Rocker shoes for ankle and foot overuse injuries

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Rocker shoes for ankle and foot overuse injuries:

a biomechanical and physiological evaluation

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To my wife **NEDA**, whose inner and outer beauty is divine

AND

To **WZ**, who showed me the path of love

CHAPTER 1

General Introduction

1. INTRODUCTION

1.1 Overuse sports injuries of the ankle and foot

Many people of different ages and with different skills participate in sports and benefit from it.[1, 2] However, sports activities are not risk-free, and in terms of severity sports injuries rank third following traffic accidents and violence.[3] About 7 million people in the United States each year seek medical attention for sports injuries (25.9 per 1000 population-year).[4, 5] A large portion of sports injuries (approximately 30 to 50%) are caused by overuse.[6-9] It is estimated that between 27% and 70% of runners sustain overuse injuries during any one year period.[10] Due to their multifactorial etiology and insidious onset, overuse injuries can be challenging to diagnose and treat.[11, 12]

Overuse injuries of the ankle and foot regions are commonly encountered in sports medicine and rehabilitation clinics.[13, 14] Considering the crucial role of the ankle and foot in athletic activities (running, jumping, cutting, acceleration and absorbing ground reaction impacts)[15], an injury to these regions can withhold athletes from full participation in sports and might even be the reason to end the athletic career. Thus, strategies to prevent and treat overuse sports injuries are necessary.

To design effective prevention programs for sports injuries van Mechelen et al.[16] outlined a prevention model as follows: "*Firstly the extent of the sports injury problem must be identified and described. Secondly the factors and mechanisms which play a part in the occurrence of sports injuries have to be identified. The third step is to introduce measures that are likely to reduce the future risk and/or severity of sports injuries*." Below, these steps will be discussed particularly related to ankle and foot overuse injuries and mechanical overload.

Extent of ankle and foot overuse injuries. In the last three decades a large number of studies have assessed the epidemiology of sports injuries including overuse problems. Although ankle and foot overuse injuries have been addressed in most of these epidemiological reports, these studies are quite diverse in research methodology (e.g. retrospective vs. prospective design), data reporting (e.g. overall injury rates vs. specific injury rate), and study outcomes (e.g. incidence vs. prevalence) within and between different sports. Therefore, no accurate estimations of extent of ankle and foot overuse injuries are available for different sports activities. An overview of current evidence can give us a better insight into this issue.

Factors and mechanisms. The etiology of overuse injuries is multifactorial and diverse.[10, 17, 18] The biomechanical overload is one of the factors that has been associated to overuse injuries.[10, 19, 20] Load applied to anatomical structures during sports activities is one possible stimulus to maintain and/or increase the strength of biological tissues such as tendons, muscles and bones.[21] However, repetitive load beyond the tensile limit of a structure may be the reason for microdamages leading to overuse injuries.[10, 21-23]

Prevention and treatment measures. Interventions that can reduce the load seem to be important in prevention and management of running related injuries.[21] One of the possibilities to reduce the load on the lower extremities is to affect the kinetics and kinematics of gait using different shoe constructions.[21, 24] To reduce the load, one could concentrate on breaking phase or propulsion phase of running. In last three decades, the main attention of scientific community has been directed to the breaking phase of running instead of the propulsion phase. Impact forces are believed to be the major factor leading to overuse running injuries and therefore, shoes with well-cushioned heels or shoes that induce forefoot landing (i.e. minimalist shoes) have been advocated and developed in the attempt to prevent or treat overuse injuries.[25, 26] However there is no conclusive evidence to support this notion.[25, 27] Internal loading in muscle-tendon units of the lower extremities is relatively small during impact phase of running compared to loads on the same structures during active (propulsion) phase.[27] Therefore, more attention should be paid also to the loads during the active phase of running. A rocker sole might influence the loads during the active phase of running.

1.2 Rocker sole shoes

Rocker soles are the most commonly prescribed external shoe modification.[28-30] To better understand the functions of rocker sole shoes, two design features need to be described: (1) apex position and (2) rocker angle. The *apex* is the bending or rolling point of the shoe. During running and walking activities with standard shoes this point is located around the metatarsal heads (Fig. 1B). Depending on desired biomechanical effect, the *apex* can be positioned anywhere proximal (Fig.1 A) or distal (Fig.2 C) of metatarsal heads to customize different types of rocker shoes for various ankle and foot pathologies.

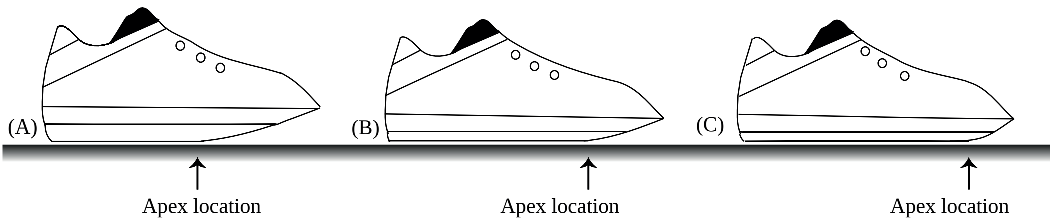

Figure 1: Three types of rocker sole: (A) proximally placed rocker, (B) normal rocker and (C) distally placed rocker

The second feature of a rocker sole is the rocker *curvature/angle*. For a given *apex* position, the rocker *curvature/angle* is typically varied by increasing or decreasing the thickness of the sole [31] (as seen in figure 1).

The rocker sole is only effective if it is adequately stiffened, otherwise the bending occurs again in the metatarsal region and thus an effective rocking will not be achieved. The stiffness is often added to the sole of the shoe using a carbon fibre or metal plates.[32]

1.2.1 Biomechanical effects

Rocker shoes with a proximally placed rocker (Fig.1 A) are commonly used in clinical practice. This type of rocker shoes has two effects during propulsion phase of stance: 1) reducing the load on the Achilles tendon and 2) reducing forefoot plantar pressure.

A proximally placed rocker reduces the length of the external dorsiflexion moment arm and with that the external dorsalflexion moment and the internal plantar flexion moment, resulting in a decrease of the load on the Achilles tendon (see section 1.2.2).

Normally the ground reaction force during the roll-off applies at the metatarsophalangeal region which is exactly the painful region in problems like metatarsalgia (pain in the plantar aspects of the metatarsal heads). By using a proximally placed rocker (with stiffened sole), during the roll-off the ground reaction force applies at the place of the rocker, and thus it offloads the metatarsophalangeal region. Mechanisms of unloading are supposed to be a combination of the following effects: shorter loading time at forefoot region, changes in force distribution and restriction of metatarsophalangeal extension (limiting downward pressure of metatarsal heads).[28, 33, 34] This biomechanical effect of rocker shoes (offloading pressure in the forefoot) has clinical applications for pathologies such as metatarsalgia, sesamoditis, and metatarsal head fractures.[31-33, 35-38]

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1.2.2 Rocker sole shoes and Achilles tendinopathy

Achilles tendinopathy is one of the most common overuse injuries in runners.[39] Achilles tendinopathy is characterized by localized pain and swelling at the Achilles tendon which often becomes a chronic condition that leads to loss of occupational capacity and reduced athletic performance.[40] Conservative treatment is commonly the first line of management for Achilles tendinopathy.[41] Eccentric loading exercises, shockwave therapy, splinting and active rest are some of the conservatives treatment methods for Achilles tendinopathy.[41] Although the etiology of Achilles tendinopathy is likely to be multifactorial, excessive repetitive overload is regarded as the main pathological stimulus that leads to Achilles tendinopathy.[23] It is estimated that the peak load imposed on the Achilles tendon can reach up to 6.1–8.2 times body weight during running, with a tensile force of more than 3 kN.[42] Therefore, reducing the load to the Achilles tendon should also be considered in both prevention and treatment of Achilles tendinopathy.

