Biomechanical Evaluation of Foot Pressure and Loading Force during Gait in Rheumatoid Arthritic Patients with and without Foot Orthosis

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Summary: Foot orthoses are commonly used in patients with rheumatoid arthritis (RA) to support the foot and relieve pain, however little is known about the biomechanical effects of in-shoe foot orthoses in reducing or redistributing high pressures and loading forces. The purpose of this study was to compare the foot pressures and loading forces during gait in rheumatoid arthritic patients and healthy subjects, and evaluate the biomechanical effects of the foot orthoses in the RA patients. Twelve female RA patients with foot pain in walking, all Steinbrocker class II, and 8 healthy women without foot pain were matched for age. Foot pressures and loading forces with and without orthoses were measured using the F-Scan program. The pressure distributions and loading forces were standardized by the body weight and compared, and the effects of the foot orthoses were evaluated. The foot orthoses of RA patients provided higher pressure reduction than those of the control group (3.00±0.38 g/cm²/BW and 3.29±0.29 g/cm²/BW respectively, p<0.001). Similar redistribution of plantar pressures and loading forces were found between two groups but the RA patients had a greater change at the stance phase of gait (p<0.0001). The foot orthosis produces greater pressure and loading force relief and redistribution in RA patients than in normal subjects.

Key words: rheumatoid arthritis, foot pressure, loading force, foot orthosis

INTRODUCTION

Rheumatoid arthritis (RA) is commonest joint disease of mankind. Foot pain and deformity frequently appear due to the combined effects of inflammation, bony destruction, and connective tissue damage. High foot pressure is often caused by various forefoot and hindfoot deformities [1,2]. Because these patients wear shoes for most of the day, and abnormally high pressures may be generated at the interface of the shoe and deformed bony prominence [3,4], quantitative in-shoe foot pressure measurements may be important in reducing pain and foot ulcers.

Foot orthoses are commonly used in patients with RA to support the foot and relieve pain [5-7]. Surprisingly, despite their widespread use, little is known about the biomechanical effects of in-shoe foot orthoses in reducing or redistributing high pressures and loading forces. With the development of small, thin sensors, more accurate in-shoe foot pressure measurement has become feasible, and may have a role in the design of foot orthoses to prevent deformity and provide pain relief [8].

In this study, we evaluated the biomechanical effects of foot orthoses on foot pressure measurements and loading distribution during gait. For this purpose, we compared in-shoe foot pressure and force with or without the foot orthoses in healthy subjects and in RA patients who had foot pain during gait.
SUBJECTS AND METHODS

The 12 female patients who volunteered for the study were in Steinbrocker functional class II and all satisfied the American Rheumatoid Association 1987 revised criteria for rheumatoid arthritis [9]. All patients were ambulatory, free from ulceration and complained of foot pain (e.g., walking on pebbles) during walking. None had undergone foot surgery. Patients with symptoms or signs in the knees, hips and back were excluded. All patients underwent a complete medical history and bilateral feet neuropathy evaluation. Hallux valgus and plantar callosities were recorded and longitudinal arch and transverse arch were determined as absent or present. Hindfoot valgus was measured by tibiocalcaneal angle as described elsewhere [2].

Dorsoplantar and lateral roentgenograms were obtained with the patient standing on each foot. Eight healthy female subjects without significant foot problems were matched for age and body weight and took part in the study as control subjects. More clinical details about the group are given in Table 1.

Foot orthoses (Fig. 1) were designed for the aim of maintaining the foot arches and supporting the entire plantar foot. For the sake of metatarsal relief, a pad with extra density and several materials was incorporated into the orthoses proximal to the metatarsal to improve longitudinal arch weight-bearing and relief of pressure points. The foot orthoses were made from a series of moldable materials, mainly polyethylene foam rubber, having the advantages of better shock absorption and accommodating and supporting deformities [3,7,10]. The foot orthoses were fitted by an orthotist who supervised their proper use while the patients were in the study.

The dynamic foot pressure was recorded using the F-Scan system® (Fig. 2), sensor presentation software version 3.623, with subjects walking in-shoe with or without foot orthoses. This system uses an 0.15 mm thick insole foil consisting of over 1000 sensor elements sandwiched between two polymer outer layers. Each element has a 5.08 mm² spatial resolution.

