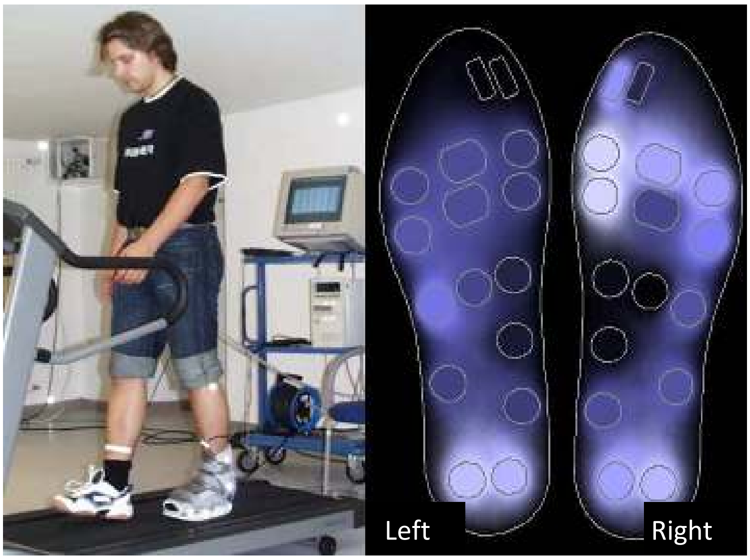
Pressure measurements on the VACOpedes forefoot relief shoe



Project: VACOpedes forefoot relief shoe
Client: OPED GmbH
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Note:

The most important results are summarized in the chapter Summary on pages 19 to 22.

The previous chapters serve mainly to explain the measurement and evaluation procedure for the reader interested in the details.

1 Introduction

In this study, the load on the foot when walking at normal speed was examined, along with what change in the distribution of the load between the back foot and the forefoot different forefoot relief shoes cause. As measuring instruments, pressure measurement soles for insertion into the shoe were used. The load in these areas can be determined from the plantar pressure distribution on the sole of the foot through integration across partial areas of the foot.

Measurements were performed on a treadmill, with a measurement duration of 40 seconds each. In this time, the test person took about 28 double steps, which were then averaged out in the evaluation.

Apart from normal walking, measurements were also taken walking half steps, walking up stairs and walking up stairs with half steps. These are not evaluated further in this report, however.

The forefoot relief shoes to be compared were:

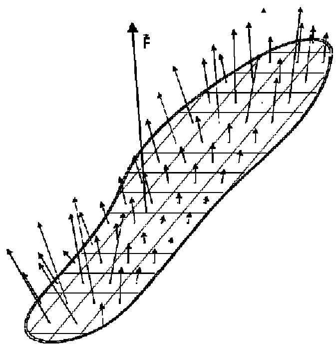
- **VACOpedes**
- **VACOpedes TC**
- **Darco**
- **Bledsoe diabetic boot**
- **Sneakers**

For the measurements, the test person always wore a therapeutic shoe on one foot and a sneaker on the other foot.

Apart from forefoot relief, the use of such relief shoes for diabetics also requires optimal uniform pressure distribution.

Plantar pressure distribution measurement

The entire gravity *F* (generated by the weight of the test person and by inertia forces) is spread over the contact surface of the foot sole to the floor. If you imagine this contact surface to be divided into small square segments, for example, then a small part of the full ground reaction force is exerted on each of these segments.



The value of the vertical force components per surface element

$$p = \frac{F_\perp}{A}$$

is referred to as the pressure and specified in N/cm² [2].

The current force application point is simply the focal point of all partial forces.

Fig. 1, schematic:
Local distribution of forces on the sole of the foot, the resulting total force and the force application point

[2] Conversion factors for frequent pressure units:
10^4 Pa = 0.1 bar = 1 N/cm^2 = 75.006 mmHg = 75.006 torr
The SI unit of pressure is the Pascal (Pa). N/cm^2 or mmHg are frequently used in the medical field.

The pressure distribution over the surface can be made visible with pressure distribution measurement systems. In biomechanics, comprehensive measurement of the pressure distribution beneath the foot sole is common using measurement platforms built into the floor and with inlay measurement soles. In the example in Fig. 2, the patient walks over the platform barefoot.

The pedogram of the test person in this study is a typical pressure distribution pattern for an adult test person. (Even with completely healthy test persons, however, the pressure distribution patterns can vary significantly.)

Typical:

- Course of the gait line starting at the middle of the heel, with a slight lateral bend, ending between D1 and D2, no break in the gait line (markings in Fig. 2b walking forward smoothly)

- Plane pressure distribution in the ball area, individual metatarsal heads not visible, all toes visible

- Pressure maxima on the heel, forefoot balls and big toe of similar intensity, values up to approx. 40 N/cm² (pressure scale in the figures), but dependent on the gait speed, low pressure values between heel and balls, no support in the medial middle foot area.

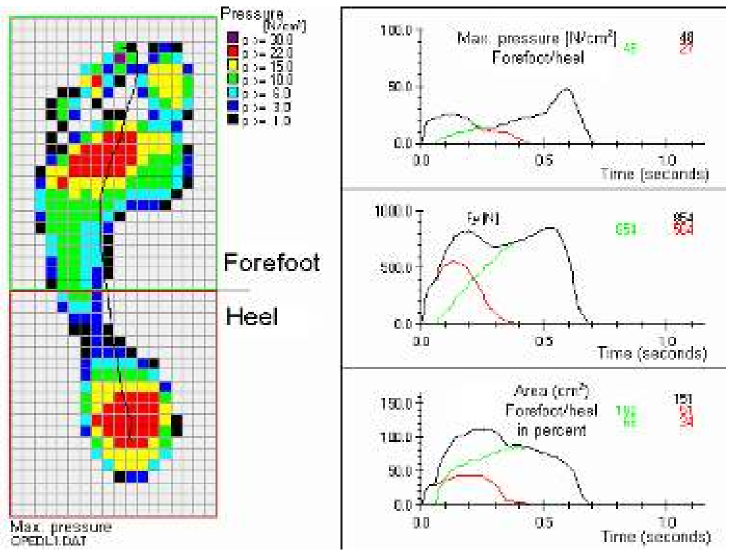


Fig. 2a, Pedogram, plantar pressure distribution when walking;
Left: Pressure maxima,; Right: Derived parameter curves,
pay special attention to the vertical force in the middle diagram

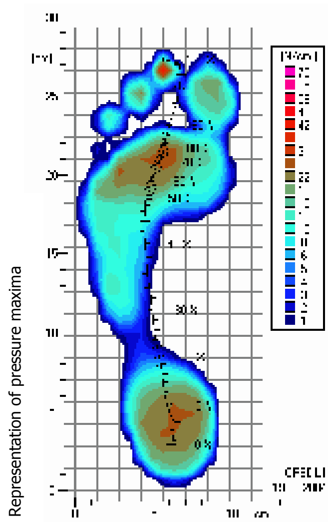


Fig. 2b, interpolated presentation

- Straight line from the center of the heel – ball of big toe – big toe

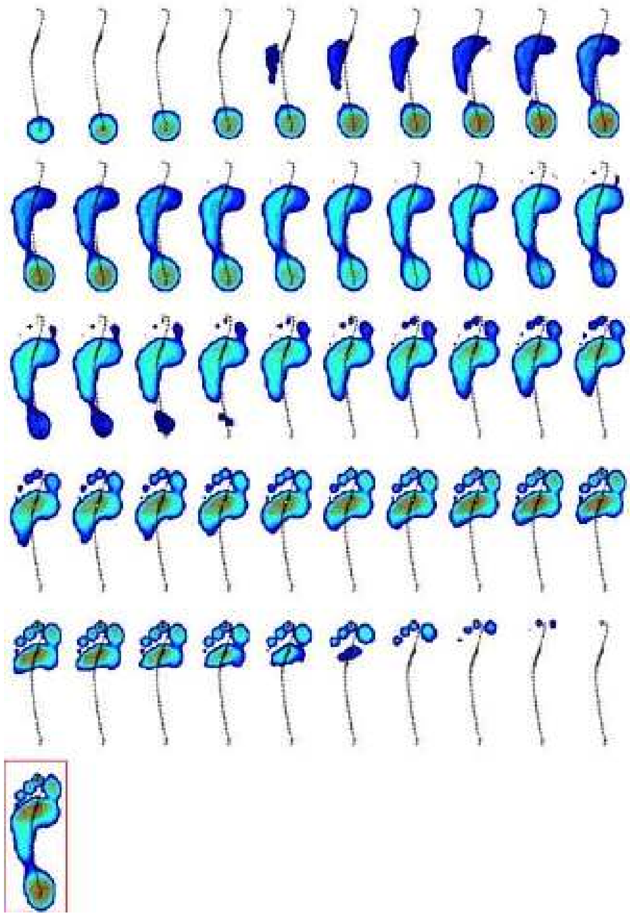


Fig. 2c, rolling of the foot picture by picture, measurement rate is 72 / full pressure distribution images per second

Pressure distribution measurements in the shoe

For the provision with orthopedic shoes, insoles etc., the measurement of the pressure distribution in the shoe is of course of crucial significance. In this study, pressure distribution measurements in the shoe were performed with Parotec pressure measurement insoles. These measurement soles are only equipped with pressure sensors in those areas corresponding to particularly loaded parts of the foot sole. The two pressure measurement soles of the left and right foot each contain 16 of these integrated hydrocells. The actual pressure sensors are piezoresistive sensors in the hydrocells. Fig. 3 shows the positions and sizes of the measurement cells in the soles. An obvious problem in these individual sensor systems is that they are shaped for an average normal foot. If the foot shape is different, anatomical structures of the foot will possibly lie beyond or just between sensors and not be registered by the measuring device. Systems with sensors covering a full area and a sufficiently high number of individual sensors would be more suitable. For the measurements for this study on the same test person, this does not present as many problems. To prevent the soles from shifting between measurements, these were glued to the foot sole of the test person.

