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Long-term pathological gait pattern changes after talus fractures — dynamic measurements with a new insole

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Abstract

Purpose The aim of the current study was to describe long-term gait changes after talus fractures, identify patterns associated with poor outcome and discuss possible treatment options based on dynamic gait analysis.

Methods Twenty-seven patients were followed-up clinically and via gait analysis after talus fracture osteosynthesis. Continuous dynamic pedobarography with a gait analysis insole was performed on a standardized parcours consisting of different gait tasks and matched to the outcome.

Results Mean follow-up was 78.3 months (range 21–150), mean AOFAS and Olerud-Molander scores 66 (range 20–100) and 54 (range 15–100). Significant correlations between fracture classification and osteoarthritis (Hawkins: $r_s = 0.67$ / Marti-Weber: $r_s = 0.5$) as well as several gait differences between injured and healthy foot with correlations to outcome were seen: decreased step load-integral/maximum-load; associations between centre-of-pressure displacement and outcome as well as between temporospatial measures and outcome. Overall, pressure-distribution was lateralized in patients with subtalar joint injury (Δ: 0.5765 N/cm^2, $p = 0.0475$).

Conclusions Talus fractures lead to chronic gait changes and restricted function. Dynamic pedobarography can identify patterns associated with poor results. The observed gait patterns suggest that changes can be addressed by physical therapy and customized orthoses to improve overall outcome. The presented insole and measurement protocol are immediately feasible as a diagnostic and rehabilitation aid.

Keywords Talus · Fracture · Gait analysis · Pedobarography

Introduction

Fractures of the talus are rare. They account for only 0.3% of all fractures and about 1% of foot and ankle-related fractures [1]. Despite ongoing medical evolution this fracture remains a challenge. Recent systematic reviews have shown high complication rates for talar neck fractures with regard to avascular necrosis and osteoarthritis [2]. A clear association between fracture severity and development of avascular necrosis has been shown. Similar results and correlations have been shown in studies including talar body fractures with long-term osteoarthritis rates of over 70% [3]. All these long-term complications are associated with significant functional impairment, especially in initially higher displaced talus fractures [4]. Furthermore, the necessity for secondary surgical procedures increases along with the amount of preoperative dislocation [5]. Associated with the functional impairments are gross gait changes that are included in different function scores and contribute to the overall clinical outcome. To our knowledge only one study has investigated the long-term gait changes after talus fractures with a stationary force plate [6]. They were able to show that, after talar neck and body fractures, patients reduce the amount of weight transferred through the injured foot. Furthermore, they were able to demonstrate changes in

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the pressure distribution underneath the foot. However, no correlations between gait changes and outcome were examined. Studies in anatomically close fracture entities have already shown markedly altered gait patterns with long follow-ups [7]. Jansen et al. were able to show long-term changes to maximum loading, force time integral, and pressure distribution in pilon fractures that were associated with initial fracture severity and functional outcome. Similar results have been shown in fractures of the calcaneus by several groups [8, 9], suggesting that comparable gait changes might also be found in talus fracture patients. Based on the current literature, changes to the pressure distribution, resulting forces, and also temporal spatial parameters (stance/swing time, double support time, cadence, gait cycle time) have to be expected in relation to the outcome [10]. By using dynamic pedobarography with this novel analysis insole [11], patients can be monitored during free-field gait conditions; thus, providing outcome correlations in addition to those obtained by gait analysis under stationary conditions [12].

There are gait changes after talus fractures. We hypothesize that additional changes can be found when measuring under free-field conditions with a pedobarography insole and that correlations between outcome and the above-mentioned gait parameters can be found. The aim of this retrospective, observational study was to investigate these changes, find possible associations to fracture severity as well as radiographic and clinical outcome, and discuss possible treatment options based on gait analysis.

Methods

A retrospective, observational study design was chosen. Inclusion criteria were all operatively-treated, unilateral talar body and neck fractures between 2002 and 2014. Exclusion criteria were impaired mobility, gait abnormalities before the fracture event, fracture non-union, patients below the age of 18 years and patients with shoe sizes outside the range of 36–45 (EU). All identified patients were contacted and invited to participate in the study. All participating patients consented to the use of their clinical, radiographic, and gait results for study purposes. The study was approved by the local ethics committee (Aerztekammer des Saarlandes 249/14).

Gait analysis

Gait data was analyzed with the OpenGo Insole (Moticon GmbH; Munich, Germany) [13]. A sampling frequency of 50 Hz was used. The gait data was sampled during walks on a gait parcours consisting of even-level walking, stair-climbing (up/down) and slope-walking (up/down, 20° inclination angle). All patients performed at least 20 steps during every task of the gait parcours. Patients were allowed unlimited time to acclimatize to the insole and all gait tasks. The data was segmented and analyzed with the Beaker Software (Moticon GmbH; Munich, Germany). Kinetic (step-force-integral, maximum-load), temporospatial (stancetime, swingtime, double-support-time, gait-cycletime, cadence), and average anteroposterior (ap) and mediolateral (ml) centre-of-pressure (COP) excursion were calculated from the averages of all steps for each extremity and gait task independently. These parameters were chosen as they represent the standard automated output of the insole version used for this study. To compare the absolute pressure distribution, the insole sensors were divided along the anteroposterior and mediolateral midline and total pressures for the resulting quadrants analyzed (forefoot medial/lateral; rearfoot medial/lateral).

