How Does Running in Minimalist Shoes Affect Injury Risk?
- A Systematic Review

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Abstract

Aim: The aim of this systematic review was to investigate injury risk when running in minimalist shoes compared to running in traditional running shoes. The purpose of the study was also to identify risk factors that could increase the risk of developing a running related injury when running in minimalist shoes, compared to running in traditional running shoes.

Method: The databases PubMed, SportDiscus, ScienceDirect, CINAHL and Cochrane were searched for relevant studies. Ten studies were included in the systematic review and the quality of the studies was reviewed according to the PEDro Scale. Three out of ten studies were randomized controlled trials and seven studies were crossover trials. Five out of seven crossover trials described a randomized intervention order.

Results: General injury risk when running in minimalist shoes compared to running in traditional running shoes was evaluated in two randomized controlled trials. One study showed a significantly increased injury risk and one pilot study showed no significant results due to a small population size. Biomechanical factors related to injury risk were assessed in two randomized controlled trials and seven crossover studies, showing that there was a significant increase in forefoot pressure, vertical loading rate and Achilles tendon load when running in minimalist shoes compared to running in traditional running shoes. There was no significant difference in rearfoot pronation when comparing the two footwear conditions.

Conclusions: Moderate evidence shows that running in minimalist shoes increases the forefoot pressure compared to running in traditional running shoes and thereby increases the risk of developing metatarsal stress fractures. Limited to moderate evidence shows that running in minimalist shoes also increases the loading of the Achilles tendon, compared to running in traditional running shoes, which may increase the risk of developing chronic Achilles tendon pain. Starting to run in minimalist shoes, when accustomed to running in traditional running shoes, should be based on a gradual increase of training volume in order to avoid an increased injury risk.
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Appendix 1 – Search Matrix
1 Introduction

1.1 Running

Running as physical activity has gained popularity in recent years, resulting in an increase of individuals taking part in the activity (Esculier et al 2015). The popularity of running could be due to the fact that it is a convenient physical activity with low expenses that can be easily implemented (Taunton et al 2002). There are numerous health benefits from running and the activity has been shown to decrease the long term risk of mortality from cardiovascular, metabolic, neurological and infectious disease and cancer (Oja et al 2015).

Apart from positive long term health effects, running has also been shown to improve physical functions such as aerobic fitness, cardiovascular function at rest, running performance and muscular performance (Oja et al 2015). In addition to the physical effects of running, mental well-being and postural balance have also been shown to improve (Vincent & Vincent 2013). Running has also been shown to reduce weight gain in obese individuals as well as reduce inherited obesity (Vincent & Vincent 2013).

1.2 Running-related injury

Running is accessible and convenient, which has caused it to become a common form of exercise in the western world (Videbaek et al 2015). Since there is a large number of runners there is a high prevalence of running-related injuries, but there is also a high incidence. The number of running-related injuries can be measured in different ways, which causes the prevalence and the incidence of running-related injuries to vary greatly (Saragiotto et al 2014). Running-related injuries have often been measured as the number of injuries occurring in every 1000 km of running, the percentage of injuries in a total population, number of injuries to every 100 runners and number of injuries in every 1000 hours of running (Videbak et al 2015).

A higher dosage of running is more likely to cause a running-related injury and therefore there should be a relation to time spent running when comparing injury risk in different populations (Videbaek et al 2015). The number of injuries occurring in every 1000 hours of running takes the dosage of running into account and has been shown to be the most relevant measure of association when comparing running-related injury rates in different populations. Injury incidence of running-related injuries has been shown to range from 8.9 to 33 injuries among
novice runners and from 5.2 to 12.1 among recreational runners for every 1000 hours of running (Videbaek et al 2015).

1.2.1 Consensus definition
There is a high rate of variability in the measurement of running-related injuries, which has caused difficulties in producing reliable and comparable injury statistics. This variability is largely due to differences in the definition of running-related injury (Saragiotto et al 2014). To help establish a clear and consistent definition of running-related injury, a consensus definition has been presented (Yamato et al 2015). A consensus definition can also help increase the efficiency in preventing running-related injury as injury-prevention programs with a clear purpose can be developed.

The consensus definition defines running-related injury as “Running-related (training or competition) musculoskeletal pain in the lower limbs that causes a restriction on or stoppage (distance, speed, duration or training) for at least seven days or three consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional.” (Yamato et al 2015). This definition was presented recently and therefore studies testing the validity of the definition as well as translations of the definition to other languages are needed.

1.2.2 Overuse injuries
Running is a form of physical activity that involves repetitive movement resulting in repeatedly applied forces on the lower extremities (Hreljac et al 2004). When the applied forces are appropriate and the recovery time is sufficient, the total stress of the body tissue results in positive physiological effects such as increased strength. If the appropriate level of applied forces is exceeded or if there is insufficient amount of recovery, there is a higher level of stress increasing the risk of developing an overuse injury (Hreljac et al 2004).