The results of the first measurement (OPED01, cf. chapter Results), in which the test person wears sneakers on both feet, show high symmetry between left and right, so that a sufficient reproducibility of measurements in the same test person can be expected.

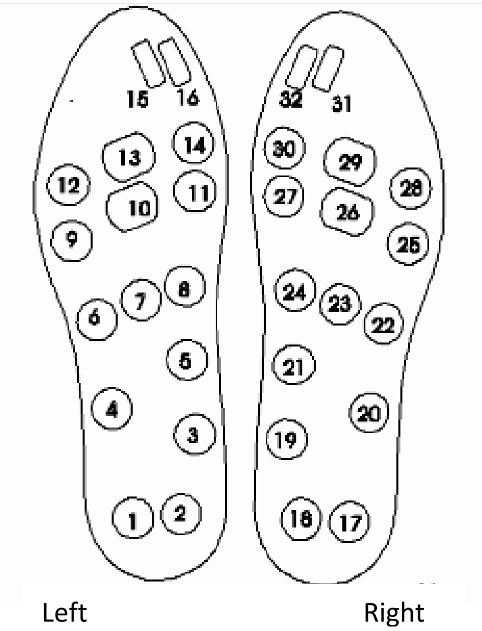


Fig. 3, to scale: Size and position of the individual pressure sensors on pressure measurement soles. The sensors are connected to a controller and a computer by wire. This way, the signals from the sensors can be read out in real time over a practically unlimited period. The time resolution of the sensors is 1000 measurements per second.

Fig. 4, pressure measurements with measurement insoles in both shoes and wire connection to the measurement computer.

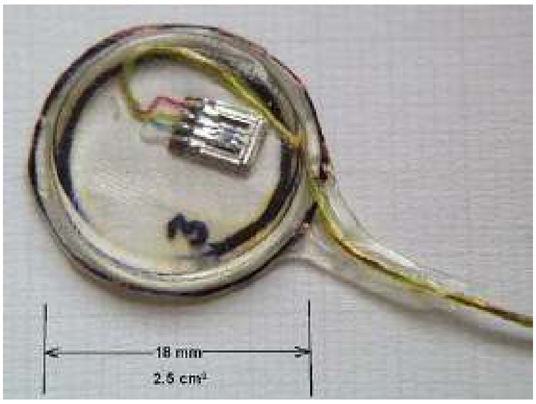


Fig. 5, single hydrocell with piezoresistive microsensor, wire connection

Time series

Fig. 6a shows the pressure profile for all 32 sensors over a measurement duration of 40 seconds when walking up stairs. In Fig. 6b, a 5-second time frame from a different measurement is enlarged. Now, the time sequence in the pressure profiles of individual sensors can be followed. In the course of ground contact, typically the sensors on the heels are loaded first, and then the sensors on the forefoot at the end of the ground contact. The highest pressure values occur at the heel, and on the balls of the forefoot. In the middle foot area, the pressure values are in part very low.

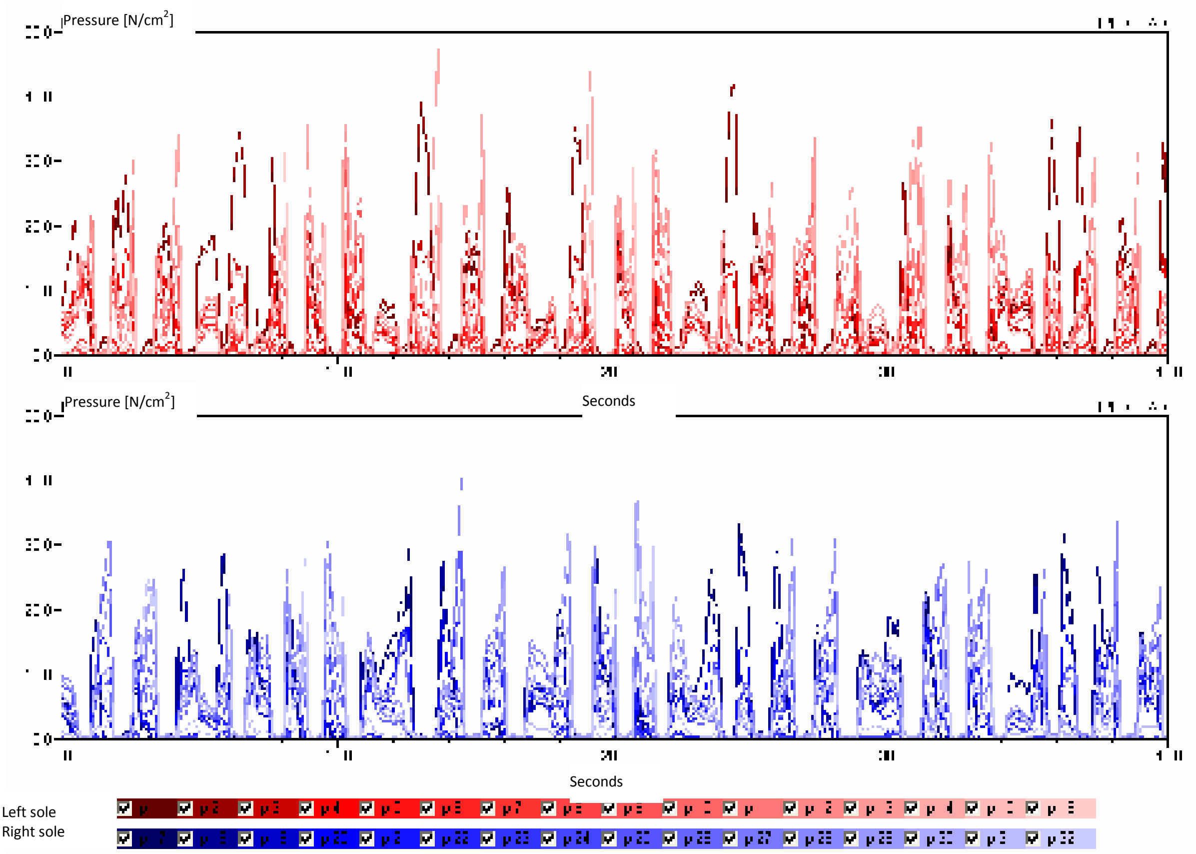


Fig. 6a, pressure profile for all 32 sensors over a measurement duration of 40 seconds, walking up and down stairs. Sensors 1 to 16 (red) on the left measurement sole, sensors 17 to 32 on the right sole.
0 to 5 seconds walking upstairs, turning, up to 11 seconds walking downstairs, turning, etc.

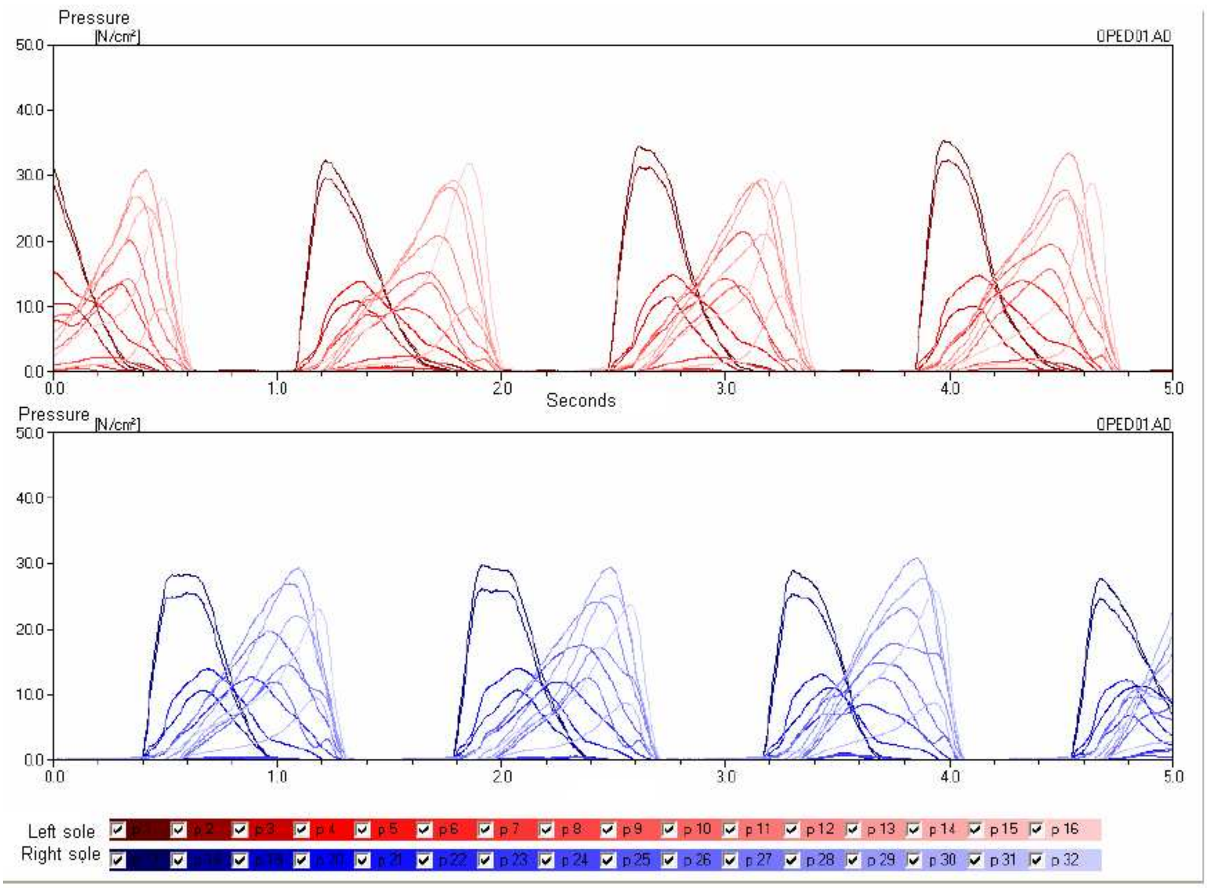


Fig. 6b, 5-second time frame from a 40-second measurement on the treadmill.