Clinical and radiographic follow-up

All participants were interviewed in person and assessed by an orthopaedic surgeon and a research student not involved in the initial treatment. The initial radiographic studies were reviewed and all fractures classified according to the Marti-Weber classification [4]. Talus neck fractures were furthermore classified according to Hawkins as modified by Canale and Kelly [14]. All patients were assessed with the American Orthopedic Foot and Ankle Society (AOFAS) and Olerud-Molander score (OMS) questionnaires [15, 16] at the follow-up. The most recent radiographs were reviewed at the follow-up, and osteoarthritis of the ankle, subtalar, and talonavicular joint were assessed and classified according to Bargon [17].

Statistical analysis

Data was screened for normality with the D'Agostino-Pearson test. Every value is reported as difference-of-the-mean (Δ). Differences between healthy and fractured extremities were compared as paired t-tests/Wilcoxon tests. Differences between non-displaced and displaced fractures were compared with the unpaired t-test/Mann Whitney test. Correlation analysis was performed as Spearman's r. For correlation analysis the differences between fractured and healthy extremities were used for all gait parameters. Positive values indicate greater values on the previously fractured side. $P < 0.05$ was defined as statistically significant. Statistical analysis was performed with Prism 6.0 (GraphPad Software Inc., La Jolla, USA).

Results

Patient demographics (Table 1)

Overall 55 patients with talus fractures from 2002 to 2014 who met the inclusion criteria were identified. A total of 27 patients responded to our study request and were included in

Table 1 Baseline cohort characteristics

Age in years (range)	50.6 (24–81)		
Follow-up in months (range)	78.3 (21–150)		
Marti-Weber Classification (%)		Hawkins classification (%)	
I	3 (11%)	I	4 (33%)
II	11 (41%)	II	2 (17%)
III	12 (44%)	III	6 (50%)
IV	1 (4%)	IV	0 (0%)
Bargon Score (range)	0.9 (0–3)		
Necrosis (%)	8 (30)		
Osteoarthritis (%)	14 (52)		
AOFAS score (range)	66 (20–100)		
Olerud Molander score (range)	54 (15–100)		

the study (loss to follow-up: 51%). Mean follow-up was at 78.3 months (21–150 months). The average patient age was 50.6 years (range 24–81 years). Eight patients initially presented concomitant lower extremity injuries: 44% were fractures around the knee, 33% were further fractures of the foot and 22% were fractures of the femur. No difference in outcome was seen between patients with and without concomitant injuries given the limited power of our study. No significant correlations between patient age and clinical scoring, or follow-up time and patient scoring were seen.

Clinical results

At the follow-up, 14 patients presented radiographic signs of osteoarthritis, with eight patients having radiographic signs of talar necrosis. Significant correlations were seen between the initial Marti-Weber classification, the Hawkins classification, and the Bargon score (Marti-Weber: $r_s = 0.50$, $p = 0.008$; Hawkins: $r_s = 0.67$, $p = 0.024$). No significant correlations between both fracture classifications and clinical outcome were observed. Osteoarthritis as measured by the Bargon score was only correlated to the OMS score in talar neck fractures ($r_s = -0.57$, $p = 0.024$). No further clinical correlations were seen.

Gait changes compared to the contralateral extremity and outcome correlations

During all gait activities significant changes between the uninjured and previously fractured extremity were seen (Fig. 1a-f). Most pronounced during every gait trial were decreases in the step-load-integral (Fig. 1e) and maximum-load (Fig. 1f) for the fractured extremity. No significant changes were seen for the average ap COP excursion (Fig. 1a). The ml COP excursion was, however, changed during stair-up, stair-down, and decreasing-slope walking (Fig. 1b). Furthermore, stance-time (Fig. 1c) and swing-time (Fig. 1d) were changed during six gait trials. Several correlations between different gait parameters and clinical as well as radiographic outcome were observed. All r_s and p values are shown in the complete correlation matrix (Table 2). During even-surface walking ap and ml COP excursion were positively correlated to the clinical outcome. During stair up walking correlations between clinical scoring and stance-time, gait-cycle-time, double-support-time, step-load integral, and cadence were seen. There were negative correlations between radiographic outcome, cadence, and stance-time. During stair-down walking negative correlations between cycle-time, double-support, and clinical scoring were seen, with a positive correlation between cadence and clinical scoring. Walking on the increasing slope showed a positive correlation between the mediolateral gait line length and the AOFAS score and negative correlations between the double-support-time and both scoring systems. Walking on the decreasing slope only showed one significant, negative correlation between the double-support-time and AOFAS score.

Pressure distribution

No difference in mean pressures between the healthy and previously injured sides rearfoot sensors was seen (Δ: −0.55 N/cm^2, $p = 0.09$). There were significant differences in mediolateral pressure both between the forefoot and rearfoot of healthy and previously injured feet (forefoot: Δ: 0.73 N/cm^2, $p = 0.001$; rearfoot: Δ: 0.85 N/cm^2, $p < 0.001$) (Fig. 2a). No correlation was discovered between mediolateral pressure differences of both forefoot and rearfoot, and for Bargon score, AOFAS score, OMS score, and Marti-Weber classification, significant overall pressure lateralization for fractures with initial subtalar fracture dislocation (Marti-Weber III, IV) was seen (Δ: 0.58 N/cm^2, $p = 0.048$) (Fig. 2b-d).