Most running-related injuries are due to overuse, although traumatic injuries such as acute muscle strains, ankle sprains and motor vehicle trauma do occur as a result of running (Wen 2007). Overuse injuries related to running typically affect lower extremities and the most commonly occurring running-related overuse injuries are patellofemoral pain syndrome, iliotibial band friction syndrome, plantar fasciitis, meniscal injuries in the knee, tibial stress syndrome and Achilles tendon pain (Hreljac et al 2004).
1.3 Risk factors

There are a number of different risk factors predicting injury and the main indicator has been shown to be previous injury in the last 12 months (Saragiotto et al 2014). High training volume (more than 32 km per week) and low running experience (less than three years) are also associated with a higher risk of developing running-related injury (Cheung et al 2011).

1.3.1 Ground reaction forces

During running, ground reaction forces are produced with every step as a result of the plantar surface of the foot making contact with the ground. When running with a rearfoot strike, i.e. the posterior part of the foot hitting the ground initially, a vertical impact peak is created (Hreljac et al 2004). The impact peak is the initial force peak and is followed by the active peak, which generally takes part in the latter 60-75 percent of the stance period (Hreljac et al 2004).

The impact peak generally occurs during the first 10 percent of the stance period and produces forces up to 1.5 to 5 times body weight. Depending on the duration of time from initial impact to impact peak a vertical loading rate of varying magnitude is created. Studies has shown that increased vertical loading may increase the risk of developing metatarsal stress fractures (Van der Worp et al 2015, Zadpoor & Nikooyan 2011).

Figure 1 - Graph of ground reaction forces according to Cavanagh & LaFortune (1980).

1.3.2 Foot pronation

Rearfoot pronation is a combination of ankle dorsiflexion, rearfoot eversion and forefoot abduction (Ferber et al 2009). Low to moderate rearfoot pronation has been shown to not increase injury risk, but excessive uncontrolled rearfoot pronation has been shown to increase
medial plantar loading (Cheung et al 2011). Increased plantar loading could increase the risk of developing metatarsal stress fracture (Weist et al 2014). Excessive foot pronation is commonly controlled with motion control footwear, which primarily decreases the rearfoot eversion and thereby tibial rotation (Hintermann & Nigg 1998). Tibial rotation influences the mechanics of the lower extremity in a potentially harmful way, meaning uncontrolled excessive foot pronation could increase the risk of developing injury in the lower extremity (Ferber et al 2009).

1.4 Minimalist shoes

In recent years and especially since 2010, there has been a large increase in the amount of runners wearing minimalist shoes instead of traditional running shoes (Cheung & Ngai 2016). This might be due to the fact that possible advantages of running in minimalist shoes, such as injury prevention, increased running efficiency and improved running performance have been widely highlighted in the running community and in society in general (Perkins et al 2014). In the last few years, scientific research has shown that these claims may not be fully supported by scientific evidence. The scientific evaluation of the minimalist shoe has been further restrained since there has not been a clear definition of this footwear until recently.

1.4.1 Consensus definition

A consensus definition describing the minimalist shoe was defined in 2015. The minimalist shoe is described as “Footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height and the absence of motion control and stability devices.” (Esculier et al 2015). The minimalist shoe is thereby a minimally cushioned lightweight shoe with low stability and support. A traditional running shoe is characterized by a well-cushioned shoe sole, stability devices that guide the motion of the foot and often a higher heel to toe drop.

1.4.2 Footstrike pattern

Minimalist shoes are characterized by a low height difference between the front and the rear part of the shoe, resulting in a low heel to toe drop. The low heel to toe drop and the minimal cushioning of the minimalist shoe promotes running with a forefoot strike, since the heel of the shoe is less accentuated and running with a rearfoot strike can be painful in a minimalist shoe due to the lack of cushioning (Gillinov et al 2015). Running with a forefoot strike has been shown to reduce the vertical impact peak that is created when running with a rearfoot
strike (Perkins et al 2014). Running with a forefoot strike has also been sown to decrease the loading of the knee.

When running with a forefoot strike pattern dorsiflexion in the ankle is decreased compared to running in a traditional running shoe, since the rear part of the foot does not make contact with the ground (Hashizume & Yanagiya 2015). The decreased dorsiflexion in the ankle increases the need for eccentric work of the triceps surae muscle, in order to control the increased plantarflexion during the first phase of ground contact. Running with a forefoot strike pattern therefore requires a higher activation of the triceps surae muscle, which could increase the load of the Achilles tendon (Perkins et al 2014).

1.4.3 Injury risk
Tibial and metatarsal stress fractures are common injuries among runners, accounting for 15-20% of all lower limb injuries (Wright et al 2015). The greatest risk factors related to an increased risk of developing a stress fracture are previous stress fracture and female sex. Stress fractures seem to be more frequent in society in general and running in minimalist shoes, lacking shock absorbing cushioning and promoting a forefoot strike, could increase the risk by increasing plantar pressure in the forefoot (Kernozek et al 2014).

