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Plantar Pressure Asymmetry in Patients Six Months after Surgical Treatment of Calcaneal Fractures in Adults

Soňa Jandová[1,2*], Martina Černeková[3] and Jan Pazour[4]

[1]Technical University of Liberec, Studentská 2, 461 17 Liberec, Czech Republic.
[2]Faculty of Physical Education and Sports, Charles University, José Martího 31, 162 52 Prague, Czech Republic.
[3]Faculty of Technology, Tomas Bata University in Zlín, Zlín, Czech Republic.
[4]Regional Hospital of Liberec, Husova, 460 01 Liberec, Czech Republic.

Authors' contributions

This work was carried out in collaboration between all authors. Author SJ designed the study, performed the measurement and data analysis, wrote the protocol and wrote the first draft of the manuscript. Author MC managed the analyses of the study. Author JP was responsible for the operative treatment, communication with patients and measurement. All authors read and approved the final manuscript.

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Short Research Article

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ABSTRACT

Aim: To compare plantar pressure distribution and contact time in patients in month 6 following operative treatment of calcaneal fractures.
Study Design: Walking on the tensometric platform.
Place and Duration of Study: Regional Hospital, Trauma Centrum, between September 2014 and October 2015.
Methodology: Gait analysis was carried out on seven patients (38±9 years; 1.79±0.05 m; 83±8 kg). Measurements were made using a pedobarography platform. The factors observed comprised: total contact time (CT), peak pressure (PP), maximum vertical force (Fz), heel contact time (CT-heel), peak pressure under the heel (PP-heel), and the force-time integral (FTI). The

**Corresponding author: E-mail: sona.jandova@tul.cz;*

analysis was based on the data from both the healthy and the affected lower limb; values for symmetry index (SI) were computed.
Results: Out of 7 patients, all patients with a longer contact time on the healthy feet were documented. The healthy limbs demonstrated peak pressure values that were predominantly higher beneath the heel, and under the first metatarsus head and under the big toe. On the affected limbs centre of pressure line shifted laterally. Foot contact was applied more often on the outer side of the foot. Not a clear trend was found in the contact time beneath the heel with the ground when 4 patients shortened the duration of the heel contact on the affected limb.
Conclusion: The observed patients still show significant lateral changes in dynamic parameters, which is also reflected in the duration of the individual phases of the gait cycle. The calculation of the index of symmetry for the tracked variables showed significant differences between healthy and affected limbs, although all the patients had returned to their working environments at the time of the measurement. This pilot study is a starting point for future work and co-operation between the University and the Trauma Centrum.

Keywords: Gait; pressure distribution; symmetry; contact time.

1. INTRODUCTION

Walking represents a fundamental form of human locomotion. Interaction between the central nervous system and various muscles ensures the erect posture of a human and the ability to respond to various ambient stimuli that affect balance [1]. Ideally, both lower limbs should act in symmetry when walking. Nevertheless, previous studies on laterality of the lower limbs [2] have reported that humans often possess a limb that is dominant, thereby potentially affecting gait symmetry to a significant degree. In general, a phenomenon (object) that becomes identical with itself is referred to as a symmetrical phenomenon. This definition makes it clear that, due to lateralization of both structure and functions, the human gait cannot be considered symmetrical in the true sense of the word.

A number of studies can be found in the literature from the 1980s and 1990s that track functional differences between the left and right lower limb [3-5]. The rate of significance of these differences was addressed by several authors [6-8]. In such early studies, discourse is given on the activity of muscles in the left and the right lower limb as actually being identical in healthy individuals [9-11]. However, this is a simple portrayal of walking, and such research is no longer acceptable in this age of advanced technology.

At present, the lateralization of both structure and functions during walking is generally recognized [12-14]. Indeed, the symmetry of gait is viewed from different perspectives. The most frequent aspects to be analysed pertain to kinematic parameters [15-17], dynamic parameters [18-20], and muscle activation via electromyography [21].