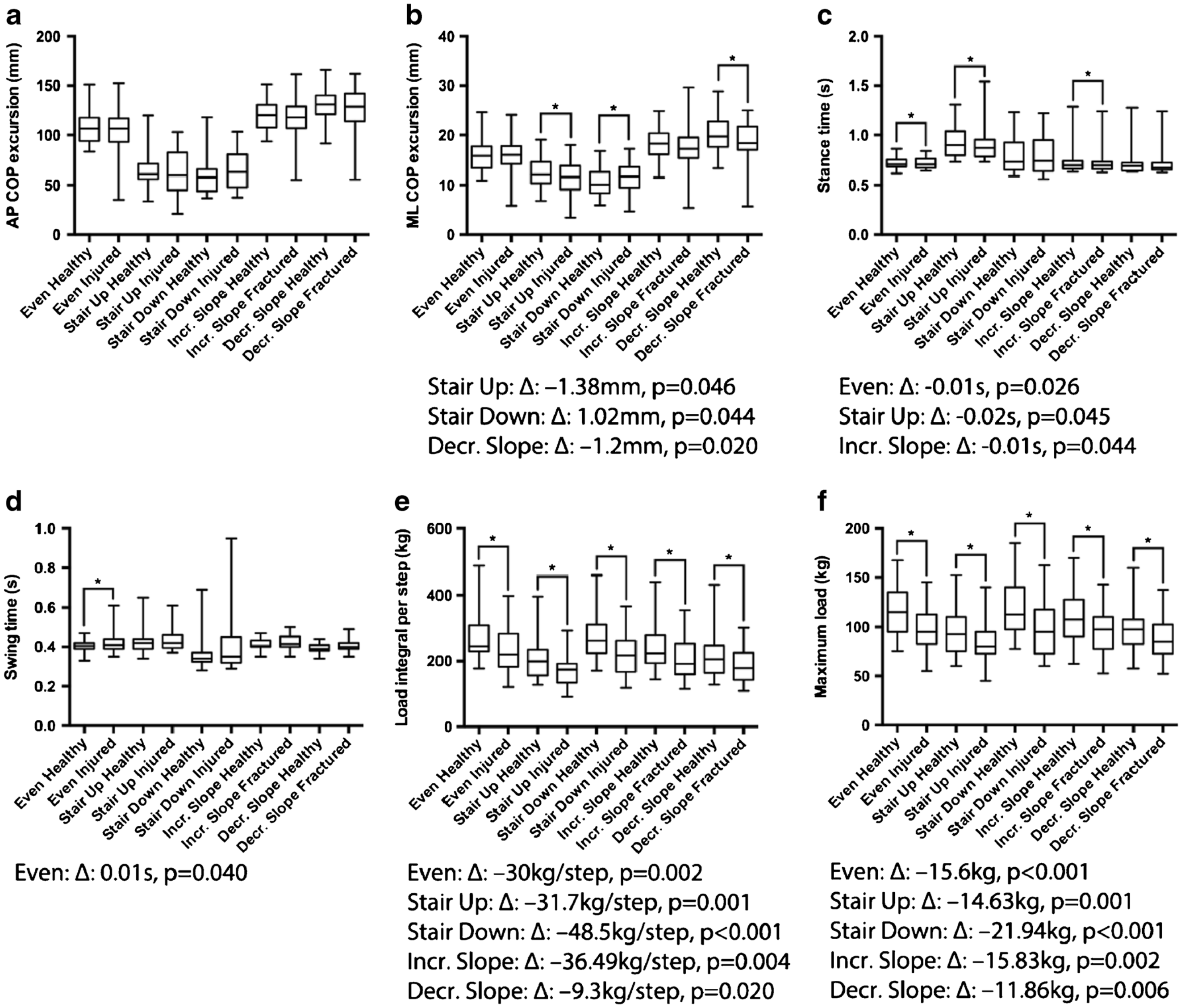

Fig. 1 Box plots show results for several gait parameters for both the uninjured (healthy) and previously fractured (injured) extremity: anteroposterior COP excursion (**a**), mediolateral COP excursion (**b**), stance-time (**c**), swing-time (**d**), step-load-integral (**e**), and maximum-load (**f**) are shown. Boxes show 1st and 3rd quartiles and mean. Whiskers show min. to max. values. *$p < 0.05$. Significant differences per gait trial are displayed underneath each box plot

Discussion

Fractures of the talus most commonly result from falls from great heights and vehicle accidents [4]. Due to the high impact mechanisms, these fractures are often accompanied by other lower extremity injuries [18]. In our study eight patients presented with concomitant lower extremity injuries. These injuries had no significant influence on clinical and radiographic outcome so they were included into the study. Even though this adds bias and might well be an effect of lacking power, we chose to include these cases to not further decrease our patient number. This is supported by previous studies that have shown no significant influences of additional lower extremity injuries on the overall clinical outcome; thus, suggesting that talus fractures are the most outcome influencing factors in these cases [5]. Furthermore, no correlation between outcome and age or follow-up was seen. Irrespective of the associated injuries, the long-term outcomes after talus fractures are complicated by high rates of osteonecrosis [19] and osteoarthritis of the peritalar joints [20]. In our study osteoarthritis was only moderately correlated to the OMS function score, but higher correlations were seen toward the initial fracture classification of talar body and especially talar neck fractures. This outcome association of clinical scoring has been shown in previous studies, with the same effect of higher correlations for talar neck fractures, explained by greater vascular compromise [4]. Overall, the radiographic results of talar fractures are associated with the initial severity of the

