# How the new running shoe technologies influence biomechanics and injury outcomes in recreational runners

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## ABSTRACT

The biomechanical study of 38 male and female recreational runners demonstrates the relationship between the four most frequently used footwear technologies and the biomechanical loading of the lower extremities in running. Running in the four midsole technologies (1. NEUTRAL (N_RS): neutral, cushioning running shoes, 2. SUPPORT (S_RS): support, motion control running shoes, 3. MAX (M_RS): maximalist, carbon-fiber plate running shoes, and 4. UTEC (U_RS): running shoes with a U-shaped midsole construction and highly cushioning foam) indicate a strong impact of midsole technology on the kinetics of the lower extremities. Midsole construction and material of the four running shoe categories systematically modulate the joint moments at the foot, the ankle joint, and the knee joint and thus the mechanical loading of the biological structures of the lower extremities in every step when running. The data demonstrates no significant differences in running kinetics between NEUTRAL running shoes and SUPPORT running shoes while MAX running shoes increase and UTEC running shoes decrease ankle joint and knee joint loading during the stance phase.
A 12-month standardized and randomized intervention trial surveyed 1697 recreational runners who used one of the four dedicated running shoe categories in more than 75% of their runs. The results demonstrate a strong relation between the development of running-associated injuries in general and knee and Achilles tendon problems in particular and the footwear categories. While neutral and support running shoes show no significant differences in the development of running-related injuries, M_RS increase and U_RS decrease this risk, especially the occurrence of knee pain. Other risk factors, like age, gender, BMI, running distance, average speed, surface as well as foot morphology and leg axis, only have a minor effect on the development of running-related injuries in the 12-months survey. Running shoe midsole technologies provide access to a sophisticated causal explanation of overload injuries of biological structures of the lower extremity during running and the resulting running-related injuries.

## Keywords

New running shoe technologies. musculoskeletal loading, running-related injuries, Achilles tendon overuse, knee joint injuries

## Introduction

With the running boom in the 1970s, the development of technical running shoes (RS) was primarily aimed at reducing the risk of overuse injuries [1]. The paradigms of impact cushioning and pronation control significantly determined the technical development of neutral, cushioning shoes and supportive running shoes with midsoles made of different hard materials or with medial support elements. Both paradigms and the technical concepts derived from them failed [2-5], with the result that no change in the incidence of running-related injuries (RRI) has been reported in more than 40 years [6-8]. A recent Cochrane report on systematic reviews and meta-analyses ("Running shoes for preventing lower limb running injuries") found no, little or even contradictory evidence of neutral, cushioned or support shoes as a factor in the development or prevention of running injuries [9].

Around 2015, the industry changed its focus, concentrating on improving the performance of the runner and promising enhancing performance when using the new technologies. The new midsole technology consists of a thick (35 to 45 mm) midsole made of soft, elastic foam with high resilience or energy return. The outsole is also convex in the sense of a rocker sole to facilitate rolling. Stiffening elements (carbon plates) are integrated into the thick midsole to increase the longitudinal stiffness of the sole. The biomechanical effects and physiological benefits in terms of improving running economy have been impressively demonstrated in trained runners with up to 4% less oxygen consumption [10]. The improved records of all runners over longer distances also speak for the efficiency of the new technology [11]. The shoes described are known in practice as "super shoes" or "maximalist" shoes. Such "super shoes" are now offered by all major running shoe manufacturers. While the potential for improved performance through "super shoes" is obvious [11,12], the question of increased mechanical stress and increased risk of injury remains open. Initial studies and practical experience point to a risk of repetitive overloading of bony structures and soft tissue [13].

The paradigm of injury prevention was taken up again in 2018 with the development of a U-shaped, double-rounded midsole made of soft elastic material. The so-called U-TECH™ technology (U_RS) developed, patented, engineered and manufactured by True Motion Running (Germany) claims to reduce the torques on the knee and ankle joint in the frontal and transverse planes by controlling the point of force application, thereby reducing the load on the knee joint in every stance phase during running and modulating the load on the Achilles tendon by controlling the path of the point of force application [14].

This means there are currently four major running shoes technologies on the market:

(1) NEUTRAL (N_RS): Neutral cushioned running shoes,
(2) SUPPORT (S_RS): Support (medially supportive) running shoes,
(3) MAX (M_RS): "Maximalist" running shoes with thick, convexly curved rocker soles and longitudinal stiffening (partly with carbon plates),
(4) UTEC (U_RS): Cushioned running shoes with a U-shaped midsole construction (U-TECH™).

This article is initially dedicated to the possible influence of the four running shoe technologies on stress and strain on the joints, tendons and muscles of the lower extremities. The primary consideration of the forces and torques acting on the joints is justified by the fact that only forces and torques can cause overloading and thus damage to biological structures. The second part of the article reports on a 12-month controlled wear study with four cohorts who randomized to one of the four running shoe technologies and documented training and running injuries over a year.

Finally, the questions of (1) whether the four running shoe technologies influence the load on the lower extremity during running and (2) whether a possible load variation due to shoe technology is reflected in the development of running injuries will be investigated.

