Arch Orthop Trauma Surg (2011) 131:197–203
DOI 10.1007/s00402-010-1127-y

Biomechanics of postoperative shoes: plantar pressure distribution, wearing characteristics and design criteria: a preliminary study

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Received: 22 February 2010 / Published online: 12 June 2010

Abstract

Background Modern concepts in the postoperative treatment of first metatarsal osteotomies include special shoes that should decrease stress in the forefoot region. The purpose of this study was to determine plantar pressure distribution, wearing characteristics and stress-reducing effectiveness of five different types of commonly used postoperative shoes. Additionally, we wanted to modify the shoe that revealed the most favourable results in a way that improves forefoot relief as well as provides comfort to the patients.

Methods Eight persons consented to participate in the study. Plantar pressure distribution in five different types of postoperative shoes (Rathgeber® normal, Rathgeber® modified, 4. Darco® flat, Darco® VFE, Wocker®) was assessed using Mediologic® insoles. Also, subjective criteria considering wearing comfort, stability and rolling characteristics were evaluated. Based on the postoperative shoe revealing the most favourable results, further prototypes were developed. Each new model was targeted to meet the given requirements, minimal forefoot pressure, in a different way.

Results The Rathgeber® modified model revealed the most favourable results concerning plantar pressure distribution as well as subjective wearing characteristics. Therefore, it was chosen for further modifications. After adding an extra layer of high elastic and springy material for shock absorption at the hallux region, forefoot relief and wearing characteristics showed improved results.

Conclusion The results of the present study indicate that damping material in the hallux region of postoperative shoes minimises stress in this region and improves patient's comfort.

Keywords Plantar pressure distribution · Hallux valgus · Postoperative shoes · Forefoot relief

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Introduction

Several methods exist for the operative treatment of hallux valgus deformity, from soft tissue procedures to certain osteotomies of the first metatarsal [4, 5, 14, 17]. Modern concepts in the postoperative regimen of first metatarsal osteotomies for correction of hallux valgus deformity include special shoes that should decrease stress in the forefoot region [4, 14]. Trnka et al. have shown that repetitive loading is the limiting factor for postoperative stability of osteotomies. Adequate fixation of osteotomies is necessary to ensure osseous union, and screw fixation generally is sufficient. However, during healing, the osteotomy must be protected for 2–6 weeks [7, 13, 18]. Some surgeons allow full weight bearing immediately following surgery. This may lead to loss of fixation and malunion or nonunion of the osteotomy [8]. As the first ray is the most heavily loaded structure of the foot, it requires immobilisation and relief to undergo bony healing [3, 6]. The ideal postoperative shoe minimises load on the hallux and the first ray region, whilst allowing the patient to walk as gently as possible.

A number of authors have studied the plantar pressure characteristics of different types of postoperative shoes [2, 9–11, 16, 19]. However, none of these studies have examined the characteristics of the shoe in relation to the preferences and comfort of the patient. The postoperative shoe should be designed in a way that also addresses the demands of the patient in these aspects.

Orthopaedic foot and ankle surgeons need proof that a prescribed postoperative shoe reduces loading of the forefoot. Also, the shoe has to provide sufficient comfort to the patient.

The aims of the present study were: (1) to determine the plantar pressure distribution, wearing characteristics and stress-reducing effectiveness of five different types of commonly used postoperative shoes (Fig. 1a, b); (2) to modify based on previous results the most effective shoes in a way that improves comfort to the patient.

Materials and methods

Subjects

Eight persons (five men, three women) consented to participate in the study. They were healthy subjects without any complaints of their feet, callus, deformation, or history of trauma or surgery. Their mean height was 172 cm (SD 5.1), mean weight was 63 kg (SD 9.3) and average age was 26 years (range, 21 to 28). The study was performed with the approval of our institution's human subjects review board, and all participants signed an approved informed consent form.

