ankle replacement (TAR) must be based on restoring  
5     reasonable mechanical balance with anatomical structures that can produce mechanical  
6     joint work through elastic (e.g., tendons, fascia) or viscoelastic (e.g., heel pad)  
7     mechanisms, or by active muscle contractions. Yet, quantifying the work distribution  
8     across the affected joint and the neighbouring foot joints after TAR is lacking.  
9     Therefore, the objective of this study was to investigate if there is a change in the joint  
10    work distribution across the Ankle, Chopart, Lisfranc and Metatarso-phalangeal joints  
11    during level walking before and after patients undergo TAR.

12    **Methods:** Fifteen patients with end-stage ankle osteoarthritis scheduled for primary  
13    TAR for pain relief were recruited and peer-matched with a sample of 15 control  
14    subjects. All patients underwent a 3D gait analysis before and after surgery, during  
15    which a kinetic multisegment foot model was used to quantify inter-segmental joint  
16    work.

17    **Results:** The contribution of the ankle joint ( $P = .007$ ) to the total foot and ankle  
18    positive work increased significantly after TAR. In contrast, a significant decrease in  
19    the contribution to the total foot and ankle joint positive work ( $P < .001$ ) were found at  
20    the Chopart joint after TAR. The foot joints combined produced a significant increase  
21    in a net mechanical work from + 0.01 J/kg before surgery to + 0.05 J/kg after TAR ( $P$   
22    = .006).

23    **Conclusions:** The findings of this study corroborate the theoretical rationale that TAR  
24    reduces significantly the compensatory strategy in the Chopart joint in patients  
25    suffering from end-stage ankle osteoarthritis after TAR. However, the findings also  
26    showed that the contribution of the ankle joint of patients after TAR to the total foot  
27    and ankle joint positive work remained impaired compared to the control group.

28 **Level of evidence:** Level III

29 **Keywords :** Total Ankle Replacement; Ankle Osteoarthritis; Mechanical Work  
30 Demand

31

## 32 INTRODUCTION

33 End-stage ankle osteoarthritis is a chronic debilitating disease characterized by  
34 cartilage breakdown, significant pain and disability.<sup>1,30</sup> It is estimated that  
35 approximately 1% of the world's adult population is living with symptomatic ankle  
36 osteoarthritis.<sup>1,30</sup> Once the pain associated with end-stage ankle osteoarthritis is no  
37 longer manageable through conservative treatment, current surgical treatment options  
38 include total ankle replacement (TAR) and ankle arthrodesis, with TAR becoming  
39 increasingly popular.<sup>3,26,27,32</sup> While ankle arthrodesis (fusion of tibio-talar joint) is  
40 considered to be the “gold standard” operative treatment strategy, TAR has been  
41 encouraged during the last decade as it has the potential to maintain the existing  
42 preoperative ankle range of motion and to protect the more distally located joints of the  
43 foot.<sup>2,18</sup> However, the latter has not yet been investigated from a mechanical joint work  
44 perspective.

45 Recently developed 3D multi-segmental kinetic foot models were created  
46 to provide estimations of joint mechanics and energetics across various subsections of  
47 the foot and ankle to provide deeper insight into the complex behaviour of the foot and  
48 ankle during walking.<sup>4,13,31</sup> Although still explorative in nature, the importance of these  
49 models should not be underestimated, and use of such models has indicated altered  
50 inter-segmental power at the more distally located foot joints in patients suffering from  
51 ankle osteoarthritis.<sup>11,13,28</sup> Recently, a first insight into the kinetics of the midfoot  
52 following TAR was provided by DiLiberto et al. (2021) with findings suggesting that  
53 no changes in midfoot region peak power generation and absorption occurred between  
54 preoperative and 6 months postoperative conditions.<sup>11</sup> A drawback of the latter study,

55 however, is the oversimplification of foot mechanics neglecting the complex interaction  
56 between forefoot, midfoot and hindfoot.<sup>39</sup>

57 The success of a surgical intervention must be based on restoring reasonable  
58 balance of joint mechanics and energetics across the affected joint and the neighbouring  
59 joints. Biomechanical work measured at the level of specific joints is critical for  
60 understanding the work produced by all the anatomical structures crossing the joint  
61 center such as fascia, muscles, tendons and other structures at each joint.<sup>33</sup> For example,  
62 one of the major contributors of positive work production (i.e. energy generation)  
63 within the foot and ankle is the plantarflexor muscle-tendon structures during push-  
64 off.<sup>10,33</sup> In contrast, the metatarso-phalangeal joints tend to produce more negative work  
65 (i.e. energy absorption) than the joints distal to the ankle joint during propulsion as they  
66 stabilize the toes against the ground to counteract the ground reaction forces.<sup>33</sup>

67 Understanding where in the foot this work is performed and how it is distributed among  
68 the foot joints is useful for discerning fundamental mechanisms of how TAR benefits  
69 or degrades biomechanical performance in the affected ankle joint as well as in the  
70 neighbouring foot joints. This is of clinical relevance as progression of osteoarthritis of  
71 the neighbouring foot joints after TAR was observed in 15% to 19.6% of the cases.<sup>19,37</sup>

72 Increased tissue trauma caused by functional compensatory mechanism in the  
73 ipsilateral joints adjacent to the affected ankle is thought to contribute to the progression  
74 of these secondary postoperative arthritic changes. Despite the fact that gait mechanics  
75 after TAR is an active area of research, yet to our knowledge, no study so far has  
76 actually investigated the work distribution in the affected ankle joint and the  
77 neighbouring joints of the foot after TAR by making use of a four-segmented kinetic  
78 foot model.<sup>3,26</sup> Therefore, the purpose of this study was to explore the changes  
79 occurring in the work distribution of the affected ankle joint as well as the neighbouring  
80 joints of the foot during level walking before and after patients undergo a TAR, using  
81 a four-segmented foot model.

82 Therefore, we asked, (1) Is there a change in the joint work distribution across  
83 the Ankle, Chopart, Lisfranc and Metatarso-phalangeal joints during level walking  
84 before and after patients undergo TAR? Our hypothesis was that the ankle joint will  
85 increase its contribution to the total foot and ankle positive work after surgery. We  
86 further hypothesized that the adjacent Chopart joint of the affected ankle will  
87 significantly decrease its contribution to the total foot and ankle positive and negative  
88 work after surgery. **This hypothesis is underpinned by the findings of previous studies  
89 that found compensatory strategies in the distal foot joints triggered to compensate for  
90 the altered ankle joint biomechanics in patients suffering from ankle osteoarthritis  
91 compared to healthy reference data during walking.**<sup>5,20</sup> (2) Following TAR surgery,  
92 does the joint work distribution across the intrinsic joints of the foot approach the values  
93 of the control group of asymptomatic subjects? We hypothesized that the mechanical  
94 contribution of the ankle joint after surgery would remain impaired compared with  
95 control subjects and that it would be partially compensated by the distal joints of the  
96 foot.

