Analysis of Bending and Torsional Stress on the Foot in Different Offloading Shoes

Original Research Report

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Abstract

This study compares the bending and torsional stress acting on the foot in the Darco Relief Dual offloading shoe to that of an already licensed competitor. Levels of functional limitation and forefoot offloading were analysed in 22 healthy subjects (9f, 13m; 35 ± 8y) using the vebitoSCIENCE measuring system. 30 gait cycles were monitored and the mean values calculated for selected parameters. The Darco Relief Dual significantly reduced ($p<0.05$) maximum dorsal extension moments at MTP I and V. There was also a significant reduction in the range of motion at MTP V and a significant decrease in the total load on MTP I and V over the entire gait cycle. In the competitor shoe, a significantly reduced maximum plantar flexion moment and alternating load were measured at MTP I and DIP I.

Keywords: Bending moment, torsional moment, stress, offloading shoes

Specialized orthopedic devices for stabilizing and offloading the foot are often used to support the rehabilitation process after foot surgery [2]. There are different types of shoes prescribed after surgery, such as those specialized for wound management or with offloading functions. In Germany, these therapeutic shoes must meet essential requirements to receive an official number in the German register of medical technical aids and it is therefore necessary to test their quality and functions. Wound management requires antibacterial material and postoperative shoes have to be firmly affixed to the foot to reduce loading in the forefoot area. Postoperative shoes must also be comfortable, even if the foot is bandaged. Forefoot offloading shoes are used when load has to be taken off the injured area but the patient needs to stay mobile, for example, after hallux valgus surgery.

How much the injured area is offloaded can generally be justified by measuring plantar pressure. In addition to plantar pressure, however, multidimensional stresses like bending and torsional moments also act on the foot.

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Bending moments, which are calculated by multiplying the acting force by the respective lever arm, cause bending deformations in the shoe; or rather, on the foot in the shoe. If, for instance, the forefoot is extended dorsally with respect to the hindfoot, there is an acting dorsal extension moment. In the case of a cyclical movement like walking, alternating loading occurs in the form of both dorsal extension and plantar flexion moment. Alternating load cannot be detected by conventional pressure measurement systems [5].

The first findings on bending loads acting on the foot were published by Arndt et al. (2002) [1]. The authors conducted an in-vivo study in which strain gauges were surgically implanted into the second dorsal metatarsal bone. These measured strain on the 2nd metatarsal head during walking and were capable of detecting both tensional stress and compression stress. In the past, invasive procedures such as this were the only way to measure bending and torsional stresses acting on the foot in shoes. However, a new, non-invasive insole measurement system, developed at the Biomechanics Research Laboratory at Münster University of Applied Sciences (Germany), is now available.

Stief and Peikenkamp presented the first results obtained with the new insole measuring system in 2015, demonstrating that it could detect plantarflexion stress followed by dorsiflexion stress during each gait cycle [4, 5].

After aggregating their calibration results, they concluded that the insole measuring system is able to easily and reliably measure bending and torsional moments at the forefoot [5].

This study analysed the effects of two different offloading shoes on bending and torsional moments at the forefoot: the Relief Dual offloading shoe (Darco Europe GmbH, Raisting, Germany) and a competitor post-op shoe. Both are postoperative offloading shoes, but their designs are very different. The competitor shoe is indexed in the German register of medical technical aids, which is a precondition for the reimbursement through the health insurance. The aim of the study was to investigate whether the mechanical conditions present in the two shoes have comparable or significantly different influences on stress at the forefoot.

The insole measuring system vebitoSCIENCE (vebitosolution GmbH, Steinfurt, Germany) was used to monitor bending and torsional stress. This system uses 5 parameters to measure a shoe's functional limitation and forefoot offloading effect.

22 healthy subjects (mean age: 35 years; 9 female, 13 male) participated in the present study. Loading curves for 30 consecutive gait cycles were acquired from each test person, after which the mean values were calculated. The curve of bending and torsional moments were measured at five different sensor positions and parameters like maxima, range and alterna-

1 The offloading shoe Relief Dual (DARCO International Inc., Huntington, USA)

ting stress were analysed statistically.