Instrumentation

Medilogic® (T&T medilogic Medizintechnik GmbH, Unterschleissheim, Germany) insoles were used to measure the pressure distribution on the plantar surface of the feet during walking with various types of postoperative shoes (Fig. 1a, b). Each insole consists of 130 8-bit sensors, each designed to withhold a maximum pressure of 64 N/cm^2. The data were collected at 50 Hz and transmitted by cable from the Medilogic insoles to a Medilogic A/D synchronisation box worn at the subject's waist. The data were then relayed from the Medilogic data box to a computer. A 15-m flat indoor walking surface was used for the measurement setup.

Measurements

Before data collection, each subject's age, height and weight was recorded. The measurements were performed with eight healthy subjects wearing different models of postoperative shoes. Additionally, measurements were performed whilst the subjects walked barefoot.

The sensors of the Medilogic insoles were printed on paper in the scale 1:1. The outline of the feet of each subject was copied onto this paper to ensure the correlation between the Medilogic insoles and the outline of the subject's feet.

The Medilogic insoles were applied directly to the subject's feet and placed exactly at the specific anatomic regions of the foot: the heel, as well as the medial and lateral forefoot. Normal sports socks were applied to ensure stable fixation of the insoles. The order of placement under the subject's feet was sock, Medilogic insole, sports sock and the postoperative shoe.

A commercially available Nordic walking shoe was chosen as standard shoe on the left foot for all except the bare foot measurements. On the right foot, the subjects wore the different types of postoperative shoes; the order of the different shoe types was randomised. Each subject underwent eight consecutive walking trials and a different postoperative shoe was used for each trial.

Rosenbaum et al. [15] have shown that walking speed may influence plantar pressure distribution. To guarantee a high level of standardisation, the same walking speed, cadence as well as the same step length were chosen for all subjects. An acoustic signal provided a rate of 92 beats per min for the steps of the subjects. The standardised step length was set to 50 cm, which was realised by placing marks on the test track to provide a visual guide for the subjects, thus resulting in a walking speed of 0.76 m/s (2.76 km/h). This walking speed represents the postoperative walking speed of patients who undergo forefoot surgery.

As soon as the subject made the first step, all measurement units were started. Each subject walked 15 gait cycles (30 steps). Before data collection, each subject walked across the walkway two times to become accustomed to the different shoe types. To ensure correct pressure data, a zero load measurement was recorded for each insole prior to testing by consecutively lifting the feet off the floor.

A patient satisfaction score ranging from 1 to 5 was used to evaluate subjective feeling (1 being very bad and 5 being very good). The probands were instructed to consider three parameters for their evaluation: comfort, stability and rolling characteristics.

Data processing

The probands wore the postoperative shoes on the right and the reference shoe on the left foot. Data from both legs were collected and 30 complete stance phase recordings of each trial were analysed. The data collecting system