From a biomechanical perspective, the use of shoes with a proximally placed rocker (referred to "rocker shoe" hereafter)(Fig. 1A), might reduce the load on the Achilles tendon. The triceps surae, with the Achilles as the common tendon, are the main contributors to the push-off (propulsion) phase of gait by generating *internal plantar flexion moment* (PFM) around the ankle joint.[43, 44] Rocker shoes can possibly reduce PFM and therefore decrease the load to the Achilles tendon. The biomechanical mechanism is simplified, as a static condition, and illustrated in figure 2.

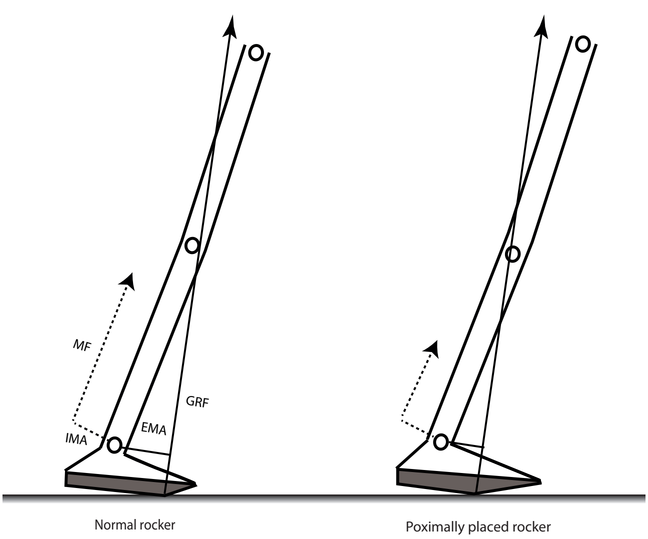

Figure 2. The effect of proximally placed rocker profile on external and internal moments around the ankle joint during terminal stance of gait. GRF= ground reaction force; EMA= external moment arm; MF= muscle force generated by triceps surae; IMA= internal moment arm. Length of forces and moment arms are not in actual scale.

It should be noted that in order to propel forward in a dynamic situation, the internal moment (force of calf muscles X internal moment arm) during the push-off phase needs to be bigger than the external dorsiflexion moment (ground reaction force X external moment arm).

Tendinopathic pain is supposed to be induced by load either singular or cumulative load.[45] Decrease of PFM by means of rocker shoes decreases the load on the Achilles tendon and might result in pain relief in Achilles tendinopathy patients. This effect might be eventually beneficial in early and recovery (back to sports) phases of Achilles tendinopathy. Observations regarding this biomechanical effect of rocker shoes (reduced PFM) and its side-effects are scarce in running and controversial in walking. For instance, while some studies observed significant reduction in PFM moment during terminal stance of walking with rocker shoes compared with standard shoes,[46-48] other studies have not reported such effect or, at the most, small changes which were not considered clinically significant[49, 50]. In addition, effects of rocker shoes on lower limb muscular activity have not been well documented in running and walking.

1.2.3 Rocker sole shoes and forefoot overuse injuries

In-shoe plantar pressure assessment is commonly used in research and clinical practice to evaluate foot problems and prescribing orthoses or footwear.[51] Although the force platforms provide valuable information regarding the net vector and point of application of ground reaction force, they provide no information on plantar pressure (force distribution over the plantar surface of the foot).[52, 53] Excessive plantar pressure appears to be the cause of many overuse problems of the foot including metatarsalgia and metatarsal stress fractures.[54-57] Treatment, therefore, is often aimed to reduce high-pressure regions of the foot using insoles and footwear modification.[52, 55]

The rocker shoe is one of the footwear modifications that is commonly used to reduce forefoot plantar pressures during gait.[32] This biomechanical effect of rocker shoes has been subject to a number of studies.[28, 29, 33, 58-60] These studies, however, are limited to walking activities, and no information is still available in running.

1.2.4 Rocker sole shoes and running economy

Running economy is defined as the energy cost of running at a submaximal velocity, and often determined by measuring steady-state oxygen consumption during submaximal running.[61] Running economy is a good indicator of running performance.[62] As running economy can be influenced by running shoes,[62] it can be a major concern in the choice of footwear for runners. To date, the physiological aspects of rocker shoes are largely unexplored. For example, no comparison has been made yet between rocker shoes and other running shoes regarding running economy. Some studies have investigated metabolic costs of walking with rocker shoes.[63-65] In running, however, we found no data on this regard.

1.3 Rationale

The general aim of this thesis is to investigate the potentials of rocker shoes for the management/prevention of ankle and foot overuse injuries, particularly for Achilles tendinopathy and forefoot overuse problems. This general aim was subdivided into four objectives: (1) to identify the extent of the ankle and foot overuse injuries in different sports activities, (2) to examine the biomechanical potential of rocker shoes in reducing the load on the Achilles tendon and accompanied side-effects in healthy runners and Achilles tendinopathy patients, (3) to examine the biomechanical potential of rocker shoes in reducing forefoot plantar pressure, and (4) to assess the effect of rocker shoes on metabolic cost of running.

To address the *first objective*, the extent of the ankle and foot overuse injuries in different sports activities and the methodological quality of published studies are systematically reviewed.

To address the *second objective*, the effects of rocker shoes on ankle kinetics, in particular PFM, are examined in two studies; first in a healthy group and then in patients with Achilles tendinopathy.

Healthy group. The first study deals with healthy runners. One part of this study is aimed to test our biomechanical theory that rocker shoes are able to reduce PFM in slow running and walking. Confirming this theory in a healthy group would suggest a potential of rocker shoes in both prevention and treatment of Achilles tendinopathy. From a prevention perspective, the findings of this study can be a basis for future prospective studies to measure the effectiveness of rocker shoes in reducing the incidence rate of Achilles tendinopathy in runners. From a treatment perspective, this study can be viewed as a phase I clinical trial where the safety of the new intervention, rocker shoes, is evaluated in a group of healthy volunteers. Therefore, the second part of this study explores adaptations in the hip and knee joints as well as lower limb muscular activities in response to rocker shoes.

Patient group. There is a possibility that patients with painful Achilles tendon have an adapted gait pattern and a different biomechanical reaction to rocker shoes than healthy people. For that reason we first tested our theory in healthy subjects. By gaining sufficient biomechanical evidence from the first study in healthy population, a similar study is repeated in a group of patients with Achilles tendinopathy. The aim of this study is to determine if the biomechanical theory related to rocker shoes and PFM can also be observed in the patient group. This study can be viewed as a phase II clinical trial that examines PFM as a surrogate outcome. A surrogate outcome is a substitute (e.g. a laboratory measurement) for a clinical outcome measure (e.g. pain, daily function).[66] Changes induced by a surrogate outcome are expected to be related to clinical outcome.[66] In our current setting, it is not yet clear if and how PFM would be related to a clinical outcome. Results from the patient group, with PFM as a surrogate outcome, may provide the basis for a phase III clinical trial. This trial should then evaluate the effect of rocker shoes on clinically relevant outcomes.

It should be mentioned that there are two central assumptions for these two studies (healthy and patient groups): (1) reduced PFM causes less tensional load on the Achilles tendon, and (2) less load on the Achilles tendon should be beneficial in prevention (reduction in injury rates) and/or management of Achilles tendinopathy (see section 1.2.1).

To address the *third objective*, another study presented in this thesis examines the theory of the potential of rocker shoes in reducing the forefoot plantar pressure in healthy runners. The shoe comfort and plantar pressure patterns in other areas of the foot are also evaluated to check for possible side-effects. This study is also partly related to a phase I clinical trial where the side-effects of wearing rocker shoes on plantar pressure parameters and shoe- comfort are explored in healthy volunteers. This study can serve as a basis for future phase II and III trials.

To address the *forth objective*, the final experimental study of this thesis compares the metabolic cost of running across three types of shoes: rocker shoe, standard shoe, and minimalist shoe. This chapter enhances our understanding of how running economy (consequently runners' performance) could positively or negatively be affected by rocker shoes compared with other running shoes.