Quantitative indicators and statistical methods are used to evaluate the symmetry of the lower limbs or walking [4,6,12,18,22,23]. Often, different evaluative indexes are utilized that have their own thresholds. They cannot capture the localization of asymmetry, and are characterized by relatively low sensitivity [10].

The most common deviations from expression of symmetry in the left and right lower limb, or more specifically a healthy and injured lower limb, can be tracked in patients with various disabilities affecting the lower limb [24]. Such differences are described, for example, in patients after Anterior Crutiate ligament (ACL) trauma [25], in hemiplegics [7], and in hemiparetic patients [26]. Additionally, Kaufman et al. [27] focus on gait asymmetry in individuals with lower limbs of differing length.

Fractures of the calcanea account for about 2% of all fractures [28]. Males are affected ten times more frequently than women. Intra-articular fractures are prevalent (75%), the remainder of 25% pertaining to extra-articular fractures. Landing or falling from a height onto outstretched lower limbs is a typical mechanism of fracture. In order to select the relevant surgical strategy and to determine a long-term prognosis, especially one for development of subtalar arthrosis, classifying the intra-articular calcaneal fractures according to the procedure of Sanders is beneficial, and presently stands as the most widely used method. Based on a CT scan of the lower limb, such classification includes categorizing the fracture in the respective groups

according to the number and location of fracture lines in the back of the articular surface of the talocalcaneal joint. Treating calcaneal fractures involves either operative or conservative techniques. The aim of surgical treatment is to achieve anatomic reduction of the articular surface, and restoration of the shape and axis of the calcaneus. Evaluating the therapy given is normally based on analysing postoperative X-ray findings (calcaneus shape restoration, reduction of the articular surface, the degree of arthritis in the talocalcaneal and calcaneocuboid joint) and clinical evaluation. The latter of these usually utilizes what is known as the Ankle Hindfoot Score (AOFAS - American Orthopaedic Foot and Ankle Society), which evaluates the subjective symptoms of the patient, as well as the need for assistive aids and objective clinical findings in the lower limb, i.e. the axial position and stance phase of gait cycle [29]. Calcaneal fractures can be followed by various gait deviations [30,31].

The aim of the pilot study herein is to compare plantar pressure distribution and contact time in patients in month 6 following operative treatment for calcaneal fractures of type II - IV according to the classification given by Sanders [32], i.e. the time when patients are reintegrated at work. We hypothetise that in these patient there are still significant differences in the distribution of plantar pressure and gait remains asymmetrical.

2. MATERIALS AND METHODS

2.1 Participants

Gait analysis in this pilot study was carried out on seven patients - men (age 38±9 years; height 1.79±0.05 m; weight 83±8 kg). All the patients had received operative treatment for calcaneal fractures of type II - IV according to the classification given by Sanders. Fracture classification was performed on the basis of a CT scan, while operative treatment was conducted via osteosynthesis. The selected patients were not known to have had any other disorder affecting their gait or axial system prior to suffering from accidents; all of them had led an active life involving recreational sport before their accidents. No preliminary tests had been done prior to the accidents, i.e. the stage without health complications.

2.2 Study Design

Measurements took place over the six months following surgery, and since it is a pilot study, they are scheduled to continue in months 12, 24 and 36 after the dates of surgery or accident for a larger sample of patients; this activity is now underway. Surgery was carried out by the same surgeon. All patients were indicated to undergo the same form of rehabilitation, aimed at mobilizing the talocrural and subtalar joints, reducing swelling and, once tread was permitted, practising their normal walking style. The process of rehabilitation started on day 2 post-surgery in the hospital area and continued, under the supervision of a physiotherapist, 2-3 times per week and then at home once they had received proper instruction. All the patients monitored were able to walk without any means of support at the time of measurement.