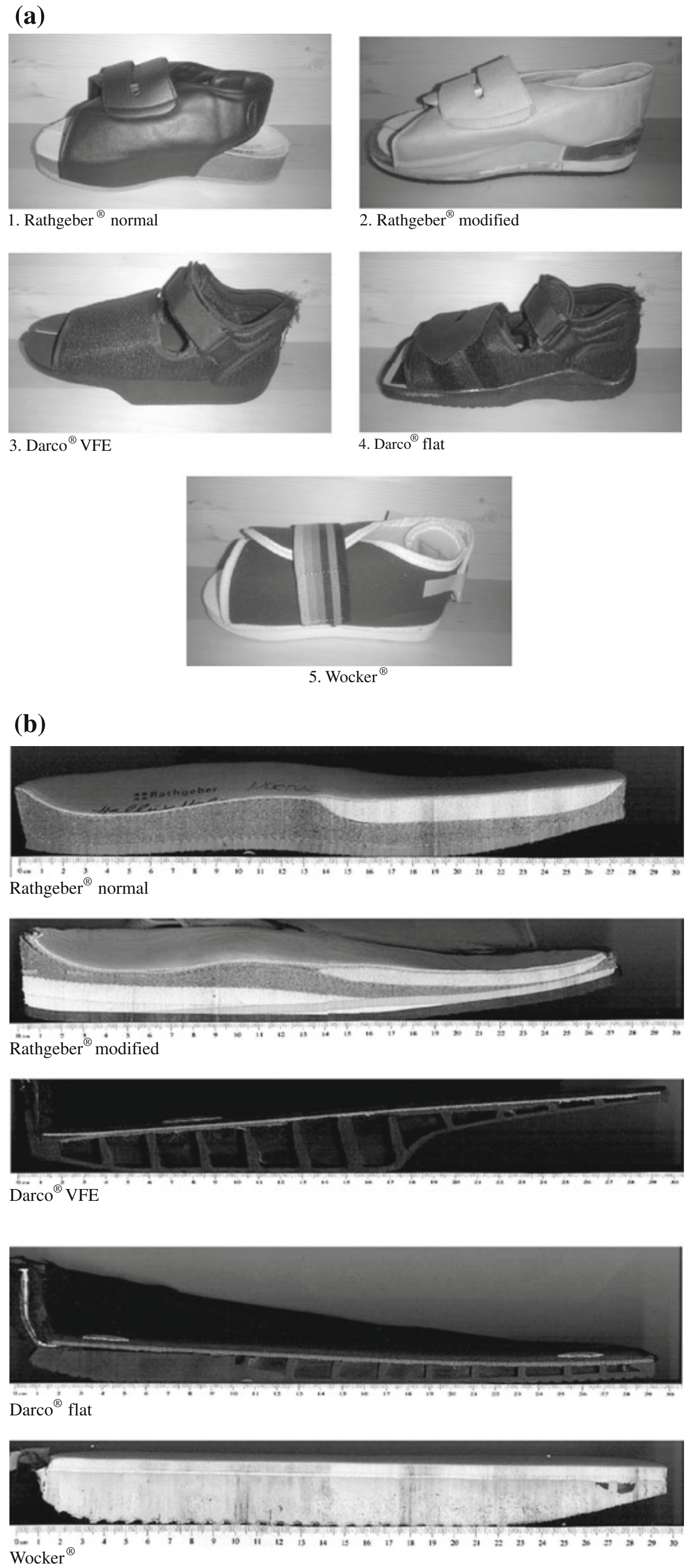

Fig. 1 **a** Five different types of postoperative shoes. **b** Transverse view of sole charactersitics of the different postoperative shoes

consisted of two main components, namely the Medilogic in-shoe pressure distribution measurement unit and a video camera used as a visual backup. The foot was divided into biomechanical useful sections according to Nyska et al. [12]. The foot was divided into seven sections: heel (H); midfoot (MF); forefoot lateral (FL); forefoot intermedial (FIM); forefoot medial (FM); lesser toes 2, 3, 4 and 5 (LT); and big toe (BT) (Fig. 2).

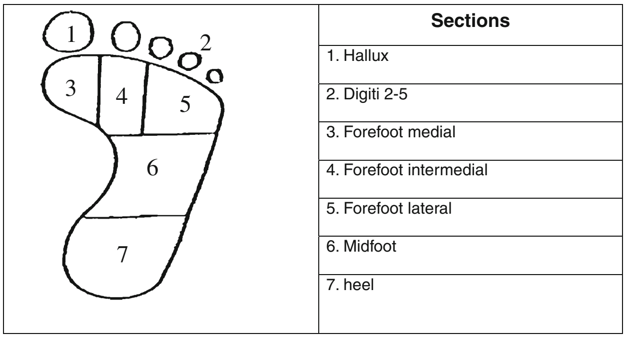

Fig. 2 Biomechanical sections of the foot according to Nyska et al. [14]

The mean of all steps of the following variables was used for the statistical analysis: mean force and maximum force.