Another common injury among runners is Achilles tendon pain with a prevalence of 11% among runners (Zafar et al 2009). A dysfunction in the triceps surae muscle and an increased rearfoot pronation are factors that have been linked to increasing the risk of developing Achilles tendon pain. Running in minimalist shoes with low stability and stimulating a forefoot strike, which increases the load of the triceps surae muscle and Achilles tendon, could increase the risk further.

1.5 Aim and thesis
The popularity of running in minimalist shoes increased rapidly several years ago. It is however still not clear what the effects on injury risk are when running in a lightweight shoe lacking cushioning and stability devices. The purpose of this systematic review is to evaluate existing research in order to further investigate the injury risk when running in minimalist shoes and identify potential risk factors that increase the risk of developing running related injury. By investigating potential risk factors concerning running in minimalist shoes a conclusion regarding the injury risk can be established, preventing future training errors and the development of injury. The main research question of this thesis was:
“What is the current evidence regarding effect on injury risk and injury risk in regard to changes in lower limb loading, ground reaction forces and ankle joint movement among runners when running in minimalist shoes, compared to running in traditional running shoes?”
2 Method

2.1 Study design

The aim of a systematic review is to critically evaluate and synthesize results of existing scientific studies or trials (Harris et al 2014). A statement conclusion based on the best existing evidence is created, providing answers to a specific clinical question. To be able to provide a clear and consensus conclusion, the research question that is formulated should be specific and answerable (Harris et al 2014). The research question indirectly determines what articles will be included, which later will form the results and conclusion. The research question of this systematic review was formulated with regards to PICO criteria, addressing population, intervention, comparison and outcome (Wright et al 2007). PICO criteria helps create a specific and relevant research question with regards to relevant aspects.

The systematic review was written with regards to PRISMA guidelines (Moher et al 2009), addressing certain specified criteria ensuring the quality of the study. Inclusion criteria were formulated prior to conducting the search for studies, in order to prevent bias. To ensure a thorough identification of studies, five relevant databases were searched (Harris et al 2014). Studies relevant for inclusion in the systematic review were identified by the author in collaboration with the supervisor of the study. To further prevent bias the study quality of all included articles were reviewed and evaluated according to criteria established in the PEDro scale (The George Institute for Global Health 2016). The PEDro scale has been shown to be a valid measure for rating the methodological quality of clinical trials (De Morton 2009).

2.2 Inclusion criteria

Inclusion criteria were formulated to ensure that the systematic review was based upon relevant articles. In order for an article to be included in the systematic review the inclusion criteria must be fulfilled. Inclusion criteria in this review were that biomechanical factors describing loading of the lower limb, vertical ground reaction forces or foot joint movement must be evaluated in a study where test subjects practiced running. The running shoes worn by the test subjects in the study had to be defined as minimalist shoes, alternatively be described according to the consensus definition of the minimalist shoe.

The articles were also required to include a comparison between running in minimalist shoes and traditional running shoes regarding at least one factor relevant to injury risk. To be included the article had to be an original article available in full text, written in English. The
search area is relatively new and scientific material might be limited. Although randomized controlled trials (RCTs) are the highest level of evidence, all available studies that fulfill the inclusion criteria were included, to create a reliable result of the systematic review (Wright et al 2007).

2.3 Search for articles

Studies were identified through database searches on two occasions. The first search was conducted on February 9th 2016 and a total of ten articles were included in the study. Databases that were searched for studies in this search were PubMed, SportDiscus and CINAHL. The search term minimalist shoes, without quotation marks, was used when searching in PubMed receiving a total of 51 search hits. Out of 51 studies 40 were excluded after reading the titles and abstracts. Thereby 11 studies were read in full text and 8 of these studies were included in the systematic review.

The remaining three studies were excluded due to not meeting the inclusion criteria. The first study by Bonacci et al (2013) was excluded due to the fact that the aim did not focus on running in minimalist shoes and was therefore not fully relevant. The study included a minimalist shoe and the subject’s regular running shoe, which was not defined as a traditional running shoe. It was therefore also unclear whether a traditional running shoe had been included in the study. The second study by Kernozek et al (2014) was excluded since no traditional running shoe was included in the study. In the third study that was excluded after reading the full text, there were no baseline data on foot edema which means no conclusions could be drawn from the data (Johnson et al 2016).

The databases SportDiscus and CINAHL were searched using the search terms minimalist AND shoes. Searching SportDiscus received 49 hits and eleven of the studies were already included. Out of the 38 remaining studies, one study was included in the systematic review and 37 studies were excluded by reading titles and abstracts. Searching CINAHL received 17 search hits and four of the hits were already included. All remaining 13 studies were excluded by reading titles and abstracts.

The second search was conducted on March 28th 2016 and databases that were searched were PubMed, SportDiscus and CINAHL, complemented with ScienceDirect and Cochrane. The same search terms were used searching PubMed, SportDiscus and CINAHL and no additional studies were included in the systematic review. ScienceDirect was searched by using the search term “minimalist shoes” receiving 44 search hits. Three of the studies were already
included and 40 studies were excluded by reading titles and abstract. One study by Lussiana et al (2015) was excluded after reading the full text due to not evaluating vertical loading force. Thereby no additional studies were included. See appendix 1 for additional information about the article search. One additional study by Sinclair et al (2013) was included in the systematic review after searching through the scientific journal Footwear Science.