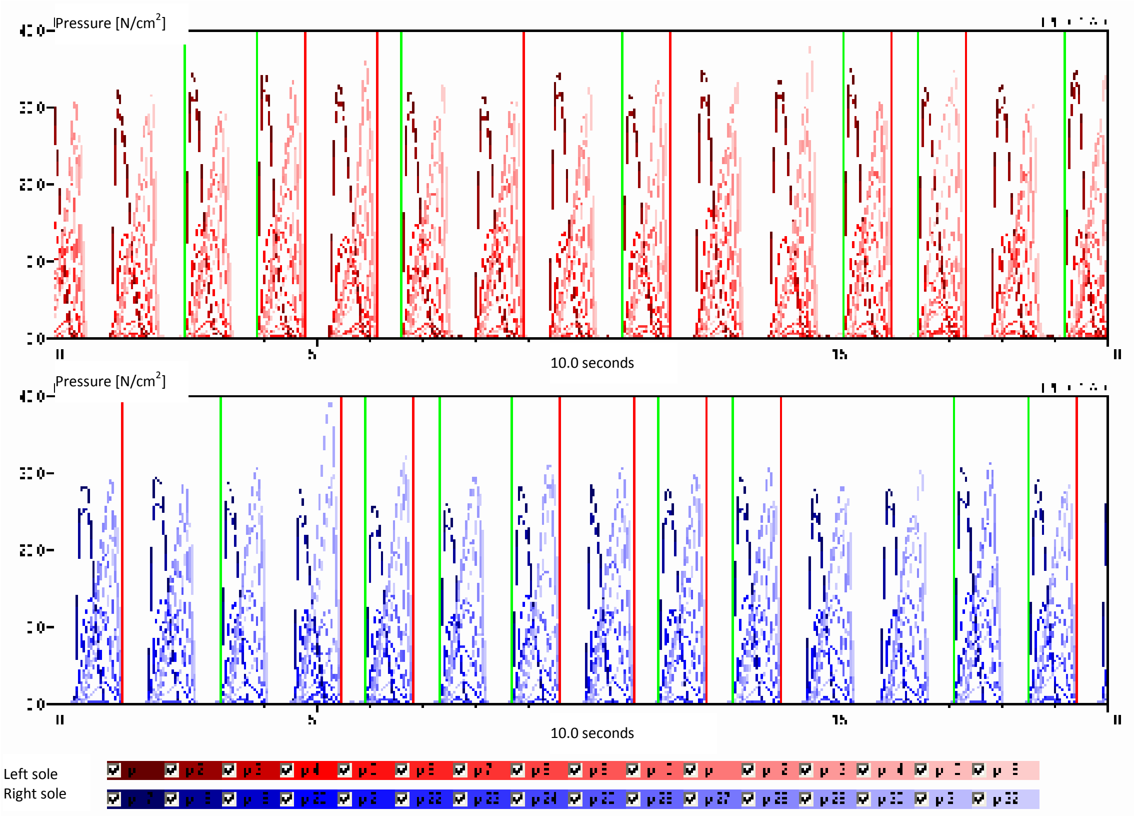


Fig. 7, separation of measurement data into step sequences: When the heel makes contact with the floor, the floor contact phase begins (green marking) when the toes lift off from the floor, it ends again (red marking). Average values can subsequently be determined via individual floor contact phases.

Maximum pressure analysis

A method of data analysis (which can be applied in a similar manner for quite different problems and measurement procedures, e.g. EMG measurements): the pressure curves are examined for the frequency of all pressure values that occur. During the 40-second measurement period, each pressure sensor is recorded 40·400=16000 times: All measurement values are entered in a frequency register with a resolution of 0.1 N/cm² printing width. The larger the pressure variations, the wider and flatter the distribution (e.g. Fig. 8). The more constant the pressure, the narrower and the more linear the distribution. The frequency distribution itself is then examined at its maximum points (blue and red markings in Fig. 8). To avoid the effects of individual measurement 'outliers', not the absolute pressure maximum of the distribution is sought, but rather the value at which a certain percentage (1 percent) of all measured values lies above the limit (cf. Fig. 9). Alternatively, the value could be chosen as the limit at which the distribution exceeds a certain percentage of the overall maximum of the distribution.

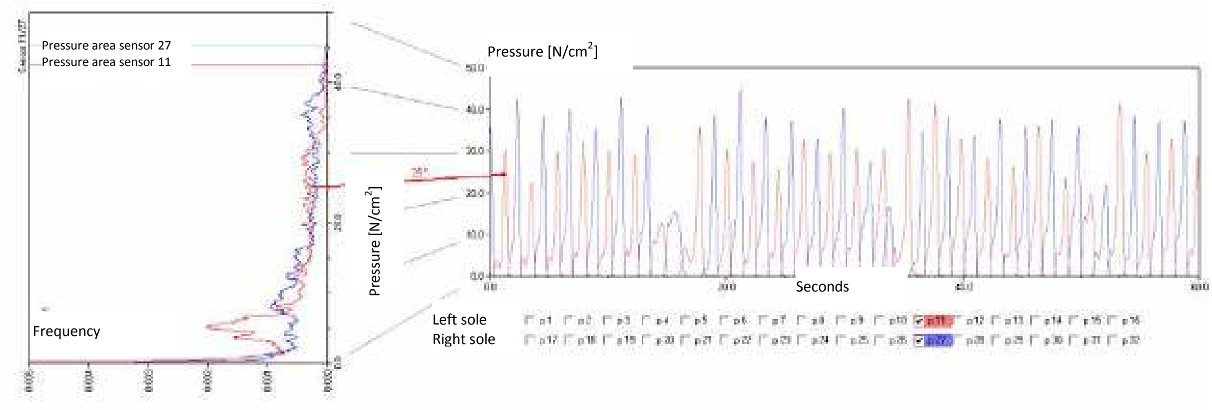


Fig. 8, to determine the frequency distribution of the pressure values of a measurement, each of the 16,000 measured pressure values (right) is entered in a count register (left). The upper limit is defined in the distribution. The frequency distribution is standardized so that the surface lies below curve 1.

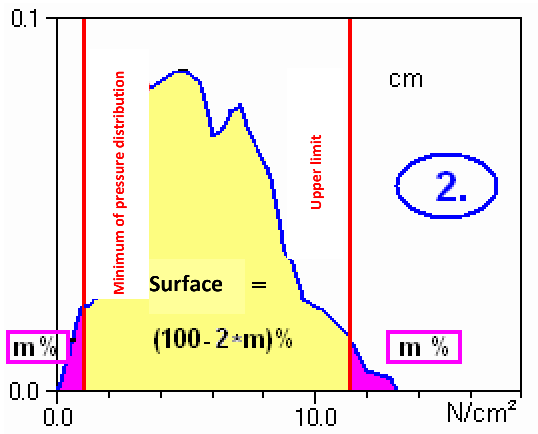


Fig. 9, to determine the upper limit of the frequency distribution for the measured pressure values of a sensor.
m = 1

The pressure range upper limits determined in this way are compared between the left foot (test shoe) and the right foot (normal shoe) and between different therapeutic solutions for the left foot. These pressure values are reproduced as pressure distributions in Fig. 10 on the left. Fig. 7 on the right shows the plantar pressure distribution pattern of the test person for the measurements walking barefoot.

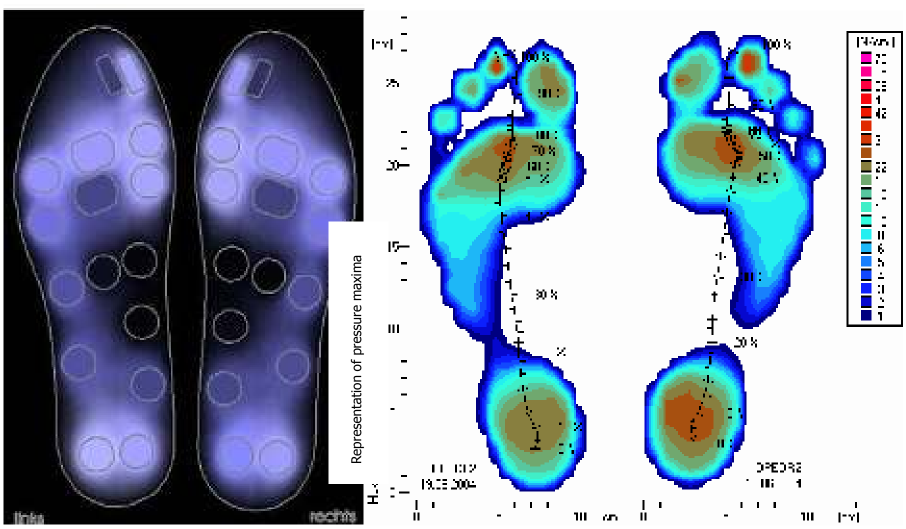


Fig. 10, measured pressure values represented as pressure distribution pattern. Here: normal shoe on left and right foot (measurement OPED01). Higher pressure values are shown as lighter shades.

Far right: high-resolution pressure distribution pattern under the sole of the foot when walking barefoot, pressure maxima pattern (pressure scale on the right)

Load analysis

Crucial for the further evaluation is the research problem at hand. In our case, we are interested in the suitability of various means of forefoot relief. The distribution of the overall load over the different areas of the foot is concentrated on the heel area, to provide relief to the forefoot.

For the analysis, the pressure sensors are divided into four groups - the heel, middle foot, balls of the forefoot, big toe (cf. Fig. 11), and simplified further into two groups, the back foot and forefoot (Fig. 12).