97

## 98 PATIENTS AND METHODS

### 99 Patients

100 Between March 2017 and June 2020, 102 eligible patients suffering from end-stage  
101 ankle osteoarthritis, Takakura stage 3 – 4 (4 being complete obliteration of the joint  
102 space) scheduled for primary TAR for pain relief, were invited to participate in  
103 prospective data collection in the gait analysis laboratory. Of those, 46% (46) of  
104 patients were enrolled. From this database, a convenience sample of 15 symptomatic  
105 patients were peer-matched with 15 asymptomatic control subjects **according to their  
106 demographics and their postoperative walking speed and stride length** to participate in  
107 this retrospective study (Table 1). This sample size provides 80% power and a p-value  
108 at 0.05 to detect a higher contribution of the ankle joint to the total foot and ankle

109 positive and negative work after surgery and a lower contribution of the adjacent  
110 Chopart joint of the affected ankle to the total foot and ankle positive and negative work  
111 after surgery. The hypothetical effect size for this analysis was estimated based on pilot  
112 results reported by Deleu et al. (2021),<sup>7</sup> which can be found in Supplementary material.  
113 The inclusion criteria were (1) diagnosis of posttraumatic end-stage ankle osteoarthritis  
114 with an indication for TAR established by two senior orthopaedic surgeons, (2)  
115 scheduled to undergo TAR (CADENCE® fixed-bearing prosthesis, Smith & Nephew,  
116 London, UK) within 4 weeks of preoperative gait testing and to be tested again 1 year  
117 after surgery, (3) being older than 18 years of age, (4) absence of systemic or  
118 neurological diseases, (5) capable of walking at least 100 meters without an assistive  
119 device and without rest. Exclusion criteria were (1) major lower limb orthopedic  
120 pathologies or surgeries, (2) pain in more than one lower-extremity joint in either limb,  
121 and (3) any medical problem other than posttraumatic end-stage ankle osteoarthritis  
122 that could possibly affect gait. Exclusion criteria of the control group comprised of any  
123 medical condition possibly affecting normal gait. Participant's demographic data are  
124 reported in Table 1. The local ethical committee approved the study and all participants  
125 signed an informed consent form.

126

### 127 **Fixed-bearing prosthesis**

128 The Cadence prosthesis (Smith & Nephew, London, UK) is a new generation two-  
129 component, fixed-bearing, semi-constrained TAR system. The prosthesis is  
130 characterized by an anatomic shaped bone-anchored talar component (cobalt chrome  
131 alloy) and a polyethylene meniscal insert attached to a bone-anchored tibial component  
132 (titanium alloy).<sup>21,29</sup> The articular surface pattern of talar dome is characterized by two  
133 condylar surfaces.<sup>34</sup> The lateral condyle of the talar dome has a larger radius of  
134 curvature compared to the medial condyle of the talar dome.<sup>34</sup> The articular bearing



135 surface of polyethylene meniscal insert is shaped similarly to the surface pattern of the  
136 talar dome in order to achieve a congruent fit between the two prosthesis components.<sup>34</sup>

137

### 138 **Data Capture and Analysis**

139 A ten-camera optoelectronic motion analysis system sampling at 200Hz, was used  
140 to track the trajectories of markers (Miquis, Qualysis, Göteborg Sweden) used in  
141 conjunction with a Footscan® pressure plate (0.5m x 0.4m, 4,096 sensors, 2.8 sensors  
142 per cm<sup>2</sup>; RSscan International, Paal, Belgium) mounted on the top of a AMTI-force  
143 plate (0.5 x 0.4m; Advanced Mechanical Technology, Inc., Watertown, MA, USA).  
144 Both plates were embedded in a 10-m walkway in a gait laboratory, enabling the  
145 collection of data regarding joint mechanics and ground reaction forces. The force plate  
146 was custom-made to fit the surface dimensions of the pressure plate and both plates  
147 were sampled at 200Hz. This set-up provided continuous calibration of the pressure  
148 plate with respect to the force plate, using an RsScan® 3D box (RSscan International,  
149 Paal, Belgium).

150 A marker set of sixteen retro-reflective skin markers ( $\varnothing = 8$  mm) was placed on the  
151 foot and shank of each patient in accordance with the marker placement protocol of the  
152 Rizzoli four segment foot model (Figure 1).<sup>22</sup> This multi-segment foot model has  
153 revealed the kinematic and kinetic alterations occurring in the joints of the foot other  
154 than the affected ankle in patients suffering from end-stage ankle osteoarthritis.<sup>5,6,13,14</sup>  
155 Patients were instructed to walk at a self-selected, comfortable speed barefoot across  
156 the walkway. A minimum of five representative trials were collected per patient, a trial  
157 being considered representative when the foot of interest made clear contact with the  
158 pressure plate without visual adjustments in walking behavior.

159 Inter-segmental angle calculations were performed between the shank (Sha),  
160 calcaneus (Cal), midfoot (Mid), metatarsus (Met) and hallux (Hx) segments according  
161 to the modified Rizzoli multi-segment foot model (IOR-4Segment-model 1).<sup>4,9</sup> The

162 term joint is used in this manuscript to represent the modelled biomechanical interaction  
163 between two adjacent foot segments.<sup>39</sup> The following inter-segmental center (joint)  
164 definitions of the four segment foot model were applied in accordance with **previously**  
165 **investigated** kinetic Rizzoli multi-segment foot model<sup>5,6,9,14</sup> : 1) ankle joint (Sha-Cal)  
166 center defined as the midpoint between the malleoli **skin** markers, and motion at this  
167 joint was considered between the calcaneus and the shank segments, 2) Chopart joint  
168 (Cal-Mid) center defined as the midpoint between the cuboid and the navicular bone,  
169 and motion at this joints was considered between the calcaneus and the midfoot  
170 segments, 3) Lisfranc joint (Mid-Met) center defined as being on the base of the second  
171 metatarsal, and motion at this joint was considered between the midfoot and the  
172 metatarsus segments, 4) first metatarso-phalangeal joint center (Met-Hx) defined as  
173 being at intersection of the projection of the first metatarsal head **skin** marker vertically  
174 at mid distance and the floor, and motion at this joint was considered between the  
175 metatarsus and the hallux segments.<sup>9</sup>

176 Inter-segmental forces (F) and moments (M) were calculated in the Joint  
177 Coordinate System using a bottom-up inverse dynamic method.<sup>8,23</sup> Kinematic and force  
178 data were filtered using a low-pass zero-lag, 4<sup>th</sup> order, Butterworth filter, with a cut-off  
179 frequency of 10 Hz. Inertia and mass parameters of each foot segment were not  
180 accounted for considering that the inertia effects were negligible during stance in  
181 comparison to the external forces.<sup>16,28</sup> The force plate data were distributed over the  
182 segments of the Rizzoli foot model using a proportionality scheme (**i.e. if 20% of the**  
183 **total vertical force acted on the midfoot, it was assumed that 20% of the total horizontal**  
184 **force and vertical moment also acted on the midfoot**), which was validated in a similar  
185 population study.<sup>15</sup> For every sample, the estimation of the ground contact area of each  
186 foot segment was achieved by projecting the markers' position vertically onto the  
187 sensor matrix of the pressure platform. The resulting center of pressure (CoP) of each  
188 estimated ground contact area was then used as the CoP for the corresponding foot

189 segment in the inverse dynamics calculations. Inter-segmental kinetic data were  
190 calculated using an in-house written Matlab© program (Mathworks Inc., Natick, US).  
191 Internal inter-segmental moments, power and work were normalized by subject-mass,  
192 and all variables were time-normalized to 100% of the stance phase.

