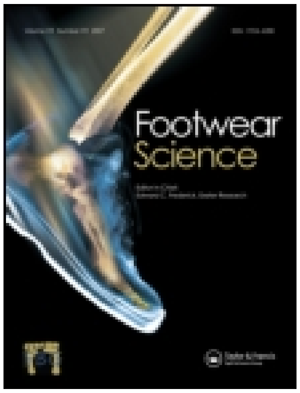

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Systematically modified crash-pad reduces impact shock in running shoes

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The purpose of this study was to compare the effect of (a) crash-pad thickness and (b) midsole height at the heel to reduce heel impact load during running. Twenty male runners performed heel-toe runs in four different shoe conditions. While three shoe conditions had systematic changes in crash-pad thickness without changing general heel height, a fourth shoe condition differed only in overall heel height. Kinetic and kinematic running variables were quantified by using a force platform and an electrogoniometer. Data were collected for five valid running trials at a constant running speed of $3.5 \pm 0.1\,\mathrm{m\,s^{-1}}$. Kolmogorov–Smirnov tests, a one-way repeated measures ANOVA ($P < 0.05$) as well as effect sizes (η^2) were calculated for all variables. The findings of this study showed that (a) increasing crash-pad thickness resulted in reduced impact variables without influencing traditional rearfoot motion variables. Furthermore, reduced heel height (b) is influencing predominantly rearfoot stability. Consequently, crash-pad modification can be used to improve cushioning properties without influences on rearfoot stability. Furthermore, crash-pad modification allows reducing shoe weight while maintaining cushioning properties.

Keywords: running; running shoes; shod running; cushioning; shock attenuation; midsole material; rearfoot control

1. Introduction

Apart from protecting runner's feet against environmental circumstances like rough surfaces and temperature, running shoes can reduce repetitive impact shocks on the human body. On the other hand, running shoes cause kinematic changes of rearfoot motion by increasing the lever arm compared to barefoot running (Stacoff and Luethi 1986). Even though repetitive shock is not necessarily regarded as primarily harmful for runners (Nigg 2001) there is still a need to attenuate shock for comfort reasons.

Therefore, current research focuses on the possibilities to improve shoe comfort and performance. Studies showed coherences between shoe comfort and shock attenuation (Milani *et al*. 1997, Goonetilleke 1999) as well as between shoe weight and performance (Frederick 1985, Cavanagh and Kram 1990). Thus, the knowledge about functional modifications to affect shock attenuation is a key factor to develop running shoes.

It was shown that mechanically as 'soft' characterized running shoes extend time to impact peak compared to 'hard' running shoes while magnitude of impact peak remained unchanged (Clarke *et al*. 1983a). These results were enhanced by Nigg *et al*. (1986) by testing different midsole hardness at varying running speeds between 3 and $6\,\mathrm{m\,s^{-1}}$. However, it was found that lower midsole hardness increased rearfoot motion as well (Clarke *et al*. 1983b). Subsequently, researchers aimed to improve cushioning properties while maintaining rearfoot stability. It was found that rearfoot motion can be decreased by using higher midsole hardness in the medial part of the heel, marking the beginning of dual density technology (Nigg *et al*. 1986). Additionally, varus wedged shoes can be used to control rearfoot motion (Milani *et al*. 1995, Brauner *et al*. 2009).

In recent years lower shoe constructions became more popular in order to reduce lever arms to achieve higher rearfoot stability. This concept was based on earlier findings (Stacoff and Kaelin 1983). However, the decrease of heel height results in less shock absorbing material. Nevertheless, acceptable cushioning properties should be provided.

During heel strike running the shoe touches the ground with the lateral border of the heel (Cavanagh and Lafortune 1980), generally. Based on these findings the authors stated that impact area of shoes ranged from zero to 60% of shoe length, orientated from heel.

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The element touching the ground initially is a critical component to influence impact variables. Thereby, size of contact area and material properties of the damping elements are most important (Cavanagh 1982, Nigg 1983).

Due to these findings, goal of this study was to examine the effect of systematically altered crash-pad thickness on impact load during running by testing the following hypotheses: (H1) impact load can be reduced by using softer material at the lateral part of the heel (called crash-pad material), and (H2) impact load decreased gradually with increasing crash-pad height.