Table 2 Spearman correlation matrix between gait parameters and outcome

	Even Surface			Stair Up			Stair Down			Increasing Slope			Decreasing Slope		
	Bargon	AOFAS	OMS	Bargon	AOFAS	OMS	Bargon	AOFAS	OMS	Bargon	AOFAS	OMS	Bargon	AOFAS	OMS
GLL AP	r_s= -0.17	r_s= 0.46	r_s= 0.43	r_s= 0.06	r_s= 0.14	r_s= 0.31	r_s= -0.13	r_s= -0.07	r_s= -0.04	r_s= -0.08	r_s= 0.29	r_s= 0.31	r_s= -0.18	r_s= 0.33	r_s= 0.36
	p = 0.39	p = 0.016	p = 0.024	p = 0.75	p = 0.48	p = 0.11	p = 0.51	p = 0.73	p = 0.86	p = 0.68	p = 0.14	p = 0.12	p = 0.36	p = 0.10	p = 0.07
GLL ML	r_s= 0.00	r_s= 0.53	r_s= 0.36	r_s= 0.12	r_s= 0.20	r_s= 0.30	r_s= 0.05	r_s= 0.39	r_s= 0.23	r_s= 0.29	r_s= 0.41	r_s= 0.23	r_s= -0.03	r_s= 0.45	r_s= 0.27
	p = 0.99	p = 0.004	p = 0.06	p = 0.56	p = 0.32	p = 0.12	p = 0.82	p = 0.05	p = 0.26	p = 0.14	p = 0.03	p = 0.24	p = 0.89	p < 0.05	p = 0.18
Stance Time	r_s= 0.38	r_s= -0.04	r_s= -0.15	r_s= -0.46	r_s= 0.33	r_s= 0.46	r_s= 0.10	r_s= 0.17	r_s= 0.27	r_s= 0.13	r_s= 0.00	r_s= 0.00	r_s= 0.16	r_s= 0.06	r_s= 0.02
	p = 0.06	p = 0.84	p = 0.45	p = 0.02	p = 0.10	p = 0.02	p = 0.64	p = 0.42	p = 0.20	p = 0.52	p = 0.98	p = 0.99	p = 0.43	p = 0.77	p = 0.90
Swing Time	r_s= -0.04	r_s= -0.05	r_s= -0.05	r_s= 0.28	r_s= -0.08	r_s= -0.17	r_s= -0.23	r_s= -0.18	r_s= -0.20	r_s= -0.18	r_s= 0.15	r_s= 0.00	r_s= -0.19	r_s= -0.06	r_s= -0.10
	p = 0.83	p = 0.81	p = 0.80	p = 0.17	p = 0.72	p = 0.41	p = 0.28	p = 0.38	p = 0.33	p = 0.37	p = 0.45	p = 0.97	p = 0.35	p = 0.77	p = 0.60
Integral	r_s= 0.07	r_s= 0.26	r_s= 0.23	r_s= 0.09	r_s= 0.45	r_s= 0.45	r_s= 0.04	r_s= 0.30	r_s= 0.28	r_s= -0.07	r_s= 0.22	r_s= 0.17	r_s= 0.18	r_s= 0.21	r_s= 0.16
	p = 0.73	p = 0.19	p = 0.26	p = 0.64	p = 0.019	p = 0.02	p = 0.86	p = 0.13	p = 0.15	p = 0.71	p = 0.26	p = 0.39	p = 0.37	p = 0.29	p = 0.43
Max Load	r_s= 0.21	r_s= 0.20	r_s= 0.10	r_s= 0.04	r_s= 0.31	r_s= 0.31	r_s= -0.02	r_s= 0.13	r_s= 0.14	r_s= 0.00	r_s= 0.15	r_s= 0.05	r_s= 0.05	r_s= 0.16	r_s= 0.14
	p = 0.29	p = 0.33	p = 0.61	p = 0.81	p = 0.11	p = 0.11	p = 0.93	p = 0.53	p = 0.47	p = 0.99	p = 0.46	p = 0.81	p = 0.79	p = 0.44	p = 0.47
Cycle	r_s= -0.13	r_s= 0.17	r_s= 0.21	r_s= 0.29	r_s= -0.70	r_s= -0.71	r_s= 0.32	r_s= -0.63	r_s= -0.58	r_s= -0.08	r_s= -0.14	r_s= -0.06	r_s= -0.34	r_s= -0.19	r_s= -0.17
Time	p = 0.54	p = 0.40	p = 0.30	p = 0.14	p = 0.0001	p = 0.001	p = 0.12	p = 0.001	p = 0.003	p = 0.69	p = 0.50	p = 0.76	p = 0.08	p = 0.33	p = 0.39
Cadence	r_s= 0.12	r_s= -0.17	r_s= -0.22	r_s= -0.40	r_s= 0.66	r_s= 0.67	r_s= -0.32	r_s= 0.64	r_s= 0.58	r_s= 0.08	r_s= 0.13	r_s= 0.06	r_s= 0.37	r_s= 0.19	r_s= 0.17
	p = 0.55	p = 0.40	p = 0.29	p = 0.049	p = 0.0003	p = 0.001	p = 0.12	p = 0.001	p = 0.03	p = 0.70	p = 0.54	p = 0.79	p = 0.06	p = 0.33	p = 0.40
Double Support	r_s= 0.03	r_s= -0.23	r_s= -0.08	r_s= 0.03	r_s= -0.29	r_s= -0.47	r_s= 0.16	r_s= -0.46	r_s= -0.37	r_s= 0.02	r_s= -0.51	r_s= -0.41	r_s= -0.15	r_s= -0.42	r_s= -0.27
	p = 0.89	p = 0.26	p = 0.71	p = 0.90	p = 0.16	p = 0.017	p = 0.43	p = 0.02	p = 0.07	p = 0.91	p = 0.01	p = 0.036	p = 0.46	p = 0.03	p = 0.18