1.4 Study design

To be able to investigate our hypotheses, the clinical trials need to be designed properly including appropriate randomization schemes. A common design that has been used in clinical trials frequently is a cross-over design. This type of design is the main method employed in the experimental studies of this thesis. In a cross-over design, participants, whether patient or healthy volunteer, are given a number of treatments (interventions) with the object of studying differences between these treatments (interventions).[67] Since in this type of design participants serve as their own control (within subject comparisons), the sources of inter-individual variability (e.g. age, height, or weight) and experimental variance can be factored out.[67, 68] Therefore, compared with parallel studies, cross-over trials require fewer participants to detect a treatment effect, which eventually leads to considerable saving in time and recourses.[67, 68] A cross-over design is essentially a repeated measures design in which all participants receive all interventions in different periods.

One possible problem with cross-over designs is that interventions may have long-lasting effects that could influence the results of other intervention in the trials, when a participant switches from one intervention to another (carry-over). When the carry-over of interventions are different, the effect of interventions cannot be estimated unbiasedly on the basis of all data. Only the data of the first period can then be used to test the hypothesis, but the test statistic compares the effect size with inter-individual variation. Another problem is that participants may provide different results when they have to perform the same activity repeatedly after each other (period-effect). Fatigue and learning are two common reasons for such an effect. The two possible issues should be addressed appropriately. In general, carry-over issues are solved by including wash-out periods to eliminate the effects of one intervention to the other intervention, and therefore making the carry-over effects of both interventions equal (zero). It is not expected that carry-over effects will be present with our type of interventions (shoes). The issue with period effect is less problematic, since the treatment effect can be estimated unbiasedly when the period effect has been estimated (i.e. correcting for periods). To be able to estimate the treatment effect unbiasedly, the order of interventions need to be changed for participants. For instance, for a 2x2 cross-over design the two orders must be involved: (1) rocker shoe - standard shoe and (2) standard shoe - rocker shoe. These orders or sequences help estimate period-effects and make it possible to test for order-effects (i.e. differences in carry-over effect of the intervention).

As indicated earlier, studies presented in chapter 3- 6 used a cross-over design. In these studies participants were randomly assigned to different sequences of experimental conditions. In general, the randomization helps prevent possible biases of measured and unmeasured confounders on the estimation of the treatment effect. Studies in chapter 3, 5, and 6 had a balanced design, and the study in chapter 4 had a partially balanced design. In addition, some statistical tests were performed at analysis stage to examine the possibility of order and/or period effects. This more rigid form of analysis has not been considered in the design of previous studies on similar topic.[29, 46, 47, 50, 69, 70]

1.5 Outline of the thesis

The incidence and prevalence rates of the ankle and foot overuse injuries are systematically reviewed and summarized for different sports in the study presented in *chapter 2*. This thesis consists of four experimental studies; three biomechanical studies (*chapter 3-6*) and one physiological study (*chapter 6*). In *chapter 3* the effects of rocker shoes on running and walking biomechanics are evaluated in healthy volunteers. *Chapter 4* is an extension of *chapter 3,* where a similar experiment is repeated in a group of patients with Achilles tendinopathy. Effect of rocker shoes on plantar pressure of female runners is studied in *chapter 5* of this thesis. In *chapter 6,* a comparison is made between rocker shoes and two other shoe conditions concerning the running economy. In *chapter 7*, the findings of *chapter 2-6* are integrated and conclusions are drawn. Clinical applications and future research are also described.

1

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CHAPTER 2

Epidemiology of ankle and foot overuse injuries in sports: a systematic review

Scand J Med Sci Sports. 2012 Jul 30. In press.

Sobhan Sobhani, Rienk Dekker, Klaas Postema and Pieter U. Dijkstra

ABSTRACT

Studies regarding ankle and foot overuse injuries are quite diverse in research methodology, data reporting and outcomes. The aims of this systematic review were to analyze the methodology of published studies regarding ankle and foot overuse injuries in different sports disciplines and to summarize epidemiological data of ankle and foot overuse injuries. Four electronic databases, PubMed (MEDLINE), EMBASE, CINAHL and SPORTDiscus®were systematically searched up to June 2011.

A total of 89 articles on 23 sports disciplines were included in this review. Soccer, running and gymnastics were the most frequently studied sports. Achilles tendinopathy, plantar fasciitis and stress fracture were the most frequently studied injuries. Study design and reporting methods were heterogeneous. Most studies suffered from a weak methodology and poor reporting. The most common weaknesses were lack of a clear case definition, describing assessment procedures and reporting sample characteristics. Due to methodological heterogeneity of studies, inter and intra-sports comparisons and meta-analysis were not possible. Methodology of most studies on incidence and prevalence of ankle and foot overuse injuries is insufficient. Based on the results we recommend authors to clearly define cases, describe assessment procedures and report sample characteristics adequately.

INTRODUCTION

Many people of different ages and skills participate in sports and benefit from it [1,2]. However, sport participation is not always beneficial. Sport injuries occur frequently [3,4], and a large portion of these injuries (30 to 50%) are caused by overuse, requiring treatment [5-7]. Overuse injuries have insidious onset and can restrain athletes from sports temporary or even permanently [8,9]. Lower leg and in particular ankle and foot are highly involved in many sports and are vulnerable to overuse injuries [10-17].

In the last three decades several studies have addressed ankle and foot overuse injuries in different types of sports. However, these studies are quite diverse in research methodology, data reporting, and study outcomes within as well as between different sports [18-26]. An overview of the methodological quality of published studies on ankle and foot overuse injuries is still missing.

This systematic review therefore had three aims: (1) to summarize epidemiological data (incidence and prevalence) of ankle and foot overuse injuries in different sports disciplines, (2) to assess methodological quality of published studies, and (3) if possible to perform a meta-analysis of the available data.

MATERIALS AND METHODS

Our review followed the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) Statement[27].

Literature search

For this systematic literature review, books[6,28-32] in orthopedics and sports medicine were studied to create a comprehensive list of ankle and foot overuse injuries related to sports. This list was used to develop the search strategy. Four electronic databases, PubMed (MEDLINE), EMBASE, CINAHL and SPORTDiscus®, were searched using a combination of related medical subject headings (MeSHs) and free-text words (see appendix 1 for database search strategy). Main keywords used were “sports”, “ankle”, “foot” and “overuse injuries” in combination with “epidemiology”, “incidence” and “prevalence”. Besides “overuse”, other terms such as “chronic” and “chronic overuse” have been interchangeably used by authors to address overuse injuries. Since there is no clear distinction between the terms “overuse” and “chronic” in the literature, we considered them to be synonyms. The first database search was performed up to 30th April 2010 and updated on 1st of June 2011. The same inclusion and exclusion criteria were considered in screening of title, abstract and full-text. Inclusion criteria were studies focusing one or more sports activities, containing epidemiological information of overuse injuries of the ankle and foot, and written in English, Dutch or German language. Excluded were studies with a military research population only, concerning acute injuries only, focusing on body part(s) other than ankle and foot, focusing on surgical procedures, treatment modalities, prevention strategies, orthopaedic examination and diagnostic methods, and reviews, case reports or case series.

Two authors (SS and RD) independently assessed titles, two authors (SS and KP) independently assessed abstracts and full texts of English articles and two authors (RD and PD) assessed German articles. Reference lists of all relevant articles were checked for additional published papers. In addition, corresponding authors of congress abstracts were contacted for detailed information regarding their studies.

Quality assessment

Since there is no standard tool to evaluate external and internal validity of observational studies [33,34], different assessment tools [33,35-38] were consulted, and 8 criteria specific to our research question were evaluated; (1) an appropriate sampling method, whole population of interest or probability sampling; (2) adequate information about participation / follow up rate; (3) participation rate $\geq$ 70% [35], to calculate participation rate for prospective studies, participation rate at the beginning (refusal rate) and final drop-out rate were both considered [39,40]; (4) use of appropriate study design for primary outcome measure, prospective cohort study for incidence and cross-sectional for prevalence; (5) providing a definition for overuse injury; (6) presentation of at least one explicit overuse diagnosis; (7) appropriate diagnostic procedures, orthopaedic physical examination was considered as the most basic and essential diagnostic procedure; and (8) sample size calculation [41,42]. These criteria were used to assess sources of bias (selection, attrition, information and detection bias), and power of the study.