2. Methods

2.1. *Subjects*

Twenty male and injury-free recreational runners (age: 26.1 ± 3.3 years, height: 176.1 ± 4.9 cm, weight: 72.1 ± 7.0 kg) participated in this study. All of them were rearfoot-strikers and had experience in laboratory measurements. Prior to the testing all participants signed informed consent. All procedures adhered to the requirements of Chemnitz University of Technology for subject testing.

2.2. *Shoe conditions*

Four lightweight running shoe conditions were used in this study. Three of them were systematically modified prototypes while the other was a commercially available running shoe.

For crash-pad intervention, the lateral heel area of three identical prototypes was systematically modified. The midsole hardness of the prototype shoes was measured according to ASTM D 2240. The verified hardness was in a range of 55–58 Asker C for midsole material. All three shoe conditions were prepared with the same upper and insole (Figure 1) to ensure identical fit.

For one shoe condition (LO), the originally midsole material was used in the lateral heel. For the other two shoe conditions 10 mm (MI), respectively 17 mm (HI) of the original midsole material in the lateral heel was cut off and replaced by crash-pad material of lower hardness (52 Asker C). Afterwards, for all three shoe conditions the same outsole was glued on. Mechanical measurements confirmed heel height and shoe weight of these three shoe conditions to be almost identical (26.07 ± 0.5 mm; 309 ± 1 g).

In order to quantify the results it seemed to be necessary to verify the effect of reduced heel height with regard to kinetics and rearfoot kinematics for the used shoe design as well. Therefore, a commercially

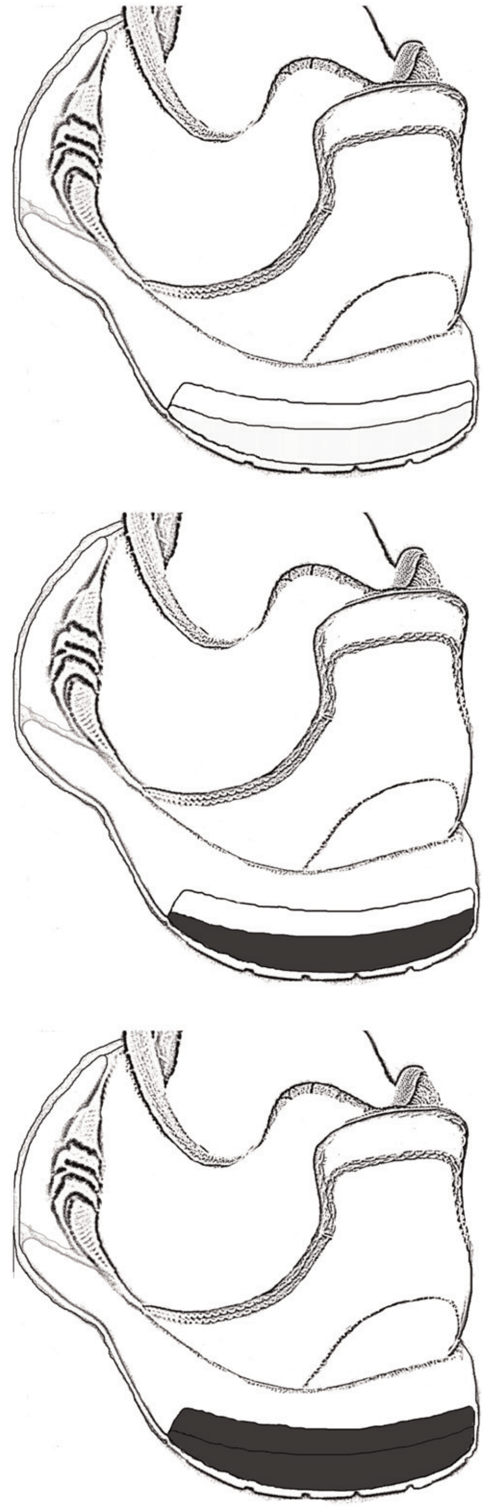

Figure 1. Shoe conditions – crash-pad intervention (LO: 0 mm crash-pad, MI: 10 mm crash-pad, HI: 17 mm crash-pad).

available running shoe 'Puma Complete Road Racer' (CO) was used to compare the effects of different heel height. The same EVA midsole hardness like the modified prototype shoes (55 Asker C) and a comparable upper were used. However, midsole height was reduced by 21% to 20.6 mm. Shoe weight was 240 g. In this shoe no crash-pad was integrated.