193

#### 194 **Study endpoints and statistical analysis**

195 The primary outcome measure was mechanical work (calculated respectively, as the  
196 negative and positive time-integral of power) of the Ankle (Sha-Cal), Chopart (Cal-  
197 Mid), Lisfranc (Mid-Met) and MTP1 (Met-Hx) joints during the stance phase of the  
198 gait cycle (Absolute values). In this study, the term work is referred to the mechanical  
199 action produced by all the anatomical structures crossing the joint center such as skin,  
200 fat, fascia, muscles, ligaments, together with friction and contact between the articular  
201 surfaces.<sup>8</sup> Positive work was normalized by the summed positive work of all joints of  
202 the foot and ankle to account for potential increases in the total foot and ankle positive  
203 work after TAR, given the expected increase in walking speed and allowing for the  
204 expression of individual foot joint contributions to the total foot and ankle joint positive  
205 work as a percentage (Relative values). The same approach was used for the  
206 normalization of negative work. In addition, the total positive and negative work as  
207 well as the net work performed by the entire foot and ankle joints during the stance  
208 phase were also calculated across conditions and timepoints. Therefore, these outcome  
209 measures can be compared between assessment dates (preoperatively and 1 year  
210 postoperatively). Comparisons were performed within patients (preoperative versus  
211 postoperative variables) and between groups (postoperative versus control). Normality  
212 and heteroskedasticity of continuous data were assessed with Shapiro-Wilk and  
213 Levene's test respectively. When the data was normally distributed, paired T-tests  
214 (within patients) and independent sample T-tests (post-op patient group vs control  
215 subject group) were performed. When the data was not normally distributed, Wilcoxon

216 signed rank (within patients) and Mann-Whitney test (post-op vs control) were used.  
217 An adjusted  $P$ -value ( $0.05/4=0.013$  for each individual joint comparison;  $0.05/2= 0.025$   
218 for the absolute total positive and negative work as well as for the net mechanical work)  
219 was used to control the type 1 error rate when performing multiple comparisons. All  
220 statistical tests used R software, version 3.4.3. (<https://www.r-project.org/>; The R  
221 Foundation for Statistical Computing, Vienna, Austria).

222

## 223 RESULTS

### 224 Demographic and spatio-temporal data

225 No significant differences between the two groups were found for age ( $P =$   
226  $.717$ ), weight ( $P = .781$ ), height ( $P = .504$ ) and BMI ( $P = .428$ ). The spatiotemporal  
227 parameters showed a statistically significant increase after surgery in walking speed ( $P$   
228  $= .001$ ) and stride length ( $P < .001$ ) being comparable with that of the controls (Table  
229 1 & 2).

230

### 231 Pre- versus postoperative condition

232 The Ankle (Sha-Cal; 0.09 J/kg), Chopart (Cal-Mid; 0.03 J/kg), Lisfranc (Mid-  
233 Met; 0.04 J/kg) and MTP1 (Met-Hx; 0.002 J/kg) joints combined produced a total  
234 preoperative positive work of 0.16 J/kg during the stance phase of gait. After TAR, the  
235 positive work of each foot joint increased significantly except for the Chopart joint  
236 (Table 3 & Figure 2). The total postoperative positive work produced in the foot and  
237 ankle increased significantly to 0.25 J/kg ( $P < .001$ ) (Ankle (Sha-Cal; 0.15 J/kg);  
238 Chopart (Cal-Mid; 0.03 J/kg); Lisfranc (Mid-Met; 0.07 J/kg); MTP1 (Met-Hx; 0.004  
239 J/kg)). As for the negative mechanical work, 0.15 J/kg was absorbed in the foot and  
240 ankle before surgery during the stance phase of gait (Ankle (Sha-Cal; -0.07 J/kg);  
241 Chopart (Cal-Mid; -0.05 J/kg); Lisfranc (Mid-Met; -0.01 J/kg); MTP1 (Met-Hx; -0.02  
242 J/kg)). The latter increased significantly after surgery to 0.20 J/kg ( $P = .001$ ). Only the

243 Ankle joint produced a significantly increased negative mechanical work after surgery  
244 (Sha-Cal = -0.1 J/kg;  $P = .003$ ). This resulted in a net mechanical work of + 0.01 J/kg  
245 before surgery and of + 0.05 J/kg after TAR, embodying a significant increase of 0.04  
246 J/kg ( $P = .006$ ).

247 The relative distribution of the mechanical work across the intrinsic joints of the  
248 foot changed significantly after TAR (Figures 3 & 4, Table 4). The contribution of the  
249 Ankle (Sha-Cal) (mean ( $\pm$  SD) preoperative 52.4%  $\pm$  9.8, mean ( $\pm$  SD) postoperative  
250 57.2%  $\pm$  7.4,  $P = .007$ ) to the total foot and ankle positive work increased significantly  
251 after surgery. In contrast, a significant decrease in the contribution to the total foot and  
252 ankle joint positive work (mean ( $\pm$  SD) preoperative 21.6%  $\pm$  7.6, mean ( $\pm$  SD)  
253 postoperative 13.2%  $\pm$  5.5,  $P < .001$ ) was found at the Chopart (Cal-Mid) joint after  
254 TAR (Table 4).

255

#### 256 **Control subjects versus patients after TAR**

257 Patients after TAR had a significantly lower mechanical positive work of Ankle  
258 (Sha-Cal = 0.15 J/kg) compared to the control group (Sha-Cal = 0.22 J/kg;  $P < .001$ )  
259 (Table 3 & Figure 2). The total postoperative positive work produced in the foot and  
260 ankle (0.25 J/kg) was significantly lower compared to the control group (0.35 J/kg) ( $P$   
261  $< .001$ ). As for the total negative mechanical work, no significant difference was found  
262 between the two groups. The net mechanical work was significantly lower in the patient  
263 group after TAR (+ 0.05 J/Kg) compared to the control group (0.10 J/kg) ( $P = .017$ ).

264 Patients after TAR had no significant differences in terms of the contribution of  
265 each individual joint to the total foot and ankle positive and negative work after surgery  
266 compared to the control group (Figures 3 & 4, Table 4).

267

268

269

270 **DISCUSSION**

271 This prospective exploratory study was designed to compare pre- and postoperative  
272 contribution of the affected ankle joint as well as the neighbouring joints of the foot to  
273 the total foot and ankle mechanical work during gait of patients with end-stage ankle  
274 osteoarthritis treated with a TAR. The **outcome of this study confirmed our** first  
275 hypothesis **and showed** that **TAR increased** the contribution of the ankle joint (Sha-Cal)  
276 to the total foot and ankle positive work after surgery, as well as decreased the  
277 contribution of the Chopart (Cal-Mid) joint after surgery. Furthermore, **there exists a**  
278 **trend toward decrease in** the contribution of Chopart (Cal-Mid) joint to the total foot  
279 and ankle joint negative work after TAR. These results corroborate the suggestion that  
280 TAR improves the mechanical contribution of the ankle (Sha-Cal) and has the potential  
281 to protect the adjacent joints of the foot after surgery.<sup>2,18</sup> **These findings are in contrast**  
282 **to that of DiLiberto et al. (2021) who found no differences in midfoot function between**  
283 **the preoperative and 6-month postoperative conditions in their TAR group. While our**  
284 **absolute Chopart (Cal-Mid) joint work values would corroborate the findings of**  
285 **DiLiberto et al. (2021), the individual contribution of each joint as percentages of the**  
286 **total foot and ankle work contradicts their findings, and shows as a significant**  
287 **postoperative decrease of 8.1 percent in the contribution of the Chopart (Cal-Mid) joint**  
288 **to the total foot and ankle joint positive work. This combination of findings provides**  
289 **some support for a more holistic and functional approach towards foot and ankle**  
290 **dynamics rather than an analytical, traditional single foot segment approach.**

291 The ankle joint is one of the body's major sources of positive work produced mainly  
292 by the plantarflexor muscle-tendon structures during walking.<sup>10</sup> The increased positive  
293 ankle (Sha-Cal) work values found after TAR are therefore a good indicator of an  
294 improvement in the ability to use the ankle to propel forward and an increase in strength  
295 of the calf muscles.<sup>18</sup> These findings are indirectly corroborated by a recent meta-  
296 analysis that found moderate evidence of an increase in ankle power generation after

297 TAR compared to pre-operative levels.<sup>3</sup> Although the mechanical behavior of the  
298 affected ankle joint (Sha-Cal) appears to have improved postoperatively, the extent to  
299 which these changes in the contribution of the ankle joint (Sha-Cal) to the total foot and  
300 ankle positive work after surgery are attributable to pain relief and production of a more  
301 mechanically ‘functional’ ankle, cannot be determined.