## The biomechanics of recreational runners in four different running shoe technologies: a randomized interventional biomechanical study

### Purpose

While the traditional categories (N_RS: neutral, cushioning running shoes, S_RS: supportive, motion-controlling running shoes) pursue the concept of injury prevention, the “maximalist” running shoes (M_RS) are clearly designed to increase performance by improving running economy. U_RS pursue the goal of reducing stress and the risk of running injuries. To our knowledge, the biomechanical effectiveness of the four competing shoe technologies has not yet been systematically investigated experimentally.

The purpose of the present study is to analyze the musculoskeletal loading of the lower extremity during running with the four competing running shoe technologies, to quantify the biomechanical loading variables of the foot, ankle, knee and hip joint and to compare them between the shoe technologies.

Thus, we report on a randomized biomechanical intervention study with shoes of the four technology groups N_RS, S_RS, M_RS and U_RS. As representatives of the technologies, popular and frequently worn shoes of the corresponding category among recreational runners are chosen for the biomechanical experiment.

### Material and methods

#### Study participants

38 subjects (17 women, 21 men) (age: 46.2±9.6 years, BMI: 23.5±2.8 kg/m2) were recruited for the biomechanical intervention study. The study participants can be classified as “experienced or ambitious recreational runners” with regular running training, several years of running experience and a weekly running distance of 15 to 30 km. All subjects were orthopedically and neurologically normal. Before participating, all subjects signed a consent and data protection declaration.

#### Shoe conditions

All subjects completed running tests in randomized order in four running shoes representing the four running shoe categories N_RS, S_RS, M_RS and U_RS. Study participants and investigators were not explicitly informed about the different technologies and their hypothetical mode of action. The midsole foam used by the representatives are from the categories of thermoplastics and elastomers with similar material properties. The technical details can be found in Table 1.

#### Experimental setup and protocol

After a 5-minute run-in, the test subjects ran at their individual training speed (10-11.5 km/h) on a 30 m long running track into which two 6-component force measurement platforms (AMTI, 600x900 mm) were embedded. The individual running speed was controlled with light barriers and kept constant with a deviation of ±0.2 m/s in all shoe conditions. Ten runs per leg and shoe condition were averaged.

Table 1: Test shoes/representatives of the four running shoe categories NEUTRAL, SUPPORT, MAX), UTECH.

| Category | Representative | | Stack height[1] rear/front | Energy dissipation[2] | Energy loss[3] |
|---|---|---|---|---|---|
| | Model | Brand | | | |
| NEUTRAL(N_RS) | Glycerin 15 | Brooks | 20 mm/10 mm | 5 joules | app.30% |
| SUPPORT (S_RS) | Adrenalin 18 | Brooks | 20 mm/10 mm | 4 joules | app.30 % |
| MAX (M_RS) | Clifton 8 | Hoka one one | 40 mm/30 mm | 11 joules | 20-25% |
| UTEC (U_RS) | Nevos 1 | True Motion | 30 mm/20 mm | 10 joules | 20-25% |

[1] For sample size US 9.5, unloaded. [2] Dissipation of elastic energy when a typical running compression force of 2 kN is applied to the midsole using a material testing machine. [3] Energy loss during the return of stored energy after compression of the midsole with 2 kN.

Fourteen infrared cameras (Qualisys) recorded the runners with a frame rate of 200 Hz. Forty retroreflective spherical markers were applied to anatomical landmarks and as clusters on the upper and lower legs. The two 6-component force measurement platforms (AMTI) integrated into the running track allowed the measurement of the 3 components of the ground reaction force (x, y, z) and the position of the point of force application with a sampling rate of 2,000 Hz. Using inverse dynamic modeling, the external torques at the ankle, knee and hip joints could be calculated in all three joint and spatial planes.

### Statistics

For the statistical analysis, mean values and standard deviations were calculated for all variables. Analysis of variance (ANOVA) with repeated measures was used to compare the shoe conditions. For pairwise comparison between midsoles, we used Bonferroni corrected paired t-tests.

## Results

The plantar flexion moment (PFM) at the ankle joint describes the load on the Achilles tendon and the muscle-tendon unit (MTU) of the triceps surae (TS). The maximum load on the Achilles tendon is significantly influenced by running shoes ($p<0.05$) and the impulse of the Achilles tendon force is highly significantly influenced ($p=0.01$). The lowest loads on the MTU of the TS are found at MAX running shoes ((M_RS) (0.23±0.03 Nms/kg), followed by UTEC running shoes (U_RS) (0.26±0.04 Nms/kg).
The maximum extension moment at the knee (KEM), the load indicator for the MSE of the quadriceps, quadriceps and patellar tendon as well as the patellofemoral joint, as well as the impulse of the joint moment is significantly ($p=0.015$) influenced by running shoe technologies. The MAX running shoes (M_RS) with rocker technology increases the knee loads compared to all other sole technologies (+15% to UTEC (U_RS)).