2.3. *Measurement setup and parameters*

Each subject performed five valid running trials in all shoe conditions. Running speed was set to $3.5 \pm 0.1\,\mathrm{m\,s^{-1}}$ and observed by three light barriers arranged right in front of, in the middle, and right behind the force platform.

The force platform (KISTLER 9287BA; 60×90 cm) was integrated into a 13-m indoor running surface. Ground reaction force in vertical direction (F_z) was analyzed. Parameters of the impact peak were calculated after normalizing force by bodyweight. Peak impact force (PIF), its corresponding time (TPIF), and mean force rising rate (FRN) from touch down to peak impact force were obtained. In addition, maximum force rising rate (FRX) within impact peak was calculated.

Peak tibial acceleration (PTA) was measured at touchdown with a miniature accelerometer (Entran EGAX-F-100 $\pm$ 100 g). It was attached to the medial aspect of the tibia at mid location between malleolus and the tibia plateau fixed with double-side tape and an elastic strap to increase coupling between transducer and bone and to ensure pretension of the skin (Schnabel and Hennig 1995). For all trials the sensor remained at the same position (Nigg 1999).

A light weight electrogoniometer (Megatron MP10 1 kOhm) was fixed to the shoe heel counter with its axis of rotation at the approximate height of the subtalar joint (Milani *et al.* 1995). Zero degree of rearfoot motion was individually defined for each subject in each shoe condition during a static trial. Subjects stood on a calibration plate with guided foot placement and parallel feet 100 mm apart. Goniometer and accelerometer data were amplified by a custom built amplifier positioned in a belt bag at the back of the subjects.

A digital filter (third-order, zero-lag Butterworth low pass filter) was applied to the electrogoniometer data (50 Hz), respectively to the GRF data (100 Hz). Afterwards, total pronation (TPR) from maximum supination angle (MSA) after foot strike to maximum pronation (MPA) during ground contact, and initial pronation angle (IPA) at 10% after ground contact (Nigg *et al.* 1986) were calculated. All measurement devices recorded data at a sampling rate of 1000 Hz and were run by Labview 8.0 (National Instruments$^{\mathrm{TM}}$, Austin, TX, USA). Data post processing were done with DIAdem (National Instruments$^{\mathrm{TM}}$).

2.4. *Statistics*

Means and standard deviations across five repetitive trials, for each shoe and subject were used for further statistical analysis. Kolmogorov–Smirnov tests were applied for each parameter to test for normal distribution. Afterwards, a one-way repeated measures ANOVA ($P < 0.05$) and *post-hoc* tests (Fisher's LSD) were used to identify differences between shoe conditions. Furthermore, effect sizes (η^2) according to Bakeman (2005) were calculated between the systematically modified shoe conditions (LO, MI, and HI). Additionally, Pearson correlations were used for the different impact variables of each shoe condition.

3. Results

All parameters in this study were normally distributed. Therefore, all trials of all subjects were used for data analysis.

3.1. *Heel height*

FRN significantly decreased with increasing heel height from CO to LO by 6% ($P < 0.01$). Furthermore, the other impact variables (PIF, TPIF, FRX) were also slightly reduced ($P < 0.05$).

Furthermore, the increase of heel height also results in an increase of maximum pronation angle by 17% ($P < 0.05$). A similar trend could be observed for initial pronation angle. However, this result was found to be not statistical significant.

3.2. *Crash-pad*

For the three prototype shoes (LO, MI, HI) highest impact variables were found for shoe condition LO and lowest for shoe condition HI. The time to peak impact force values increasing from LO to HI, indicate better shock attenuation, respectively.

Pair wise *post-hoc* comparisons (Table 1) showed that there exist significant differences in a number of cases between the three modified shoe conditions.

Thus, gradual increase of crash-pad height leads to gradual increase of shock attenuation (Figure 2). For instance, an increase of crash-pad height decreased FRN in two steps by approximately 12% each, across the three shoe conditions. Similar findings were

Table 1. Mean and standard deviation of impact variables.