Statistical analysis

Matlab® (MathWorks, Natik, MA, USA) was used to evaluate and compare the plantar pressure data. Statistical analysis was also performed via Matlab using Student's *t* test. Subjective wearing characteristics were analysed using MS Excel 2007 (Microsoft Corp., Redmond, V; USA) performing multifactorial ANOVAs. The level of significance was set at 0.05.

Results

Measurement 1: comparison of already existing postoperative shoes

The results of plantar pressure distribution and subjective wearing charactersistics of the different postoperaive shoe types are summarised in Table 1; Fig. 3, respectively.

The type Darco flat® (DF) as well as the type Wocker® (W) showed very high peak pressure under the medial forefoot compared to the others (Table 1).

Though Darco VFE® (DVF) delivered the lowest peak pressure in the hallux area, there were high forces acting on the medial forefoot. The Rathgeber® models showed the most favourable test results concerning forces acting on the forefoot and the hallux region, respectively. Extra elements with elastic and springy properties for shock absorption to decrease foot–ground reaction force were attached to the sole of the Rathgeber modified® (RM) model, which made it an improved version of the original. Especially, the forefoot showed low pressure parameters compared to all the other postoperative shoe types.

The Rathgeber models (RM and RN) revealed the most favourable results for comfort, stability and rolling characteristics. DF showed good results for stability; however, the results concerning rolling characteristics were worse than those of the Rathgeber models.

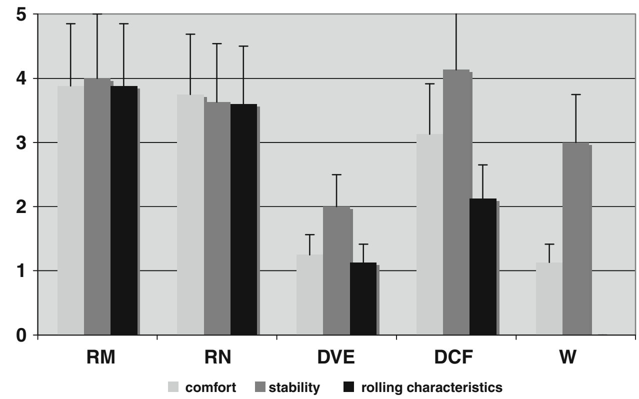

Fig. 3 Results of wearing charactersistics of five different postoperative shoes. ANOVA revealed statistically significant difference ($p < 0.001$) for comfort, stability and rolling characteristics between the different types. The *error bars* indicate the standard deviation

Table 1 Results of plantar pressure distribution measurements in different types of postoperative shoes [mean *xx* (SD *yy*)]

Shoe type	Abbreviation	Mean preassure (N/cm^2)		Peak preassure (N/cm^2)	
		Hallux	Forefoot	Hallux	Forefoot
Rathgeber normal	RN	5.6 (1.7)*	5.4 (1.2)*	28.7 (6.5)*	27.3 (15.5)*
Rathgeber modified	RM	5.0 (1.0)*	4.0 (1.0)*	32.3 (16.6)	17.9 (5.1)*
Darco VFE	DVF	3.7 (2.1)*	6.0 (1.1)*	16.8 (7.8)*	36.3 (14.2)
Darco flat	DF	7.3 (1.9)	8.1 (1.9)*	49.7 (11.8)	49.2 (12.7)
Wocker	W	6.4 (2.0)*	7.5 (1.4)*	38.8 (16.7)	39.9 (12.1)
Barefoot	WF	10.3 (3.6)*	11.1 (1.7)*	51.7 (12.6)	53.0 (11.9)
Reference shoe	RS	15.0 (2.2)	7.6 (1.3)	45.0 (8.3)	42.1 (9.4)
Negative heel	NH	4.8 (1.0)*	5.1 (1.1)*	30.4 (7.0)*	19.7 (6.9)*
Extra cushioning	SS	5.2 (0.7)*	4.9 (1.0)	31.5 (11.6)	19.2 (6.0)*
Antipronation	AP	5.6 (1.3)	5.5 (1.2)	33.1 (7.9)*	27.85 (6.4)*
Carbon	C	7.6 (2.1)	5.5 (1.8)	39.0 (11.6)	21.6 (6.5)*

* Statistically significant difference between the reference shoe and the postoperative shoe (Student's *t* test, $p < 0.05$)

Therefore, RM was chosen as a prototype for further research and development, with the goal of reducing the force acting on the forefoot regions even more.