302 The second hypothesis, that after surgery the ankle joint remained impaired  
303 compared with control subjects, was partially confirmed by the absolute Ankle (Sha-  
304 Cal) joint work values. Since the plantarflexor muscle-tendon structures are the main  
305 contributor of the foot and ankle positive work, the impaired postoperative work  
306 production observed at the Ankle (Sha-Cal) joint also seems to affect the total  
307 postoperative positive work as well as the net total mechanical work produced in the  
308 foot and ankle which are significantly lower compared to control subjects. A possible  
309 explanation for these results may be related to the findings of Valderrabano et al. (2007)  
310 who reported that the torque produced by the arthritic ankles at one year after TAR  
311 recovered partially to 83% for dorsiflexion and to 86% for plantarflexion compared to  
312 the contralateral healthy ankle joint.<sup>35</sup> They further found that the preoperative calf  
313 muscle atrophy did not change over the 1-year rehabilitation period after TAR. This  
314 combination of findings provides some support to the theory that patients with TAR  
315 may retain their muscle strength deficits due to a selective muscle fiber type loss or to  
316 a sustained preoperative disuse.<sup>35</sup>

317 The findings of this study further revealed an interesting biomechanical  
318 phenomenon, in which TAR seems successfully to increase the mechanical contribution  
319 of the ankle joint (Sha-Cal) and to reduce the need for compensatory mechanical work  
320 in the Chopart (Cal-Mid) joint. This is of clinical interest, as the results corroborate the  
321 theoretical rationale of choosing TAR over ankle arthrodesis. It is hypothesized that  
322 TAR preserves the preoperative ankle range of motion, and protects the more distally  
323 located joints of the foot.<sup>2,18</sup> Based on the results, it is therefore plausible to suggest that

324 the compensatory strategy in the distal joints of the foot in patients suffering from end-  
325 stage ankle osteoarthritis after TAR are reduced, especially in the Chopart (Cal-Mid)  
326 joint, but remain present in the neighboring joints of the foot to compensate for the  
327 residual mechanical deficit of the affected ankle joint. These residual compensatory  
328 adaptations, and their impact on structures of neighboring joints during activities of  
329 daily living, may result in tissue trauma and the development of adjacent hindfoot and  
330 midfoot osteoarthritis.<sup>17</sup> Previous studies have reported progressive osteoarthritis in the  
331 more distally located joints of the foot in 15 to 19.6% of the cases after TAR.<sup>19,38</sup> Since  
332 progressive osteoarthritis in distal joints of the foot has been reported after TAR, as  
333 well as after ankle arthrodesis, during the postoperative follow-up, future  
334 biomechanical studies should compare the compensatory adaptations in the  
335 neighboring joints of both cohorts of subjects and their relationship with the  
336 development and/or progression of adjacent foot joint osteoarthritis.

337 The findings of this study should be considered in the context of several  
338 limitations. A first limitation is the observed increase in walking speed after TAR. Since  
339 walking speed affects foot power and joint work, caution should be exercised when  
340 interpreting the differences in joint power and joint work between pre- and  
341 postoperative conditions.<sup>12</sup> A recent study suggested that power variables significantly  
342 differ when walking speed increases by 37.5% (0.48 m/s). However, the results of the  
343 study reported in this paper show an increase of only 15.6% (0.16 m/s) between pre-  
344 and postoperative measurements. Furthermore, Eerdeken et al. (2019) showed that an  
345 increase in walking speed did not change the positive work distribution across the foot  
346 and ankle joints. A second limitation is the estimation of motion of foot bones using  
347 skin markers, especially in complex joints such as the Subtalar, Chopart and Lisfranc  
348 joints. The complexity resides in capturing relatively small motions occurring at these  
349 joints composed by a group of relatively small foot bones. Over the last decade, multi-  
350 segment foot models using skin markers have been proposed to estimate the mechanical



351 behaviour of foot joints by grouping foot bones into segments (e.g. hindfoot, midfoot,  
352 forefoot), the clinical value of which has been shown through the detection of intrinsic  
353 foot mobility impairments.<sup>5-7,11</sup> However, because these foot models do not account for  
354 individual bone-to-bone motion, they may therefore violate rigid-body assumptions and  
355 lead to inaccuracies in foot joint kinematic and kinetic estimations.<sup>25,36</sup> To overcome  
356 these challenges, methods using biplanar videoradiography have been used to provide  
357 more accurate measures of foot joint motion, which can be difficult to discern with skin  
358 mounted markers.<sup>25,36</sup> Recently, Lenz et al. (2022) used biplanar videoradiography to  
359 capture postoperatively the kinematics at the prosthetic ankle joint as well as the  
360 adjacent subtalar joint.<sup>24</sup> They found symmetrical ankle and subtalar kinematics  
361 between operated and nonoperated limbs after TAR during walking and double heel-  
362 rise tasks. However, the invasive/ ionising nature of these alternative methods precludes  
363 their use in routine clinical analysis. A third limitation was the relatively small patient  
364 population. To avoid clinical misinterpretations of the results due to differences in  
365 spatio-temporal variables as well as demographic variables between the patient and the  
366 control groups, strict inclusion criteria had to be met. By doing so, our study population  
367 was limited to 15 patients from a prospectively collected database consisting of 46  
368 patients. Future studies could perhaps broaden the inclusion criteria to provide more  
369 generalizable clinical significance for this quite heterogeneous patient population in  
370 terms of etiology and its associated osteo-articular deformity.

371 In conclusion, the results from this study **seem to** corroborate the theoretical  
372 rationale that TAR significantly reduces the compensatory strategy in the Chopart (Cal-  
373 Mid) joint in patients suffering from end-stage ankle osteoarthritis. The residual  
374 mechanical deficit of the affected ankle (Sha-Cal) joint **observed in patients after TAR**  
375 **should be addressed with intensive physiotherapeutic rehabilitation program and**  
376 **patients should be encouraged to perform regular strengthening exercises of the ankle**  
377 **joint plantarflexor muscle-tendon structures even 1 year after TAR.**

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379 **DECLARATION OF CONFLICTING INTERESTS**

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

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For Peer Review

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540 **LEGENDS**541 **Table 1:** Participant's demographic data.542 **Table 2:** Participant's spatio-temporal data.

543 **Table 3:** Absolute joint work (J/kg) across the intrinsic joints of the foot during level  
544 walking preoperatively, 1 year postoperatively and compared to a control group.  
545 (Abbreviations: Ankle OA, Ankle Osteoarthritis; CTRL, control group; SD, standard  
546 deviation; J, joule; preop, preoperative; postop, postoperative).

547 **Table 4:** Normalized joint work across the intrinsic joints of the foot during level  
548 walking preoperatively, 1 year postoperatively and compared to a control group.  
549 (Abbreviations: Ankle OA, Ankle Osteoarthritis; CTRL, control group; SD, standard  
550 deviation; J, joule ; preop, preoperative; postop, postoperative)

551 **Figure 1:** A) Inter-segment center definitions were defined according to an adapted  
552 version of Rizzoli foot model (Leardini et al. 2007) developed by Deschamps et al.  
553 (2017) (IOR-4Segment-model 1). Markers name: upper ridge of the posterior surface  
554 of the calcaneus (FC); peroneal tubercle (FPT); sustentaculum tali (FST); virtual cuboid  
555 marker (FCub), tuberosity of the navicular bone (FNT); first, second and fifth  
556 metatarsal base (FMB, SMB, FMT); first, second and fifth metatarsal head (FM1,FM2,  
557 FM5); PD6: distal dorso-medial aspect of the head of the proximal phalanx of the  
558 hallux; hallux-metatarsus joint center (FM1; midfoot-metatarsus center (SMB);  
559 calcaneus-midfoot center (ID); B) Experimental apparatus with the instrumented foot  
560 over the platforms.