Impact variables	CO	LO	MI	HI	ANOVA *p*-value	Effect size η^2
PTA [g]	9.9 ± 2.7	9.3 ± 2.1	9.1 ± 2.7	7.7 ± 2.0	<0.001	0.42
FRX [BW/s]	118 ± 17.0	113 ± 16.7	107 ± 17.4	93 ± 15.8	<0.001	0.55
FRN [BW/s]	70.3 ± 8.2	66.0 ± 9.5	57.7 ± 7.8	49.6 ± 7.2	<0.001	0.76
TPIF [ms]	26.2 ± 1.6	27.2 ± 1.9	30.8 ± 2.6	35.3 ± 2.7	<0.001	0.89
PIF [BW]	1.83 ± 0.22	1.78 ± 0.24	1.76 ± 0.20	1.74 ± 0.25	=0.001	-/-

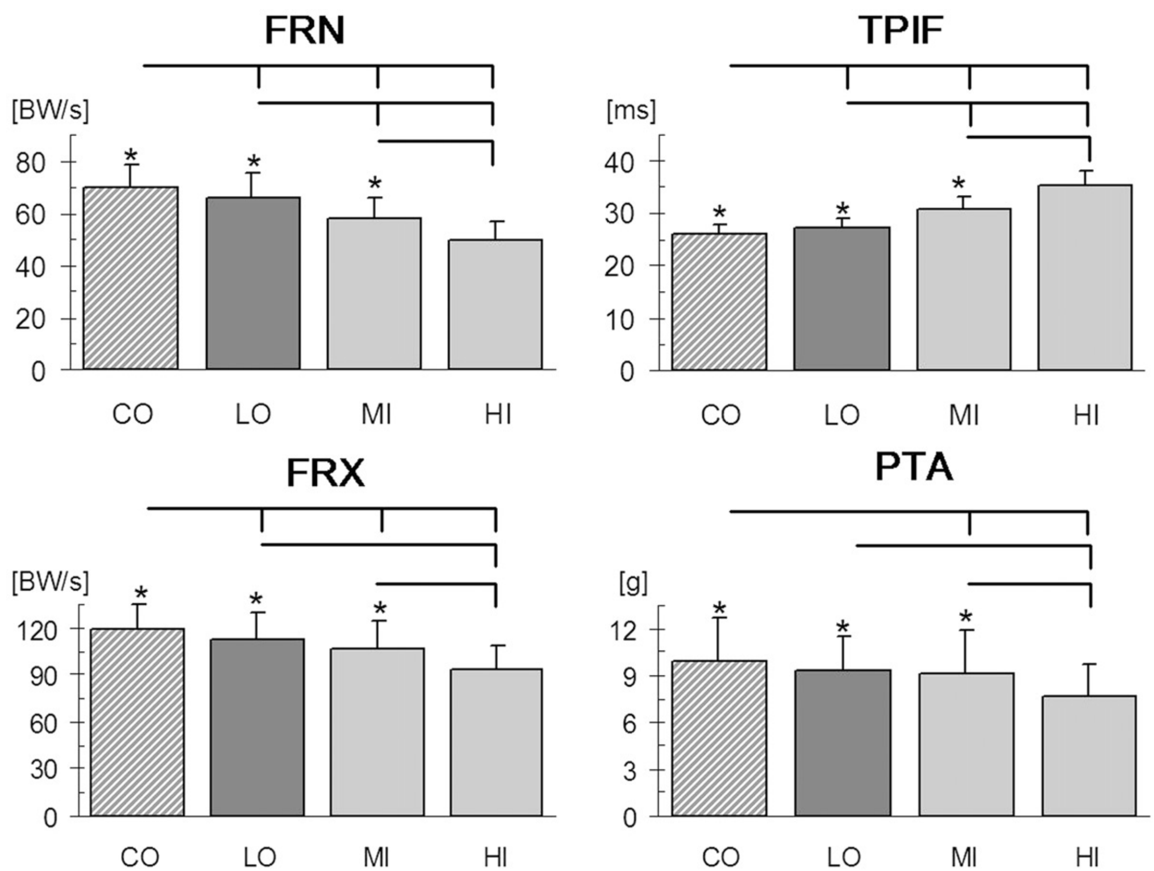

Figure 2. Impact variables (FRN, mean force rate; TPIF, time to peak impact force; FRX, maximum force rate; PTA, peak tibial acceleration).

observed for all other impact variables (FRX, PTA, TPIF). Confirming earlier findings (Clarke *et al.* 1983a) PIF remained constant across all shoe conditions.

Overall, variables of the three prototype shoes were shown to be altered up to 29.4% for TPIF, 24.8% for FRN, 17.5% FRX, 17.4% PTA (Table 1).