Methods

Participants

The loads occurring under the different shoe conditions were recorded in trials with 22 test persons (mean age: 35 ± 8 years, between 25 and 52). Nine of the 22 subjects were female. Age and normal, physiological gait pattern were the selection factors for choosing test persons.

Relevant data on the test persons and their medical history were collected using a questionnaire before any measurement took place. An examination to identify abnormal gait patterns and malpositioning of the feet, hip and knee joints was conducted for each subject. In addition, the range of motion of the upper and lower ankle joint was determined according to the neutral-zero method. Subjects with notable limitations of movement or pathological abnormalities were excluded from measurement. Subjects gave their written consent before participating in this study.

Shoe Conditions

In this study, two different shoe conditions were analysed for the right foot. On their left foot, participants wore a neutral shoe with height compensation (Adidas Samba; Adidas AG, Germany). Height compensation was modified in each case to match shoe height for each individual shoe condition and shoe size.

In this study, the offloading shoes Relief Dual (DARCO International Inc., Huntington, USA) (see Figure 1) and a postoperative shoe from a competitor were compared.

For more information about the competitor shoe please contact the author.

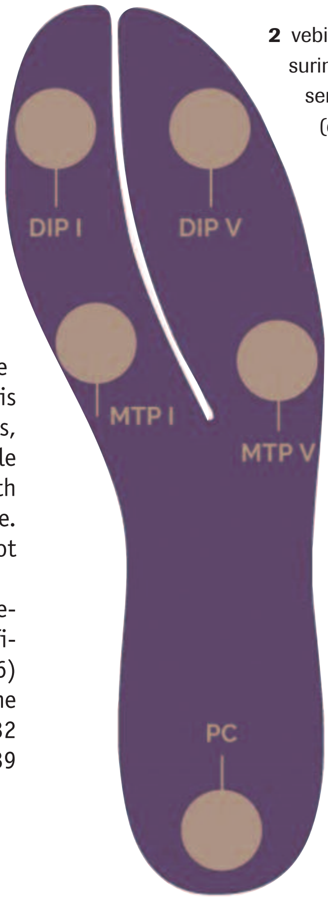
Both shoes were offloading shoes. The competitor shoe is indexed in the German register of medical technical aids, which is a precondition for the reimbursement through the health insurance (medical technical aids classification number group: 31.03.03.). The Darco Relief Dual did not have an medical technical aids classification number at the beginning of this study. The offloading shoes are very different in design. The competitor is a closed model with cushioned interior, featuring a rigid, full outsole with a double-rocker. The Relief Dual is an open shoe, which protects the toes, with an extended outsole. The outsole is made of two different materials with a continuous, rigid stiffening sole. Both shoes are fastened to the foot with Velcro.

In total, seven shoe sizes of the Relief Dual (34 female – 48 male) and five sizes of the competitor (37 – 46) were compared. Heel heights of the competitor shoes ranged from 30 – 32 mm and the Relief Dual from 31 – 39 mm.

Bending and torsional insole measurements

The vebitoSCIENCE insole measurement system described above was used to measure bending and torsional stress (5 sensor positions, 125 Hz, 16 bit).