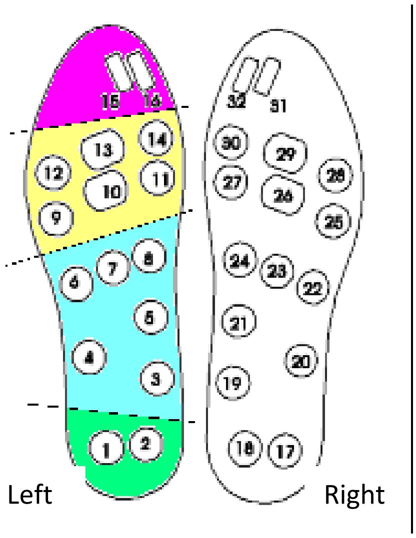


Fig. 11, summary of pressure sensors for four groups, heel, middle foot, balls of forefoot, big toe.

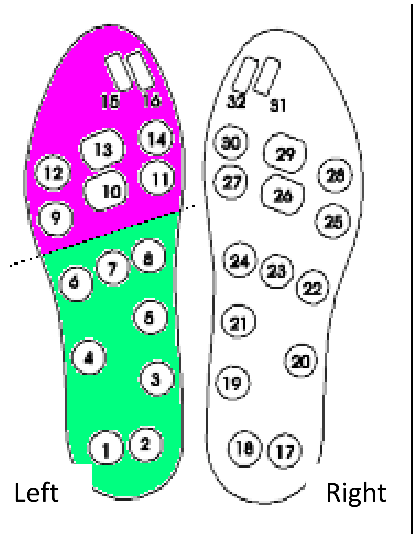
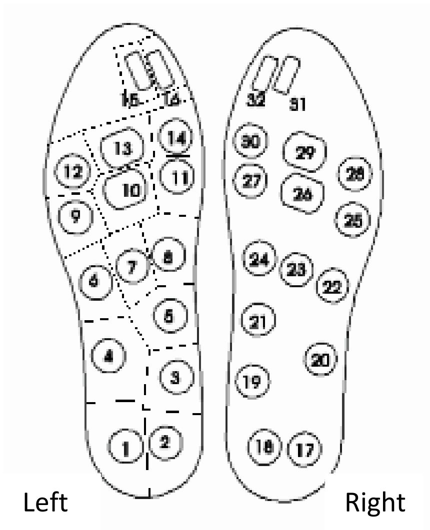


Fig. 12, summary of pressure sensors for two groups, back foot and forefoot.

If you rewind the sequence from Fig. 1 and the pressure distribution is again integrated across individual areas of the foot, then you obtain the gravity exerted on these selected areas (to be precise, the vertical component of the force, which is by far the predominant part). In the case of a punctual measurement with individual pressure sensors, integration must take place not only across the area of the sensors themselves, but also over the blind areas between the sensors with an unknown amount of pressure. To simplify matters, you could consider each individual sensor to be representative for its surroundings and assume that the pressure in this area remains constant and is the same as the measured pressure of the sensor (Fig. 13).

Fig. 13, allocation of representative surfaces to individual pressure sensors.



Sensor	Area (%)
1	8.4
2	7.0
3	5.9
4	8.7
5	6.0
6	5.6
7	4.7
8	5.5
9	4.9
10	5.8
11	4.7
12	4.5
13	5.2
14	4.2
15	2.9
16	2.4

in percentage of the overall surface of a sole

This allocation of representative surfaces may be influenced by random factors, so that the gravity determined is probably not completely reliable. Because the pressure sensor lies in the center of its represented area, the actual average pressure will in reality usually be less. Because of this, there is a tendency to overestimate the gravity.

To improve this procedure, an additional scaling factor is obtained from the graph for the total force across all surface segments recorded for each foot. It is taken into account here that the total force in the middle section of the ground contact phase corresponds roughly to the known body weight of the test person. The test person for the measurement in Fig. 14 has a body weight of 78 kg (780 N), the measurement on the other hand results in a weight of 1500 Nm, the corrective scaling factor is therefore 780 N / 1500 N = 0.52.

Fig. 14a, in the middle standing phase, the entire gravity in the middle should correspond to the body weight exactly. If there is no weight standardization, this results in a weight that is too large by a factor of about 2 and a calibration factor of about 0.5.

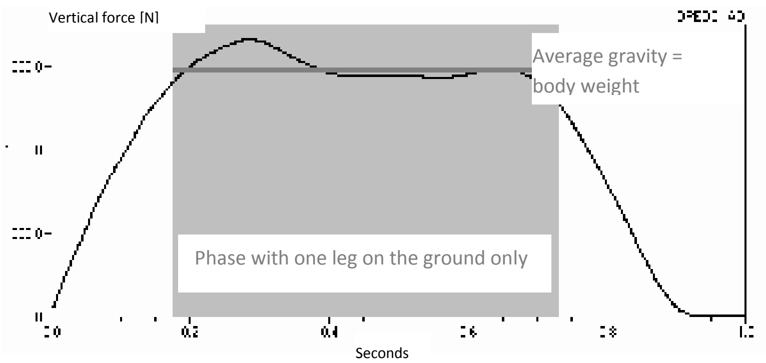
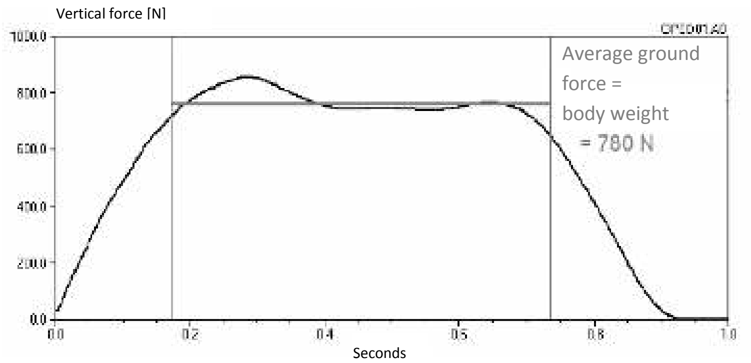


Fig. 14b, gravity standardized to the body weight



Mathematical summary of load analysis

1. The sensor *i* measures the pressure $p_i(t)$ at each point in time *t* in the course of rolling the foot,
2. Each individual pressure sensor *i*, is geometrically assigned a representative area a_i (cf. Fig. 13), pressure $p_i(t)$ times area a_i results in the force exerted on this partial area,
3. The total force F_{total} in the standing phase is determined by the body weight *M* of the test person (in kg)

   $$F_{total} = M \cdot g \text{ ,}$$

   $$g = 9.8 \ \frac{m}{\sec^2}$$

4. The summation of the pressure values of all sensors multiplied by their represented area must also result, in the middle part of the standing phase, in the body weight (cf. Fig. 14), and a scaling factor *s* is introduced for this purpose so that:

   $$F_{total} = M \cdot g = s \cdot \sum_{i}^{all\_sensors} a_i \cdot p_i(t)$$

   and.:

   $$s = (M \cdot g) / (\sum_{i}^{all\_sensors} a_i \cdot p_i(t))$$

   (since the total force also varies somewhat in the middle standing phase, an average value is formed),
5. So that the load on partial areas of the foot sole can now be calculated for each point in time *t*:

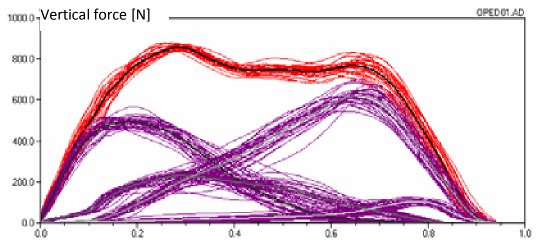
   $$F_{part}(t) = s \cdot \sum_{i}^{Sensors\ in\ the\ partial\ area} a_i \cdot p_i(t)$$

6. If the partial force F_{part} is integrated over the period of time of the ground contact, this results in the overall load (the impulse *K*) in this area:

   $$K_{part} = \int_{t=Putting\ foot\ down}^{Lifingt\ foot} F_{part} \cdot dt$$

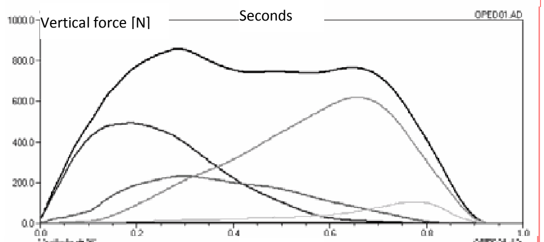
7. The overall measurement time is divided into individual step cycles. An average step cycle is formed from these individual sequences. This averaging out can in principle be performed at almost any point in the entire procedure: If it is for example performed straight after point 1, you will obtain average pressure profiles for individual sensors.

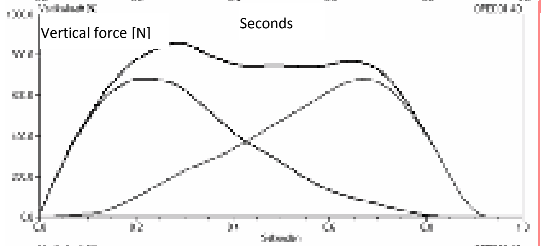
Fig. 15, partial forces in the four foot areas from Fig. 11 in the course of rolling the foot.



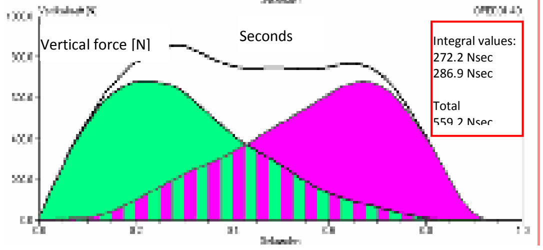
By means of the representative sensor areas described in Fig. 13, **forces** are first assigned to the pressure values of individual sensors and then added, via the groups, to the local gravity and via the sole total area to the 'total' vertical force.

In the upper diagram, all individual step cycles are overlaid, and **average force curves** are formed in the four groups. In the second diagram, only the average curves are reproduced.
The grayscale selection in the force curves is as follows: From the heel group to the toes, the gray value gradually becomes lighter, the total force curve is black.
The total force curve corresponds roughly to the normal twin-peak profile of the vertical force in the gait analysis, and the average maximum level corresponds to the body weight of the test person.