Measurement 2: comparison of newly developed postoperative shoes

Based on the shoes that delivered the most favourable test results, the RM, further prototypes were developed. Each new model was targeted to meet the given requirements, minimal forefoot pressures, in a different way.

Table 1; Fig. 4 show plantar pressure distribution and subjective wearing characteristics, respectively, of those prototypes.

The main idea of the "antipronation shoe" (AP) was to channel the force away from the medial side of the foot and to distribute the pressure along the lateral side, thus relieving the traumatised regions. To do this, the sole of the shoe was gradually flattened towards the lateral side of the shoe. The subject was therefore compelled to exert the main force away from the medial region.

The "negative heel" (NH) model was an attempt to combine the positive effects of a negative heel shoe: the low forces acting in the hallux region (e.g. DVF) with the characteristics of a pronation friendly shoe. The degree of incline of the sole was chosen at a lesser degree than that of the DVF. Furthermore, the rocker line was moved slightly dorsally to shift the peak pressures from the forefoot towards the hind foot region. This shoe also showed acceptable results regarding forefoot relief, but subjective evaluation did not meet the requirements.

The "carbon shoe" (C) was enforced along the hallux with a carbon strengthening to minimise torque and thereby reduce the overall pressure. Due to the high stiffness of carbon though, the force was enhanced rather than reduced, with the mere ground reaction force exerting high pressure on the hallux.

The best shoe, considering numerical values as well as subjective opinions was the "extra cushioning shoe" (EC).

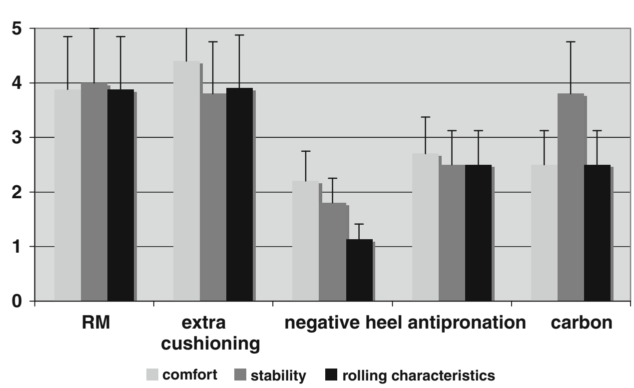

Fig. 4 Results of wearing charactersistics of an already existing postoperative shoe and four prototypes. ANOVA revealed statistically significant difference ($p < 0.001$) for comfort, stability and rolling characteristics between the different models. The *error bars* indicate the standard deviation

Discussion

Osteotomies of the first metatarsal are a well-established method for the operative treatment of hallux valgus deformity. [4, 5, 14] To ensure bony healing, postoperative shoes that decrease the load in the traumatised region are used for the postoperative treatment of metatarsal osteotomies [4, 14]. For patients who undergo surgery, the postoperative period is painful. Also, the functional limitations resulting from the trauma that is caused by the operation lead to discomfort. Because of this postoperative treatment, devices should be designed in a way that offers the patient as much comfort as possible.

Pedobarographic measurements are an effective tool to assess the effectiveness of load restriction of forefoot relief shoes [2, 9, 11]. Our study focused on plantar pressure characteristics as well as wearing comfort of different types of postoperative shoes. The results of this present study show that a precise design is important to decrease loading of the operated area.