2.4 Study quality

All studies included in the systematic review were reviewed according to the PEDro scale, to assess the study quality. Assessment of study quality should involve at least two independent reviewers to receive a complete and trustworthy result (Harris et al 2014). The included studies were reviewed by the author in collaboration with the supervisor of the study. The included studies were reviewed at one occasion and the assessment was revised at a later occasion, to ensure a correct perception of the criteria and the studies.

A maximum of ten points can be awarded when reviewing studies according to the PEDro scale (The George Institute for Global Health 2016). The PEDro scale contains eleven criteria, but criteria one is not included in the final score. Criteria two and three in the PEDro scale concern randomization and allocation of intervention groups. Criteria four concerns characteristics of intervention groups at baseline. Criteria five, six and seven address blinding of subjects, blinding of therapists and blinding of assessors. Criteria eight and nine addresses rate of adherence and intention to treat. Criteria ten and eleven concerns statistical comparisons between groups and measures of variability.

2.4 Ethics

When creating a systematic review existing studies are evaluated, meaning an experiment requiring human test subjects is not carried out. Thereby human test subjects are not involved and there is not a need of receiving ethical approval in order to conduct the study. By evaluating all existing studies in a certain area the results can be interpreted as a group, increasing the reliability and the general applicability of the results. Creating a systematic review is therefore ethically approvable since information with a potentially higher reliability and more generally applicability is made available to the readers.
3 Results

3.1 Included studies
The aim of the systematic review was to investigate injury risk and biomechanical factors related to injury risk when running in minimalist shoes, compared to running in traditional running shoes. Ten studies were included in the systematic review. Three out of ten studies were RCTs and seven were crossover trials. Five out of seven crossover trials described a randomized group allocation and thereby reduced the risk of bias by eliminating effect of order.

The results will be presented according to study quality, according to the identified biomechanical factors loading of the lower limb, vertical ground reaction forces and foot joint movement and according to general injury risk. Biomechanical factors related to injury risk were further divided into the subgroups forefoot pressure, vertical loading rate, Achilles tendon load and rearfoot pronation. See table 2 for an overview of the results according to biomechanical factors and general injury risk.

3.2 Study quality
In the studies that were included in this systematic review it would not have been possible to blind the subjects from being aware of the received treatment, according to criteria five, since the treatment is the intervention of running in minimalist shoes. The subjects were therefore aware of the intervention as they knew whether a minimalist shoe or a traditional running shoe was worn. None of the included studies therefore fulfilled criteria five in the PEDro scale. Blinding therapists from being aware of what type of running shoe that was worn by each subject, according to criteria six, was not possible in the included studies with a crossover design, since the interventions took place in laboratory environments with the therapists present. None of the studies with a crossover design therefore fulfilled criteria six.

Criteria six states that all therapists have to be blinded at all times and therefore none of the RCTs fulfills criteria six either. None of the included studies fulfilled criteria seven regarding blinding of assessors, but in the study by Dubois et al (2015) only one therapist was involved in the administration of the running shoes and the running sessions in the intervention were unsupervised. Blinding all therapists but one increases study quality and the risk of bias is decreased, compared to blinding none of the therapists. In the study by Dubois et al (2015) assessors were at least partly blinded, since physicians and therapists assessing potential
running related injuries during the intervention were blinded to what type of running shoe the injured subject was assigned to. The study by Ridge et al (2013) fulfilled criteria seven, concerning blinding of assessors.

Seven out of ten included studies received seven points when reviewed according to the PEDro scale and the study by Dubios et al (2015) received six points, in which two additional criteria were partly fulfilled. The remaining two studies by Sinclair (2014) and Sinclair et al (2013) received five points due to the fact that it was not possible, from reading the full text, to determine whether criteria two and three were fulfilled. Due to the limitations regarding blinding in the reviewed studies it was not possible to receive ten points, since criteria five could not be fulfilled and criteria six and seven were challenging or impossible to fulfill. See table 1 for further information regarding the review according to the PEDro scale. Seven out of ten studies stated that the subjects were new to running in minimalist shoes.

Table 1 - Results of the review according to the PEDro scale. The criteria is fulfilled when the box is marked and when the criteria is partly fulfilled the box is marked *.  

<table>
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<th>Study (author)</th>
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3.3 General injury risk

General running-related injury risk, when running in minimalist shoes, was investigated in two RCTs (Dubois et al 2015, Ryan et al 2014). The study by Dubois et al (2015) was a pilot study and therefore included a smaller population of 24 subjects. Regarding running experience, subjects had to be able to run for 20 minutes continuously. Subjects could choose from several different shoe models, in order to find a shoe that fit their foot well. Three running-related injuries occurred in both the minimalist shoe (MS) group and in the traditional running shoe (TS) group. Three subjects in the MS group and one subject in the TS group did not complete the trial. Due to the small population in the study, no significant difference regarding injury risk could be verified when comparing the MS group and the TS group.