Significant correlations are marked in gray. For every analysis r_s and corresponding *p* value are shown

injury, whereas there is only a weak association between osteoarthritis and clinical function.

Gait changes in the injured foot

A comparison of the previously injured extremity with the uninjured one revealed several characteristic gait changes. The most marked change was that step-force-integral and maximum load were reduced in every one of the gait tasks. This shows that, despite the long follow-up times, patients still reduce the amount of transferred weight placed on their previously injured extremity. This is to be expected as almost all patients have at least some amount of functional impairment or residual pain as seen in the scoring outcomes. The amount of functional impairment and residual pain for talus fractures has been shown in previous studies [5]. Studies of closely related fractures have shown similar gait results: Jansen et al. showed reduced overall pressure underneath the foot in calcaneus fractures with an average follow-up of 34 months [9] and Genc et al. were able to show the same effects with an average follow-up of 22 months [21]. In accordance with these observations, the stance-time on the previously injured extremity was reduced in three of the five gait tasks in our study. Swing, stance-time, and gait speed are associated with the overall foot function [22] and correlated with foot pain [10, 23]. Through the reduction of stance-time and maximum-load, less weight is put on the injured extremity for a shorter time.

Interestingly, no significant changes were seen between the uninjured and injured extremities in ap COP excursions, suggesting that the foot roll-over motion is similar on both sides. In our study the mediolateral COP excursion was decreased during stair-up and decreasing slope walking and increased during stair-down walking. Mediolateral shift in the COP during the stance phase of walking is caused by the muscle activity necessary to achieve postural stability [24]. Decreased ml COP displacements and, thus, decreased muscle activity to maintain postural stability can be explained by the reduced stance-time during stair-up walking and a tendency for decreased stance-time during decreasing slope walking. The decreased ground contact times require less muscular activity and, thus, generate less COP sway. However, the stance times between both extremities are comparable during the high impact task of stair-down walking. More muscle activity is required in order to achieve postural stability in the previously injured extremity during this difficult gait task and mediolateral centre-of-pressure sway is increased.

Overall, the changes in maximum load seen in our study are comparable to those observed by Colak in his study on long-term gait changes in talus fracture patients using a stationary force plate [6]. However, Colak was able to show changes in pressure distribution between forefoot and rearfoot; a result which we were not able to observe in our study. One explanation for this could be reduced detection resolution due to the lower number of pressure sensors in