561 **Figure 2:** A) Positive and negative mechanical work contributions from subareas  
562 within the foot and ankle Preop : Pre-operative data (blue), postop : postoperative data  
563 (green), ctrl : control data (grey); B) The total foot and ankle positive and negative  
564 mechanical work contributions from subareas within the foot and ankle : Preop : Pre-  
565 operative data (blue), postop : postoperative data (green), ctrl : control data (grey); C)



566 The total net mechanical work from the total foot and ankle structures : Preop : Pre-  
567 operative data (blue), postop : postoperative data (green), ctrl : control data (grey);

568 **Figure 3:** Relative contribution of each foot and ankle joint (Ankle (Sha-Cal) joint =  
569 blue, Chopart (Cal-Mid) joint = orange, Lisfranc (Mid-Met) joint =grey , MTP1 (Met-  
570 Hx) = yellow) to the total foot and ankle joint positive work during level walking  
571 preoperatively, 1 year postoperatively and compared to a control group. To show the  
572 percentage of mechanical work that each joint contributed to the total work of the foot  
573 and ankle, the work of individual joints has been divided by the total positive work of  
574 the foot and ankle. The contribution of the foot and ankle totals 1.0, and a comparison  
575 between pre- and postoperatively indicates which joint changes the most after TAR,  
576 and if the joint work distribution across the intrinsic joints of the foot are similar to the  
577 values of the control group of asymptomatic subjects. The height of each bar represents  
578 the mean for the total sample.

579 **Figure 4:** Relative contribution of each foot and ankle joint (Ankle (Sha-Cal) joint =  
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581 Hx) = yellow) to the total foot and ankle joint negative work during level walking  
582 preoperatively, 1 year postoperatively and compared to a control group. To show the  
583 percentage of mechanical work that each joint contributed to the total work of the foot  
584 and ankle, the work of individual joints has been divided by the total positive work of  
585 the foot and ankle. The contribution of the foot and ankle totals 1.0, and a comparison  
586 between pre- and postoperatively indicates which joint changes the most after TAR,  
587 and if the joint work distribution across the intrinsic joints of the foot are similar to the  
588 values of the control group of asymptomatic subjects. The height of each bar represents  
589 the mean for the total sample.

590 **Supplementary material 1:** A priori power analysis

591 **Supplementary material 2:** Joint angles, moments and power waveforms

592 representation with +/- 1 standard deviation cloud for the intrinsic foot joints between

593 the groups (pre- and postoperative patient and control groups) during the stance phase  
594 of gait: Sha-Cal: shank-calcaneus; Cal-Mid: calcaneus-midfoot; Midt-Met: midfoot-  
595 metatarsus; Met-Hx: hallux-metatarsus: Pre-operative condition in green and post-  
596 operative condition in blue; control group in red; DF: dorsiflexion ; PF: plantarflexion;  
597 Add: Adduction ; Abd :Abduction ; Inv: Inversion ; Ev: Eversion.

For Peer Review

Table 1: Participant's demographic data (Abbreviations: Ankle OA, Ankle Osteoarthritis; CTRL, Control; SD, Standard Deviation)

Demographics	Ankle OA		CTRL		Ankle OA vs CTRL ( <i>P value</i> )
	Mean	SD	Mean	SD	
Age (years)	59.07	9.78	57.80	9.17	0.717
Height (meters)	1.71	0.08	1.73	0.08	0.504
Weight (kg)	78.00	14.57	76.40	16.60	0.781
BMI	26.63	4.41	25.36	4.26	0.428
Gender (M/F)	10 : 5		7 : 8		Not applicable

Table 2: Participant’s spatiotemporal data (Abbreviations: Ankle OA, Ankle Osteoarthritis; CTRL, Control; SD, Standard Deviation; m, meters; preop, pre-operative; postop, post-operative)

Spatio-temporal factors		Ankle OA		CTRL		Preop versus Postop ( <i>P</i> value)
		Mean	SD	Mean	SD	
Walking speed (m/s)	Preop	1.02	0.13	1.22	0.12	<b>.001</b>
	Postop	1.20	0.11			
Cycle Length (m)	Preop	1.14	0.15	1.32	0.11	<b>&lt; .001</b>
	Postop	1.29	0.13			

Table 3: Absolute joint work (J/kg) across the intrinsic joints of the foot during level walking preoperatively, 1 year postoperatively and compared to a control group. (Abbreviations: Ankle OA, Ankle Osteoarthritis; CTRL. Control; SD, Standard Deviation; J, Joule; preop, pre-operative; postop, post-operative)

<b>Positive Work (J/kg)</b>	<b>PREOP</b>	<b>SD</b>	<b>POSTOP</b>	<b>SD</b>	<b>CTRL</b>	<b>SD</b>	<b>Pre-op vs Post-op (P value)</b>	<b>Post-op vs CTRL (P value)</b>
Ankle (Shank-Calcaneus)	0.09	0.05	0.15	0.05	0.22	0.04	< .001	< .001
Chopart (Calcaneus-Midfoot)	0.03	0.01	0.03	0.01	0.04	0.02	.730	.076
Lisfranc (Midfoot-Metatarsus)	0.04	0.02	0.07	0.02	0.09	0.03	< .001	.037
MTP1 (Metatarsus-Hallux)	0.002	0.002	0.004	0.003	0.003	0.002	.007	.320
<b>Total Positive Work (J/kg)</b>	0.16	0.06	0.25	0.06	0.35	0.06	< .001	< .001
<b>Negative Work (J/kg)</b>	<b>PREOP</b>	<b>SD</b>	<b>POSTOP</b>	<b>SD</b>	<b>CTRL</b>	<b>SD</b>	<b>Pre-op vs Post-op (P value)</b>	<b>Post-op vs CTRL (P value)</b>
Ankle (Shank-Calcaneus)	-0.07	0.04	-0.1	0.04	-0.12	0.04	.003	.062
Chopart (Calcaneus-Midfoot)	-0.05	0.02	-0.05	0.02	-0.06	0.02	.587	.312
Lisfranc (Midfoot-Metatarsus)	-0.01	0.005	-0.01	0.01	-0.01	0.01	.106	.457
MTP1 (Metatarsus-Hallux)	-0.02	0.03	-0.04	0.03	-0.06	0.04	.022	.100
<b>Total Negative Work (J/kg)</b>	-0.15	0.06	-0.20	0.05	-0.25	0.07	.001	.035
<b>Total Net Work (J/kg)</b>	0.01	0.05	0.05	0.05	0.10	0.06	.006	.017

Table 4: Normalized joint work across the intrinsic joints of the foot during level walking preoperatively, 1 year postoperatively and compared to a control group. (Abbreviations: Ankle OA, Ankle Osteoarthritis; CTRL. Control; SD, Standard Deviation; J, Joule; preop, pre-operative; postop, post-operative)

Positive Work	PREOP	SD	POSTOP	SD	CTRL	SD	Pre-op vs Post-op ( <i>P</i> value)	Post-op vs CTRL ( <i>P</i> value)
Ankle (Shank-Calcaneus)	52.4%	9.8%	57.2%	7.4%	61.7%	4.6%	.007	.026
Chopart (Calcaneus-Midfoot)	21.6%	7.6%	13.5%	5.5%	12.2%	5.4%	< .001	.531
Lisfranc (Midfoot-Metatarsus)	24.3%	7.4%	28.6%	6.6%	25.3%	4.5%	.014	.142
MTP1 (Metatarsus-Hallux)	1.8%	1.4%	1.1%	1.1%	0.6%	0.7%	.599	.056