Table 2: Biomechanical loading of ankle (AJ) and knee joint (KJ) in the sagittal, frontal and transverse planes when running with the four footwear technologies at a running speed of 3,0 m/s.

| | | Running shoe technologies | | | | |
|---|---|---|---|---|---|---|
| | | NEUTRAL (N_RS) | SUPPORT (S_RS) | MAX (M_RS) | UTEC (U_RS) | ME |
| Variable | Unit | Mean ± SD | Mean ± SD | Mean ± SD | Mean ± SD | *p* |
| AJ: max. PFM | Nm/kg | 2.237±0.278 | 2.241±0.236 | 1.995±0.318* | 2.111±0.235*# | **0.048** |
| AJ: imp. PFM | Nms/kg | 0.283±0,036 | 0.278±0.032 | 0,228±0.034* | 0.262±0.041*# | **0.011** |
| KJ: max. KEM | Nm/kg | 2.866±0.429 | 2.862±0.423 | 3.224±0.549* | 2.804±0.461# | **0.015** |
| KJ: imp. KEM | Nms/kg | 0.328±0.058 | 0.326±0.065 | 0.332±0.06 | 0.314±0.063*# | **0.045** |
| KJ: max. KAM | Nm/kg | 0.704±0.364 | 0.719±0.311 | 0.733±0.310* | 0.655±0.279*# | **0.011** |
| KJ: imp. KAM | Nms/kg | 0.095±0.057 | 0.095±0.049 | 0.087±0.049* | 0.051±0.037*# | **0.001** |
| KJ: max. KRM | Nm/kg | 0.171±0.066 | 0.178±0.067 | 0.173±0.066 | 0.164±0.063*# | **0.045** |
| KJ: imp. KRM | Nms/kg | 0.095±0.057 | 0.094±0.049 | 0.085±0.049* | 0.055±0.027*# | **0.001** |

AJ: Ankle joint, KJ: Knee joint, PFM: Plantar flexion moment, KEM: Knee extension moment, KAM: Knee adduction moment, KRM: Knie rotation moment, max.: Maximum, Imp.: Impulse, SD: Standard deviation, ME: Main effect (*p*),
* Value significantly ($p<0.05$) different from N_RS, # value significantly ($p<0.05$) different from M_RS.

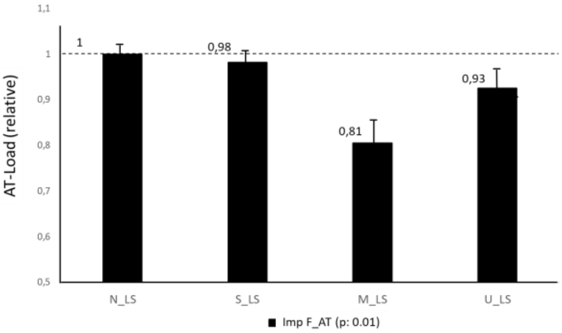


Figure 1. Achilles tendon (AT) load (normalized to load at N_RS). Mean and standard deviation of impulse.

The risk variables of the load on the knee joint (external adduction moment (KAM), internal rotation moment (KRM)) [15,16] are highly significantly influenced by shoe technology. We observed the lowest values of KAM and the impulse of the KAM at UTEC running shoes (KAM: 0.65±0.27 Nm/kg; impulse KAM: 0.05±0.03 Nms/kg) and the highest values at MAX running shoes (KAM: 0.73±0.31 Nm/kg; impulse KAM: 0.08±0.04 Nms/kg). The KRM variables show a significant difference between the sole technologies ($p<0.05$), with the highest values of the load parameters for SUPPORT (S_RS) and the lowest for UTEC (U_RS). Midsole technology UTEC (U_RS) reduces the KRM by at least 5% and the impulse of the KRM by ≥40% compared to all other shoes.

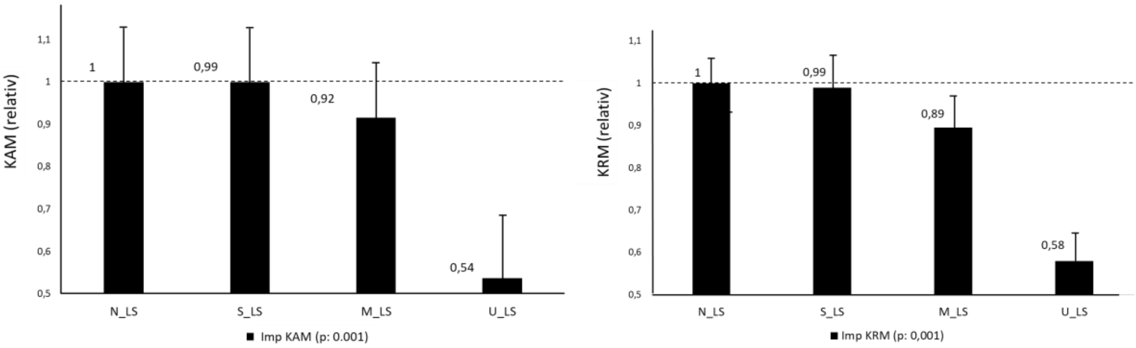


Figure 2. Left: Knee adduction moment. Right: Kee internal rotation moment. Data normalized to load at N_RS. Mean and standard deviation of impulse