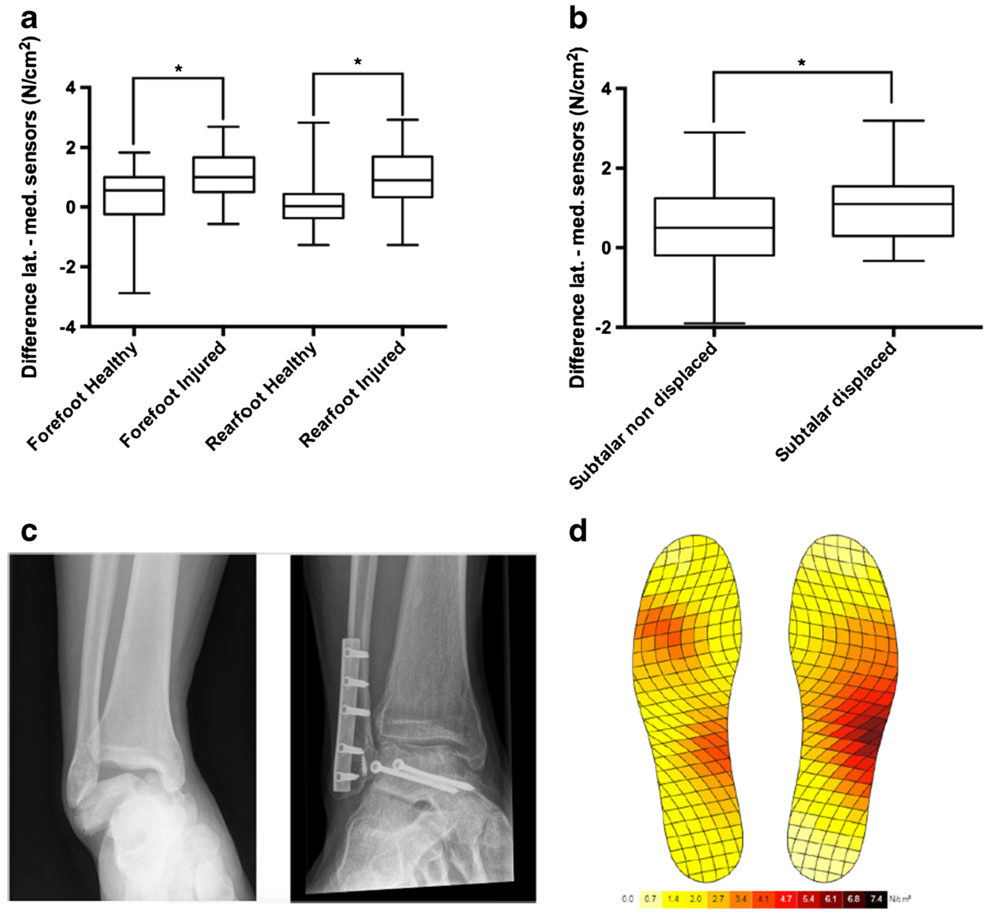

Fig. 2 Box plots (**a**) show the average difference between medial and lateral pressure sensor measurements in the forefoot and rearfoot of the healthy and previously fractured foot (injured), as well as the average difference between medial and lateral pressure sensor measurements in patients with and without subtalar fracture displacement (**b**). Positive values indicate greater pressures laterally. Boxes show 1st and 3rd quartiles and mean. Whiskers show min. to max. values. *$p < 0.05$. Pre-operative and 45 months post-operative radiographic results after talar neck fracture in an ap mortise view (**c**). The associated average pressure profile shows a pressure maximum in the lateral rear, to midfoot sensors (**d**)

the insole. This applies especially to the toes, where the insole only has one sensor for the greater toe; thus, rendering measurements in the forefoot less precise. Further diverging factors in the studies are the different average follow-up times and differences in fracture severity, doubtlessly due to the relative rarity of talus fractures.

Changed pressure-distribution and gait timing is associated with clinical outcome and injury severity

When correlating gait parameters to outcome, several moderate associations were seen depending on the gait task. During even-surface walking and increasing slope walking, increased ap and ml COP displacement was associated with better clinical results. The ap COP displacement is a measure of the fluency of the stance phase during regular gait, and has been used to analyze unilaterally impaired gait, with higher ap COP displacement and gait line length indicating a more physiological gait pattern [25, 26]. Accordingly, patients with better overall function have more fluent, physiological gait patterns. These associations were most pronounced during even surface walking. One reason for the lack of correlation during more complex gait tasks could be a generally more cautious approach to the difficult gait situation, reflected in the reduced load integral and maximum loads. Greater focus on a gait task has been shown to increase postural stability, compared to gait tasks performed under cognitive distraction [27]. Patients in our study performing these difficult gait tasks displayed gait patterns associated with decreased gait speed. Poorer clinical outcomes were associated in all other gait tasks with increased double-support-time or cycle-time and/or decreased cadence. Patients with worse clinical functions thus seem to reduce gait speeds during more difficult tasks. This is understandable, as slower gait speeds have been shown to increase postural stability during difficult gait tasks [28].

The observed mediolateral pressure-distribution changes in our study have previously been shown for fractures immediately below (Calcaneus) [9, 21] and also immediately above (Pilon) the talus [7], but have never before been demonstrated in the talus itself. The effect can be explained by decreased eversion motion of the hind foot [29], as fractures around the subtalar joint are associated with decreased subtalar motion [30]. This restriction of eversion through subtalar injury/dislocation [31] explains the significantly increased pressure lateralization in patients with Marti-Weber type III and IV fractures. Eversion is part of the subtalar motion range and is needed to allow talus rotation during load transformation from heel contact to full support. Limited eversion motion leads to more inverted foot positions, shifting the transferred load laterally and reducing the foot's ability to accept weight during stance [30, 32].

Therapy implications of observed gait results

Our results show changes in gait timing and pressure-distribution, both associated with the long-term clinical outcome. Hirschmueller et al. were able to show comparable correlations of gait speeds with clinical outcome as measured with the AOFAS score in patients with calcaneal fractures and subtalar injury combined with equally disturbed pressure-distribution patterns, suggesting that an emphasis on sensorimotor training during early rehabilitation could improve the clinical outcome [8]. Similar gait results were shown by Jansen et al. again in calcaneus fractures, further highlighting that pedobarography-assisted physical therapy and customized orthoses could potentially minimize the pathological pressure patterns and improve early and late clinical results [9]. The measurement protocol presented here could thus serve two purposes during rehabilitation: early detection of the described gait impairments and monitoring of the therapy progress. Feedback training with the insole version presented is already possible either through live, concurrent, or delayed feedback (knowledge of results), training techniques increasing both short and long-term compliance [33]. The general effect of training with wearable gait analysis systems has already been shown in various studies [34, 35]. The measurement protocol presented here could be immediately implemented in further clinical and interventional studies to determine the effect of the proposed training measures on the clinical outcome after talus fractures, but also further lower extremity injuries [36, 37].