Negative Work	PREOP	SD	POSTOP	SD	CTRL	SD	Pre-op vs Post-op ( <i>P</i> value)	Post-op vs CTRL ( <i>P</i> value)
Ankle (Shank-Calcaneus)	43.9%	16.2%	48.6%	13.7%	48.1%	11.1%	.200	.456
Chopart (Calcaneus-Midfoot)	35.5%	17.8%	27.4%	15.5%	24.6%	3.0%	.018	.999
Lisfranc (Midfoot-Metatarsus)	6.4%	2.8%	6.9%	4.4%	4.9%	6.8%	.599	.229
MTP1 (Metatarsus-Hallux)	14.1%	13.2%	17.2%	13.4%	22.4%	11.2%	.151	.256

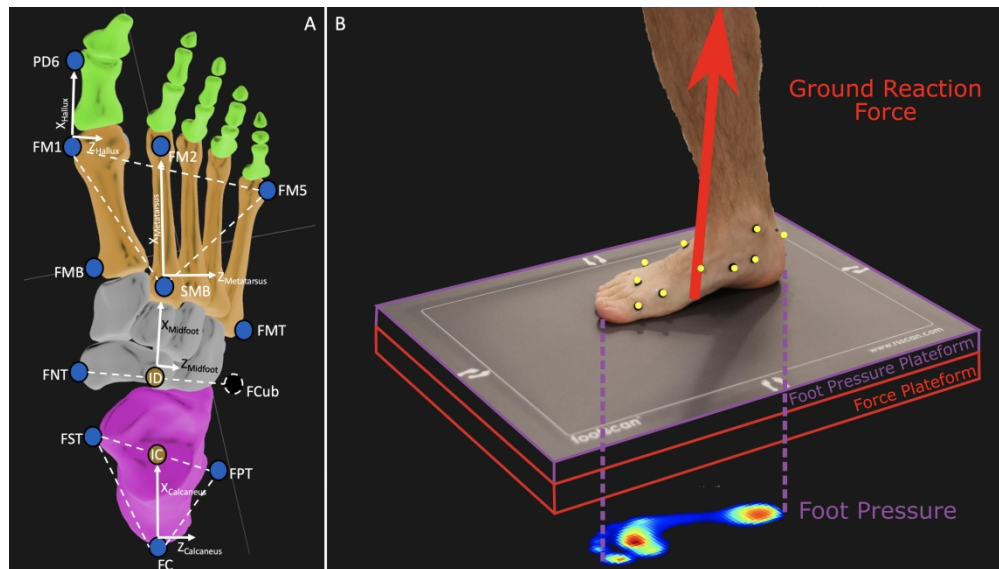


Figure 1: A) Inter-segment center definitions were defined according to an adapted version of Rizzoli foot model (Leardini et al. 2007) developed by Deschamps et al. (2017) (IOR-4Segment-model 1). Markers name: upper ridge of the posterior surface of the calcaneus (FC); peroneal tubercle (FPT); sustentaculum 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); B) Experimental apparatus with the instrumented foot over the platforms.

624x353mm (144 x 144 DPI)

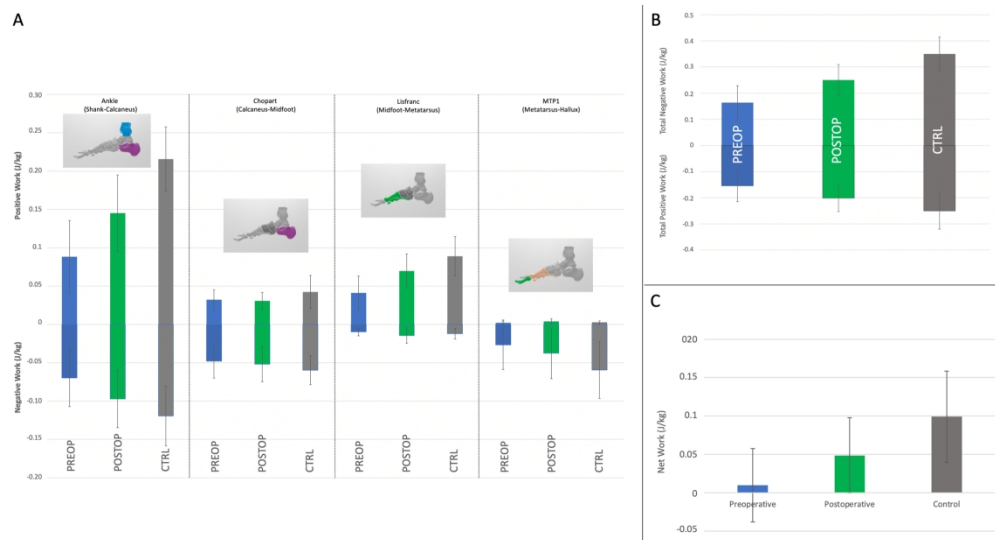


Figure 2: A) Positive and negative mechanical work contributions from subareas within the foot and ankle  
 Preop : Pre-operative data (blue), postop : postoperative data (green), ctrl : control data (grey); B) The total foot and ankle positive and negative mechanical work contributions from subareas within the foot and ankle : Preop : Pre-operative data (blue), postop : postoperative data (green), ctrl : control data (grey); C) The total net mechanical work from the total foot and ankle structures : Preop : Pre-operative data (blue), postop : postoperative data (green), ctrl : control data (grey);

451x244mm (144 x 144 DPI)



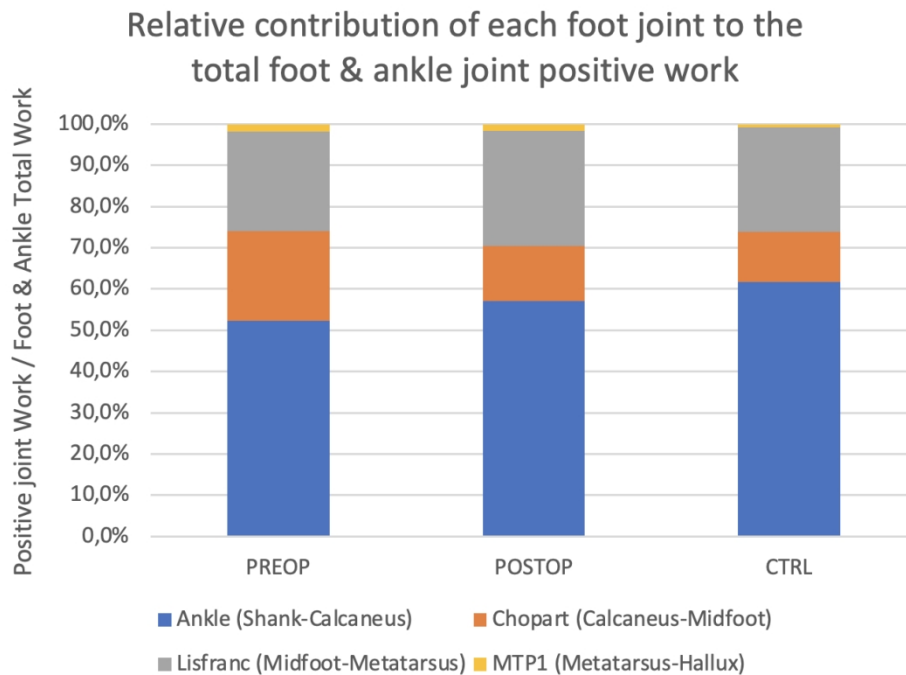


Figure 3: Relative contribution of each foot and ankle joint (Ankle (Sha-Cal) joint = blue, Chopart (Cal-Mid) joint = orange, Lisfranc (Mid-Met) joint =grey , MTP1 (Met-Hx) = yellow) to the total foot and ankle joint positive work during level walking preoperatively, 1 year postoperatively and compared to a control group.