All patients wore standard commercial sport socks and were studied at a room temperature maintained at 20 °C. Sensors were cut to accommodate shoe size and placed between the foot orthosis

Table 1. Subject characteristic

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>RA group</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>48.5 (37-59)</td>
<td>47.1 (42-53)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>50.1±7.44</td>
<td>56.8±8.86</td>
</tr>
<tr>
<td>Gender</td>
<td>female</td>
<td>female</td>
</tr>
<tr>
<td>Steinbrocker class</td>
<td>2</td>
<td>—</td>
</tr>
</tbody>
</table>

Fig. 1. The foot orthoses made mainly with polyethylene foam rubber with metatarsal pad, longitudinal arch support, and transverse arch support.

Fig. 2. The F-Scan measurement during walking.

a. Tekscan, Inc, South Boston, MA, USA
and the sole (with orthosis) or between the foot and
the sole (without orthosis). Calibration of the F-Scan
was performed before each measurement using
subjects’ body weights as the applied force in a
single-limb support model.

The subjects walked in-their shoes at a comfort-
able speed, and pressures and forces with and with-
out the foot orthoses were recorded. Measurements
were performed and recorded three times for three
consecutive footsteps for each condition in bilateral
feet. A new sensor (Fig. 3) and insole were used for
each new subject.

The peak pressures and peak forces over the
entire foot as well as the hindfoot, the midfoot, the
forefoot were measured. The loading distributions
during the stance phase of gait were also observed.
The data was standardized by the body weight of
each subject, and the mean and standard deviations
of the data were calculated for the statistical analysis.
Comparisons were made using the F distribution and
the two-tailed student’s t test in the different mea-
surements in the same group or between the two
groups. P values of less than or equal to 0.05 was
considered to be significant.

RESULTS

Peak pressure distribution (Table 2)

The peak pressures over the entire foot as well as the
hindfoot, the midfoot, the forefoot were normal-
ized for respective body weights (BW) of subjects in
both groups.

In the control group, the total peak pressure over
the whole foot with orthoses was 3.29±0.29
g/cm²/BW, and without orthoses, 3.29±0.29
g/cm²/BW. The significant differences were found
between the two measurements (p<0.05). When the
foot was divided into three areas, they were 8.66±
1.34 g/cm²/BW and 9.53±1.81 g/cm²/BW over the
hindfoot, 4.56±0.83 g/cm²/BW and 3.90±1.30
g/cm²/BW over the midfoot, 8.06±1.18 g/cm²/BW
and 8.66±2.08 g/cm²/BW over the forefoot respec-
tively. The peak pressures under the hindfoot and the
forefoot with orthoses were less than those without
orthoses (p<0.001 and p<0.05, respectively).
However, the peak pressures under the midfoot with
orthoses were higher than those without orthoses
(p<0.001).

In the RA group, the similar results were found.
The total peak pressure over the whole foot with
orthoses was 3.00±0.38 g/cm²/BW, and without
orthoses, 3.21±0.42 g/cm²/BW. The significant dif-
fences were found between the two measurements
(p<0.001). When the foot was divided into three
areas, they were 7.59±1.57 g/cm²/BW and 8.34±
2.00 g/cm²/BW over the hindfoot, 5.80±1.30
g/cm²/BW and 4.96±1.50 g/cm²/BW over the mid-

![Fig. 3. The sensor used for foot pressure measure-
ment.](image)
foot, 5.69±1.30 g/cm²/BW and 6.10±2.33 g/cm²/BW over the forefoot respectively. The peak pressures under the entire foot, the hindfoot and the forefoot with orthoses were less than those without orthoses (p<0.001, p<0.0001 respectively). However the peak pressures under the midfoot increased greatly with orthoses (p<0.0001).

When compared with the control group, the peak pressures, except under the midfoot, were less in the RA group than those in the control group both with and without orthoses. The significant differences were found between the two groups with or without orthoses respectively (p<0.0001).

**Peak force distribution (Table 3)**

In the control group, the total peak force over the whole foot with orthoses was 1.06±0.25 kg/BW, and without orthoses, 1.10±0.19 kg/BW. When the foot was divided into three areas, they were 0.78±0.22 kg/BW and 0.83±0.13 kg/BW over hind foot, 0.37±0.09 kg/BW and 0.35±0.14 kg/BW over the midfoot, and 0.68±0.12 kg/BW and 0.67±0.20 kg/BW over the forefoot respectively. In the control group, the orthotic wear had no significant effects on the peak forces under the entire foot, the hindfoot, the midfoot and forefoot in the different measurements.