These findings were supported by effect size analysis. Considerably high effect sizes were present for FRN ($\eta^2 = 0.76$) and for TPIF ($\eta^2 = 0.89$). In contrast, effect sizes of FRX ($\eta^2 = 0.55$) and PTA ($\eta^2 = 0.42$) were found to be relatively low.

Correlation analyses of impact variables for each of the four shoe conditions were calculated. Thereby, four pairs of impact variables revealed meaningful relationships. High correlations (mean of four shoe conditions) were found between FRN-FRX ($r = 0.88$), FRN-PIF ($r = 0.84$), and FRX-PIF ($r = 0.76$). Low correlation was present between FRN-PTA ($r = 0.56$). TPIF was not correlated to any of the other impact variables (Table 2).

No significant differences were found for rearfoot motion variables by increasing crash-pad

Table 2. Coefficient of correlation for impact variables.

Pearson correlation	CO	LO	MI	HI	Mean ± SD	*p*-value
FRN-FRX	0.9	0.93	0.88	0.83	0.88 ± 0.04	<0.001
FRN-PIF	0.85	0.88	0.79	0.84	0.84 ± 0.04	<0.001
FRX-PIF	0.81	0.86	0.73	0.66	0.76 ± 0.09	<0.001
FRN-PTA	0.56	0.46	0.68	0.52	0.56 ± 0.10	<0.05

Table 3. Mean and standard deviation of pronation variables.

Pronation variables	CO	LO	MI	HI	ANOVA *p*-value
MSA [°]	−6.5 ± 3.4	−6.2 ± 3.4	−6.2 ± 3.8	−6.3 ± 3.1	n.s.
IPA [°]	−1.5 ± 2.6	−2.1 ± 3.0	−1.5 ± 2.7	−1.3 ± 2.7	<0.001
MPA [°]	4.7 ± 2.4	5.5 ± 2.7	5.3 ± 2.7	5.4 ± 2.5	<0.001
TPR [°]	11.2 ± 3.1	11.7 ± 2.7	11.5 ± 2.8	11.7 ± 2.7	n.s.

height (Table 3). Only for IPA a significant reduction was found between shoe condition LO and HI (Figure 3).

4. Discussion

The purpose of this study was to examine the effect of systematically altered crash-pad thickness on impact load during running. Furthermore, the effect of reduced heel height with regard to rearfoot motion should be confirmed according to Stacoff and Kaelin (1983).

The results of this study provide evidence to our hypotheses. It is proven that impact shock can be reduced by using a softer material at the lateral part of the heel (H1). Furthermore, increasing crash-pad height gradually increases impact shock (H2). Additionally, initial pronation was decreased by using a crash-pad height of 17 mm. To improve initial pronation is in accordance with former studies (Nigg *et al*. 1986). However, further rearfoot motion variables were not affected by this modification. Significant reduction of impact values indicated increased shock attenuation.

The calculated effect sizes showed that the proportion of the total variance that is attributed to the used crash-pad intervention is 89% (TPIF), 76% (FRN), respectively. This means that the effect of crash-pad intervention had a considerable influence on the improvement of shock attenuation. Lower effect sizes of FRX (55%) and PTA (42%) are mainly caused by higher interindividual variability between subjects. Thus, variables characterizing a time period (TPIF, FRN) may be stronger influenced by the crash-pad modification than discrete variables (FRX, PTA). However, this assumption should be investigated in further studies.

Clarke *et al*. (1983a) compared running shoes of considerable midsole hardness differences. The cushioning difference was mechanically proved by 50%. They reported a difference in time to peak vertical impact force by 18% when comparing a soft and a hard shoe condition. In our study this variable was increased by 29% for a crash-pad intervention of 17 mm. Therefore, crash-pad intervention is more effective than decreasing the hardness of the whole midsole material.

Similar to earlier studies (Clarke *et al*. 1983b, Heidenfelder *et al*. 2008) peak impact force did not change. Therefore, former suggestions towards running style adaptation (Nigg and Liu 1999) resulting in constant peak impact force was confirmed for crash-pad intervention as well. In a recent study it could be shown that maximum force rate is not influenced by the adaptation of sagittal heel strike angle (Heidenfelder 2008). Therefore, one may assume that the effect of crash-pad intervention is merely the result of mechanical material properties than kinematically mediated. Correlation results of a dynamic material test design and biomechanical measurements confirmed this assumption, since energy absorption increased in those shoes with decreasing impact shock (FRX, PTA).