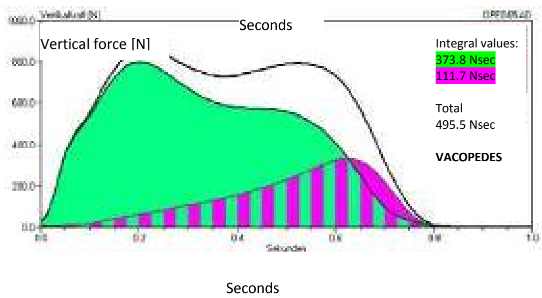
In the third diagram, only two groups, the forefoot and the rear foot, are defined as shown in Fig. 12, as well as the total force curve.



To make things clearer, in the fourth diagram the areas below the curves are colored in for the forefoot and rear foot
(green = rear foot, pink = forefoot).

In the red box at the top right, the sizes of the colored curve areas are listed (in force x time units, these are physical impulses in Newton seconds).

Green areas therefore represent rear foot load,
red areas represent forefoot load.



The final diagram shows a corresponding measurement on a forefoot relief shoe: compared to the normal shoe in the previous diagram, the load has clearly shifted towards the heel.

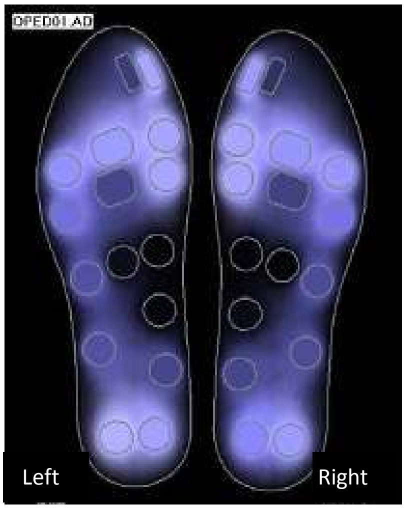
2 Measurement results

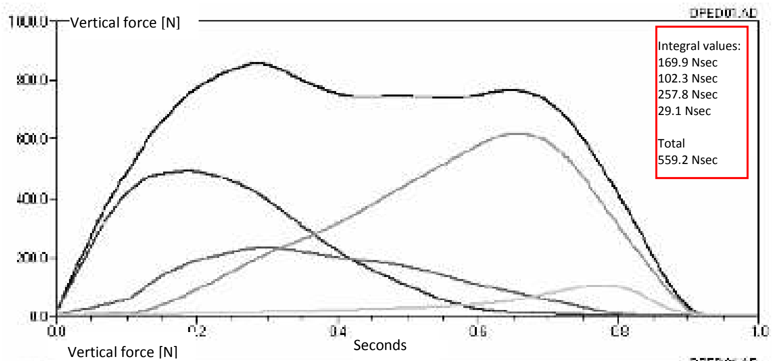
Walking on the treadmill, 3 km/h

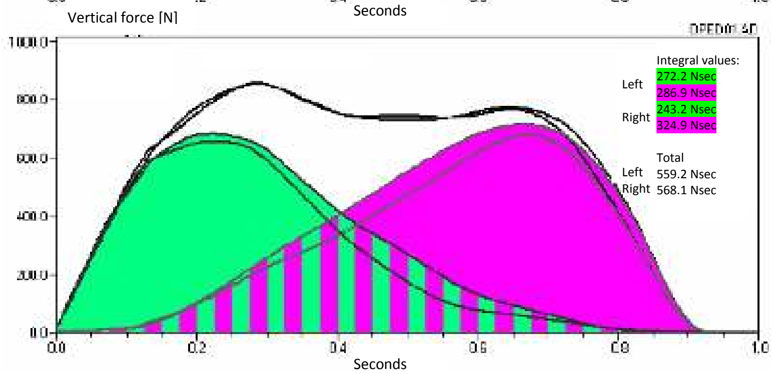
Measurement

OPED01, sneakers

(left and right sole)







Pressure distribution pattern:

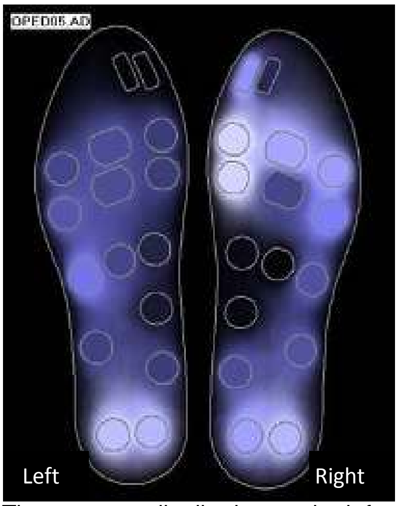
High symmetry between the right and left sole, pressure on heel and forefoot of similar intensity, low pressure in middle foot area (cf. Fig. 10).

Top diagram: Only left sole, four sensor groups (heel, middle foot, balls of forefoot, big toe and the overall curve).
Bottom diagram: Only two sensor groups (rear foot and forefoot), with the representation of the two feet superimposed. Only slight deviations in the curves between left and right. Proportion of rear foot load to forefoot load on average at approx.: 45% to 55%
(The grayscale selection in the diagrams is as following: from the heel group to the toes, the gray value gradually becomes lighter, the total curve is black.)

The high symmetry of the measurement results of both pressure distribution and load analysis between the left and right foot shows that the measurement method, despite misgivings in terms of measurement precision, is quite sufficient for the requirements of the research problem of this study.

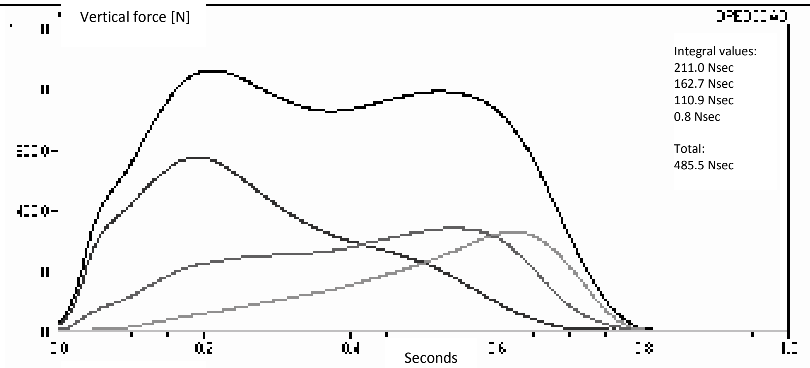
OPED05, VACOpedes

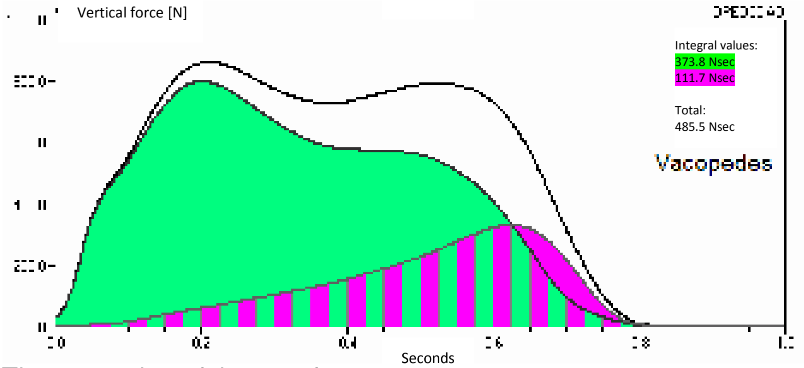
(left sole, normal shoe on the right)



The pressure distribution on the left is more equally spread than with the normal shoe on the right; no pressure on the big toe; the pressure focal point is on the heel.

The pressure distribution with the normal shoe (on the right) is maintained, with increased medial load on the balls of the forefoot.

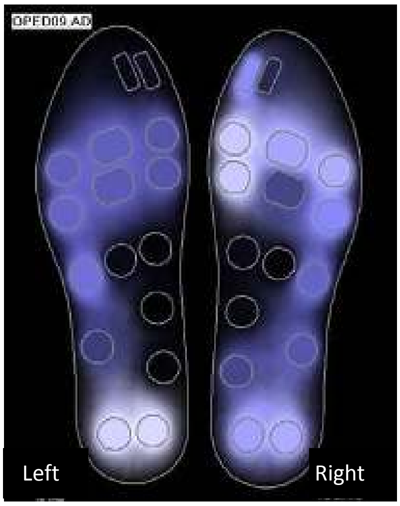




The proportion of the rear foot load to the forefoot load is at: 77% to 23%

OPED09, Darco

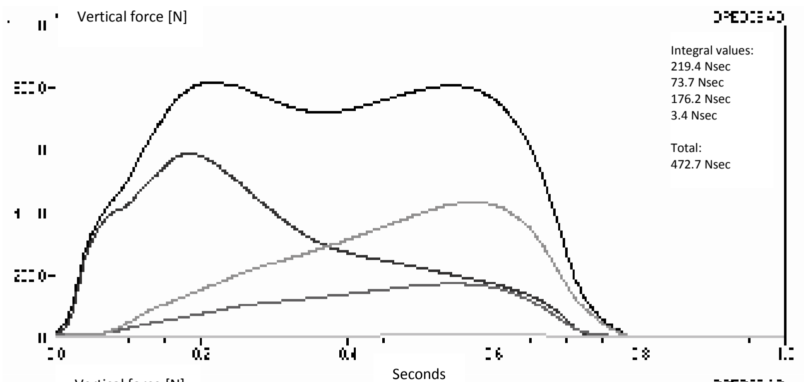
(left sole, right normal shoe)

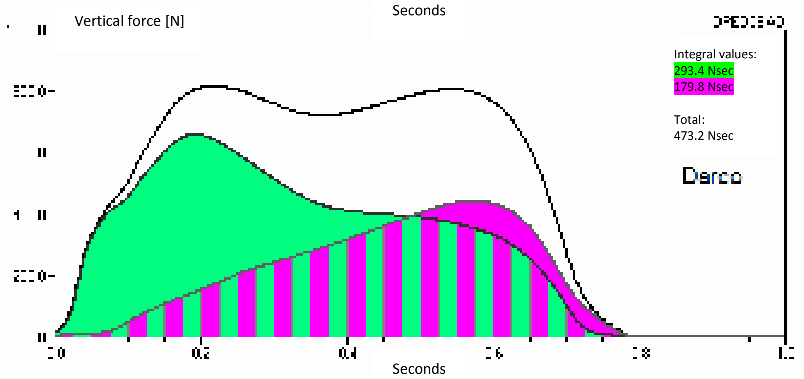


The pressure distribution on the forefoot on the left is more equally spread than with the normal shoe on the right; no pressure on the big toe; considerably increased pressure focal point on heel.