The analysis of the (negative and positive) joint work found a significant main effect ($p=0.005$) of the four shoe technologies examined at the ankle joint with the lowest workload in category M_RS (0.77±0.10 J/kg) and the greatest joint work in S_RS (0.94±0.08 J/kg;). There was also a significant main effect of the four shoe technologies on joint work at the knee joint ($p<0.05$). Significantly more joint work is required at the knee when running with shoes in the categories N_RS 5%, S_RS 5.5% and M_RS 6.5% than with U_RS.

The total joint work on the supporting leg (ankle joint, knee joint and hip joint) shows a highly significant main effect ($p=0.006$) and indicates the different muscular requirements of the four shoe technologies.

Table 3: Joint work at ankle joint (AJ), knee joint (KJ) and hip joint (HJ) with the four running shoes at a running speed of 3.0 m/s.

| | | Running shoe technologies | | | | |
|---|---|---|---|---|---|---|
| | | NEUTRAL (N_LS) | SUPPORT (S_LS) | MAX (M_LS) | UTEC (U_LS) | ME |
| Variable | Unit | Mean ± SD | Mean ± SD | Mean ± SD | Mean ± SD | *p* |
| AJ: Negative work | J/kg | 0.420±0.083 | 0.431±0.079 | 0.371±0.086* | 0.395±0.079* | **0.008** |
| AJ: Positive work | J/kg | 0.496±0.083 | 0.513±0.084 | 0.404±0.117* | 0.474±0.084*# | **0.002** |
| KJ: Negative work | J/kg | 0.632±0.167 | 0.634±0.162 | 0.608±0.219* | 0.593±0.177*# | **0.010** |
| KJ: Positive work | J/kg | 0.447±0.127 | 0.456±0.129 | 0.489±0.124* | 0.432±0.137*# | **0.009** |
| HJ: Negative work | J/kg | 0.169±0.081 | 0.197±0.071 | 0.156±0.053* | 0.157±0.076* | 0.055 |
| HJ: Positive work | J/kg | 0.300±0.098 | 0.293±0.095 | 0.317±0.057 | 0.267±0.056 | 0.150 |
| AJ: Total work | J/kg | 0.916±0.082 | 0.944±0.081 | 0.775±0.101* | 0.869±0.081*# | **0.005** |
| KJ: Total work | J/kg | 1.079±0.147 | 1.090±0.146 | 1.097±0.172* | 1.026±0.157*# | **0.041** |
| HJ: Total work | J/kg | 0.470±0.089 | 0.491±0.083 | 0.473±0.055 | 0.424±0.066*# | 0.090 |
| Total work | J/kg | 2.465±0.106 | 2.525±0.104 | 2.345±0.109* | 2.319±0.102* | **0.006** |

AJ: Ankle joint, KJ: Knee joint, SD: Standard deviation, ME: Main effect (*p*), *: value significantly different (p<0.05) from N_RS, #: Value significantly different (p<0.05) from M_RS.

## Discussion

The biomechanical study shows significant effects of shoe or midsole technology on the loading of the lower extremity. In particular, the loads on the knee joint in the frontal and transverse planes are striking with UTEC (U_RS) with a reduction in the maximum KAM of 10.6% and the impulse of the KAM of 41% compared to MAX (M_RS) and 9% (KAM) and 46% (impulse KAM) compared to SUPPORT (S_RS). It can be confirmed that with UTEC (U_RS), the centering and lateralization of the point of force application during the entire stance phase reduces the load on the knee joint in the frontal plane (adduction moment, KAM) and in the transverse plane (internal rotation moment, KRM) by an average of around 10% compared to all other sole technologies investigated.

As Sobhani et al. (2017) have already shown with experimental shoes, running shoes with convex soles (rocker soles) lead to a reduction in the plantar flexion moment (PFM) and thus a reduction in the load on the Achilles tendon compared to neutral running soles, but at the same time to an increase in the extension moment (KEM) at the knee joint [17].

The hypothesis formulated by Hoogkamer et al. (2019), according to which the braking and acceleration work on the ankle joint is reduced by running shoes in the MAX (M_RS) category compared to conventional running shoes [18], could also be verified for recreational runners with lower running speeds. In contrast, joint work and therefore muscle work on the knee joint was significantly reduced in the UTEC (U_RS) category. With the demonstrated reduction in joint work around the ankle, knee and hip joints, the plantar flexors as well as the knee and hip extensors are less stressed and ultimately the muscular energy requirement for MAX (M_RS) and UTEC (U_RS) is reduced compared to the traditional technology NEUTRAL (N_RS) and SUPPORT (S_RS).