In the study by Ryan et al (2014) a larger population of 103 subjects was included. To be included subjects had to be able to run for 60 minutes continuously. In the final analysis 99 subjects were included, since four subjects withdrew before the start of the training program of 16 weeks. A total of 23 running related injuries were reported during the trial that included two different minimalist shoe groups, one without cushioning (MS1) and one with light cushioning (MS2). The TS group reported four injuries, the MS1 group reported seven injuries and the MS2 group reported twelve injuries. Running in minimalist shoes was shown to be related to a significantly higher risk of developing a running-related injury.
Table 2 - Overview of the results according to general injury risk and biomechanical factors when running in minimalist shoes compared to running in traditional running shoes.

<table>
<thead>
<tr>
<th>Study</th>
<th>Design</th>
<th>Population</th>
<th>Intervention</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Bergstra et al (2015)</td>
<td>Randomized</td>
<td>18 women</td>
<td>Five runway (22 m) running trials in MS and TS.</td>
<td>↑ Forefoot pressure</td>
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<tr>
<td>Dubois et al (2015)</td>
<td>RCT</td>
<td>17 women 7 men</td>
<td>Running for 16 weeks according to a standardized training program towards half-marathon in MS or TS.</td>
<td>↑ Injury risk</td>
</tr>
<tr>
<td>Lussiana et al (2016)</td>
<td>Randomized</td>
<td>13 men</td>
<td>Treadmill running for 50 minutes with various inclination in MS and TS.</td>
<td>↑ Forefoot pressure</td>
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<tr>
<td>Peltz et al (2014)</td>
<td>Randomized</td>
<td>6 women 6 men</td>
<td>Three runway (15 m) running trials in MS and TS.</td>
<td>→ Rearfoot pronation</td>
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<tr>
<td>Ryan et al (2014)</td>
<td>RCT</td>
<td>60 women 39 men</td>
<td>Running for 12 weeks according to a training program towards 10 km in MS1, MS2 or TS.</td>
<td>↑ Injury risk</td>
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<td>↑ Achilles tendon load</td>
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<tr>
<td>Sinclair et al (2013)</td>
<td>Crossover</td>
<td>12 participants (unknown sex)</td>
<td>Six runway trials (22 m) in MS and TS.</td>
<td>↑ Vertical loading rate</td>
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<td></td>
<td>→ Rearfoot pronation</td>
</tr>
<tr>
<td>Sinclair (2014)</td>
<td>Crossover</td>
<td>30 men</td>
<td>Ten runway (22 m) running trials in MS1, MS2, MS3 and TS.</td>
<td>↑ Achilles tendon load</td>
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<tr>
<td>Warne et al (2014)</td>
<td>Randomized</td>
<td>10 women</td>
<td>Treadmill running at two occasions, before and after a 4 week transition period, in MS and TS.</td>
<td>↑ Forefoot pressure</td>
</tr>
<tr>
<td>Willy &amp; Davis (2014)</td>
<td>Randomized</td>
<td>14 men</td>
<td>Treadmill running for 10 minutes plus five steps in MS and TS.</td>
<td>↑ Vertical loading rate</td>
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</table>
3.4 Biomechanical factors


Table 3 - Overview of the results according to biomechanical factors when running in minimalist shoes compared to running in traditional running shoes. An increase is marked by + and no difference is marked by +/-.

<table>
<thead>
<tr>
<th>Study</th>
<th>Forefoot pressure</th>
<th>Vertical loading rate</th>
<th>Achilles tendon load</th>
<th>Rearfoot pronation</th>
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<tr>
<td>Dubois et al (2015)</td>
<td></td>
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<td></td>
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<tr>
<td>Lussiana et al (2016)</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Peltz et al (2014)</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Ridge et al (2013)</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Sinclair et al (2013)</td>
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<td></td>
<td></td>
<td>+/-</td>
</tr>
<tr>
<td>Sinclair (2014)</td>
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<td></td>
<td>+</td>
</tr>
<tr>
<td>Warne et al (2014)</td>
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<td></td>
</tr>
<tr>
<td>Willy &amp; Davis (2014)</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
</tr>
</tbody>
</table>

3.4.1 Forefoot pressure

The study by Bergstra et al (2015) showed a significant increase in peak pressure and the maximum mean pressure in the medial, central and lateral forefoot when running in minimalist shoes, compared to running in traditional running shoes. In the study by Warne et al (2014) mean maximum pressure in the plantar was tested at two occasions separated by a four week familiarization period in order to accustom to running in minimalist shoes. There was a significant increase in mean maximum pressure in the medial, central and lateral
forefoot when running in minimalist shoes, compared to running in traditional running shoes, before and after the familiarization period. In both studies all subjects were women.

