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Short communication

Vertical ground reaction forces in patients after calcaneal trauma surgery

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ABSTRACT

Introduction: Vertical ground reaction forces (VGRFs) are altered in patients after foot trauma. It is not known if this correlates with ankle kinematics. The aim of this study was to analyze VGRFs in patients after calcaneal trauma and correlate them to patient-reported outcome measures (PROMs), radiographic findings and kinematic analysis, using a multi-segment foot model. In addition, we determined the predictive value of VGRFs to identify patients with altered foot kinematics.
Methods: Thirteen patients (13 feet) with displaced intra-articular calcaneal fractures, were included an average of two years after trauma surgery. PROMs, radiographic findings on postoperative computed tomography scans, gait analysis using the Oxford foot model and VGRFs were analysed during gait. Results were compared with those of 11 healthy subjects (20 feet). Speed was equal in both groups, with healthy subjects walking at self-selected slow speed (0.94 ± 0.18m/s) and patients after surgery walking at self-selected normal speed (0.94 ± 0.29 m/s). ROC curves were used to determine the predictive value.
Results: Patients after calcaneal surgery showed a lower minimum force during midstance ($p = 0.004$) and a lower maximum force during toe-off ($p = 0.011$). This parameter correlated significantly with the range of motion in the sagittal plane during the push-off phase (r 0.523, $p = 0.002$), as well as with PROMs and with postoperative residual step-off (r 0.423, $p = 0.016$). Combining these two parameters yielded a cut-off value of 193% ($p < 0.001$), area under the curve 0.93 (95%confidence interval 0.84–1.00).
Conclusion: Patients after calcaneal fracture showed lower minimum force during midstance and lower maximum force during toe-off compared to healthy subjects. This lower maximum force during push-off correlated significantly with PROMs, range of motion in the sagittal plane during push-off and radiographic postoperative residual step-off in the posterior facet of the calcaneal bone. VGRFs are a valuable screening tool for identifying patients with altered gait patterns.

1. Introduction

Previous studies found that vertical ground reaction forces (VGRFs) and kinematics were altered in patients after calcaneal bone pathology [1–7]. It is unclear whether altered kinematics in patients correlate with altered VGRFs, but if so, then VGRFs can hypothetically be used as a screening instrument to identify patients with altered foot and ankle kinematics who need a more detailed kinematic analysis with a multi-segment foot model (MSFM) [8–11].

The aim of this study was to examine the VGRFs of patients after calcaneal surgery and correlate them to kinematics, patient-reported outcome measures (PROMs) and radiographic findings. Healthy subjects were used as a control group. The hypothesis we tested was that patients after calcaneal surgery would show lower VGRFs during push-off compared to healthy subjects, and that this would correlate with kinematics, PROMs and radiographic findings.

2. Methods

2.1. Study population

Thirteen patients (13 feet) who had undergone calcaneal surgery were included. All patients had displaced intra-articular calcaneal fractures and had surgical treatment with open reduction and internal fixation (ORIF) with an L-shaped incision and plate and screw osteosynthesis. They were included an average of two years after surgery. Exclusion criteria were surgery and/or fractures of the contralateral foot, congenital abnormalities of the lower extremities, concomitant neurotrauma and pathologic fractures. The results were compared with those of 11 healthy subjects (20 feet). All patients signed an informed

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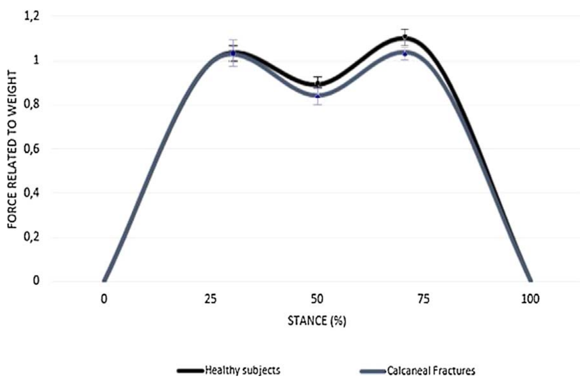

Fig. 1. Vertical ground reaction forces during stance for patients after calcaneal surgery and healthy subjects.

consent form before participation, and the study was approved by the medical ethics committee (METC 10-3-072 and NCT02576730).

2.2. Protocol

All participants were analysed separately on different days, by one experienced researcher. Participants were asked to walk at self-selected normal, slow and fast speeds. VGRF graphs were made from heel strike to toe-off. (Fig. 1) [12,13]. Absolute maximum forces (Newton) during heel landing (first peak/phase 1) and toe-off (second peak, phase 3), and minimum forces during midstance (phase 2), were recorded for all participants. In addition, the absolute difference in force (Newton) between these phases was noted. All results were also calculated as percentages of weight.