A checklist (calibrated on 10 excluded papers) was used to identify relevant information related to quality items (Appendix 2). The quality of papers was independently assessed by two pairs of authors; English language papers by SS and RD and German language papers by PD and RD. All items were weighted equally and based on the sum of the quality items; studies received a score from “0” (no criteria fulfilled) to 8 (all criteria fulfilled). In all selection and quality assessment procedures, disagreements were resolved in a consensus meeting. If no consensus could be reached, a third observer gave the final verdict (PD for English language and KP for German language papers).

Calculations

Prevalence rate was calculated as the number of existing injuries in the sample population divided by the total number of participants at a particular time (point prevalence) or over a specific period of time (period prevalence). Incidence rate was calculated as the number of new injuries divided by the total number of athletes observed during the time period, and normalized per 1,000 athletes. In case of an observation period of several years and in order to create more homogeneity within the studies, incidence rates were year-adjusted. Incidence and prevalence rates and 95% confidence intervals (CI) were calculated using a computer software (Confidence Interval Analysis, version 2.1.2) [43]. Age of the total population was calculated as follows: per study the mean age was multiplied by the number of participants. Then these values were added and divided by the total number of participants in all studies providing relevant data.

RESULTS

Study Selection

The primary search resulted in 4,314 titles, and after removing duplicates 3,004 titles remained. In the title screening we excluded 21 articles because they were written in other languages than Dutch, German or English (two Turkish, one Spanish, five Italian, five Japanese, two Polish, three Chinese, one Danish, one Hungarian and one French). In total 759 articles were selected for abstract reading. After reading the abstracts, 404 abstracts were excluded because they did not fulfil the inclusion criteria. No abstract was available for 15 articles, therefore; these articles were directly added for the full-text reading stage. Two out of five corresponding authors of congress abstracts responded stating that no further information was available. After assessing articles` full-texts, 86 articles were selected as relevant. Checking the references of selected full-text articles yielded 22 more articles. Eventually, 108 articles were selected for quality assessment. The flowchart of the result from the database search, inclusion of articles and inter-observer agreement for the different steps of study selection are presented in figure 1.

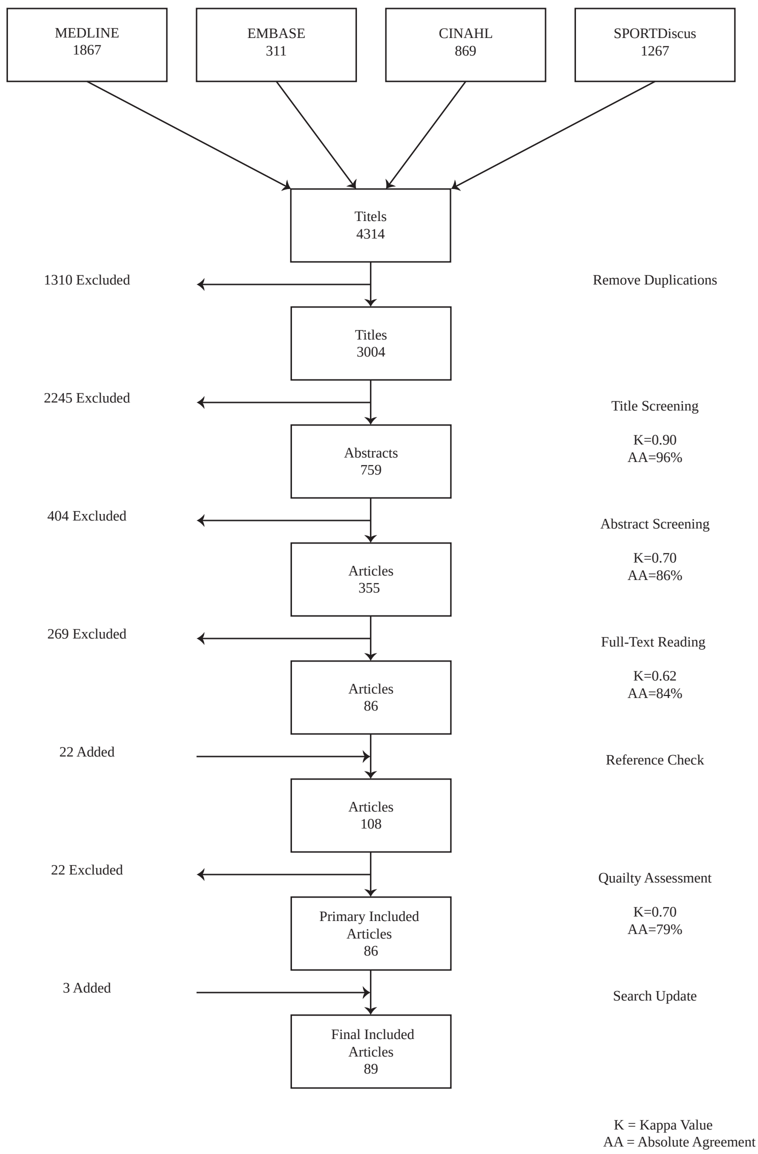

Figure 1. Flow chart of database search and inclusion procedure

Throughout the quality appraisal process, 22 of 108 primary included articles were excluded for following reasons: time of assessment (point or period) was not clear for prevalence rate, three studies [44-46], no specific data for ankle and foot regions, five studies [47-51], unclear injury reporting in graphs, seven studies [52-58], prevalence reporting based on availability of athletes (missed games/hours) not actual number of injured athlete, two studies [59,60], population at risk was not reported, one study,[61] and number of overuse injuries was not reported, four studies [62-65]. Each database search was updated to 1st of June 2011, and after applying the same inclusion procedure as initial screening, three more articles were added. Therefore, finally 89 articles (English language, 81; German language, 8) were included in this review with publication year between 1982 and 2010 (see appendix 3 for characteristics of the included studies).

Description of the studies

In total 23 different sports disciplines were investigated. Soccer and running were the most frequently studied sports. The majority of studies reported incidence rates with exposure time reported in seven different ways. Period prevalence was reported in eight different ways. About half of the studies were prospective. Sampling method was unclear in 40% of the studies. In most studies (90%) sample characteristics were incompletely reported and in 65% participation rates were not clearly reported. A definition of overuse injuries was not provided in almost two thirds of the studies. In almost half of the studies the assessment tool was not clearly described, and one third of the studies used a questionnaire for overuse injury assessment.

Overall, the methodological quality score varied from 1 to 6, while the majority of studies (about 80%) had a quality score less than 5. None of the studies received a score of 7 or 8. Studies with higher scores were mostly in soccer, and published in the last decade.

Rates and characteristics of the included studies are presented in table 1 (incidence) and table 2 (prevalence).