Difference from the VACOped: there is no medial ground contact of the foot in the middle of the foot.

The pressure distribution with the normal shoe (on the right) is maintained, as is on the balls of the forefoot with increased medial load.

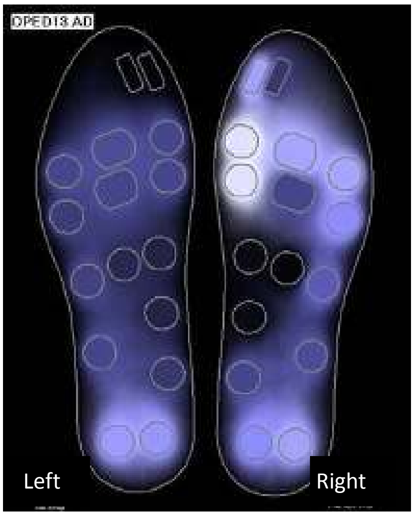




With the Darco, the shift to the rear foot is smaller than with the VACOpedes, the proportion of the rear foot load to forefoot load lies at 62% to 38%

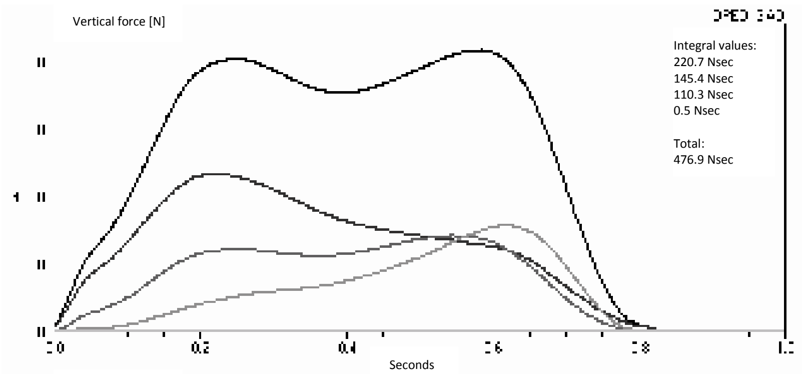
OPED13, VACOped TC

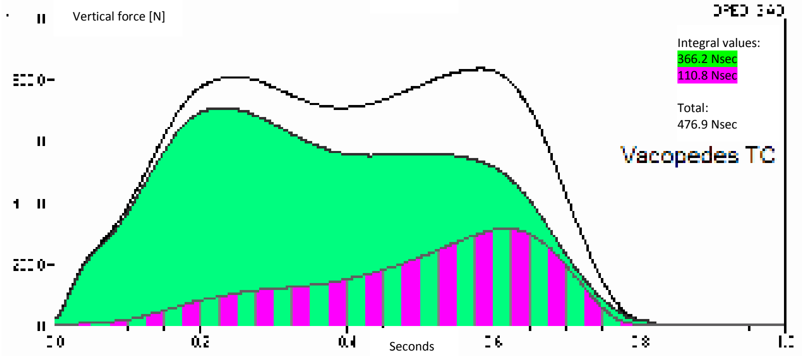
(left sole, right normal shoe)



The pressure distribution on the left is even more equally spread than in the VACOped; no pressure on the big toe; pressure focal point on heel.

The pressure distribution in the normal shoe (on the right) is maintained, the medial load on the balls of the forefoot increased.

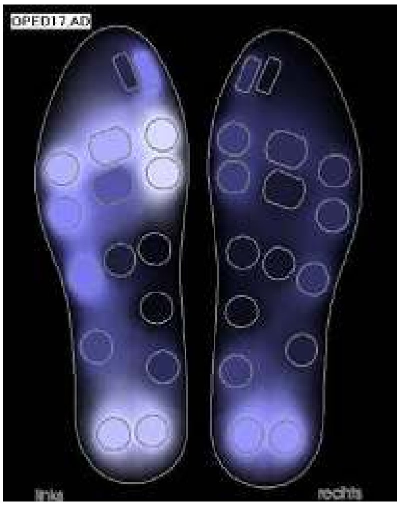




With the VACOpedes TC the proportion of rear foot load to forefoot load is exactly the same as with the VACOped: 77% to 23%

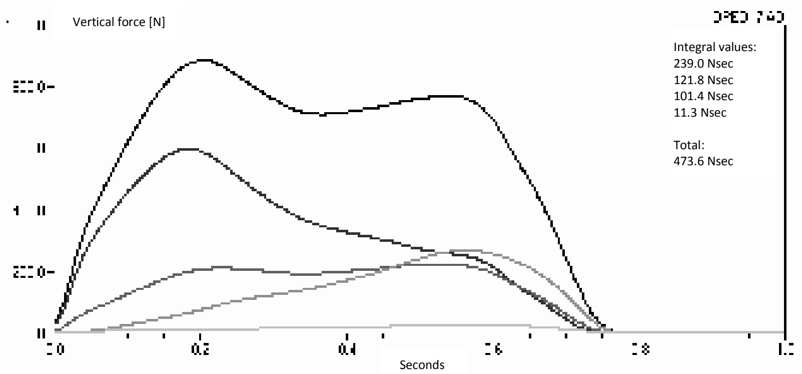
OPED17, Bledsoe diabetic boot

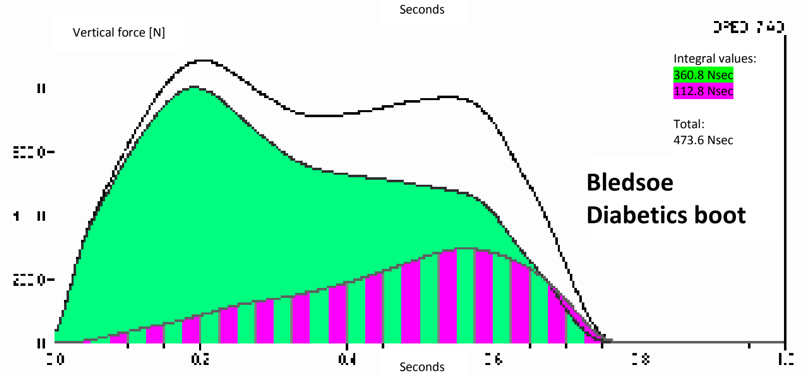
(right sole, normal shoe on the left)



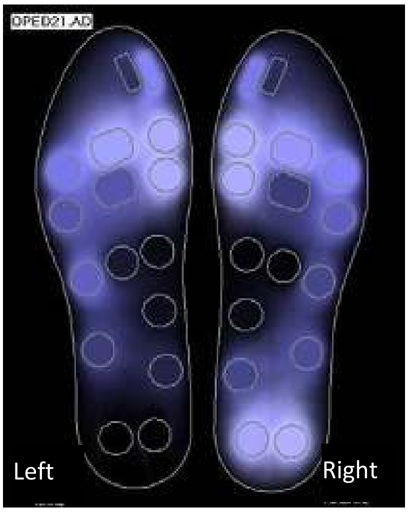
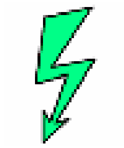
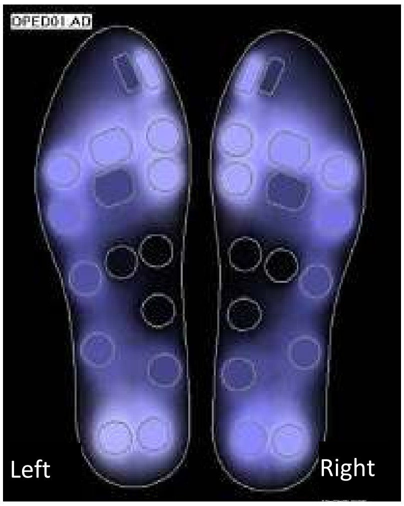
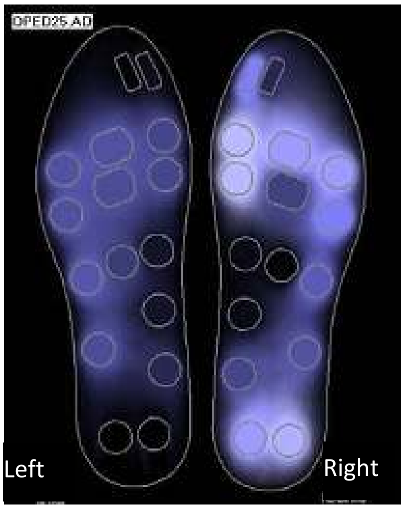
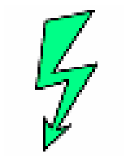
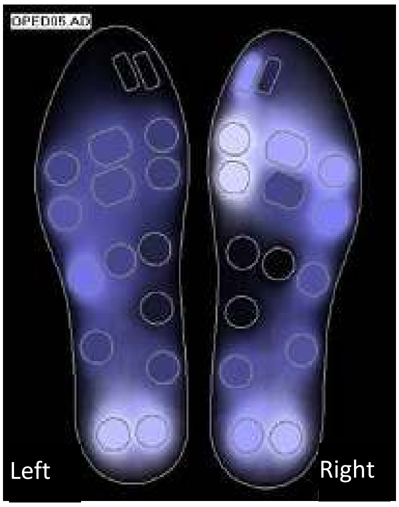
Very low pressure maxima on the right, not quite as evenly distributed as with the VACOped TC.