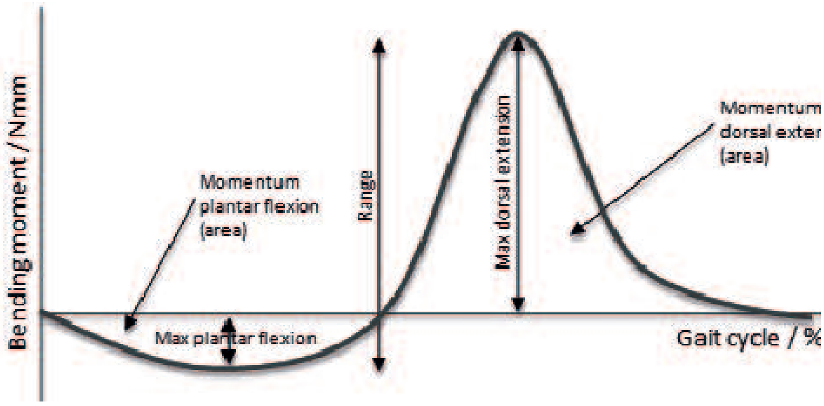
The vebitoSCIENCE measurement system was developed by the Biomechanics Research Laboratory, Münster University of Applied Sciences, Germany. Strain gauges are fixed to a specially shaped flexible layer in the insoles. The purpose of the special shaping is to detect bending and torsional loads independent of the medial and lateral forefoot. Mirror-inverted and interconnected strain gauges can be found on both the upper and bottom surface. The interconnection of the strain gauges into half bridge circuits for bending and full bridge circuits for torsion allows both loads to be measured at the same time. The measuring frequency is 125 Hz. Sensors are placed proximal to metatarsophalangeal joints I and V (MTP I and V), proximal to the distal interphalangeal joints I and V (DIP I and DIP V) and distal to the processus calcaneus(see Figure 2). Data are transferred wirelessly to a notebook via Bluetooth. The calibration results presented a coefficient of determination of $R^2 > 0.999$ and a linearity factor of almost 1.0 [5].



2 vebitoSCIENCE measuring sole with five sensor positions (distal interphalangeal joints I and V, metatarsophalangeal joints I and V and processus calcaneus).

The measuring insoles were placed in the shoes and cables were affixed to the participants' legs with flexible Velcro® straps. To avoid distorted results due to fatigue or testing order, the order of shoe conditions tested was randomized. Subjects wore the different test shoes on their right foot. On their left foot, they wore an Adidas Samba with additional height compensation matching that of the offloading shoe being tested. The measuring insoles were worn on both feet. The system requires an initially unloaded state, which was measured with subjects sitting on a raised chair with legs and feet hanging and immobile. The measurements were taken on a Sprintex slat belt treadmill (SPRINTEX Trainingsgeräte GmbH, Kleines Wiesental, Germany).

Before data acquisition, participants were given five minutes of familiarization per shoe condition, during which they walked on the treadmill at a self-selected speed (minimum of 2.5 km/h). The velocity chosen by the subject during this period of familiarization was maintained for the following trials. Measurement of bending



3 Exemplary curve progression for bending moments including illustration of analysed parameters.

and torsional moments was conducted once per shoe condition. For each trial, 30 gait cycles were recorded.

Data processing and evaluation

The curves of bending and torsional moments were recorded at five different measuring points by the vebitoSCIENCE measuring system. The load curves of 30 serial gait cycles (GC) were monitored and mean values were calculated. The point of reference determined automatically by the software was heel strike [3]. Before analysis, the raw data were run through low-pass filter (Butterworth, 10 Hz, second order).

The curves of the bending and torsional moments of the right foot were analyzed for all five measuring points.

Besides these load curves, five additional parameters were statistically analysed:

- maximum plantar flexion moment/ Nmm
- maximum dorsal extension moment/ Nmm
- range of bending moments/ Nmm
- alternating load of bending moments/ %
- momentum (absolute value) of bending moments/ Nmm * %

Figure 3 presents a characteristic bending moment curve, including the analysed parameters. The parameter range is an index of the range of motion over an entire gait cycle. The momentum (absolute value) has not been visualised. In this study, the term momentum (absolute value) is used to refer to the absolute value of the bending momentum. This designation is abstracted and not equivalent to the physical quantity momentum. The load over the entire gait cycle can be characterized by considering the parameter momentum (absolute value) of the bending moments.