The effects of our study were achieved by using a crash-pad of rather low density difference (3–6 durometer, Asker C scale) compared to general midsole material. It is suggested that crash-pad results for shock attenuation could be further improved by applying higher hardness differences. Otherwise, the possibility of crash-pad bottom out effects needs to be considered.

Furthermore, softer material tends to deteriorate faster than harder material. For identical load, softer material deforms in a higher degree and results in higher mechanical stress. Higher mechanical stress will decrease the durability of the material that may cause a rapid increase in impact shock during the lifetime of a running shoe (Heidenfelder *et al*. 2009). Moreover, increasing impact shock results in an uncomfortable running behaviour (Zhang *et al*. 1991, Goonetilleke 1999). Therefore, the lower limit of crash-pad hardness needs to be identified in further studies.

Additionally, this study confirms that decreasing midsole height within an applicable range improves

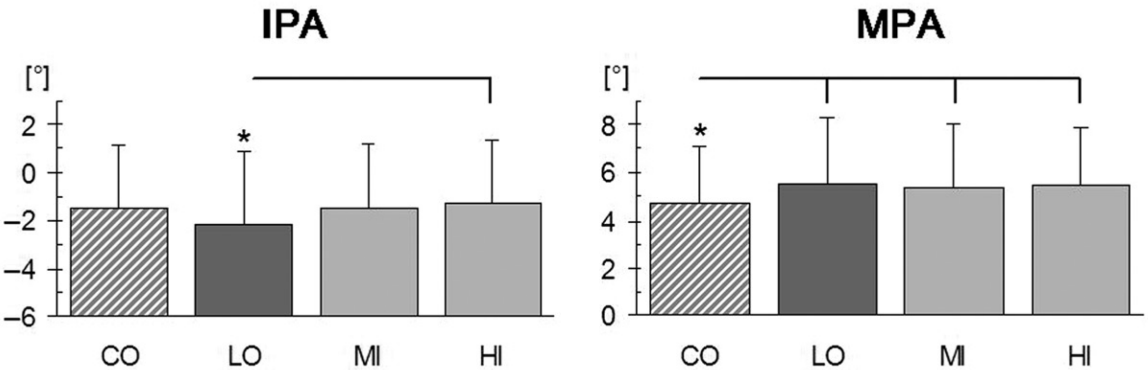

Figure 3. Pronation variables (IPA, initial pronation angle; MPA, maximum pronation angle).

rearfoot stability (Stacoff and Kaelin 1983). Together with the dual-density approach and varus modifications, there exist three well functioning concepts to control rearfoot motion in running.

The reduction of midsole height is used to reduce shoe weight as well, normally resulting in increased impact loads. Incorporating crash-pad technology compensates for this mechanism.

Shoe weight benefit is illustrated by the following example. For a running shoe with a total weight of 330 g and a commonly used relation between midsole material and other shoe parts (shaft, outsole, insole) of 1 : 2, the weight of the midsole material is 110 g. This study indicates that the midsole height of this shoe can be reduced by 30% when crash-pad technology is used. This results in a reduction of shoe weight by 10% to 297 g while maintaining cushion properties constant. Therefore, the results of the study allow to state that crash-pad technology is able to reduce running shoe weight while maintaining impact load constant.

Reduction of shoe weight might lead to improve running performance by reducing cardio-respiratory demands (Frederick 1985). Even though small changes in shoe weight may not reliably able to influence endurance running performance, shoe weight will still be considered as an important purchase argument of competitive runners.

5. Conclusion

Usage of material with lower density in the lateral heel is suitable to improve shock attenuation. In fact, it seems to be more effective than reducing the whole midsole hardness of the shoe or placing high amounts of midsole material under the heel in order to improve shock attenuation. Since it was shown that crash-pad technology did not weaken stability properties of running shoes, its use is recommended.

Furthermore, crash-pad technology benefits in a reduction of shoe weight by keeping cushioning properties constant. For implementation, shoe design and heel lift does not need to be modified at all.

Perspectively, the effect of crash-pads should also be analyzed for other shoe categories. It is hypothesized that hiking and working boots are suited to implement crash-pad technology as well.

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