In summary, it can be stated that the running shoe technologies examined influence the load on the joints of the lower extremities. While the shoes in the SUPPORT (S_RS) category are not able to reduce the load on the foot, ankle and knee joint compared to NEUTRAL (N_RS), this technology (S_RS) increases the load on the knee joint, especially in the frontal and transverse planes. "Maximalist" shoes with rocker soles (M_RS) relieve the Achilles tendon due to the convex shape of the sole, but at the same time increase the load on the knee joint. UTEC running shoes (U_RS) are characterized in particular by a significant reduction in the critical load variables of the knee joint. The investigated representative of the MAX (M_RS) category has no stiffening carbon plate and generates its longitudinal stiffness from the material thickness of the midsole. If an M_RS running shoe is additionally equipped with a stiffening carbon plate, the force application point can be shifted in front of the base of the MI and MII during push-off, the lever of the external force to the ankle joint is increased and the Achilles tendon load increases [19].

The presented study shows the systematic influence of four competing sole technologies on the biomechanics and loading of the lower extremity during the stance phase in recreational running.

## The influence of four different running shoe technologies on the development of running injuries: A retrospective randomized 12-month cohort study of 1,697 runners

## Purpose

The influence of running shoe technologies on the incidence of running injuries (RRI) and the type of injury has long been sparsely investigated. A prospective study that experimentally addressed the effect of midsole cushioning on injury incidence did not report a significant decrease in injury incidence by changing midsole hardness [7]. In a 6-months intervention study with a total of 372 participants, Malisoux et al (2016) showed a lower incidence of RRI in runners wearing a support shoe (S_RS) than in those runners who were fitted with standard shoes (N_RS). It is of interest that the incidence of knee injuries was reported to be significantly higher (127%) in the group wearing the supported shoe for 6 months than in runners wearing the standard neutral shoe [8].

Neutral cushioned running shoes (N_RS), support shoes (S_RS) or even minimalist running shoes have not yet been shown to have any rigorous evidence of reducing the incidence of RRI. To the best of our knowledge, there is no scientific research on the possible influence of MAX (M_RS) and UTEC (U_RS) running shoe technologies on the risk of RRI.

The aim of this article is to analyze the influence of current sole technologies on the risk of self-reported complaints and injuries in a 12-months randomized observational study of 1697 recreational runners.

## Material and methods

### Study participants and study design

Regular recreational runners were recruited for a randomized retrospective study on running behavior, running injuries and running shoes used via the running magazine “Laufen.de” (DLM RunMedia GmbH, Cologne, Germany) and other social media channels. In total, over 2,300 volunteers submitted an online questionnaire on running behavior and recorded complaints and injuries as well as the running shoes they primarily used (brand, model) in the 2022/2023 running season. Together with this information, additional demographic and anthropometric data (age, gender, height, weight, self-assessed leg axis and foot morphology) allowed the inclusion of runners according to the defined inclusion and exclusion criteria (age: ≥18 years, running experience: >1 year, minimum running distance per week: ≥10 km, regular running training: ≥1 training session per week, no acute neurological or orthopedic pathologies, ≥75% of training runs in the 2022/2023 season in the specified shoe technology, full details of shoes used during the survey period). Ultimately, 1697 recreational runners (971 men and 726 women) with complete data over 12 months were included in the study.

**Shoe conditions**

The assignment of the running shoes used (brand, model) to the technology groups or categories (1) Neutral, cushioning (N_RS), (2) Support (S_RS), (3) Maximalist with convex sole (partly with carbon plates) (M_RS), and (4) Softly cushioned, U-shaped sole (U_RS) was carried out by two experts from Laufen.de (Running magazine of DLM, RunMedia Cologne, Germany) on the basis of the manufacturer's specifications and/or by direct inspection. All participants chose their shoes themselves and independently of the study, so that a random assignment of shoe technologies can be assumed.
Of the 1697 study participants, 1014 participants stated that they primarily ran in N_LS (neutral, cushioning) during the study period, 307 participants ran in S_RS (support), 180 in M_RS (Maximalist, convex arched soles) and 140 runners completed most of their runs in U_RS (U-shaped sole technology). A further 56 study participants used M_RS with stiffening carbon plates.

**Data analysis and statistics**

Data on demographic and anthropometric variables, running behavior, running shoe technologies used (running shoes) as well as injuries and complaints were available in a blinded and anonymized form for further analysis for at least 10 months from all runners included in the study.

The incidence of a running injury was determined by the number of injuries in the observation period (12 months) and the number of injuries per 1000 kilometers of running.  The relative chance of suffering a running injury was described using the ODD ratio (OR) in relation to the N_RS condition (neutral, cuhioning). The effect of the recorded demographic, anthropometric and running behavior data and the effect of the four shoe technologies on the occurrence of running injuries was tested using $\chi 2$ tests.