If there are no moments in the direction of a plantar flexion, the minimum of the dorsal extension moments is shown. The alternating load (AL) is calculated as shown in formula (1). If there is no plantar flexion or dorsal extension moment, then there is no alternating load, either.

$$AL = 200 * min\left(\frac{|d\_max|}{|p\_max| + |d\_max|}; \frac{|p\_max|}{|p\_max| + |d\_max|}\right)$$

A two-sided paired t-test was conducted to detect significant differences ($p < 0.05$).

Results

Curves

The continuous curves present the mean values, the dotted curves present the standard deviation (SD) . The blue curves describe the loading in the Relief Dual shoe as a function of the GC and the red curves the loading in the competitor shoe. For each graph, the number of subjects (N) used to calculate the mean value is given.

If there were measurement errors with regards to individual test persons, then N < 22.

Bending moments

The mean bending moment at the heel produces a similar curve in both shoe conditions, with a small SD. The curves first show a dorsal extension moment with a local peak at about 10 – 20% gait cycle, followed by a slow decrease that reaches zero at about 60 – 70% GC. The measurement for the Relief Dual shows a slightly higher dorsal extension moment and an additional plantar flexion moment (Figure 4).

Starting from about 40% GC, bending moments at measuring point MTP I show very similar curves with small SDs, whereas the competitor presents considerably higher dorsal extension moments. After heel strike until about 45 % GC, a slight plantar flexion moment can be observed in the Relief Dual. By contrast, the competitor presents a dorsal extension moment.

At measuring point MTP V, the bending moment curves differ little and present small SDs. After heel strike, a local maximum occurs at about 10 – 20% GC. At 30 – 40% GC, a local minimum can be observed. At about 60% GC, a conspicuous local maximum occurs, afterwards showing a steep decrease. The dorsal extension moments of the Relief Dual also have considerably lower values in comparison to the competitor at this measuring point. There is no plantar flexion moment for either shoe condition at measuring point MTP V.

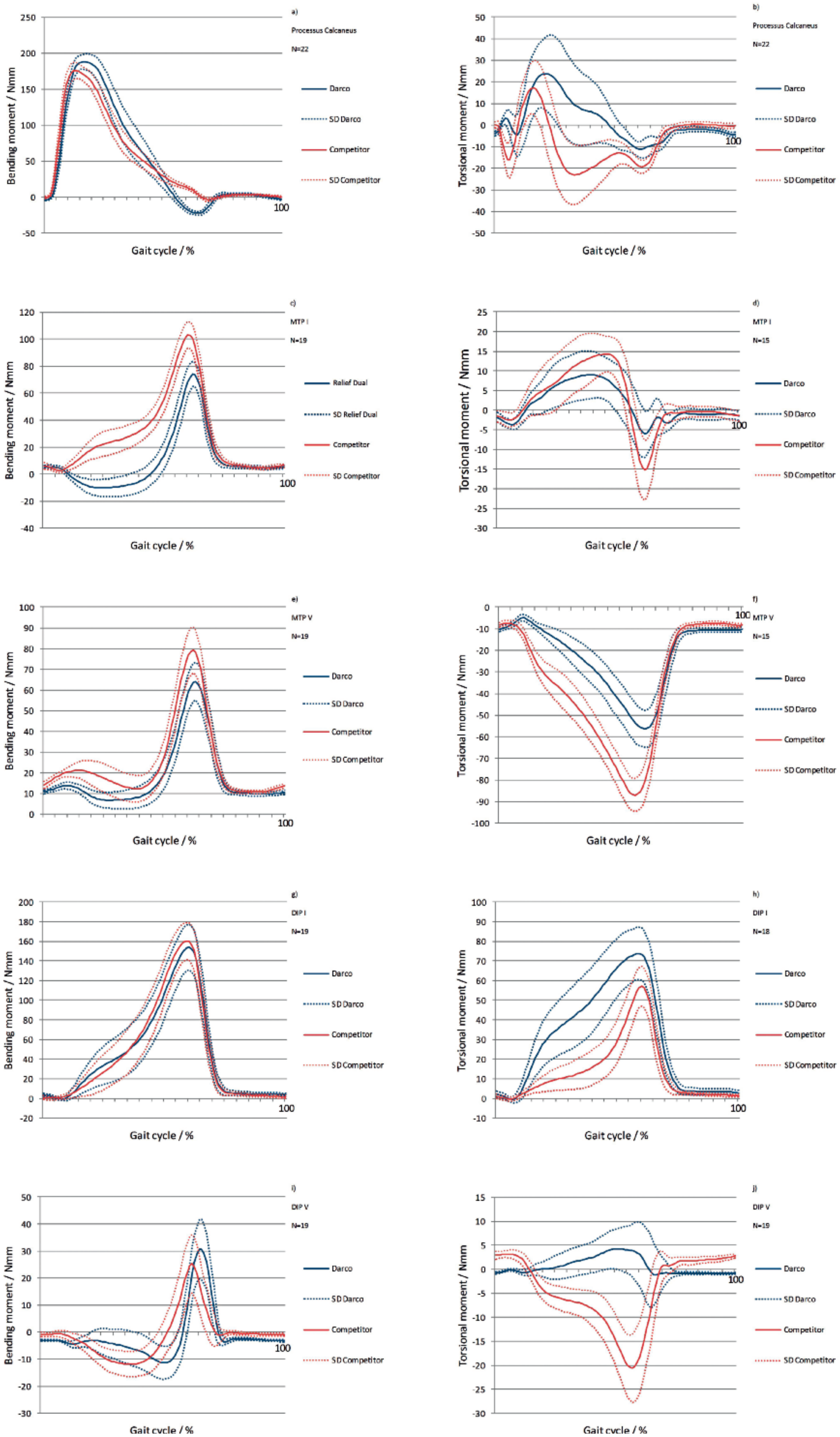
Both mean bending moment curves are almost identical at measuring point DIP I. There is a local maximum at about 60 – 70% GC. A relatively high SD exists in the first phase of the gait cycle (until approx. 50%). After the local maximum is reached, both curves show a steep decrease. At this measuring point, both shoe conditions display a dominant dorsal extension moment.