2.3 Measurement and Data Analysis

Pilot pedobarography measurements were made using an Emed-c pressure plate (Novel, De). Every third step of the healthy lower limb and of the limb after surgery was measured for each patient; the steps measured amounted to ten steps per limb. Scanning frequency was 100 Hz and the data was subsequently processed by the appropriate software (Novel, De). The factors observed comprised the following: total contact time (CT), peak pressure (PP), maximum vertical force (Fz), heel contact time (CT-heel), peak pressure under the heel (PP-heel), and the force-time integral (FTI) - here the size depends on the amount of force and the time over which such force acts. Pressure (kPa) is defined as force acting on the surface; the methodology applied makes use of a pedography platform with 4 sensors per square cm. The pressure placed on a sensor is multiplied by the sensor area to indicate (vertical) force on that sensor. The sum of these forces from the individual sensors gives the vertical reaction force at the level of contact of the foot and the ground. Pressure measurement error equals 3.03% [33]. Analysis was based on data on both the healthy and affected lower limb; statistical processing was conducted using paired t-test (statistical significance $p = .05$); values for symmetry index (SI) were also computed.

3. RESULTS AND DISCUSSION

For the group of selected patients, the values for tracked variables (Table 1) were found to differ between the healthy and the injured lower limb. The healthy limb demonstrated peak pressure values that were predominantly higher beneath the heel, and under the head of the first metatarsus and under the big toe (Fig. 1). The

affected limb (to the right) showed values that were lower, with the point of centre of pressure (CoP) line shifted laterally. Foot contact was applied more often on the outer side of the foot.

The pilot study herein focused on evaluating lateral changes in plantar pressure distribution in the gait of patients who had received operative treatment for calcaneal fractures. The differences between the healthy and affected limbs were even apparent from the actual graphical record of the measurements. Such visualization clearly shows that peak plantar pressure values for the healthy limb are significantly higher, particularly in the areas beneath the heel, under the first metatarsus and under the big toe. It is also possible to monitor variation in the centre of pressure (COP). For the operated limb there is a lateral shift in COP, and patients make contact with the ground more frequently with the outer side of the foot. Heel fractures could potentially cause the lower limb to shorten (for example, due to post-traumatic flat foot); consequently, the centre of gravity excessively deflects sideways [30].

The calculation of the index of symmetry for the tracked variables showed significant differences between healthy and affected limbs, although all the patients had returned to their working environments at the time of measurement (month 6 after surgery) and their gaits no longer needed supporting aids; effectively, in medical terms, the patients were already healthy. However anatomic/functional disproportion of the lower limbs significantly affects gait symmetry [24].

3.1 Contact Time

The largest SI deviations from zero were found in patient #7, meaning that the gait of the patient was highly asymmetrical in contact time for both limbs. For the affected limb, contact time was lesser for all patients compared with the healthy one, which represented a statistically significant difference. This can be explained by the fact that patients in month 6 after surgery still did not utilize the affected limb during the support stage to the same extent as the healthy one, thereby diminishing this support stage, whether consciously or sub-consciously [30,31].

3.2 Peak Pressure

For peak pressure, the largest degree of asymmetry was computed for patient #6. In six of the seven patients, peak pressure was lower for the affected limb. These patients demonstrated significant elimination in the impacts made, especially in the first phase - the stance phase. The heel strike was very cautious [30,31]. The lowest deviation from zero SI (i.e. the largest symmetry) was found for patient #3. The peak pressure differences were statistically significant.