Table 1: Incidence rates of ankle and foot overuse injuries and details of the included studies*

Authors (Year)	Sport	QS	Level	Number (M/F)	Age[a]	SM	PR (%)	Overuse Definition	AT	Design	Incidence Rate (95% CI) [b]	Expression Per 1000 Athletes
Jorgensen et al (1987) [66]	Badminton	5	M	303 (194/109)	24.9 (14-55)	R	-	Developed gradually and couldn`t be explained by a single trauma	-	Prospective	Ankle & Foot 128.7 (91.5 to 176.0)	Season
											Achilles Tend 59.4 (35.2 to 93.9)	Season
Hickey et al (1997) [26]	Basketball	2	E	49 (0/49)	-	-	-	Chronic overload	-	Retrospective	Ankle & Foot [g] 54.4 (31.1 to 88.4)	Year
											Stress Fracture [g] 17.0 (5.5 to 39.7)	Year
Dick et al (2007) [67]	Basketball	1	-	(-/0)	-	C	-	-	-	Retrospective	Stress Fracture [i] $0.5x10^{-1}$ ($0.4x10^{-1}$ to $0.5x10^{-1}$)	Exposure
Agel et al (2007) [68]	Basketball	1	-	(0/-)	-	C	-	-	-	Retrospective	Achilles Tend $0.4x10^{-1}$ ($0.3x10^{-1}$ to $0.5x10^{-1}$)	Exposure
											Stress Fracture $0.9x10^{-1}$ ($0.6x10^{-1}$ to$1.2x10^{-1}$) Game	Exposure
											Stress Fracture $0.9x10^{-1}$ ($0.8x10^{-1}$ to $1.1x10^{-1}$) Practice	Exposure
Dannenberg et al (1996) [69]	Cycling	4	A	1094	-	WP	65	Non-acute musculoskeletal pain numbness or swelling	Q	Prospective	Ankle & Foot $0.2x10^{-1}$ ($0.1x10^{-1}$ to $0.4x10^{-1}$)	Mile Exposure
Weiss (1985) [70]	Cycling	4	A	113 (78/35)	40.8±11.1 (18-71)	WP	86	-	Q	Cross Sectional	Achilles Tend 8.9 (0.2 to 49.3)	Race
Tuffery (1989) [71]	Dance (Morris)	3	A	149	-	WP	29	Injury aggriviated by dancing either prevented dancing or caused considerable discomfort	Q	Cross Sectional	Ankle & Foot $0.5x10^{-1}$ ($0.2x10^{-1}$ to$1.1x10^{-1}$)	Hour Exposure
Nilsson et al (2001) [72]	Dance (Ballet)	2	E	78 (46/32)	28.3 (14-47)	WP	-	-	-	Ambispective	Ankle & Foot [g] 338.5 (283.2 to 401.4)	Season
											Achilles Tend [g] 53.8 (33.3 to 82.3)	Season
											Peroneal Tend 30.8 [g] (15.9 to 53.7)	Season
											Flexor Hallucis Longus Tend [g] 76.9 (51.9 to 109.8)	Season
											Tibialis Posterior Tend [g] 23.1 (10.6 to 43.8)	Season
											Ankle Impingement [g] 28.2 (14.1 to 50.5)	Season
											Stress Fracture[g] 12.8 (4.2 to 29.9)	Season
											Metatarsalgia [g] 46.2 (27.4 to 72.9)	Season

Authors (Year)	Sport	QS	Level	Number (M/F)	Age[a]	SM	PR (%)	Overuse Definition	AT	Design	Incidence Rate (95% CI) [b]	Expression Per 1000 Athletes
Rovere et al (1983) [73]	Dance (Theatrical)	1	-	218 (56/162)	-	-	-	-	-	Retrospective	Ankle & Foot 261.5 (198.0 to 338.8)	Year
											Achilles Tend 151.4 (104.2 to 212.6)	Year
											Peroneal Tend 22.9 (7.4 to 53.5)	Year
											Toe Extensor Tend 41.3 (18.9 to 78.4)	Year
											Os Trigeonum 4.6 (0.1 to 25.6)	Year
											Stress Fracture 22.9 (7.4 to 53.5)	Year
											Achilles Bursitis 18.3 (5.0 to 47.0)	Year
											Plantar Fasciits 9.2 (1.1 to 33.1)	Year
Dick et al (2007) [74]	Field-Hockey	1	-	(0/-)	-	C	-	-	-	Retrospective	Achilles Tend [i] $0.4x10^{-1}$ ($0.3x10^{-1}$ to $0.6x10^{-1}$)	Exposure
Wadley et al (1993) [75]	Gymnastics	5	-	(0/26)	-	WP	-	Gradual onset	-	Prospective	Ankle & Foot 188.7 (90.5 to 347.0)	Season
											Ankle Impingement 188.7 (90.5 to 347.0)	Season
Harringe et al (2007) [76]	Gymnastics	4	E	42 (16/26)	19.4±2.2[c]	-	-	Gradually developed over a period of time	OPE&Ax	Prospective	Ankle & Foot 23.8(0.6 to 132.7)	Season
											Sural Nerve Entrapment 23.8 (0.6 to 132.7)	Season
Kirialanis et al (2002) [18]	Gymnastics	3	E	187 (100/87)	12.3±2.8[c]	WP	-	-	-	Prospective	Ankle & Foot 181.8 (125.9 to 254.1)	Year
Caine et al (1989) [77]	Gymnastics	3	E	50 (0/50)	12.6	-	-	Gradual onset	I	Prospective	Ankle & Foot 380.0 (228.8 to 593.4)	Year
Bak et al (1994) [19]	Gymnastics	3	M	117 (52/65)	16 (8-25)	-	-	Pain or inhibition of activity with Gradual onset	-	Prospective	Ankle & Foot 17.4 (2.1 to 62.8)	Year
Lindner et al (1990) [78]	Gymnastics	3	M	178 (178/0)	-	-	-	Gradual onset	Q	Prospective	Ankle & Foot $0.4x10^{-1}$ ($0.2x10^{-1}$ to $0.9x10^{-1}$)	Hour Exposure
Olsen et al (2006) [79]	Handball	5	A	428 (107/321)	-	R	85	Injury with a gradual onset without any known trauma	-	Prospective	Ankle & Foot $0.2x10^{-1}$ ($0.0x10^{-1}$ to$1.3x10^{-1}$)	Hour Exposure
Seil et al (1998) [80]	Handball	3	A	186 (186/0)	25.8	WP	-	-	Q	Prospective	Ankle 0.8 (0.5 to 1.1)	Hour Exposure
Hopper (1995) [81]	Netball	3	M	72 (0/72)	20.6±3.6 (15-36)	-	-	-	OPE	Prospective	Ankle & Foot 13.9 (0.4 to 77.4)	Season
											Achilles Tend 13.9 (0.4 to 77.4)	Season
Hopper et al (1995) [82]	Netball	2	M	11288	-	WP	-	-	-	Prospective	Ankle & Foot [g] 3.1 (2.7 to 3.6)	Year

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Authors (Year)	Sport	QS	Level	Number (M/F)	Age[a]	SM	PR (%)	Overuse Definition	AT	Design	Incidence Rate (95% CI) [b]	Expression Per 1000 Athletes
Knobloch et al (2006) [83]	Nordic Pole Walking	1	-	137 (101/36 or 102/35)[d]	53.5±12	-	-	-	Q	Cross Sectional	Stress Fracture [j] 0.0 (0.0 to 0.1)	Hour Exposure
Linde (1986) [84]	Orienteering	4	E	42 (28/14)	24 (19-34)	-	-	Overuse of tissue structures loaded in a normal motor pattern	Q	Prospective	Ankle & Foot 381.0 (217.7 to 618.6)	Year
											Achilles Tend 119.0 (38.7 to 277.8)	Year
											Peroneal Tend 119.0 (38.7 to 277.8)	Year
											Extensor Digitorum Tend 23.8 (0.6 to 132.7)	Year
											Plantar Fasciitis 47.6 (5.8 to 172.0)	Year
											Metatarsalgia 71.4 (14.7 to 208.7)	Year
Folan (1982) [85]	Orienteering	3	M	285	-	WP	-	-	-	Prospective	Ankle & Foot 3.5 (0.1 to 19.6)	Exposure
											Achilles Tend 3.5 (0.1 to 19.6)	Exposure
Johansson (1986) [86]	Orienteering	3	-	89 (56/33)	17.5±1.5	-	-	-	OPE,Ax&I	Prospective	Ankle & Foot 157.3 (86.0 to 263.9)	Year
											Achilles Tend 67.4 (24.7 to 146.7)	Year
Backe et al (2009) [87]	Rock-Climbing	3	M	355 (249/106)	30 (9-67)	R	63	Repeated micro-trauma without a single identifiable event	Q	Cross Sectional	Ankle & Foot 0.2 (0.1 to 0.4)	Hour Exposure
Sankey et al (2008) [88]	Rugby	5	E	546 (546/0)	-	-	-	-	OPE&Ax	Prospective	Ankle & Foot 1.3 (0.8 to 1.9) Game	Hour Exposure
											Ankle & Foot $0.7x10^{-1}$ ($0.4x10^{-1}$ to$1.2x10^{-1}$) Practice	Hour Exposure
											Achilles Tend 0.8 (0.4 to 1.3) Game	Hour Exposure
											Achilles Tend $0.5x10^{-1}$ ($0.2x10^{-1}$ to $0.9x10^{-1}$) Practice	Hour Exposure
											Ankle Impingement 0.5 (0.2 to 0.9) Game	Hour Exposure
											Ankle Impingement $0.2x10^{-1}$ ($0.0x10^{-1}$ to $0.5x10^{-1}$) Practice	Hour Exposure
Brooks et al (2005) [89]	Rugby	3	E	502 (502/0)	25.4±4.2	-	-	-	-	Prospective	Stress Fracture [i] $0.3x10^{-1}$	Hour Exposure
Bishop et al (1999) [20]	Running	5	-	17 (16/1)	47	WP	82	-	-	Prospective	Achilles Tend 411.8 (165.5 to 848.4)	Race