In the RA group, different results were found. The total peak force over the whole foot with orthoses was 1.00±0.14 kg/BW, and without orthoses, 1.01±0.15 kg/BW. They were 0.65±0.12 kg/BW and 0.70±0.13 kg/BW over hindfoot, 0.49±0.11 kg/BW and 0.43±0.14 kg/BW over the midfoot, and 0.46±0.15 kg/BW and 0.47±0.16 kg/BW respectively. The peak forces under the entire foot and the forefoot did not differ significantly with orthotic wear, hindfoot and midfoot peak forces differed significantly (p<0.005).

When compared with the control group, significant differences were found in the peak forces under the entire foot and any other areas with or without orthoses (p<0.0001). In contrast with respective body weight, the loading ratios under the hindfoot and forefoot in both two groups became less, and that under the midfoot, however, became greater.

**Loading at the stance phase of gait**

The loading distribution under the foot during stance was also studied with the foot support patterns in various measurements. Two peak values (F₁, F₃) and one valley value (F₂) were measured during stance, and the differences in loading timing of these values were compared with each other (Fig. 4).

In the control group, F₁ with orthoses was 1.05±0.26 kg/BW, and without orthoses, 1.10±0.20 kg/BW. F₂ with orthoses was 0.75±0.14 kg/BW, and without orthoses, 0.78±0.17 kg/BW. F₃ with orthoses was 0.95±0.12 kg/BW, and without orthoses, 0.93±0.16 kg/BW.

In the RA group, F₁ with orthoses was 0.98±0.14 kg/BW, and without orthoses, 1.02±0.12 kg/BW. F₂ with orthoses was 0.81±0.09 kg/BW, and without orthoses, 0.84±0.11 kg/BW. F₃ with orthoses was 0.91±0.13 kg/BW, and without orthoses, 0.92±0.13 kg/BW.

No differences were found in F₁, F₃ and F₂ between with and without orthoses within the two

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**Table 3.**

<table>
<thead>
<tr>
<th>Forces</th>
<th>RA group</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>with orthosis</td>
<td>without orthosis</td>
</tr>
<tr>
<td>Total</td>
<td>1.00±0.14</td>
<td>1.01±0.15</td>
</tr>
<tr>
<td></td>
<td>N.S.</td>
<td>*</td>
</tr>
<tr>
<td>Hindfoot</td>
<td>0.62±0.12</td>
<td>0.70±0.13</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>N.S.</td>
</tr>
<tr>
<td>Midfoot</td>
<td>0.49±0.11</td>
<td>0.43±0.14</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>N.S.</td>
</tr>
<tr>
<td>Forefoot</td>
<td>0.46±0.15</td>
<td>0.47±0.16</td>
</tr>
</tbody>
</table>

Data are means ± SD. N.S. : not significant *p<.005
When compared with each other between the two groups, all p<.0001 respectively.

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**Fig. 4.** The loading distribution during stance phase, and parameters for evaluation.
TABLE 4.
Results of F1, F2, F3 measurements (kg/BW)

<table>
<thead>
<tr>
<th>Pressures</th>
<th>RA group with orthosis</th>
<th>RA group without orthosis</th>
<th>Control group with orthosis</th>
<th>Control group without orthosis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N.S.</td>
<td>N.S.</td>
<td>N.S.</td>
<td>N.S.</td>
</tr>
<tr>
<td>F1</td>
<td>0.98±0.14 1.02±0.12</td>
<td>1.05±0.26 1.10±0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>0.81±0.09 0.84±0.11</td>
<td>0.75±0.14 0.78±0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3</td>
<td>0.91±1.30 4.96±1.50</td>
<td>4.56±0.83 3.90±1.30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data are means ±SD. N.S.: not significant
When compared with each other between the two groups, all p < .0001 respectively.

DISCUSSION

The F-Scan pressure sensor system has been developed and used in clinic and biomechanical studies because of its dynamic response to loading and multiple sensor cells to determine pressure distribution between two contact surfaces [8,22-24], such as the foot and the shoe during walking [25]. The thin sensors can be placed within the subject’s shoes or under foot orthoses without occupying much space. Previous researches had employed the F-Scan system to measure barefoot or in-shoe pressure, and discussed its reproducibility and reliability [8,24,26]. Because variations exist from sensor to sensor, calibration was applied using subjects’ body weights in actual experimental conditions prior to measurement in the present study [24,25]. In order to have accurate measurement, calibration was recommended in actual clinical or experimental conditions, loading speeds and temperature environment [24], and we performed this study with taking care of these factors. It was also pointed out that the sensor system was not suitable for hard surface contact [24]. The other previous study, in which hard surface contact was used for laboratory experiment, pointed out that this sensor was inappropriate for accurate dynamic measurement [25], however the study performed using such hard contact surface may not be appropriate to discuss its accuracy for gait test.