## Results

The sample (n=1697) consisted of 971 men and 726 women. 59.8% of the study participants stated that they primarily ran in a running shoe in the neutral category (NEUTRAL; N_RS) during the study period, 18% used shoes in the support category (SUPPORT; S_RS), 14% used maximalist shoes with thick, curved soles and partially stiffened with carbon plates (MAX; M_RS), and 8.2% completed their running training in running shoes with a soft U-shaped sole (UTEC; U_RS). The distribution of women and men shows no difference in the four running shoe categories. Age and BMI did not differ across the running shoe categories. With an average of 2.64 training sessions per week, the sample is characterized as experienced recreational runners. There were no differences between the four shoe categories. The kilometers run per week also did not differ between the shoe groups, with an average of 31.7 kilometers. The participants in the study ran an average of well over 1500 kilometers in the study year. The present study thus documents over 2.5 million kilometers running in relation to injuries that occurred.

Table 4: Demographics and anthropometrics of all participants (ALL) and of the subjects of the four shoe technologies categories (NEUTRAL: N_RS, SUPPORT: S_RS, MAX: M_RS, UTEC: U_RS), running habits, self-reported RRI without and with missed training units (TU) and the 1000 km RRI-incidence. Means and standard deviation. ME: Main effect.

| | ALL | NEUTRAL (N_RS) | SUPPORT (S_RS) | MAX (M_RS) | UTEC (U_RS) | ME, *p* |
|---|---|---|---|---|---|---|
| Number | 1697 | 1014 (59.8%) | 307 (18%) | 236 (14%) | 140 (8.2%) | |
| Male (%) | 971 (57.2 %) | 553 (54.5 %) | 174 (56.7 %) | 160 (67.8 %) | 84 (60.0 %) | 0.150 |
| Female (%) | 726 (42.8 %) | 461 (45.5) | 133 (43.3 %) | 76 (32.2 %) | 56 (40.0 %) | |
| Age (years) | 46.3±9.6 | 45.5±9,5 | 46.5±9,6 | 44.5±9,5 | 47.5±11 | 0.894 |
| BMI (kg/m²) | 23.5±2.8 | 23.5±2.7 | 23.7±2.8 | 23.2±2.2 | 23.4±2.3 | 0.750 |
| Sessions per week | 2.64±0.70 | 2.64±0.78 | 2.53±070 | 2.74±057 | 2.59±0.71 | 0.080 |
| Distance per week (km) | 31.73±12.1 | 32.12±12.5 | 29.27±12.4 | 33.92±11.5 | 30.60±12.57 | 0.105 |
| RRI (%) | 52.94 % | 54.78 % | 48.38 % | 56.78 % | 43.26 % | **0.008** |
| 1000 km RRI-Incidence | 0.6552 | 0.6677 | 0.6378 | 0.,6855 | 0.5481 | **0.015** |
| RRI_1, 1-2 TU missed | 14.65 % | 16.36 % | 12.66 % | 13.56 % | 8.51 % | **0.005** |
| RRI_2, ≥1-3 TU missed | 38.12 % | 41.67 % | 36.69 % | 40.25 % | 12.14 % | **0.001** |
| RRI_3, >3 TU missed | 23.47 % | 25.32 % | 24.03 % | 26.69 % | 3.55 % | **0,001** |

52.94% of the study participants reported at least one running injury in the study year, with complaints documented during or after running. With a highly significant main effect (p=0.008), there is a strong influence of the running shoe technology used on the risk of developing a running injury. Running shoes in the U_RS category show the lowest risk of injury (43.26%), while the highest risk is observed with M_RS at 56.78%. The 12-month incidence data is supported by the 1000 km incidence (injuries per 1000 km of activity). The 1000 km incidence is reduced by 18% for U_RS compared to the Neutral (N_RS) shoe category and 20% compared to M_RS. The OR (ODD ratio to N_RS) confirms the described effects and is 1.13 for M_RS, 0.78 for S_RS and 0.63 for U_RS. The influence of footwear technology appears to increase further with more severe complaints and more serious injuries. If injuries that resulted in a loss of 1 - 2 training sessions are considered, the 12-month incidence is highly significantly different between the shoe groups. The difference becomes extreme in the case of serious injuries with absences of more than 3 training sessions. Here there are differences in risk of 85% between the shoe categories.

At 26.2%, the most common running injuries affect the knee joint, with the anterior aspect and thus the patellofemoral joint being mentioned most frequently. There is a highly significant main effect in relation to the technology groups (ME: p<0.01). The N_RS group shows the most frequent knee injuries (27.78%), the lowest frequency the U_LS technology (13.48%) (S_RS: 27.27, M_RS: 25.42). The second highest frequency of injury was in the muscle-tendon unit of the triceps surae at 23.59%. The main effect of shoe technology is significant in relation to the Achilles tendon (ME: p<0.05) and confirms the connection between running shoe technology and overloading of the Achilles tendon. Of the 180 study participants in the M_RS group, 56 runners stated that they regularly ran with carbon-stiffened M shoes. This subgroup reported a significantly increased risk (17.8%) of Achilles tendon injuries (free tendon, tendon insertion). This can be interpreted as a clear indication of increased Achilles tendon strain with carbon stiffened soles. In terms of frequency, Achilles tendon injuries are followed by complaints in the back and lumbar spine. The effect of the technology groups is highly significant (ME: p<0.01). The lowest risk can be assigned to the U_RS category (7.09%); the three other shoe categories do not differ in terms of the risk of injury to the back (12.66 - 13.50%). Complaints in the foot and ankle are reported at an average of 4.88% and 9.12% respectively and are not significantly influenced by the shoe technology worn.