Authors (Year)	Sport	QS	Level	Number (M/F)	Age[a]	SM	PR (%)	Overuse Definition	AT	Design	Incidence Rate (95% CI) [b]	Expression Per 1000 Athletes
											Tibialis Posterior Tend 58.8 (1.49 to 32.7)	
											Extensor Digitorum Tend 176.5 (15.7 to 752.7)	
											Metatarsalgia 117.6 (14.3 to 425.0)	
Wen et al (1998) [90]	Running	3	E	255	-	C	-	Gradual onset or a self-reported diagnosis that is generally considered as overuse injury	-	Prospective	Ankle & Foot 109.8 (73.0 to 158.7)	Week
Lysholm et al (1987) [91]	Running	3	M	60 (44/16)	27.9±5.9[c]	-	-	-	-	Prospective	Ankle & Foot 233.3 (127.6 to 391.5)	Year
											Achilles Tend 83.3 (27.1 to 194.5)	Year
											Tibialis Posterior Tend 33.3 (4.0 to 120.4)	Year
											Toe Extensor Tend 33.3 (4.0 to 120.4)	Year
											Plantar Fasciitis 66.7 (18.2 to 170.7)	Year
											Metatarsalgia 16.7 (0.4 to 92.9)	Year
Van Ginckel et al (2009) [92]	Running	3	A	129 (19/110)	39±10	C	-	Musculoskeletal ailment that causes a restriction of running speed distance duration or frequency for at least 1 week	-	Prospective	Ankle & Foot 147.3 (8.9 to 230.0)	Week
											Achilles Tend 7.8 (3.7 to 14.3)	Week
Beukeboom et al (2000) [93]	Running	3	-	25 (7/18)	20.3[c]	C	-	-	-	Prospective	Ankle & Foot 250.0 (100.5 to 515.1)	Season
											Achilles Tend 107.1 (22.1 to 313.1)	Season
											Metatarsalgia 35.7 (0.9 to 199.0)	Season
											Plantar Fasciitis 71.4 (8.7 to 258.0)	Season
											Talus Osteochondritis Dissecans 35.7 (0.9 to 199.0)	Season
Fallon (1996) [25]	Running	3	-	32	(23-53)	WP	-	-	-	Prospective	Achilles Tend 687.5 (430.9 to 1040.9)	Race
											Extensor Digitorum Tend 687.5 (430.9 to 1040.9)	
											Extensor Hallucis Longus Tend 62.5 (7.6 to 225.8)	
											Peroneal Tend 62.5 (7.6 to 225.8)	

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Authors (Year)	Sport	QS	Level	Number (M/F)	Age[a]	SM	PR (%)	Overuse Definition	AT	Design	Incidence Rate (95% CI) [b]	Expression Per 1000 Athletes
Knobloch et al (2008) [94]	Running	2	E	291 (248/41)[f]	42±9	C	-	Injury with a gradual onset which influenced performance during competition or training	Q	Cross Sectional	Achilles Tend [i] $1.5x10^{-2}$	Kilometre Exposure
											Plantar Fasciitis [i] $0.3x10^{-2}$	Kilometre Exposure
Smith et al (1989) [95]	Skating	3	E	48	20.1 (10.9-27.9)	-	-	Repetitive micro-trauma	-	Perospective	Ankle & Foot 187.5 (85.7 to 355.9)	Season
											Achilles Tend 41.7 (5.0 to 150.5)	Season
											Peroneal Tend 41.7 (5.0 to 150.5)	Season
											Tibialis Anterior Tend 20.8 (0.5 to 116.1)	Season
											Metatarsophalangeal Synovitis 20.8 (0.5 to 116.1)	Season
											Malleolar Bursitis 62.5 (12.9 to 182.7)	Season
Torjussen et al (2006) [96]	Snowboarding	4	E	258	23	WP	91	Injury with a gradual onset which influenced performance during competition or training "	I	Cross Sectional	Foot 0.4 (0.2 to 0.6)	Exposure
[97]Le Gall et al (2008) [97]	Soccer	6	E	119 (0/119)	(15-19)	WP	100	Consequence of repetitive micro-trauma	-	Prospective	Stress Fracture [i] $0.2x10^{-1}$	Hour Exposure
											Ankle Impingement [i] $0.2x10^{-1}$	Hour Exposure
											Accessory Navicular Syndrome [i] $0.2x10^{-1}$	Hour Exposure
Tegnander et al (2008) [22]	Soccer	5	E	181 (0/181)	23±4 (17-34)	WP	100	Gradual onset without any known trauma	-	Prospective	Ankle & Foot $0.6 x10^{-1}$ ($0.0x10^{-1}$ to $2.3x10^{-1}$)	Hour Exposure
Jacobson et al (2007) [98]	Soccer	5	E	195 (0/195)	23±4 (16-36)	WP	72	Injury without any known trauma	-	Prospective	Ankle & Foot [i] 0.2	Hour Exposure
Walden et al (2005) [99]	Soccer	5	E	266	26±4	-	88	Pain syndrome of the musculoskeletal system with insidious onset and without any known trauma or disease that might have given previous symptoms	-	Prospective	Achilles Tend 0.3 (0.2 to 0.5)	Hour Exposure
Arnason et al (2004) [100]	Soccer	5	E	306 (306/0)	24 (16-38)	WP	85	Injuries with an insidious onset with a gradually increasing intensity of discomfort without an obvious trauma	-	Prospective	Ankle & Foot $0.3 x10^{-1}$ ($0.1 x10^{-2}$ to 0.2)	Hour Exposure
Engstrom et al (1991) [101]	Soccer	5	E	41 (0/41)	21 (16-28)	WP	100	Gradual onset of symptoms	-	Prospective	Ankle & Foot 0.6 (0.2 to 1.5)	Hour Exposure
Price et al (2004) [102]	Soccer	5	-	4773	(9-19)	WP	76	-	-	Prospective	Sever`s disease [g] 6.0 (4.5 to 7.7)	Year