Baseline data were derived from the case record form, secondary PROMs (American Orthopaedic Foot and Ankle Society [AOFAS] ankle-hindfoot score, Foot Ankle Disability Index [FADI], Visual Analogue Scale [VAS] for pain, Short Form-36 Health Survey [SF36]) were filled out [14]. Radiographic findings on postoperative computed tomography scans (6 months after surgery) were analysed by two independent researchers blinded to the VGRF results. All fractures were classified by the Sanders classification, and the step-off and the gap in the posterior facet of the calcaneal bone were measured. In the movement laboratory, kinematic parameters during gait were analysed using the Oxford Foot model (OFM) [7,10,11].

2.3. Equipment

VGRFs were determined during gait. A force plate (Kistler 9282E) was used to identify the contact with the floor. Other kinematic parameters were analysed with the VICON MX 3 system. In this setting, eight cameras were used (6 MX3 and 2 T20 running at 200 Hz). Markers were attached with double-sided tape at specific anatomic points, following the guidelines of the OFM [7,10,11].

2.4. Data analysis and statistics

Vicon data was converted with Matlab (version 7.12,2011) and analysed in SPSS (IBM Statistics, version 20). The patient characteristics were analysed using descriptive statistics. Distribution was tested with the Shapiro-Wilk test. The independent samples *t*-test was used to find differences; with a *p*-value below 0.05 being considered statistically significant. The Pearson correlation test was used to find correlations. ROC curves were used to determine the predictive value of VGRFs. First, all participants with altered kinematics were defined, by selecting all subjects who deviated by one standard deviation for all kinematic parameters. Subsequently, ROC curves were constructed from the results of all participants. The cut-off point for VGRFs was determined at 100% sensitivity to find all patients with altered gait. Results are presented with area under the curve (AUC) and 95% confidence interval (CI).

Table 1
Participants Characteristics.

	Calcaneal Fractures	Healthy Control	p-value
Patiënt (n, feet)	13,13	11,20	
Age (years)	50.6 ± 15.8 (25–81)	43.1 ± 18.2 (20–65)	0.245
Gender (n, % Male)	13, 100%	9, 82%	0.163
Side (n,% right)	3, 23%	10,50%	0.167
Height (m)	1.74 ± 0.08 (1.60-1.87)	1.80 ± 0.05 (1.69-1.85)	0.068
Weight (kg)	77.8 ± 12.2 (51–90)	76.4 ± 9.3 (62–91)	0.745
BMI	25.5 ± 3.5(19.9–31.1)	23.6 ± 2.4 (19.4-26.9)	0.144
Sanders Classification	2A 1		
	2B 8		
	3AB 1		
	3BC 2		
	4 1		
Questionnaires			
FADI	71.7 ± 15.2 (30.8-96.2)		
AOFAS	70.7 ± 14.9 (33–93)		
SF-36 physical funct.	64.2 ± 22.4 (15–95)		
VAS	4.0 ± 2.7 (0–9)		
Kinematics Hindfoot-Tibia			
Loading Phase			
Sagittal Plane	7.45 ± 2.95 (4.12-16.00)	10.72 ± 2.16 (6.92-14.78)	**0.001**
Frontal Plane	11.13 ± 4.25 (5.94-18.56)	11.76 ± 3.02 (7.22-17.03)	0.790
Transverse Plane	4.97 ± 1.86 (3.28-9.71)	6.27 ± 2.04 (2.95-11.21)	0.140
Hindfoot-Tibia			
Push-off Phase			
Sagittal Plane	7.32 ± 2.78 (3.67-11.64)	13.14 ± 3.26 (7.60-18.35)	**< 0.001**
Frontal Plane	12.83 ± 4.06 (6.86-21.83)	10.79 ± 4.85 (5.84-27.25)	0.152
Transverse Plane	6.96 ± 3.58 (1.95-13.03)	10.58 ± 3.76 (4.94-17.89)	**0.027**

Data are presented as mean ± standard deviation (min-max) or n (percentage).
All the bold values are significantly differences between groups.

Table 2
Speed and vertical ground reaction forces in patients after calcaneal surgery and healthy subjects.

	Healthy subjects	Calcaneal Fractures	p-value
Speed (m/s)	0.94 ± 0.18 (0.66–1.23)	0.94 ± 0.29 (0.17–1.35)	0.999
Slow	0.94 ± 0.18 (0.66–1.23)	0.73 ± 0.26 (0.16–1.06)	**0.014**
Normal	1.21 ± 0.20 (0.91–1.59)	0.94 ± 0.29 (0.17–1.35)	**0.008**
Fast	1.62 ± 0.27 (1.25–2.11)	1.20 ± 0.33 (0.48–1.60)	**0.001**
Absolute Forces (Newton)			
Phase 1 Maximum peak force during loading phase	762 ± 101 (606–914)	776 ± 154 (443–943)	0.746
Phase 2 Minimum peak force during midstance	684 ± 90 (567–829)	650 ± 107 (438–786)	0.323
Phase 3 Maximum peak force during push-off	817 ± 112 (650–1041)	783 ± 130 (495–950)	0.425
difference between phase 1 and 2	77.2 ± 49.4 (25.0-208)	126 ± 86.0 (5.00-291)	0.079
difference between phase 2 and 3	133 ± 72.7 (38.0-333)	133 ± 65.2 (42.0-267)	0.993
Forces related to weight (%)			
Phase 1 Maximum peak force during loading phase	99 ± 5 (88–110)	99 ± 7 (87–110)	0.981
Phase 2 Minimum peak force during midstance	89 ± 5 (77–98)	84 ± 5 (74–90)	**0.004**
Phase 3 Maximum peak force during push-off	106 ± 7 (98–125)	100 ± 4 (92–108)	**0.011**
difference between phase 1 and 2	10 ± 6 (4–25)	16 ± 10 (1–36)	0.062
difference between phase 2 and 3	17 ± 9 (6–40)	17 ± 7 (5–33)	0.904