Limitations

This study has several limitations. It was a single-centre, retrospective study combining different fracture types and osteosynthetic techniques to ensure adequate participant numbers. Osteosynthetic treatment was not further analyzed. Furthermore, conclusions were drawn from a relatively small cohort with a rather high rate of loss to follow up (51%), owing, in part, to the long follow-up period. The inhomogeneous follow-up was due to the rare occurrence of these fractures. Talus fractures account for less than 0.5% of all fractures and studies with larger cohorts are rare [38]. In order to avoid a further reduction in the number of patients participating in this study, we elected to include patients with further lower extremity injuries; thus, limiting the informative strength of this study. Interventional studies to determine the effect of gait analysis-assisted physical therapy studies and customized orthoses are needed.

Conclusion

Fractures of the talus lead to significant long-term radiographic and clinical changes. Pathological gait patterns associated with worse outcome can be identified by task-specific dynamic gait analysis. Changes in pressure distribution are associated with the initial severity of the injury and suggest therapeutic interventions based on the gait results. Further pedobarographic analyses focusing on therapeutic interventions are necessary.

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Compliance with ethical standards

Conflict of interest The insole material for this study was provided by the TK System of the AO Foundation. Senior Author Prof. Tim Pohlemann is Chairman of the TK System of the AO Foundation. Authors Tim Pohlemann and Benedikt Braun have served as unpaid advisors to Moticon GmbH. No further conflict of interest or funding sources exist.

References

1. Ahmad J, Raikin SM (2006) Current concepts review: talar fractures. Foot Ankle Int 27(6):475–482
2. Halvorson JJ, Winter SB, Teasdall RD, Scott AT (2013) Talar neck fractures: a systematic review of the literature. J Foot Ankle Surg 52(1):56–61. https://doi.org/10.1053/j.jfas.2012.10.008
3. Fournier A, Barba N, Steiger V, Lourdais A, Frin JM, Williams T, Falaise V, Pineau V, Salle de Chou E, Noailles T, Carvalhana G, Ruhlmann F, Huten D (2012) Total talar fracture - long-term results of internal fixation of talar fractures. A multicentric study of 114 cases. Orthop Traumatol Surg Res 98(4 Suppl):S48–S55. https://doi.org/10.1016/j.otsr.2012.04.012
4. Rammelt S, Zwipp H (2009) Talar neck and body fractures. Injury 40(2):120–135. https://doi.org/10.1016/j.injury.2008.01.021
5. Sanders DW, Busam M, Hattwick E, Edwards JR, McAndrew MP, Johnson KD (2004) Functional outcomes following displaced talar neck fractures. J Orthop Trauma 18(5):265–270
6. Colak TK, Colak I, Timurtas E, Bulut G, Polat MG (2016) Pedobarographic and radiological analysis after treating a talus neck fracture. J Foot Ankle Surg 55(6):1216–1222. https://doi.org/10.1053/j.jfas.2016.07.017
7. Jansen H, Fenwick A, Doht S, Frey S, Meffert R (2013) Clinical outcome and changes in gait pattern after pilon fractures. Int Orthop 37(1):51–58. https://doi.org/10.1007/s00264-012-1716-1
8. Hirschmuller A, Konstantinidis L, Baur H, Muller S, Mehlhorn A, Kontermann J, Grosse U, Sudkamp NP, Helwig P (2011) Do changes in dynamic plantar pressure distribution, strength capacity and postural control after intra-articular calcaneal fracture correlate with clinical and radiological outcome? Injury 42(10):1135–1143. https://doi.org/10.1016/j.injury.2010.09.040
9. Jansen H, Frey SP, Ziegler C, Meffert RH, Doht S (2013) Results of dynamic pedobarography following surgically treated intra-articular calcaneal fractures. Arch Orthop Trauma Surg 133(2):259–265. https://doi.org/10.1007/s00402-012-1655-8