Authors (Year)	Sport	QS	Level	Number (M/F)	Age[a]	SM	PR (%)	Overuse Definition	AT	Design	Incidence Rate (95% CI) [b]	Expression Per 1000 Athletes
Chomiak et al (2000) [103]	Soccer	4	M	398	19.5 ± 4.6 (14-41)	-	-	-	OPE&Q	Prospective	Ankle & Foot 15.2 (4.1 to 38.8)	Year
											Achilles Tend 7.6 (0.9 to 27.7)	Year
											Stress Fracture 7.6 (0.9 to 27.4)	Year
Soderman et al (2001) [104]	Soccer	4	M	153 (0/153)	15.9±1.2 (14.1-19.2)	C	-	Gradual onset without any known trauma	-	Prospective	Ankle & Foot 0.3 (0.1 to 0.9)	Hour Exposure
Soderman et al (2001) [105]	Soccer	4	-	221 (0/221)	20.6±4.7	-	-	-	-	Prospective	Ankle & Foot 0.3 (0.1 to 0.7)	Hour Exposure
											Metatarsophalangeal Synovitis 0.1 (0.0 to 0.3)	Hour Exposure
											Achilles Bursitis 0.2 (0.0 to 0.6)	Hour Exposure
Peterson et al (2000) [106]	Soccer	3	M	398	(14-18)[h]	-	-	-	OPE	Prospective	Ankle & Foot 0.2 (0.1 to 0.3)	Hour Exposure
Nielsen et al (1989) [107]	Soccer	3	M	123 (123/0)	(≥16)	WP	-	-	OPE	Prospective	Ankle & Foot 2.7 (0.7 to 6.9)	Hour Exposure
Volpi et al (2003) [108]	Soccer	2	E	250 (250/0)	(9-19)	-	-	-	-	Prospective	Ankle & Foot [g] 6.0 (2.2 to 13.1)	Year
											Achilles Tend [g] 2.0 (0.2 to 7.2)	Year
											Sever`s disease [g] 4.0 (1.1 to 10.2)	Year
Cloke et al (2009) [24]	Soccer	2	E	14691	(9-19)	-	-	-	OPE&Ax	Retrospective	Ankle Impingement [g] $0.2x10^{-1}$ ($0.0x10^{-1}$ to $0.8x10^{-1}$)	Year
											Sever`s disease [g] 1.0 (0.8 to 2.0)	Year
											Plantar Fasciitis [g] $0.1x10^{-1}$ ($0.0x10^{-1}$ to $0.6x10^{-1}$)	Year
Le Gall et al (2006) [109]	Soccer	2	E	(0/528)	(<16)	-	-	-	-	Prospective	Achilles Tend $0.8x10^{-2}$ ($0.1x10^{-2}$ to $0.3x10^{-1}$)	Hour Exposure
											Sever`s disease $0.4x10^{-2}$ ($0.0x10^{-2}$ to $2.3x10^{-2}$)	Hour Exposure
Carling et al (2010) [110]	Soccer	2	E	-	-	WP	-	-	-	Prospective	Ankle & Foot 0.6 (0.1 to 2.2)	Hour Exposure
Muller Rath et al (2006) [111]	Soccer	1	M	70	27.3 (16-18)[e]	WP	-	-	-	Retrospective	Foot $0.3x10^{-1}$ ($0.0x10^{-1}$ to $1.8x10^{-1}$)	Hour Exposure
Dick et al (2007) [112]	Soccer	1	-	(0/-)	-	C	-	-	-	Retrospective	Achilles Tend [i] $0.7x10^{-1}$ ($0.6x10^{-1}$ to $0.9x10^{-1}$)	Exposure
Agel et al (2007) [113]	Soccer	1	-	(0/-)	-	C	-	-	-	Retrospective	Achilles Tend [i] $0.5x10^{-1}$ ($0.4x10^{-1}$ to $0.6x10^{-1}$)	Exposure
Loosli et al (1992) [114]	Softball	2	-	24 (0/24)	20 (17-23)	-	-	Gradual onset	-	Cross Sectional	Stress Fracture 41.7 (1.1 to 232.2)	Season

Authors (Year)	Sport	QS	Level	Number (M/F)	Age[a]	SM	PR (%)	Overuse Definition	AT	Design	Incidence Rate (95% CI) [b]	Expression Per 1000 Athletes
Winge et al (1989) [115]	Tennis	5	E	89 (61/28)	26.1[c] (13-48)	R	86	Developed gradually and couldn't be explained by a single trauma	-	Prospective	Ankle & Foot 56.2 (18.2 to 131.1)	Season
Maquirriain et al (2006) [116]	Tennis	3	E	139 (91/48)	20±5	PP	-	-	OPE&Ax	Retrospective	Stress Fracture [g] 28.8 (12.4 to 56.7)	Year
Bennell et al (1996) [117]	Track and Field (General)	4	E	111 (58/53)	20.3±2	PP	-	-	OPE&Ax	Prospective	Stress Fracture 63.1 (25.4 to 129.9)	Year
Alonso et al (2009) [118]	Track and Field (General)	4	E	1660	-	WP	68	-	-	Prospective	Ankle & Foot 3.9 (2.1 to 6.6)	Championship
											Achilles Tend 2.7 (1.2 to 5.1)	Championship
Alonso et al (2010) [119]	Track and Field (General)	4	E	1486	-	WP	-	Repeated micro-trauma without a single identifiable even	-	Prospective	Achilles Tend 6.1 (3.2 to 11.5)	Championship
											Stress Fracture 2.7 (0.7 to 6.9)	Championship
											Plantar Fasciitis 0.7 (0.0 to 3.7)	Championship
Watson et al (1987) [120]	Track and Field (General)	3	-	257	15.8±1.3 (14-18)	C	-	-	-	Prospective	Ankle & Foot 38.9 (18.7 to 71.6)	Season
											Achilles Tend 3.9 (0.1 to 21.7)	Season
											Tibialis Posterior Tend 31.1 (13.4 to 61.3)	Season
											Metatarsalgia 3.9 (0.1 to 21.7)	Season
Jakobsen et al (1992) [121]	Track and Field (General)	2	M	54 (43/11)	25.3 (22-28)	-	-	-	OPE	Prospective	Ankle & Foot 74.1 (20.2 to 189.7)	Season
Verhagen et al (2004) [122]	Volleyball	3	E	419 (158/261)	24.3±5.7[c]	-	26	Without a sudden event leading to injury	Q	Prospective	Ankle [j] $0.0x10^{-1}(0.0x10^{-1}$ to $0.8x10^{-1})$	Hour Exposure
Beneka et al (2007) [123]	Volleyball	2	M	649 (318/331)	23.5±5.4[c]	-	-	-	I	Prospective	Ankle & Foot $0.8x10^{-2}(0.0x10^{-2}$ to $4.3x10^{-2})$ Elite	Hour Exposure
											Ankle & Foot [j] $0.0x10^{-2}(0.0x10^{-2}$ to $5.1x10^{-2})$ Local	Hour Exposure
Zetou et al (2006) [21]	Volleyball	1	M	114 (61/53)	22.5±4.6[c]	-	10	-	I	Cross Sectional	Ankle & Foot 0.3 (0.1 to 0.5)	Hour Exposure
Agel et al (2007) [124]	Volleyball	1	-	(0/-)	-	C	-	-	-	Retrospective	Achilles Tend [i] $0.6x10^{-1}(0.5x10^{-1}$ to $0.7x10^{-1})$	Exposure

"-"= unclear or data missing; A= amateur; AT= assessment tool; Ax= auxiliary diagnostic tools; C= convenience; E= elite; F= female; I= interview; M= Male; M= mixed; OPE= orthopaedic physical examination PR= participation/response rate; PP= Purposive; Q= questionnaire; QS= quality score of the study; R= random; SM= sampling method; Tend= tendinopathy, tendinitis. tendinosis. WP= whole population of interest.
*= Table is sorted by the name of sports (alphabetically), the quality score (descending) and the athletic level (elite, mixed group, amateur and unclear).
a= mean ± standard deviation (range). b= the rates and 95% confidence interval (values in the parentheses) were calculated by current authors for most studies. c= pooled data calculated by current authors.
d= resulting values were estimated based on percentages in the original paper. e= mean age was reported only for senior group and age range only for junior group.f= there is a mismatch between the reported numbers in the original article. g= values are 1 year-adjusted. h= age range was only reported for the youth group. i= the data was reported in the original article. z= the incidence rate was zero.