To show the percentage of mechanical work that each joint contributed to the total work of the foot and ankle, the work of individual joints has been divided by the total positive work of the foot and ankle. The contribution of the foot and ankle totals 1.0, and a comparison between pre- and postoperatively indicates which joint changes the most after TAR, and if the joint work distribution across the intrinsic joints of the foot are similar to the values of the control group of asymptomatic subjects. The height of each bar represents the mean for the total sample.

249x183mm (144 x 144 DPI)

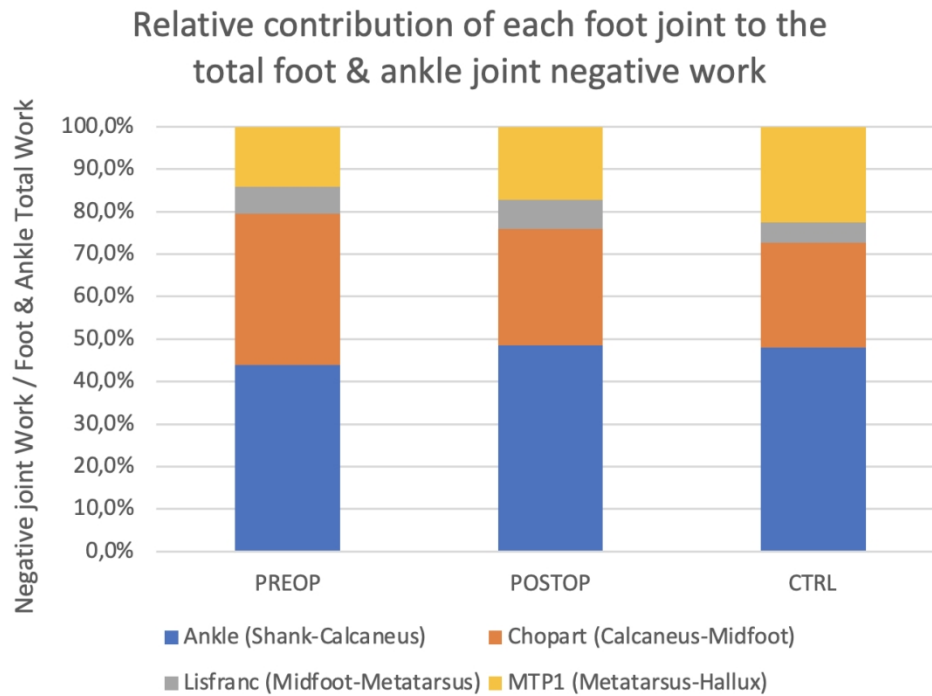


Figure 4: Relative contribution of each foot and ankle joint (Ankle (Sha-Cal) joint = blue, Chopart (Cal-Mid) joint = orange, Lisfranc (Mid-Met) joint = grey, MTP1 (Met-Hx) = yellow) to the total foot and ankle joint negative work during level walking preoperatively, 1 year postoperatively and compared to a control group.

To show the percentage of mechanical work that each joint contributed to the total work of the foot and ankle, the work of individual joints has been divided by the total positive work of the foot and ankle. The contribution of the foot and ankle totals 1.0, and a comparison between pre- and postoperatively indicates which joint changes the most after TAR, and if the joint work distribution across the intrinsic joints of the foot are similar to the values of the control group of asymptomatic subjects. The height of each bar represents the mean for the total sample.

242x176mm (144 x 144 DPI)

### Supplementary material 1

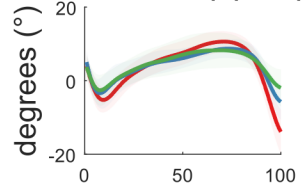
G\*Power (Version 3.1.9.6) was used to perform an a priori power analysis for a dependent groups t test comparing pre- and post-operative conditions in patients suffering from end-stage ankle osteoarthritis. This sample size provides 80% power and a p-value at 0.05 to detect a higher contribution of the ankle joint to the total foot and ankle positive and negative work after surgery and a lower contribution of the adjacent Chopart joint of the affected ankle to the total foot and ankle positive and negative work after surgery. The hypothetical effect size for this analysis was estimated based on pilot results reported by Deleu et al. (2021).

Sagittal ankle joint range of motion variables	Mean Pre-op to Post-op difference	Pooled Standard Deviation	Effect size ( $\delta$ )	Power	Alpha	Tails	N
Shank-Calcaneus Relative Positive Work Contribution	5%	7%	0.714	0.800	0.05	One-tailed	14
Shank-Calcaneus Relative Negative Work Contribution	9.5%	13.8%	0.687	0.800	0.05	One-tailed	15
Calcaneus-Midfoot Relative Positive Work Contribution	7%	6.3%	-0.707	0.800	0.05	One-tailed	14
Calcaneus-Midfoot Relative Negative Work Contribution	13.8%	12.5%	-1.10	0.800	0.05	One-tailed	8

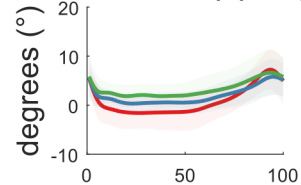
### References

Deleu PA, Naaim A, Leemrijse T, et al. Impact of foot modeling on the quantification of the effect of total ankle replacement: A pilot study. *Gait Posture*. 2021;84(December 2020):308-314. doi:10.1016/j.gaitpost.2020.12.027.

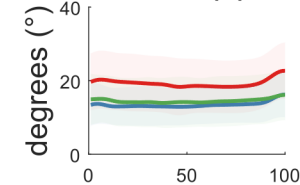
**Sha-Cal DF(+) PF(-)**



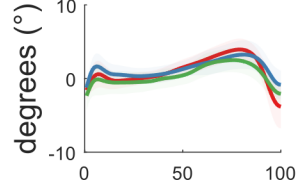
Foot & Ankle International  
**Sha-Cal Inv(+) Ev(-)**