At DIP V, the bending moments of both shoe conditions present a similar curve. The high SDs apparent here are due to the relatively high variations between individual subjects. Bending moments change their direction from a plantar flexion moment to a dorsal extension moment earlier for the competitor (at approx. 55 % GC) as compared to the Relief Dual. Dorsal extension values are slightly smaller for the competitor than for the Relief Dual.

Torsional moments

The mean torsional moment at the heel demonstrates a strongly varying curve with a large SD under both shoe conditions. The measurement taken for the Relief Dual shows a higher eversion moment as compared to the competitor. An inversion moment is dominant in the competitor shoe. High SDs indicate strong variations in the curves of the individual test persons (Figure 4).

The mean torsional moments demonstrate a similar curve, but unlike the bending moments at MTP I, higher SDs occur at this location. In addition,



4 Mean bending and torsional moments on five sensor regions. Continuous lines present the mean values, dotted lines present the standard deviation. Positive values describe a dorsal extension moment (internal rotation with regard to the central axis of the foot), negative values a plantar flexion moment (external rotation).

Parameter	Measuring point	Mean value		Standard deviation		t-test (p<0.05)
		Relief Dual	competitor	Relief Dual	competitor	
Mb max. plantar flexion / Nmm	Heel	-25	-7	17	9	0.0003
	MTP I	-19	-4	25	14	0.0040
	MTP V	2	1	13	16	0.4988
	DIP I	-2	-1	10	7	0.3990
	DIP V	-35	-25	43	40	0.2330
Mb max. dorsal extension / Nmm		Relief Dual	competitor	Relief Dual	competitor	
	Heel	195	180	61	60	0.4608
	MTP I	86	115	51	46	0.0074
	MTP V	71	95	38	39	0.0007
	DIP I	160	164	78	69	0.8068
	DIP V	44	50	39	42	0.5056
Range / Nmm		Relief Dual	competitor	Relief Dual	competitor	
	Heel	220	188	60	57	0.1053
	MTP I	104	118	44	41	0.1271
	MTP V	70	94	32	34	0.0003
	DIP I	163	165	78	69	0.8805
	DIP V	79	75	32	47	0.6605
Alternating load / %		Relief Dual	competitor	Relief Dual	competitor	
	Heel	24	12	17	10	0.0065
	MTP I	38	15	33	22	0.0162
	MTP V	-	-	-	-	-
	DIP I	11	6	11	6	0.0443
	DIP V	24	36	22	27	0.0932
Momentum (abs. value) / Nmm%		Relief Dual	competitor	Relief Dual	competitor	
	Heel	5857	5300	1852	1828	0.3292
	MTP I	2517	3155	1452	1679	0.0170
	MTP V	1969	2860	903	1294	0.0055
	DIP I	4387	4500	2162	1928	0.7739
	DIP V	1565	1475	984	1092	0.6799