Many postoperative shoes made of stiff materials, such as Darco flat® (DF) and Wocker® (W), are supposed to prohibit movement of the traumatised area. Both models showed very high peak pressures acting in the medial forefoot region. The stiff material of the sole barely allows any flexion and is supposed to prohibit movement of the traumatised area. The rigidity of the shoe leads to high torque in the foot, which results in high peak pressure acting in the area of the forefoot. These findings are supported by the results of the measurements of plantar pressure distribution of the prototype carbon shoe (C). Due to the high stiffness of the carbon element that was positioned at the hallux region, the acting force was enhanced rather than reduced.

Furthermore the types Darco flat® (DF) as well as the type Wocker® have no distinguished rocker line and do not actively support optimal rolling characteristics. The material of the ideal postoperative shoe should not be too rigid. Also, the shoe should include a rocker line that leads to acceptable rolling characteristics during the stance phase.

Though the Darco VFE® (DVF) delivers the lowest maximum force in the hallux area, it is not suitable for postoperative wear due to the high forces acting on the medial forefoot. Since it has a strong negative heel and a recess under the toes, a very prominent rocker line was created with its main force vector acting on the forefoot.

The Rathgeber® models applied the highest decrease of forces acting on the forefoot and the hallux region, respectively. Especially, the forefoot shows low pressure parameters compared to all the other postoperative shoe types, which is due to the fact that overall pressure is channelled more to the lateral side of the foot. The actual region that should be protected is embedded in a layer of extra damping material, thus reducing peak pressures.

The "antipronation shoe" (AP) as well as the "negative heel" (NH) shoe showed good numeric results. However, both models have not been evaluated well concerning their wearing characteristics. The sole of the AP shoe gradually flattened towards the lateral side of the shoe. This decreased the acting force in the hallux and forefoot region, respectively, but the subjects felt insecure whilst walking with this shoe.

The best shoe, considering numerical values as well as subjective opinions was the "extra cushioning shoe" (EC). This postoperative shoe combines all the positive elements of previous research, enabling relatively good rolling characteristics with a relatively good degree of comfort and pressure relief: the hallux region is cushioned with an extra layer of high damping material, the slightly dorsally shifted rocker line takes the pressure off the forefoot and the sealed heel straps add extra stability.

This study faces a number of limitations. First, the study was performed with healthy subjects with the aim of evaluating the characteristics of postoperative shoes. It might have been more appropriate to investigate patients who underwent hallux valgus surgery. However, a number of authors have studied the characteristics of postoperative shoes [1, 2, 9–11, 16, 18]. All of them performed their studies with healthy subjects. Also, one of our aims was to modify a commonly used shoe to improve its biomechanical characteristics. Performing the same investigations with patients in a postoperative situation would have proved much more difficult. However, our future research will focus on performing these investigations in patients in a postoperative situation.

Secondly, additional procedures such as interphalangeus correction or procedures on lesser toes might require different characteristics in postoperative shoes. We do think that proximal metatarsal osteotomies and first metatarsophalangeal joint arthrodesis require the same relief shoes as distal or diaphyseal first metatarsal osteotomies. The first ray and the hallux should be unloaded to acquire bone healing. However, the aim of this study was to investigate postoperative shoes for patients who underwent hallux valgus surgery and to improve these shoes based on objective biomechanical as well as subjective criteria.

Based on the results of this present study, we recommend the use of soft materials for the design of a postoperative shoe, especially for the sole in the forefoot region. An extremely rigid construct increases the torque in this region. Also, the ideal postoperative shoe should have no negative heel. To allow for acceptable rolling characteristics during the stance phase, the postoperative shoe should include a distinguished rocker line. Additional damping elements seem to increase the subjective wearing comfort of the shoe. Because of this, we conclude that the ideal postoperative shoe be equipped with a sufficiently large layer of damping material, especially in the traumatised region.

Orthopaedic foot and ankle surgeons need the proof that a prescribed postoperative shoe reduces the loading of the forefoot. The shoe has to support the patient with regard to pain relief. In other words, we should attempt to avoid patient discomfort with bad shoe design considering that postoperative pain is already discomforting.

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