In the study by Lussiana et al (2016) subjects ran for 50 minutes with different slope gradients. The 50-minute run was divided into four sections of running, which of three sections each of included five minutes slope gradient zero, positive five and negative five and the fourth shorter section of five minutes included only slope gradient zero. Measurements were taken for 60 seconds on ten occasions beginning in the third minute and then five minutes apart. The study showed that the mean pressure in the medial and central forefoot was significantly increased when running in minimalist shoes compared to running in traditional running shoes. All subjects were men.

The study by Ridge et al (2013) included 15 women and 21 men. Ten subjects out of 19 in the MS group and one subject out of 16 in the TS group were diagnosed with a bone marrow edema injury, according to a five step scale used to diagnose bone marrow edema and stress fractures. To be diagnosed with a bone marrow edema injury required at least two out of maximum four points. The trial was based on a gradual transition to running in minimalist shoes and showed an increased risk of developing bone morrow edema in the forefoot when running in minimalist shoes. The four studies evaluating forefoot pressure represented runners with different running experience, averaging from ten to forty-five km per week.

3.4.2 Vertical loading rate
In the study by Willy & Davis (2014) measurements were taken in the first and the tenth minute of running. There was an in-group increase in vertical loading rate during the tenth minute, compared to the first minute, when running in both minimalist shoes and traditional running shoes. The vertical loading rate was significantly higher when running in minimalist shoes compared to running in traditional running shoes in both the first and the tenth minute. All subjects were men and were observed rearfoot strikers at the start of the intervention.

The study by Sinclair et al (2013) showed that running in minimalist shoes increased average vertical loading rate, compared to running in traditional running shoes. All subjects were men and defined as rearfoot strikers at the start of the intervention. The study by Sinclair et al (2013) included experienced runners with a weekly running distance of at least 30 kilometers per week and the study by Willy & Davis (2014) included less experienced runners running at least six kilometers per week.
3.4.3 Achilles tendon function

In the study by Ryan et al (2014) Achilles tendon load was evaluated indirectly by letting the subjects assess pain according to the Visual Analogue Scale (VAS) and assess function according to the FADI Score (Martin et al 1999). Subjects in the MS1 group reported significantly higher calf pain compared to the MS2 and the TS group. There were no significant differences in FADI score when comparing the MS1, MS2 and TS group.

The study by Sinclair (2014) included three different minimalist shoes and one traditional running shoe. Regarding running experience, subjects had to run at least three times per week in order to be included in the study. Two of the included minimalist shoe models were uncushioned (MS1 and MS2) and one was lightly cushioned (MS3). The study showed a significant increase in Achilles tendon force when running in uncushioned minimalist shoes compared to running in traditional running shoes or lightly cushioned minimalist shoes.

3.4.4 Rearfoot pronation

The study by Peltz et al (2014) showed a significant increase in rearfoot eversion in the early stance phase, when running in minimalist shoes compared to running in traditional running shoes. However, there was no significant difference in tibiotalar rotation when running in minimalist shoes, compared to running in traditional running shoes. In the study by Sinclair et al (2013) there was no significant difference in rearfoot eversion when running in minimalist shoes, compared to running in traditional running shoes.
4 Discussion

4.1 General injury risk

The aim of the systematic review was to investigate injury risk when running in minimalist shoes compared to running in traditional running shoes. The purpose of the study was also to identify risk factors that could increase the risk of developing running related injury when running in minimalist shoes, compared to running in traditional running shoes. Injury risk was investigated by assessing injury incidence and the studies included in the review indicated that there was an increased injury risk when running in minimalist shoes compared to running in traditional running shoes.

4.1.1 Study design

The two studies that evaluated general injury risk when running in minimalist shoes were RCTs, including one group running in minimalist shoes and one control group running in traditional running shoes. The study by Ryan et al (2014) included a larger population of 99 subjects in the final analysis, compared to the pilot study by Dubois et al (2015) that included 24 subjects. Including a small population increases sensitivity to withdrawal and thereby increases the risk of not receiving significant results of the study. A small population also decreases the trustworthiness of the total results of the study.

4.1.2 Population

One criteria for inclusion of subjects in the study by Ryan et al (2014) was that the subject was able to run for 60 minutes continuously. Setting the inclusion criteria to a rather high running performance level excluded runners with a lower running capacity, resulting in a less generally applicable result. In the study by Dubois et al (2015) subjects with a lower capacity were included as well, resulting in a population that included a larger part of the total running population in society. Both studies included female and male participants which helped increase the general applicability of the results of the studies.

4.1.3 Intervention

The two studies by Dubois et al (2015) and Ryan et al (2014) were both based on a gradual transition to running in minimalist shoes. This is of great importance in order to avoid a rapid change in footwear and the associated change in biomechanical characteristics. If there would not have been a gradual transition there would be a substantial risk that the results of the study concerning injury incidence were due to the footwear change itself and not due to running in
minimalist shoes, instead of traditional running shoes. All participants in the study by Ryan et al (2014) were new to running in minimalist shoes, which increased the importance of the gradual transition to running in minimalist shoes, in order to avoid an increased injury risk due to change in footwear.