Table 1 Results of the five compared measuring parameters and the findings of the conducted t-test. Mean value and standard deviation (N=22) presented for each parameter for the Relief Dual and the competitor at all measuring points.

the eversion and inversion moments are higher in the competitor shoe than in the Relief Dual.

For both shoe conditions, only an inversion moment can be observed with regards to the torsional moments at MTP V. The curves are quite similar and there is a small SD. The increase in and amplitude of the inversion moment are considerably higher for the competitor in comparison to the Relief Dual.

In contrast to the bending moments, more differences are found regarding the curves of the torsional moments at DIP I. In the first phase of the gait cycle, there is a greater increase and higher values are observed for the torsional moments of the Relief Dual as compared to the competitor. Relatively high SDs can be observed with regards to torsional moments at DIP I. The variance is discernibly high, especially for the Relief Dual. Moments in the direction of an eversion are dominant for both shoe conditions.

Under both shoe conditions, the curves for torsional moments at measuring point DIP V show highly opposite trends (Fig. 4). In the curve for the Relief Dual, an eversion moment is dominant, whereas the competitor shoe generally demonstrates an inversion moment. This inversion moment is considerably higher in comparison to the corresponding values of the Relief Dual.

Comparison of selected measuring parameters

Table 1 present the findings for the selected measuring parameters of the bending and torsional measurement. To enable a direct comparison of the analysed shoe conditions, the calculated mean values of the measuring parameters are listed below. Significant differences between both shoe conditions are highlighted in grey (see Table 1).

For the Relief Dual, a significantly higher plantar flexion moment can be observed at the heel and MTP I as compared to the competitor. At the other measuring points, there is no significant difference in the plantar flexion moments.

At MTP I and MTP V, the mean values of the maximum dorsal extension moments of the competitor are significantly higher as compared to the Relief Dual. At the other measuring points, no significant difference exists for the dorsal extension moments.

Only at measuring point MTP V is there a significant difference between the two shoe conditions for the range. Here, the value of the competitor is significantly higher than that of the Relief Dual. At the other measuring points, there is no significant difference between the two shoe conditions.

The alternating load value of the Relief Dual is significantly higher than the value of the competitor at the measuring points heel, MTP I and DIP I. Because there is no plantar flexion moment, no alternating load can be determined at measuring point MTP V. At DIP V, no significant difference can be observed between the two shoe conditions.

At the measuring points MTP I and MTP V, the momentum value of the competitor is significantly higher than the value of the Relief Dual. There was no significant difference as regards the other measuring points.

Discussions

The aim of this study was to evaluate loads acting on the foot during walking in two different offloading shoes with very different shoe designs. The Relief Dual was compared to an offloading shoe that already is indexed in the German register of medical technical aids. The analysis focuses on functional limitation and relief of the forefoot. Bending and torsional loads were measured using the vebitoSCIENCE measuring system.