We have evaluated and measured in-shoe foot pressures and loading forces with or without foot orthoses in healthy subjects and rheumatoid arthritic patients. Our results showed that the foot pressures with orthoses were significantly lower than those without orthoses in both healthy subjects and rheumatoid arthritic patients. The foot orthoses of rheumatoid arthritic patients provided a higher pressure reduction and redistribution than those of the control group. This finding suggests that the foot orthoses can have a cushioning effect and can redistribute the plantar pressures.

Contrasted with the pressure, the loading force had a further complex biomechanical behavior. The foot orthoses provided a partial loading redistribution in the rheumatoid arthritic patients rather than in the control subjects. This discrepancy between the pressure and the force is not surprising, because the total force during walking is the sum of the body weight plus the force applied to propel the body forward. Our results showed that the foot orthoses can significantly improve the midfoot loading and reduce the hindfoot loading in rheumatoid arthritic patients.

In the past, ground reaction force during the stance phase of gait of barefoot walking using different system have been well analyzed [11,12], but little is known about this mechanism of normal and deformed foot in a shoe. This time, we attempted to do this work of in-shoe walking with and without foot orthoses using the F-Scan system. By imitating the barefoot support patterns, we found that in rheumatoid arthritic patients the peak F3 timing of GC was shorter than that of the control subjects. These also reflected that the normal walking sequence of heel-strike, foot flat, and toe-off was replaced by a flat footed antalgic type of gait.

The foot disorders can be a major cause of gait disturbance in patients with rheumatoid arthritis and various characteristic deformities of the forefoot and the hindfoot can be produced [2,13]. The pain and disability are more often caused by mechanical deformity than by the inflammatory process itself [14,15]. A general widening of the forefoot is accompanied by hallux valgus and hammer and claw toe deformities with subluxation or dislocation at the metatarso-phalangeal joints [8,16]. The valgus heel deformity of the hindfoot can cause high pressure on the medial heel and incorrect loading of the ankle joint [10,17]. Painful callosities and bursae may develop under the metatarsal heads and at the bony
prominences against the shoe [18,19]. Flattening of the inner arch can lead to pain on weightbearing and torsional stress or also may cause antalgic supination [16]. These raised pressures and abnormal distribution patterns are inherently associated with the pathological changes and gait modification. In our studied group (24 feet), the numbers of hallux valgus, valgus heel, spreading foot, and callosities under the metatarsal heads (Table 1), were correlated with the results of high pressures distribution under the forefoot and the hindfoot without foot orthoses. The rheumatoid arthritic patients had a greater midfoot peak pressure than the control subjects (Table 2). This was also consistent with the deformed foot pathology of longitudinal arch subsided and foot spread.

Rheumatoid foot disease is a frustrating clinical problem, and foot pain due to prominent metatarsal heads and displaced or absent fat pads is very common [20]. Various conservative and surgical treatments have been required to decrease pain and increase mobility. Foot orthoses fulfill an important complementary part in the medical treatment of patients with rheumatoid disease and are commonly used in clinical practice [5-7,10,21]. They are more than a mere adjunct in the treatment of these patients [10]. In the present study, the ability of specially designed foot orthoses to redistribute high pressures and peak forces and to prevent the development of high pressures can be seen in the areas under the foot. The mean body weight, the peak force ratios under the hindfoot and forefoot also became less, and that under the midfoot became greater in the rheumatoid arthritic patients. With these foot orthoses, the patients feel more comfortable, and the foot pain can be alleviated when they walk.

Although pressure relief and redistribution can be achieved and foot pain alleviated, it should be emphasized that the effects of the foot orthoses required further improvement. In this study, orthotic wear had no significant effects on the peak forces under the entire foot and any other areas with or without orthoses in the control group, although the subjects were also comfortable for the foot orthoses. In both groups, the effects were only 10% or so for pressures.

Because painful rheumatoid foot is mainly caused by mechanical deformities, the understanding of the redistribution and weightbearing patterns of in-shoe orthoses can be better understood and more optimal designs developed.

In summary, we have examined the biomechanical effect of the foot orthoses commonly used in rheumatoid arthritic patients with a dynamic in-shoe foot pressure measurement system. Our results show a biomechanical benefit for rheumatoid arthritic patients, in the form of greater pressure and loading force relief and redistribution.

REFERENCES