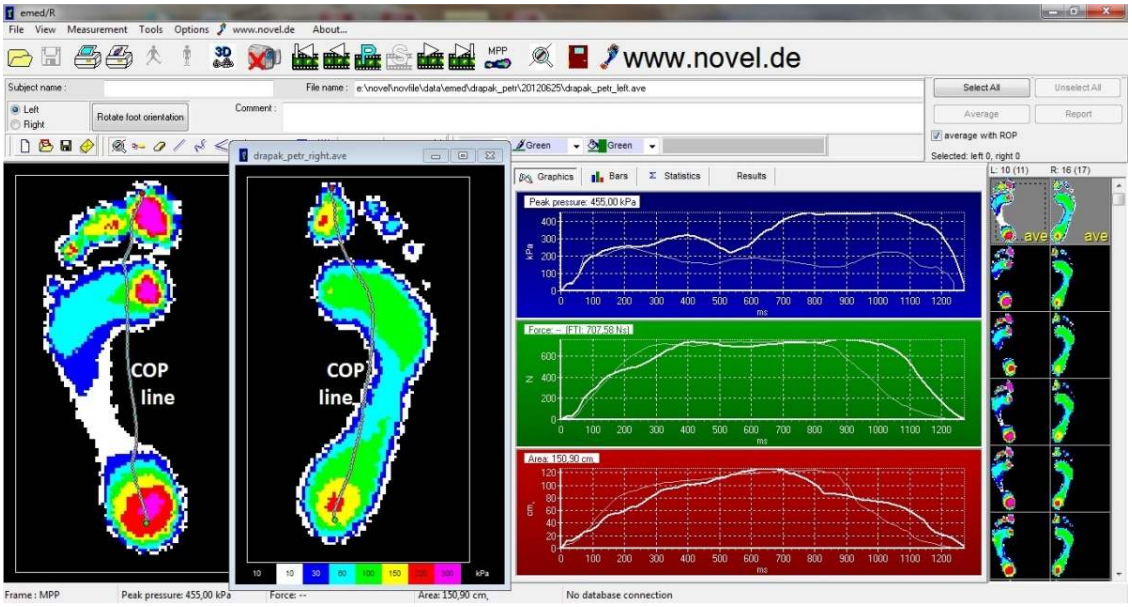

Fig. 1. Plantar pressure distribution and the centre of pressure (COP) line for a selected patient after a calcaneal fracture to the right side

Table 1. Monitored, dynamic parameters for gait and symmetry indices in healthy and injured lower limbs

N=7	CT [ms]			PP [kPa]			Fmax [N]			CT heel [ms]			PP heel [kPa]			FTI [Ns]		
	IF	HF	SI	IF	HF	SI	IF	HF	SI	IF	HF	SI	IF	HF	SI	IF	HF	SI
1	748	780	4,19	790	690	-13,51	1127	1163	3,14	441	476	7,63	350	370	5,56	557	564	12,49
2	890	900	1,12	425	640	40,38	823	863	4,74	549	600	8,88	210	295	33,66	548	547	-0,18
3	833	864	3,65	340	380	11,11	956	962	0,63	701	628	-10,99	340	375	9,79	550	622	12,29
4	804	832	3,42	320	370	14,49	864	913	5,51	689	561	-20,48	265	340	24,79	495	552	10,89
5	783	816	4,13	315	450	65,29	925	941	1,71	511	493	-3,59	315	340	7,63	539	559	3,64
6	984	1003	1,91	295	650	75,13	819	831	1,45	791	590	-29,11	255	270	5,71	522	598	13,57
7	853	916	7,12	355	705	66,04	786	799	1,64	562	624	10,46	315	375	17,39	498	539	7,91

Legenda: *IF: Injured feet; HF: Healthy feet; CT [ms]: Contact time total; PP [kPa]: Peak Pressure total; Fmax [N]: Maximal Force; CT heel [ms]: Contact time of the heel (heel = mask from Pedar); PP heel [kPa]: Peak Pressure under the heel; FTI [Ns]: Force time integral; SI: Symetry index*

3.3 Maximal Vertical Force and the Force Time Integral

When monitoring maximum vertical force, symmetry index calculations provided a basis for gauging reasonable coordination as regards the force acting on the healthy and the affected limbs. This finding may be due to the fact that the vertical component of the force when walking is related to the weight of the monitored individual, who alternates between using the healthy and affected limb during the support phase when moving without aiding equipment. The force time integral, the magnitude of which depends on the size of the force and the time over which the force acts, was found to be larger for the healthy limb in all the patients. The longer the force is applied, the greater its effect. Given that the contact time was shorter for the affected limb, the effect of the force could be assumed to be lesser as well.