10. Mayich DJ, Novak A, Vena D, Daniels TR, Brodsky JW (2014) Gait analysis in orthopedic foot and ankle surgery–topical review, part 1: principles and uses of gait analysis. Foot Ankle Int 35(1):80–90. https://doi.org/10.1177/1071100713508394
11. Braun BJ, Veith NT, Rollmann M, Orth M, Fritz T, Herath SC, Holstein JH, Pohlemann T (2017) Weight-bearing recommendations after operative fracture treatment-fact or fiction? Gait results with and feasibility of a dynamic, continuous pedobarography insole. Int Orthop 41(8):1507–1512. https://doi.org/10.1007/s00264-017-3481-7
12. Braun BJ, Bushuven E, Hell R, Veith NT, Buschbaum J, Holstein JH, Pohlemann T (2016) A novel tool for continuous fracture aftercare - clinical feasibility and first results of a new telemetric gait analysis insole. Injury 47(2):490–494. https://doi.org/10.1016/j.injury.2015.11.004
13. Braun BJ, Veith NT, Hell R, Dobele S, Roland M, Rollmann M, Holstein J, Pohlemann T (2015) Validation and reliability testing of a new, fully integrated gait analysis insole. J Foot Ankle Res 8:54. https://doi.org/10.1186/s13047-015-0111-8
14. Canale ST, Kelly FB Jr (1978) Fractures of the neck of the talus. Long-term evaluation of seventy-one cases. J Bone Joint Surg Am 60(2):143–156
15. Kubosch EJ, Erdle B, Izadpanah K, Kubosch D, Uhl M, Sudkamp NP, Niemeyer P (2016) Clinical outcome and T2 assessment following autologous matrix-induced chondrogenesis in osteochondral lesions of the talus. Int Orthop 40(1):65–71. https://doi.org/10.1007/s00264-015-2988-z
16. Olerud C, Molander H (1984) A scoring scale for symptom evaluation after ankle fracture. Arch Orthop Trauma Surg 103(3):190–194
17. Bargon G, Henkemeyer H (1977) Long-term radiological and clinical observations following surgery for tibio-fibular syndesmosis after fractures of the upper ankle joint (author's transl). RoFo 126(6):542–545. https://doi.org/10.1055/s-0029-1230633
18. Rammelt S, Biewener A, Grass R, Zwipp H (2005) Foot injuries in the polytraumatized patient. Unfallchirurg 108(10):858–865
19. Metzger MJ, Levin JS, Clancy JT (1999) Talar neck fractures and rates of avascular necrosis. J Foot Ankle Surg 38(2):154–162
20. Pajenda G, Vecsei V, Reddy B, Heinz T (2000) Treatment of talar neck fractures: clinical results of 50 patients. J Foot Ankle Surg 39(6):365–375
21. Genc Y, Gultekin A, Duymus TM, Mutlu S, Mutlu H, Komur B (2015) Pedobarography in the assessment of postoperative calcaneal fracture pressure with gait. J Foot Ankle Surg. https://doi.org/10.1053/j.jfas.2015.07.018
22. Piriou P, Culpan P, Mullins M, Cardon JN, Pozzi D, Judet T (2008) Ankle replacement versus arthrodesis: a comparative gait analysis study. Foot Ankle Int 29(1):3–9. https://doi.org/10.3113/FAI.2008.0003
23. Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR (2011) Cross-sectional analysis of foot function, functional ability, and health-related quality of life in older people with disabling foot pain. Arthritis care & research 63(11):1592–1598. https://doi.org/10.1002/acr.20578
24. Baratto L, Morasso PG, Re C, Spada G (2002) A new look at posturographic analysis in the clinical context: sway-density versus other parameterization techniques. Mot Control 6(3):246–270
25. Hesse S, Luecke D, Jahnke MT, Mauritz KH (1996) Gait function in spastic hemiparetic patients walking barefoot, with firm shoes, and with ankle-foot orthosis. Int J Rehabil Res 19(2):133–141
26. Robain G, Valentini F, Renard-Deniel S, Chennevelle JM, Piera JB (2006) A baropodometric parameter to analyze the gait of hemiparetic patients: the path of center of pressure. Ann Readapt Med Phys 49(8):609–613. https://doi.org/10.1016/j.annrmp.2006.05.002
27. Catena RD, van Donkelaar P, Chou LS (2007) Cognitive task effects on gait stability following concussion. Exp Brain Res 176(1):23–31. https://doi.org/10.1007/s00221-006-0596-2
28. Luximon Y, Cong Y, Luximon A, Zhang M (2015) Effects of heel base size, walking speed, and slope angle on center of pressure trajectory and plantar pressure when wearing high-heeled shoes. Hum Mov Sci 41:307–319. https://doi.org/10.1016/j.humov.2015.04.003
29. Rosenbaum D, Lubke B, Bauer G, Claes L (1995) Long-term effects of hindfoot fractures evaluated by means of plantar pressure analyses. Clin Biomech 10(7):345–351
30. Pozo JL, Kirwan EO, Jackson AM (1984) The long-term results of conservative management of severely displaced fractures of the calcaneus. J Bone Joint Surg Br Vol 66(3):386–390
31. Prada-Canizares A, Aunon-Martin I, Vila YRJ, Pretell-Mazzini J (2016) Subtalar dislocation: management and prognosis for an uncommon orthopaedic condition. Int Orthop 40(5):999–1007. https://doi.org/10.1007/s00264-015-2910-8
32. Spaulding SJ (2008) Basic biomechanics. In: Jacobs K (ed) Ergonomics for therapists. Elsevier, St. Louis, p 460
33. Winstein CJ, Pohl PS, Cardinale C, Green A, Scholtz L, Waters CS (1996) Learning a partial-weight-bearing skill: effectiveness of two forms of feedback. Phys Ther 76(9):985–993
34. Wall C 3rd, Wrisley DM, Statler KD (2009) Vibrotactile tilt feedback improves dynamic gait index: a fall risk indicator in older adults. Gait Posture 30(1):16–21. https://doi.org/10.1016/j.gaitpost.2009.02.019
35. Wheeler JW, Shull PB, Besier TF (2011) Real-time knee adduction moment feedback for gait retraining through visual and tactile displays. J Biomech Eng 133(4):041007. https://doi.org/10.1115/1.4003621
36. Deleanu B, Prejbeanu R, Crisan D, Predescu V, Popa I, Poenaru DV (2015) Gait characteristics before hardware removal in patients operated upon for tibial plateau fractures. Int Orthop 39(7):1411–1415. https://doi.org/10.1007/s00264-015-2691-0
37. Braito M, Dammerer D, Kaufmann G, Fischler S, Carollo J, Reinthaler A, Huber D, Biedermann R (2014) Are our expectations bigger than the results we achieve? A comparative study analysing potential advantages of ankle arthroplasty over arthrodesis. Int Orthop 38(8):1647–1653. https://doi.org/10.1007/s00264-014-2428-5
38. Court-Brown CM, Caesar B (2006) Epidemiology of adult fractures: a review. Injury 37(8):691–697. https://doi.org/10.1016/j.injury.2006.04.130