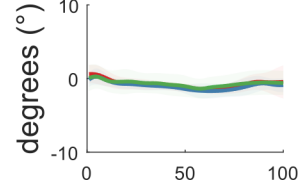
**Sha-Cal Add(+) Abd(-)**



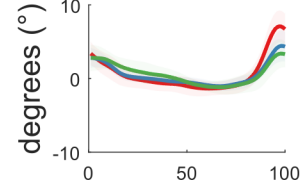
**Cal-Mid DF(+) PF(-)**



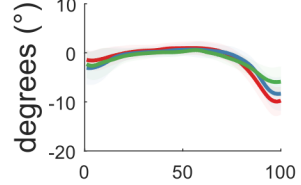
**Cal-Mid Inv(+) Ev(-)**



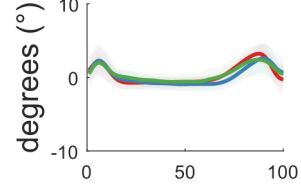
**Cal-Mid Add(+) Abd(-)**



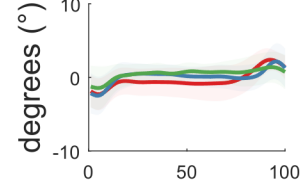
**Mid-Met DF(+) PF(-)**



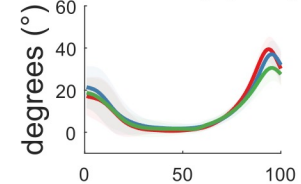
**Mid-Met Inv(+) Ev(-)**



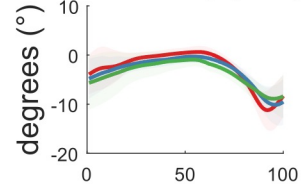
**Mid-Met Add(+) Abd(-)**



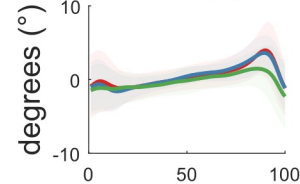
**Met-Hx DF(+) PF(-)**



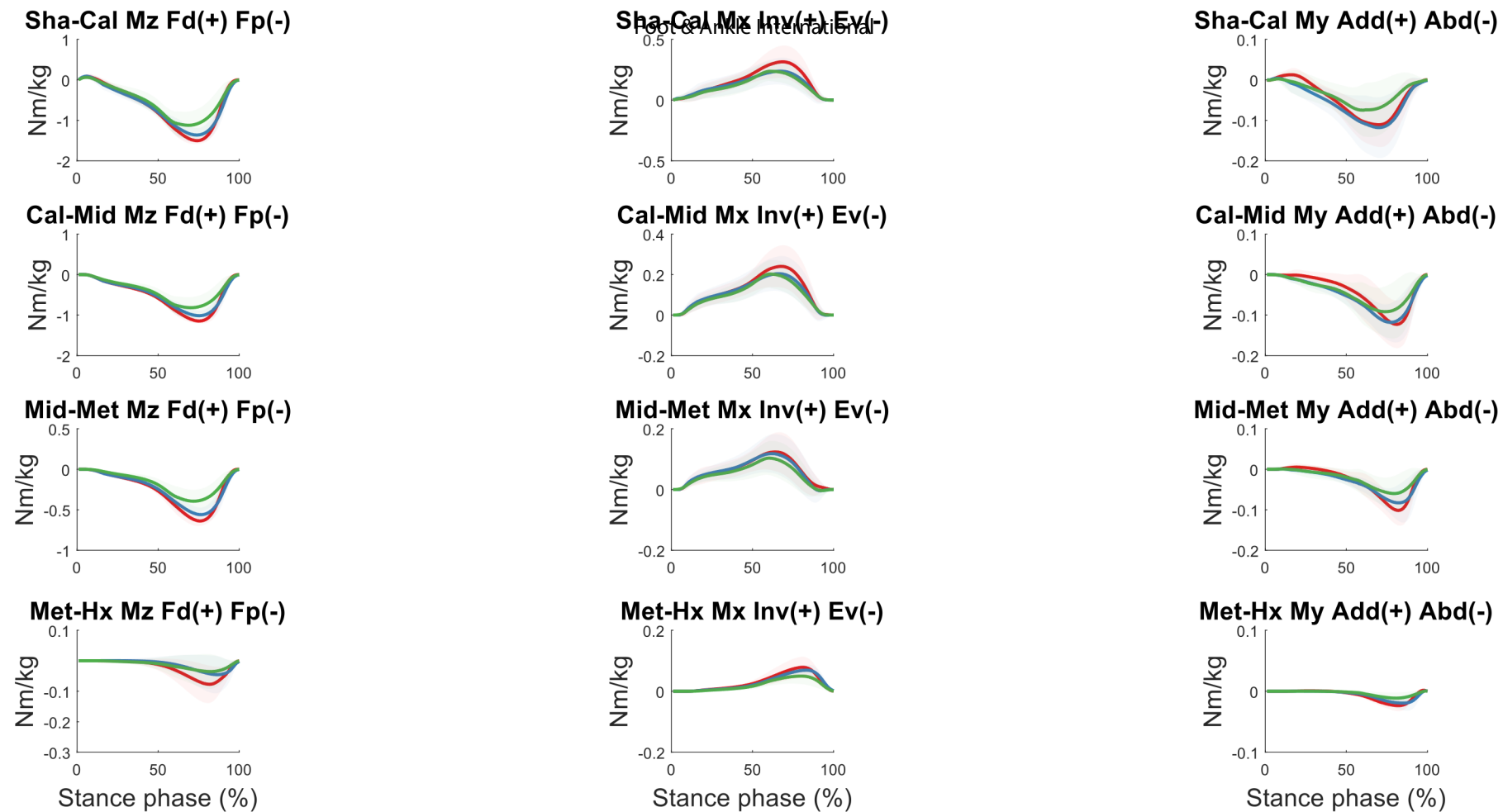
**Met-Hx Inv(+) Ev(-)**



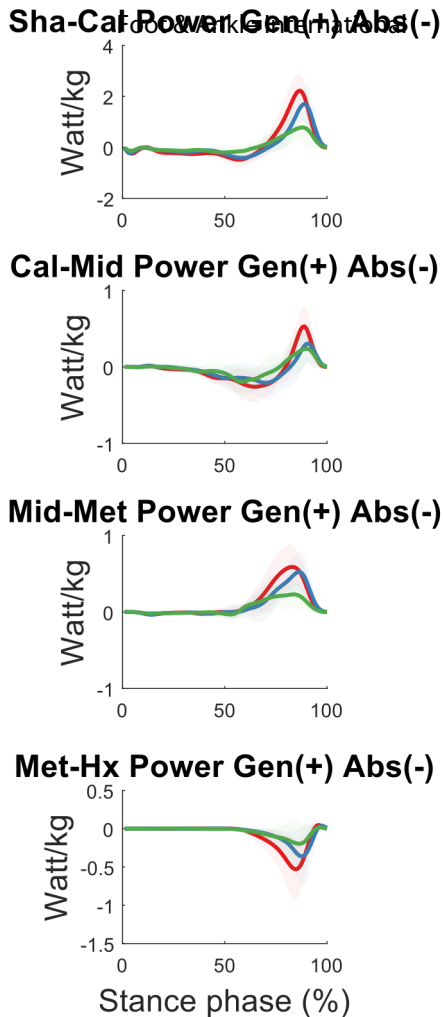
**Met-Hx Add(+) Abd(-)**



Joint angle waveforms representation with +/- 1 standard deviation cloud for the intrinsic foot joints between the groups (pre- and postoperative patient and control groups) during the stance phase of gait: Sha-Cal: shank-calcaneus; Cal-Mid: calcaneus-midfoot; Mid-Met: midfoot-metatarsus; Met-Hx: hallux-metatarsus: Pre-operative condition in green and post-operative condition in blue; control group in red; DF: dorsiflexion ; PF: plantarflexion; Add: Adduction ; Abd :Abduction ; Inv: Inversion ; Ev: Eversion.



Joint moments waveforms representation with +/- 1 standard deviation cloud for the intrinsic foot joints between the groups (pre- and postoperative patient and control groups) during the stance phase of gait: Sha-Cal: shank-calcaneus; Cal-Mid: calcaneus-midfoot; Mid-Met: midfoot-metatarsus; Met-Hx: hallux-metatarsus: Pre-operative condition in green and post-operative condition in blue; control group in red; DF: dorsiflexion ; PF: plantarflexion; Add: Adduction ; Abd :Abduction ; Inv: Inversion ; Ev: Eversion.



Joint power waveforms representation with +/- 1 standard deviation cloud for the intrinsic foot joints between the groups (pre- and postoperative patient and control groups) during the stance phase of gait: Sha-Cal: shank-calcaneus; Cal-Mid: calcaneus-midfoot; Mid-Met: midfoot-metatarsus; Met-Hx: hallux-metatarsus: Pre-operative condition in green and post-operative condition in blue; control group in red; DF: dorsiflexion ; PF:

plantarflexion; Add: Adduction ; Abd :Abduction ; Inv: Inversion ; Ev: Eversion.