The curves of the bending loads at the different measuring points are significant and will be discussed as follows. The findings of the bending and torsional measurements show that similar levels of functional stress occur under the two shoe conditions analysed. However, the Relief Dual offered the advantage of a reduced dorsal extension moment at MTP I and MTP V. The differences between the two shoe conditions especially occur at the measuring points heel, MTP I and MTP V. At DIP I and DIP V, the load curves of both shoes are similar. For the Relief Dual, an additional slight plantar flexion moment can be observed at the heel. Furthermore, the dorsal extension moment is slightly higher at this measuring point. The bending load at the heel is of subordinate importance regarding the question of functional limitation and relief of the forefoot. At these two measuring points, the dorsal extension moment of the Relief Dual is notably lower than that of the competitor. This implies greater functional limitation and increased relief of the forefoot. The pronounced occurrence of a plantar flexion moment at MTP I is of lower importance as compared to the reduced dorsal extension moment, because the highest loads at the forefoot are observed during terminal stance and can therefore be expressed well by the dorsal extension moment. At measuring point MTP V, only a reduced dorsal extension moment can be observed. The fact that no additional plantar flexion moment was observed implies that the Relief Dual provides better offloading of the forefoot.

Interpreting torsional load curves generally only allows conclusions to be drawn on the gait pattern of individual test persons. They also complicate interpretation of the occurring loads.

Due to their lack of relevance to offloading the forefoot, the heel parameters will not be discussed any further. At measuring points MTP I and MTP V, seven of the nine load parameters selected differ significantly. For five of these selected parameters, the Relief Dual demonstrates greater relief of the forefoot during walking. For two of these parameters, the competitor achieves smaller loads at the forefoot. The values of the maximum dorsal extension moment at MTP I and MTP V, of the range at MTP V and of the momentum (absolute value) at MTP I and MTP V are significantly smaller for the Relief Dual as compared to the competitor. The competitor presents a smaller maximum plantar flexion moment and an alternating load at MTP I.

At measuring points DIP I and DIP V, the competitor achieves greater relief of the forefoot for one of ten values (alternating load at DIP I). For all other parameters, both offloading shoes achieve similar functional limitation and relief of the forefoot at these measuring points.

Because of the additional plantar flexion moments of the Relief Dual and the lower alternating loads of the competitor, the competitor achieved comparatively slightly reduced loads at the forefoot. However, given that the values of the maximum dorsal extension moment and the momentum (absolute value) of the Relief Dual are significantly smaller than the values of the competitor, it can be assumed that the Relief Dual achieves similar relief of the forefoot, and in some cases even greater relief.

Individual walking speed was chosen by each participant during the first measuring condition and remained constant for the second condition. For statistical analysis, a paired t-test insensitive to the effect of interindividual differences in walking speed was used.

For the very same reason, differences in sole stiffness caused by different shoe sizes do not affect the data analysis; the shoe sizes differed from subject to subject, but remained constant for the two testing conditions.

To derive more information on the offloading effects of the two different shoe designs, the plantar pressure distribution should be analyzed as well. It is also important to what extent patients feel familiar with the shoes and how the orthopedic device influences normal gait patterns. Furthermore, to see how offloading shoes influence the gait patterns of bending and torsional stress acting on the foot, additional data should be analyzed, i.e. from the left foot wearing the control shoe, or under control conditions. To date, no information has been published on the influences of bending and torsional loads on the feet of surgery patients wearing offloading shoes.

Conclusions

Although the two shoes investigated had very different designs, there were only minor differences observed between the bending and torsional stress acting on the foot in each shoe design. That said, the offloading effects during walking measured by multidimensional parameters were attributable to demonstrable differences in bending and torsional stress under the two shoe conditions. The significant differences found for MTP I and MTP V suggest that the Relief Dual has a slightly greater offloading effect on the forefoot. After this study was completed, the Relief Dual was indexed in the German register of medical technical aids as an offloading shoe. However, to provide a more comprehensive view of stress acting on the foot, plantar pressure must be analyzed in combination with bending and torsional stress measurements in future studies. ■

Conflict of interest

This study was supported by DARCO (Europe) GmbH. This funding did not influence study design, data analyses and conclusions.

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