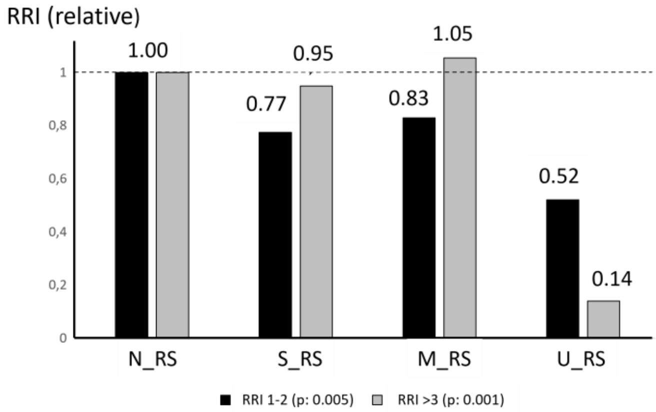


Figure 3: Relative risk of RRI with 1-2 and >3 missed Tus of the four shoes technologies; data normalized to N_RS.

Shin complaints with an average of 3.39% are most common in N_RS (4.24%) and least common in U_RS (0.71%). It is possible that the different sole geometry in the hindfoot area has an influence on the load on the m. tibialis anterior when controlling the foot strike.

Table 5: Location of running related injuries (RRI) of all participants and subjects of the four shoes technologies cohorts

| RRI location | | Running shoes technologies | | | | |
|---|---|---|---|---|---|---|
| | ALL | N_RS | S_RS | M_RS | U_RS | ME, *p* |
| Number (n) | 1697 | 1014 | 307 | 236 (180*, 56#) | 140 | |
| Knee | 26.18 % | 27..78 % | 27.27 % | 25.42 % | 13.48 % | **0.009** |
| Achilles tendon | 13.82 % | 15.,47 % | 9.74 % | 13.56% (12.2%*; 17.8%#) | 11.48 % | **0.048** |
| Back, spine | 12.47 % | 13.50 % | 12.66 % | 13.14 % | 7.09 % | **0.009** |
| Ankle joint | 9.12 % | 10.15 % | 7.47 % | 8.05 % | 7.09 % | 0.157 |
| Foot | 4.88 % | 5.91 % | 2.60 % | 4.28 % | 3.55 % | 0.058 |
| Shin | 3.39 % | 4.24 % | 2.27 % | 2.12 % | 0.71 % | **0.019** |

* M_RS without Carbon plate, M_LS with carbon plate stiffening.

The analysis of the correlations between demographic and anthropometric data and the risk of developing a running injury found no significant (p>0.05) effect of gender (p=0.46), age (p=0.69) or BMI (p=0.61). Running behavior also showed no statistically significant correlations with the occurrence of running injuries (training units/week: p=0.72; kilometers run/week: p=0.59; running experience: p=0.35). The running shoe technology used, on the other hand, shows a significant influence on running injuries (p<0.01), but also on the frequency of knee injuries (p<0.01) and Achilles tendon injuries (p<0.05). The risk factor shoe technology is associated with the lowest risk of LV in U_RS (43.3%) and the highest in M_RS (56.7%) (S_RS: 48.4%; N_RS: 54.7%).

## Discussion

726 women and 974 men took part in the study and documented running behavior and running injuries over 12 months. Overall, an injury risk of 52.96% was reported. The knee is most frequently affected at 26.1%. This is followed by the Achilles tendon and calf (23.9%), lumbar spine (12.5%), ankle (9.1%), foot (4.8%) and shin (3.4%). The study participants used their own chosen and favorite running shoes for over 75% of their runs. A randomized distribution of the shoe technologies N_RS (neutral, cushioned running shoes), S_RS (supported running shoes, M_RS (“maximalist” running shoes with

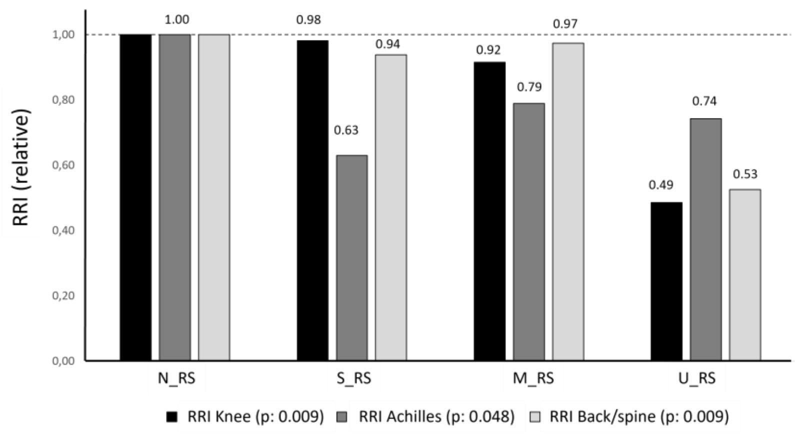


Figure 3: Relative risk of RRI at knee, Achilles tendon and lower back, normalized to RRI data of the N_RS cohort.