Normal shoe on the left again with a slightly increased medial ball load; slight distal increase of pressure in the forefoot area.



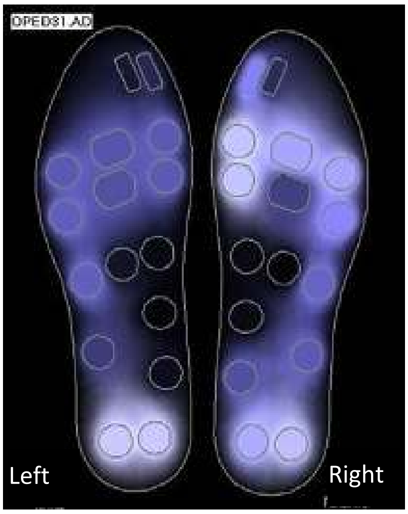


With the Bledsoe diabetic boot, the proportion of rear foot load to forefoot load is almost the same as with the VACOpedes and the VACOpedes TC: 76% to 24%

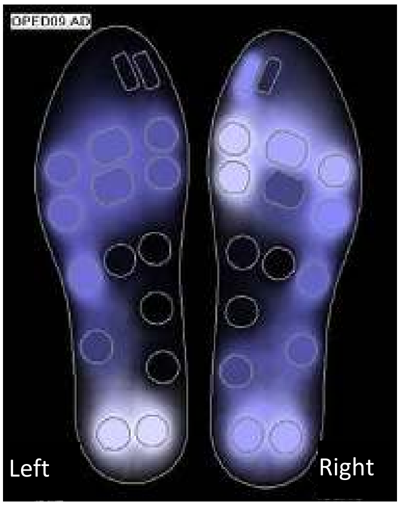
OPED02, sneaker + tape (left sole)   (the two defective heel sensors on the left were set to 0!) No clear change because of the tape.	As a comparison: Measurement OPED01 
OPED25, VACOpedes + tape (left sole)   (the two defective heel sensors on the left were set to 0!) Only small changes in pressure distribution because of the tape.	As a comparison Measurement OPED05, VACOpedes without tape 

OPED31, Darco + tape

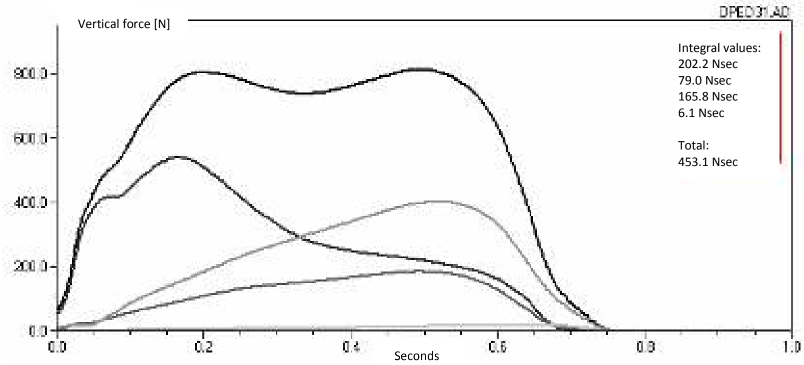
(left sole)

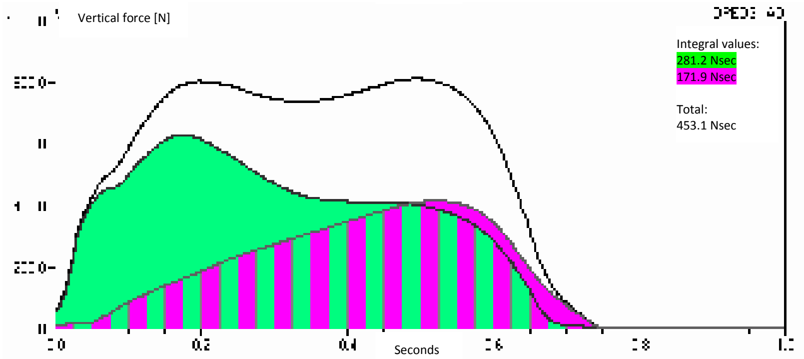


Without tape:



practically no changes in pressure distribution because of the tape.





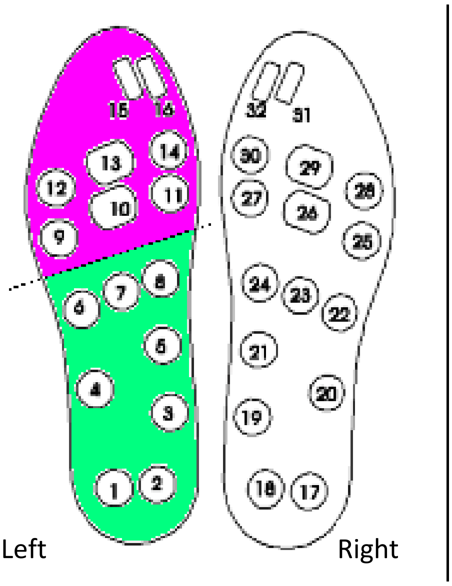
The proportion of the rear foot load to the forefoot load remains at: 62% to 38%

There is also practically no change to the curve progression.

3. Summary

With pressure measurement soles for insertion into the shoe, the pressure distribution at the foot sole was examined during normal walking. From this, the load was calculated in selected areas of the foot, defined as the product from the amount of the force (in Newton [N]) times the duration (in seconds [sec]) of the force (this is in each case the area under the curves shown in the subsequent diagrams in [Nsec], in a physical sense, this is a so-called impulse). All curves are averaged out over a measurement time of 40 seconds (about 28 double steps).

Below, the foot surface is always divided into two parts, as shown in the figure on the right, forefoot (assigned color: purple) and rear foot (assigned color: green).



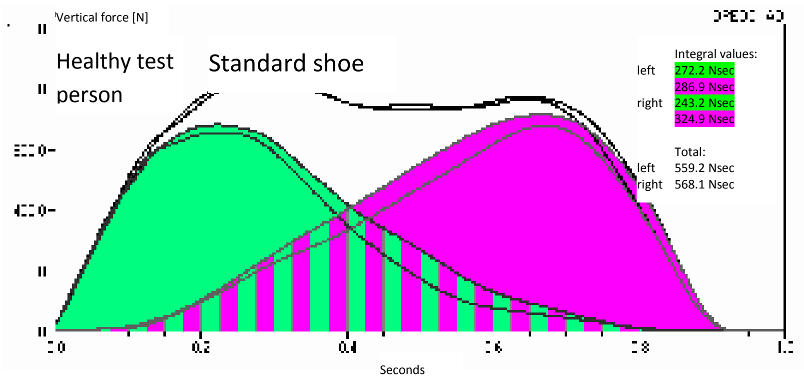
Dividing the pressure sensors into two groups: rear foot and forefoot sensors.

The following diagrams each show the profile of the force on the rear foot and forefoot and the total force from the first contact with the ground (t = 0 seconds) until the toes lift off the ground.

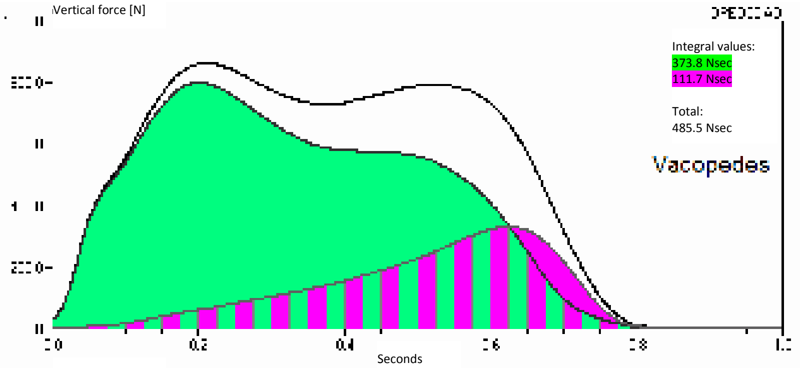
For all therapeutic shoes, the duration of ground contact is shorter than for normal shoes, probably due to the reduced plantar flexion possibility in the heel during the push-off phase.

In the **normal shoe**, the proportion of the rear foot load to forefoot load on average lies at approx. **45% to 55%**.

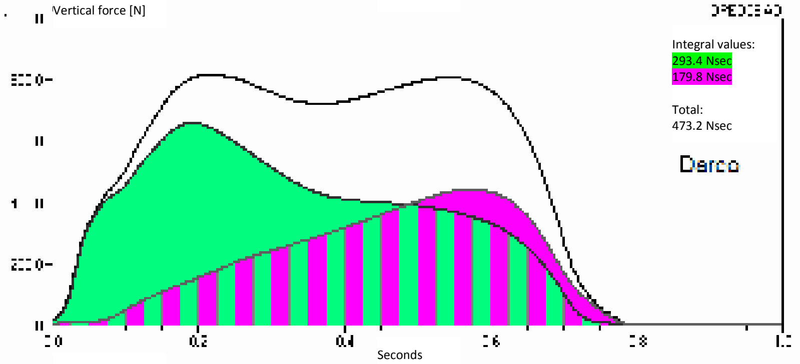
The forefoot load is consequently higher than the rear foot load.
(In the diagram on the right, the proportions are reproduced for both feet).