3.4 Contact time and Peak Pressure under the Heel

The variables peak pressure under the heel (PP - heel) and heel contact time (CT - heel) seem to be crucial to the gait of an individual following a calcaneal fracture. It turns out that patients place their heel strike on an entirely individual basis. All of them try to minimize the burden on the heel at the beginning of the stance phase. This is influenced either by treading very carefully while seeking to eliminate significant impact, or treading on the midfoot [30,31], usually on edge of the outer foot. This moves COP in a lateral direction, as mentioned above. The lack of certainty when treading with persistent pain in the region of the talocalcaneal and calcaneocuboid joints may be the cause of both choices for such foot strike pattern. No significant difference was found between the healthy and affected limb in heel contact time. The values for peak pressure under the heel measured on the healthy leg were significantly higher. Patients who had experienced calcaneal trauma substantially eliminated pressure at the level of the heel and ground, but the calculated figures for symmetry index tend to indicate differences in the case of peak pressure monitored under the entire sole of the foot. Explanation could lie in an assumption that reaction forces between the foot and the ground are under strong influence not only for injured limbs, but also for healthy limbs, when patients are likely to shift pressure from the back more towards the middle and front parts of the healthy foot, due to pathological manifestation of their gait. In order to verify this assumption, it would be appropriate to monitor more patients and conduct kinematic video analysis of gait, which is beyond the scope of this pilot study.

The pedobarography method used provides information on distribution of pressure at the level of foot-ground interaction. However, based on study of the literature and the pilot measurements taken by the authors herein, it seems reasonable to view gait symmetry in terms of comprehensive behaviour of the lower limbs, rather than on the basis of locally measured parameters. For this reason, the authors recommend carrying out pedobarography measurements combined with 3D cinematography or EMG. Nevertheless, this is no longer possible to implement in routine hospital practice; rather, it necessitates using instrumentation in specialized workplaces, e.g. at universities.

4. CONCLUSION

Based on study of the literature and the hitherto pedobarography measurements of patients following surgical treatment for unilateral calcaneal fracture, the pedobarography record of gait can be considered a highly suitable method for monitoring lateral changes in the dynamic parameters of gait.

The pilot study implemented, founded upon a sample of seven patients in month 6 following surgery for fracture to the calcaneus, has led the authors to propose the following conclusions on evaluating lateral changes at the foot-ground contact level:

- As regards the affected limb, COP shifts laterally and patients tend to make more contact with the ground via the outer side of the foot;
- The duration of foot-ground contact is significantly shorter for the affected leg;
- Peak pressures under the heel, as well as beneath the entire sole, are significantly greater for the healthy leg;
- The maximal values for the vertical component of the reaction force do not significantly differ in the stance phase for the healthy and affected leg;
- The effect of force on the affected leg is significantly less than on the healthy leg;
- Heel-ground contact can be addressed individually for different patients; some

patients tread cautiously and slowly, while others significantly reduce the duration of heel to ground contact, applying their foot strike pattern via the midfoot;

In practice, this means that patients in month 6 who have received operative treatment for a calcaneal fracture still show significant lateral changes in dynamic parameters, which is also reflected in the duration of the individual phases of the gait cycle.

From a methodological aspect, the authors conclude that symmetry index - calculated as the ratio between two values measured using pedography platform - has proven to be a useful basis for analysing gait symmetry. In order to aid more accurate location, it shall be appropriate to split the sole of the foot into smaller sections and monitor values at the level of, for example, the heel, midfoot, metatarsal heads and toes. A combination of EMG and 3D cinematic analysis is assumed to be the best practice, although it would prove very difficult to instigate such research on hospital premises.

CONSENT

The written informed consent of all the individuals participating in the research was obtained for publication of this study.

ETHICAL APPROVAL

All experiments were performed with the approval granted by the institutional Review Board. The experimental work conforms to the highest standards, levels of safety and ethics, with respect to the Declaration of Helsinki /1964) and to the national laws.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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