thick curved soles, partly reinforced with carbon plates) and U_RS (U-shaped sole construction made of soft cushioning material) can therefore be assumed. Shoe technology was found to be the dominant risk factor in explaining running injuries (p=0.008), with the lowest frequency of 43.26% for U_RS (-21% compared to N_RS) and the highest frequency of 56.28% for M_RS (+4% compared to N_RS). With "support" shoes (S_RS), there is a slightly reduced risk of injury compared to N_RS at 48.38%. This result is supported by data from a 6-month intervention study, which showed a reduced injury frequency in the group that was fitted with a supported shoe, although this effect was only observed in runners with pronated feet [8]. It is noteworthy that in our study the frequency of knee injuries increased with the use of S_RS and that this result was also reported in the 6-month intervention study [8]. For injuries to the knee, Achilles tendon, lumbar spine and tibia, there was a significant effect of the respective shoe technology used.

The analysis of demographic (age, gender, running experience) and anthropometric (height, weight, BMI) data as well as information on running behavior (km/week, training units/week) revealed no significant correlation (p<0.05) with injury frequency or injury distribution. In the present observational study, the primary running shoe technology used (>75% of all runs) was found to be the dominant factor influencing the development of running injuries.

While the conventional running shoes (N_RS and S_RS) differ only marginally in terms of injury risk, the "new" technologies (M_RS, U_RS) allow significant differences in the biomechanical load variables and consequently in the injury frequency and injury distribution to be identified. New paradigms led to novel running shoe designs, innovative sole technologies and thus also to changes in the risk of developing a running injury [22,23].

Finally, the research questions posed above have been solved in the way that the four running shoe technologies under study influence the load on the lower extremity during recreational running and that the load variation demonstrated due to shoe technology is clearly reflected in the development of running injuries.

With the given caution, it can be concluded based on the data presented: Innovative shoe technologies or midsoles of running shoes significantly influence the development of running injuries, injuries to the knee joint at the Achilles tendon and the back in recreational runners. Running behavior, training and runner demographics appear to be of secondary importance in relation to shoe technology.

## Summary and conclusion

The results presented on the biomechanical effects of four running shoe technologies make it clear that new technical solutions have been found with the “new” running shoes in the M_RS (“Maximalist”) and U_RS (“U-TECH™”) categories, which are directly reflected in the biomechanics of running in the amateur sector (recreational runners). While the conventional running shoe categories N_RS (neutral, cushioning) and S_RS (support) only lead to marginal modifications of the biomechanical load variables on the foot, ankle, knee and hip, with M_RS and U_RS we find in some cases highly significant changes in the loads but also in the joint work on the ankle, knee and hip joints. In particular, M_RS allows muscle work on the ankle joint (TS muscle tendon unit) to be reduced compared to conventional running shoes, while with U_RS this is particularly successful for the knee extensors. M_RS increases the mechanical load on the knee joint and, when using stiffening carbon plates, possibly the load on the Achilles tendon during push-off, U_RS reduces the load on the knee joint, reduces adduction moments and rotational moments at the knee and relieves the lumbar spine.

As a result, we found an increase in running injuries compared to conventional running shoes with the “Maximalist” (M_RS) and a highly significant reduction with “UTEC” (U_RS), whereby the knee is particularly affected here with over 50% reduction in knee injuries compared to runners who ran in “neutral, cushioning” running shoes (N_RS) for 12 months.

To the best of our knowledge, this is probably the first time that it has been possible to show quantitatively the biomechanical effects of the "new" sole technologies (M_RS, U_RS) on recreational runners and how the biomechanical loads on the lower extremities change compared to conventional technologies. The effects of the new technologies in the 12-month wear test with randomized cohort assignment will provide stable indications of (i) how different sole technologies affect the development of running injuries, (ii) how changes in the biomechanical load profile due to the innovative technologies (M_RS, U_RS) are reflected in the development of injuries, and (iii) whether the new technologies can be helpful for amateur or recreational runners.

Even with possible methodological weaknesses of the present study, it is already possible to derive justifiable advice on the choice of suitable running shoe technology, considering the individual goals and needs of runners.

A methodological limitation of this study is the descriptive, retrospective nature of the study and the randomized assignment of the study participants to the four shoe technologies but the very different number of cases in the cohorts. Only a prospective, interventional study with random assignment of study participants to different running shoe technologies with the largest possible number of test subjects will be able to identify causal relationships. This study can at least be used for hypothesizing.

### Author contributions statement

GPB. and EH. conceived the experiment(s), TE., EH. and SR. conducted the experiments, GPB and SR. analyzed the results. GPB, EH, SR. contributed to the manuscript. All authors reviewed the manuscript.

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