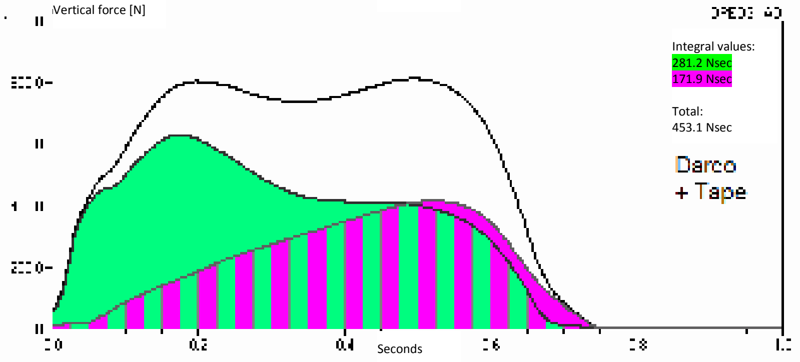
With the **VACOpedes**, the load considerably shifts to the rear foot, the proportion of the rear foot load to forefoot load lies at
77% to 23%.



With the **Darco**, the shift to the rear foot is smaller than with the VACOpedes, the proportion of the rear foot load to forefoot load lies at **62% to 38%.**



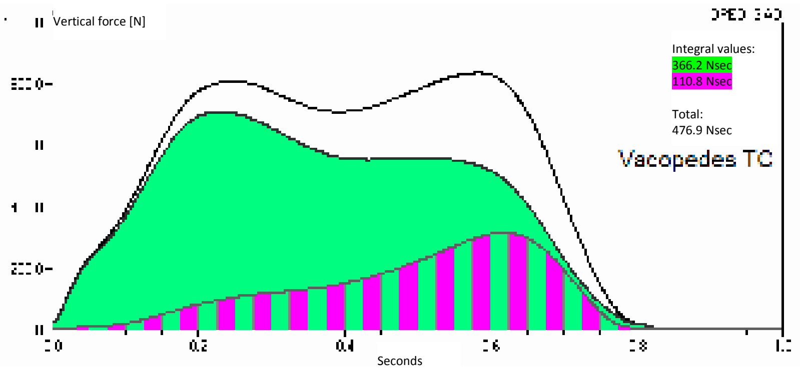
In a series of experiments, the ankle of the test person was additionally taped. The load proportions were not measurably changed by this. In the example with the Darco, the proportion of the rear foot load to the forefoot load remains at **62% to 38%**.



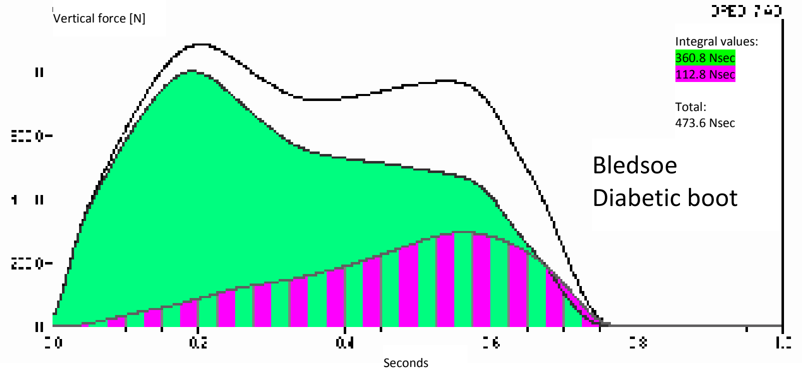
There is practically no change to the curve progression.

With the **VACOpedes TC**, the proportion of the rear foot load to forefoot load is exactly the same as with the VACOpedes:
77% to 23%.

Even until the very end of contact with the ground, the load in the rear foot area is always higher than that in the forefoot here.

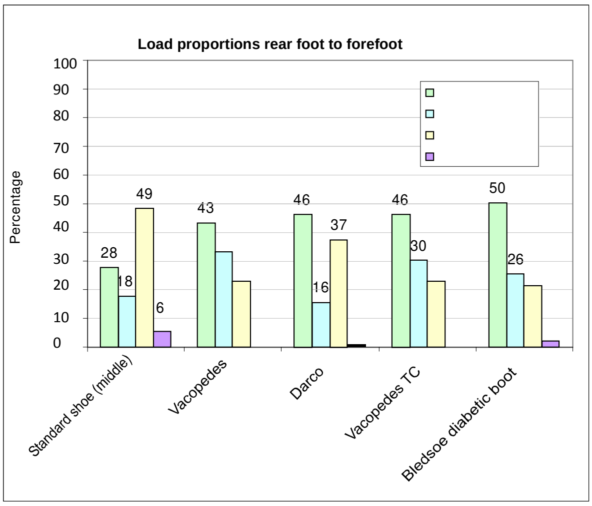


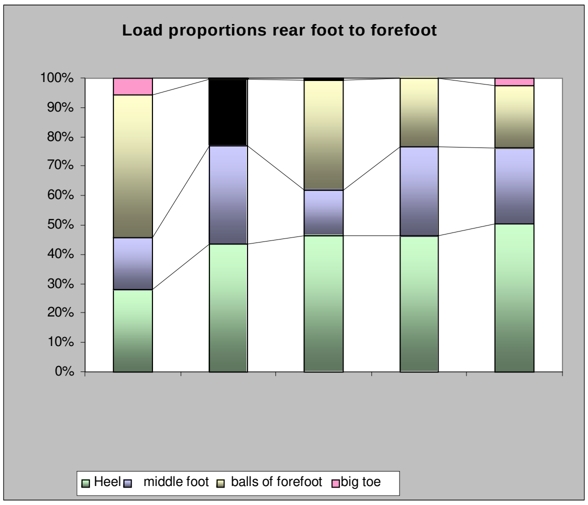
With the **Bledsoe diabetic boot**, the proportion of the rear foot load to forefoot load is almost the same as with the VACOpedes and the VACOpedes TC: **76% to 24%.**



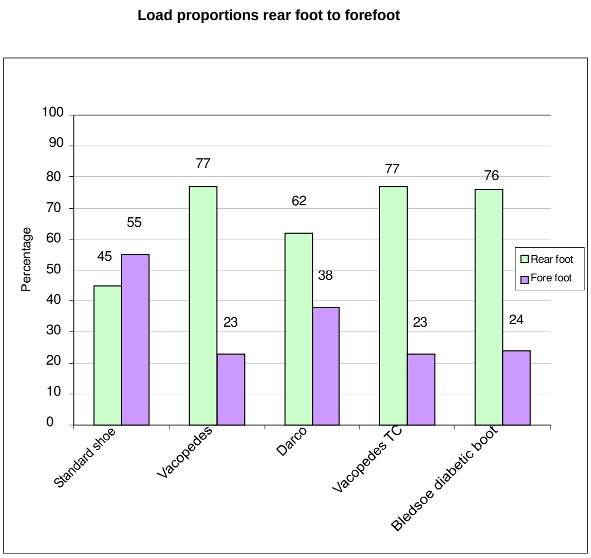
The following diagrams again present the numerical results in an overview:

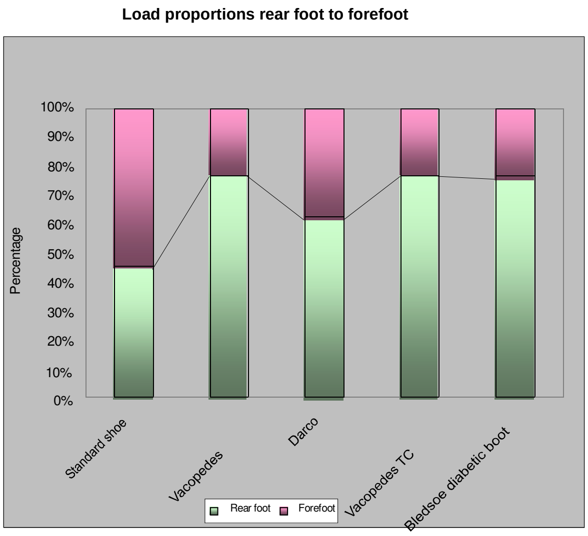
Load proportions when dividing the foot into 4 areas:





Load proportions when dividing the foot into two areas (rear foot and forefoot).
The proportion of the rear foot in the total load is shown in green,
that of the forefoot in red:





Of the four therapeutic shoes, only the Darco falls slightly out of line, since it allows less load to be taken up in the middle foot, which also means less relief for the forefoot.

4. List of measurements

On the left foot (with a sneaker worn on the right foot in each case)			File
Sneaker	Normal walking	3 km/h	OPED01
Sneaker	Walking half steps	2 km/h	OPED02
Sneaker	Stairs		OPED03
Sneaker	Stairs, half steps		OPED04
VACOpede s	Normal walking	3 km/h	OPED05
VACOpede s	Walking half steps	2 km/h	OPED06
VACOpede	Stairs		OPED07
	Stairs, half steps		OPED08
Darco	Normal walking	3 km/h	OPED09
Darco	Walking half steps	2 km/h	OPED10
Darco	Stairs		OPED11
Darco	Stairs, half steps		OPED12
VACOped TC	Normal walking	3 km/h	OPED13
VACOped TC	Walking half steps	2 km/h	OPED14
VACOped	Stairs		OPED15
	Stairs, half steps		OPED16
Bledsoe diabetic boot	Normal walking	3 km/h	OPED17
Bledsoe diabetic boot	Walking half steps	2 km/h	OPED18
Bledsoe diabetic boot	Stairs		OPED19
Bledsoe diabetic boot	Stairs, half steps		OPED20
Sneaker + tape	Normal walking	3 km/h	OPED21
Sneaker + tape	Walking half steps	2 km/h	OPED22
Sneaker + tape	Stairs		OPED23
Sneaker + tape	Stairs, half steps		OPED24
VACOpedes +	Normal walking	3 km/h	OPED25
tape VACOpedes	Walking half steps	2 km/h	OPED26
+ tape	Stairs		OPED27
VACOpedes +	Stairs, half steps		OPED28
tape VACOpedes			
VACOpedes + tape + vented	Normal walking	3 km/h	OPED29
VACOpedes + tape + vented	Walking half steps	2 km/h	OPED30
Darco + tape	Normal walking	3 km/h	OPED31
Darco + tape	Walking half steps	2 km/h	OPED32

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