The fact that all runners were new to running in minimalist shoes placed all participants on the same level at the beginning of the intervention, reducing baseline differences between the subjects. In the study by Dubois et al (2015) participants were included in the study regardless of what type of footwear they had been wearing previously. By including subjects with previous experience of running in minimalist shoes, injury risk was evaluated in a long-term perspective, instead of evaluated as a result of starting to run in minimalist shoes, which could be the case in the study by Ryan et al (2014).

4.1.4 Shoe characteristics
The study by Dubois et al (2015) included one minimalist shoe and one traditional running shoe and the study by Ryan et al (2014) included two minimalist shoes and one traditional running shoe. The first minimalist shoe (MS1) in the study by Ryan et al (2014) was uncushioned and the second minimalist shoe (MS2) was lightly cushioned. The study showed that the MS2 group had a higher injury rate and according to Ryan et al (2014) this could be due to the fact that the MS2 had substantial cushioning and stack height which could have decreased the stability of the shoe, compared to the uncushioned MS1.

In the study by Dubois et al (2015) the two intervention groups were able to choose from several different shoe models from each footwear type, in order to find in a shoe that fit properly on their foot. This makes the result of the study more general regarding minimalist shoes as a group, since not only one shoe model was evaluated, but could also add more variation to the result as there might be small differences in the characteristics of the shoe models within the footwear type. Having several different shoe models to choose from also reduced the risk of injuries occurring due to the fact that the running shoe did not fit properly on the subject’s foot during the intervention.

4.2 Biomechanical factors
Potential risk factors that could increase the injury risk when running in minimalist shoes was investigated in order to evaluate effect on injury risk. The potential risk factors that were identified were forefoot pressure, vertical loading rate, Achilles tendon load and rearfoot pronation. Running in minimalist shoes was shown to significantly increase forefoot pressure,
vertical loading rate and Achilles tendon load, compared to running in traditional running shoes. No significant difference in rearfoot pronation was detected when running in minimalist shoes, compared to running in traditional running shoes.

4.2.1 Study design

Seven out of nine studies that were included and evaluated biomechanical factors were crossover trials. Five out of seven crossover trials described a randomized shoe order during the intervention. Two studies did not describe a randomized intervention order, which could have affected the results by establishing effect of order (Sinclair et al 2013, Sinclair 2014). The remaining two studies by Ridge et al (2013) and Ryan et al (2014), that evaluated biomechanical factors, were RCTs that evaluated forefoot pressure and Achilles tendon load when running in minimalist shoes compared to running in traditional running shoes.

4.2.2 Population

Five out of seven crossover studies stated that subjects had no previous experience of running in minimalist shoes. Two of these studies evaluated forefoot pressure, two evaluated vertical loading rate and one evaluated rearfoot pronation. In the two remaining crossover studies by Bergstra et al (2015) and Sinclair (2014) it was unclear whether subjects had experience of running in minimalist shoes. Previous experience of running in minimalist shoes was not stated as an exclusion criterion in these studies, in contrast to the rest of the crossover studies. All subjects in the RCT study by Ridge et al (2013) were new to running in the minimalist shoe model that was used in the study, in order to place all participants on the same level at the start of the intervention.


Four studies evaluated forefoot pressure when running in minimalist shoes and all four studies included subjects with different running experience, which increased the reliability of the results. The studies by Bergstra et al (2015) and Warne et al (2014) included only female runners, but the study by Ridge et al (2013) included male runners as well and the study by
Lussiana et al (2016) included only male runners. Including both female and male runners increases the general applicability of the results. The two studies that evaluated vertical loading rate included exclusively male subjects, meaning female runners were not represented in the results.

4.2.3 Intervention

In three of the seven crossover studies the running intervention took place on a treadmill (Lussiana et al 2016, Warne et al 2014 and Willy & Davis 2014) and in the remaining four the running intervention took place on a laboratory runway. Running on a treadmill may result in modifications of the gait, which could lead to differences in biomechanical factors, compared to running overground (Bergstra et al 2015, Dubois et al 2015). This means that the results of studies based on treadmill running might not be fully applicable when running overground.

Forefoot pressure was evaluated in four studies and in the studies by Lussiana et al (2016) and Warne et al (2014) measurements were conducted while running on a treadmill. In the studies by Bergstra et al (2015) and Ridge et al (2013) subjects ran overground during the intervention. Gait might be modified while running on a treadmill, as stated previously, which could limit the application of the results from the two treadmill studies. All four studies showed that there was an increased forefoot pressure when running in minimalist shoes, whether on a treadmill or overground.

When running in minimalist shoes a forefoot strike seems to be promoted, but is not necessarily induced. In the studies by Sinclair et al (2013) and Willy & Davis (2014) that evaluated vertical loading rate, subjects were habitual rearfoot strikers at the start of the intervention and might have continued to run with a rearfoot strike, since the foot strike pattern was not reported during the intervention. The fact that the foot strike pattern of the subjects during the intervention was not reported makes it hard to decide whether the results of the studies were due to running in minimalist shoes or due to running with a rearfoot strike.