Data are presented as mean ± standard deviation (min-max) or n (percentage).
All the bold values are significantly differences between groups.

3. Results

3.1. Patient characteristics

The study sample consisted of 13 patients after calcaneal surgery (13 feet) and 11 healthy subjects (20 feet) (Table 1). There were no complications in terms of infections or revision surgery. Only walking speed was significantly different between the two groups when subjects walked at self-selected normal speed (0.94 ± 0.29 vs 1.22 ± 0.20 m/s $p = 0.002$). No significant differences in speed were found between patients walking at normal speed and healthy subjects walking at slow speed (0.94 ± 0.29 vs 0.94 ± 0.18 m/s $p = 0.999$) (Table 2).

3.2. Vertical ground reaction forces

Patients after calcaneal surgery exerted a significantly lower minimum force during the midstance phase than the healthy subjects ($p = 0.004$). They also had a lower maximum force during the toe-off phase ($p = 0.011$) (Table 2) (Fig. 1).

3.3. Correlations

The maximum force during toe-off correlated significantly with the ROM in the sagittal plane during the push-off phase (r 0.523, $p = 0.002$) and with the PROMs (FADI [r 0.443, $p = 0.010$], AOFAS [r 0.436, $p = 0.011$], SF-36 for physical functioning [r 0.397, $p = 0.022$] and VAS [r 0.498, $p = 0.003$]) (Supplementary Table 1). The minimum force during stance correlated significantly with the ROM in the sagittal plane during push-off (r 0.35, $p = 0.045$) Furthermore, both parameters correlated significantly with the residual step-off in the posterior facet of the calcaneal bone (r 0.423, $p = 0.016$ and r 0.353, $p = 0.047$, respectively).

3.4. Predictive value

Twelve patients after calcaneal surgery were found to have an altered gait pattern. The minimum peak force during midstance showed a cut-off point of 90% ($p = 0.002$), AUC 0.83 (95%CI 0.69–0.97). Thirteen participants (62%) without altered kinematics were identified as positive. The maximum peak force during the push-off phase showed a cut-off point of 109% ($p = 0.017$) AUC 0.75 (95%CI 0.58–0.92). Sixteen participants (76%) without altered kinematics were identified as positive. Combining these two parameters yielded a cut-off point of 193% ($p < 0.001$), AUC 0.93 (95%CI 0.84–1.00). Nine participants (43%) without altered kinematics were identified as positive (Supplementary Figs. 1–3).

4. Discussion

In previous studies we found a strong correlation between PROMs, radiographic findings and kinematic parameters for patients with calcaneal fractures [7]. The present study found a significant correlation between VGRFs, ROM, radiographic findings and PROMs. However, measuring VGRFs is less expensive and less time-consuming. Combining the VGRFs of minimum force during midstance and maximum force during push-off resulted in all patients with altered kinematics being identified. On the other hand, 43% of subjects without altered kinematics were nevertheless marked as having altered kinematics. However, in daily practice no healthy subjects without foot and ankle kinematics will visit the outpatient clinic.

This study had some limitations. As a consequence of the fracture and surgical treatment, walking speed was lower in the calcaneal surgery group. Speed has a significance influence on kinematic and dynamic data [15]. This is why we analysed the results with the patients after surgery walking at self-selected normal speed and healthy subjects walking at self-selected slow speed, resulting in equal speeds. Secondly, while gait analysis took place at least 6 months after surgery, there was a wide variety in the amount of time that had elapsed between surgery and gait analysis (6–36 months). Previous studies focusing on gait after surgery concluded that the greatest progress is found in first 6 months after surgery [12,13].

5. Conclusion

Patients after surgically treated calcaneal fractures showed lower minimum force during midstance and lower maximum force during toe-off compared to healthy subjects. This correlated significantly with PROMs, the ROM in the sagittal plane during push-off and the postoperative residual step-off in the posterior facet of the calcaneal bone. VGRFs were found to be a useful screening tool for identifying patients with altered gait patterns.

Conflicts of interest

None.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2017.09.026.

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