4.2.4 Shoe characteristics

In the studies by Peltz et al (2014) and Willy & Davis (2014) one minimalist shoe and one traditional running shoe was included in each study. The included minimalist shoe in both studies was lightly cushioned, which means that there was a difference in characteristics of the minimalist shoes that were worn during the different studies that were included in the systematic review, despite being described according to the consensus definition of a minimalist shoe. Included studies that involved a lightly cushioned minimalist shoe supported
the same general results as the included studies involving an uncushioned minimalist shoe, when evaluating the same biomechanical factor.

4.3 Level of evidence
The level of evidence of the results in a systematic review can be evaluated according to the GRADE system established by the Swedish State’s Advisory Committee for Medical Evaluation (SBU) (SBU 2014). In a first step the level of evidence is evaluated according to study design, where randomized studies receive the highest score of four points. In a second step the evidence level is evaluated according to study quality, concurrence among studies, general applicability, precision in data and risk of publication bias. If there is a deficiency in either area the score is lowered by one point for each deficiency, resulting in a final score of four points or less.

A score of four points equals high evidence, three points equals moderate evidence, two points equals limited evidence and one point or less equals insufficient evidence (SBU 2014). If a deficiency is of smaller extent it can be noted without taking a point of the score. The evidence of the results regarding general injury risk according to the GRADE system was defined as limited evidence, since there was a limitation in population size and questionable conditions regarding previous running experience in minimalist shoes.

The evidence level of the results regarding forefoot pressure was defined as moderate, since the only deficiency in the evaluated studies were inclusion of small population sizes. Regarding both Achilles tendon load and rearfoot pronation the evidence level was defined as limited to moderate due to small population sizes and one study in each area (Sinclar 2014, Sinclair et al 2013) did not have a stated randomization. The evidence level of the results regarding vertical loading rate was set to limited due to small population sizes, one study did not state randomization (Sinclair et al 2013) and both sexes were not represented in the evaluated studies.

4.4 Methodological limitations and future implications
One methodological limitation in this systematic review was that there was heterogeneity in the study design of available studies, meaning a thorough review of the available material was of great importance in order to avoid missing studies including relevant biomechanical factors. The heterogeneity of the included studies also created a division in the presentation of the results, where one part evaluated general injury risk and one part evaluated biomechanical
factors. A homogeneity in study design among the included studies would have facilitated the structuring and the presentation of the results of the systematic review.

The included studies were generally of high quality according to the PEDro Scale. Nine included studies received seven out of ten points, which of three points were impossible or challenging to fulfill. Two studies received a lower score, indicating a lower reliability of these two studies. Future research regarding running in minimalist shoes should focus on creating RCTs investigating injury risk and injury representation when running in minimalist shoes in comparison to running in traditional shoes. According to Dubois et al (2015) a number of approximately 230 subjects should create a clinically significant difference if one assumes a 20 percent injury incidence.

Future studies should also diagnose and keep statistics of occurring injuries in order to draw conclusions regarding injury representation when running in minimalist shoes, compared to running in traditional running shoes. Both female and male runners should be represented in the research. Running experience and previous footwear experience should also be key factors when designing future studies, to represent a large part of the running community. The consensus definition on minimalist shoes should be further established in order to create a uniform perception of the term minimalist shoes.

4.5 Conclusion

In seven out of ten included studies runners with previous experience from running in minimalist shoes were excluded. This means that there were only a few studies evaluating subjects with experience from running in minimalist shoes. Although several studies included a transition period in order to accustom the subjects to running in minimalist shoes, the main result of the systematic review is that individuals that ordinarily run in traditional running shoes should take caution when starting to run in minimalist shoes.

Moderate evidence shows that changing from running in traditional running shoes to running in minimalist shoes increases the risk of developing metatarsal stress fractures, due to increased loading of the forefoot. Limited evidence shows that running in minimalist shoes might also increase the vertical loading rate, at least when starting to run in minimalist shoes when accustomed to running in traditional running shoes. An increased vertical loading rate has been shown to be connected to an increased incidence of metatarsal stress fractures, which could increase the risk of developing injury.
Starting to run in minimalist shoes, when accustomed to running in traditional running shoes, requires a gradual increase of training volume in order to avoid an increased injury risk (Ryan et al 2014). Running in minimalist shoes generally requires running with a forefoot strike, and limited to moderate evidence shows that running in minimalist shoes increases the load of the triceps surae muscle and the Achilles tendon, compared to running in traditional running shoes. An increased load of the triceps surae muscle and the Achilles tendon may increase the risk of developing injuries such as chronic Achilles tendon pain.
References


Weist R, Rosenbaum D. The Influence of Muscle Fatigue on Electromyogram and plantar


## Appendix 1 - Search matrix

<table>
<thead>
<tr>
<th>Database</th>
<th>Search term</th>
<th>Search strategy</th>
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