Table 2: Prevalence rates of ankle and foot overuse injuries and details of the included studies*

Authors (Year)	Sport	QS	Level	Number (M/F)	Age[a]	SM	PR (%)	Overuse Definition	AT	Design	Prevalence Rate% (95% CI)[b]	Prevalence Type
Fahlstrom et al (2002) [125]	Badminton	5	E	66 (41/25)	23.4±4.3 (16-34)	WP	88	-	Q	Cross Sectional	Achilles Tend 3.0 (0.8 to 10.4)	5 Years
											Achilles Bursitis 6.1 (2.4 to 14.6)	5 Years
Hickey et al (1997) [26]	Basketball	2	E	49 (0/49)	-	-	-	Chronic overload		Retrospective	Ankle & Foot 32.7 (21.2 to 46.6)	6 Years
											Stress Fracture 10.2 (4.4 to 21.8)	6 Years
Pfeifer et al (1992) [126]	Basketball	2	-	473 (310/163)[d]	26.8	-	-	Chronic overload or incorrect load	Q	Cross Sectional	Ankle [f] 30.9	5 Years
Walls et al (2010) [127]	Dance (Irish)	5	E	18 (8/10)	26 (21-32)	WP	100	-	Q&Ax	Cross Sectional	Achilles Tend 7.7 (5.4 to 9.1)	Point
											Plantar Fasciitis 3.8 (2.0 to 6.1)	Point
Tuffery (1989) [71]	Dance (Morris)	4	A	149	-	WP	29	Injury aggreviated by dancing which either prevented dancing or caused considerable discomfort	Q	Cross Sectional	Ankle & Foot 0.5 (0.2 to 1.0)	1 Year
Bowling (1989) [128]	Dance (Theatrical)	3	E	141 (61/80)	(≥18)	C	75	-	Q	Cross Sectional	Ankle & Foot 1.2 (0.7 to 1.8)	6 Months
Arendt et al (2003) [57]	Dance (Ballet)	2	E	77 (35/42)	26.1 (20 - 34)[c]	-	-	Repetetive micro-trauma or overload or incorrect load	Q	Cross Sectional	Ankle & Foot 2.2 (1.4 to 3.2)	5 Years
Gosheger et al (2003) [129]	Golf	2	M	703 (510/193)	46.2±17.3	R	-	-	Q	Cross Sectional	Ankle & Foot 1.6 (0.9 to 2.8)	Sports Career
Purnell et al** (2010) [130]	Gymnastics	3	M	73 (4/69)	13.7±3.9[c] (8-26)	C	-	an injury which currently affects acrobatic gymnastics training or performance and has given you continuing problems for 3 months or more	Q	Cross Sectional	Ankle & Foot 6.8 (2.9 to 15.1)	Point
Creagh et al (1998) [131]	Orienteering	4	M	28 (0/28)	-	C	100	-	Q	Cross Sectional	Achilles Tend [g] 0.0 (0.0 to 1.2)	1 Year
Backe et al (2009) [87]	Rock-Climbing	4	M	355 (249/106)	30 (9 - 67)	R	63	Repeated micro-trauma without a single identifiable event	Q	Cross Sectional	Ankle & Foot 3.1 (1.7 to 5.5)	1.5 Years
Smoljanovic et al (2009) [132]	Rowing	3	E	398 (231/167)	18	C	67	Chronic long - lasting pain usually connected to sport activity for which the rowers could not report a specific inciting event	Q&I	Cross Sectional	Ankle & Foot 1.3 (0.5 to 2.9)	1 Year

Authors (Year)	Sport	QS	Level	Number (M/F)	Age[a]	SM	PR (%)	Overuse Definition	AT	Design	Prevalence Rate% (95% CI)[b]	Prevalence Type
Jacobs et al (1986) [133]	Running	5	M	451 (355/96)	33.5 (8 - 64)[c]	R	87	-	Q	Cross Sectional	Achilles Tend 2.9 (1.7 to 4.9)	2 Years
											Plantar Fasciitis 2.4 (1.4 to 4.3)	2 Years
Marti et al (1988) [134]	Running	5	-	4358 (4358/0)	(≥17)	WP	84	-	Q	Cross Sectional	Achilles Tend 2.1 (1.7 to 2.6)	1 Year
Hirschmuller et al (2010)[135]	Running	2	-	953 (656/297)	42.3±10.4 (18-73)	-	-	-	Ax&I	Cross Sectional	Achilles Tend 33.1 (30.1 to 36.1)	Point
Barrow et al (1988) [136]	Running	2	-	241 (0/241)	-	-	-	-	Q	Cross Sectional	Stress Fracture 12.9 (9.2 to 17.7)	Sports Career
Dubravcic - Simunjak et al (2006) [137]	Skating	6	E	528 (14/514)	19.4 (15 - 32)[c]	WP	100	No specific occurrence time	Q	Cross Sectional	Achilles Tend 2.8 (1.7 to 4.6)	Sports Career
											Plantar Fasciitis 2.7 (1.6 to 4.4)	Sports Career
											Ankle Impingement 1.9 (1.0 to 3.5)	Sports Career
Pecina et al (1990) [138]	Skating	2	E	42	-	-	-	-	Q	Cross Sectional	Stress Fracture 16.7 (8.3 to 30.6)	Sports Career
Cloke et al (2009) [24]	Soccer	2	E	14691	(9 - 19)	-	-	-	OPE&Ax	Retrospective	Sever`s Disease 0.6 (0.5 to 0.7)	6 Years
											Ankle Impingement $0.1x10^{-1}$ ($0.3x10^{-2}$ to $0.4x10^{-1}$)	6 Years
											Plantar Fasciitis $0.6x10^{-2}$ ($0.1x10^{-2}$ to $0.3x10^{-1}$)	6 Years
Muller Rath et al (2006) [111]	Soccer	1	M	70	27.3 (16 - 18)[e]	WP	-	-	-	Retrospective	Foot 1.4 (0.3 to 7.7)	1 Year
Hill et al (2004) [139]	Softball	2	-	181 (0/181)	(18 - 26)	-	18	-	Q	Cross Sectional	Ankle 1.7 (0.6 to 4.8)	1 Year
Kuhne et al (2004) [140]	Tennis	1	M	110 (86/24[d])	37.5[c] (16 - 68)	-	-	-	Q	Prospective	Achilles Tend 3.6 (1.4 to 9.0)	2 Years
											Plantar Fasciitis 3.6 (1.4 to 9.0)	2 Years
Longo et al (2009) [141]	Track and Field (General)	3	E	178 (110/68)	53.2±10.9 (35 - 94)[c]	C	3	-	Q	Cross Sectional	Achilles Tend 4.7 (4.0 to 5.5)	Point
Collins et al (1989) [142]	Triathlon	3	M	257 (197/60)	32	-	45	-	Q	Cross Sectional	Ankle 10.5 (7.3 to 14.9)	1 Year
											Plantar Fasciitis 3.9 (2.1 to 7.0)	1 Year
O`Toole et al (1989) [7]	Triathlon	3	M	95 (75/20)	35.2[c]	-	9	-	Q	Cross Sectional	Ankle & Foot [f] 61	1 Year
Manninen et al (1996) [143]	Triathlon	2	M	92 (70/22)	31.3±7.4 (19 - 56)	C	55	-	Q	Cross Sectional	Ankle & Foot 18.5 (1.1 to 2.7)	1 Year

Authors (Year)	Sport	QS	Level	Number (M/F)	Age[a]	SM	PR (%)	Overuse Definition	AT	Design	Prevalence Rate% (95% CI)[b]	Prevalence Type
Migliorini (1991) [23]	Triathlon	1	E	24	26±5	-	-	-	-	-	Achilles Tend 8.3 (2.3 to 25.8)	4 Year s
											Plantar Fasciitis 8.3 (2.3 to 25.8)	4 Year s
											Sesamoiditis 4.2 (0.7 to 20.2)	4 Years
Zetou et al (2006) [21]	Volleyball	1	M	114 (61/53)	22.5±4.6[c]	-	10	-	I	Cross Sectional	Ankle & Foot 7.9 (4.2 to 14.3)	5 Years

"-" = unclear or data missing; A= amateur; AT= assessment tool; Ax= auxiliary diagnostic tools; C= convenience; E= elite; F= female; I=interview; M= male; OPE= orthopaedic physical examination; PR= participation/response rate; Q= questionnaire; QS= quality score of the study; R= random; SM= sampling method; WP= whole population of interest; Tend= tendinopathy, tendinitis, tendinosis.

*= Table is sorted by the name of sports (alphabetically), the quality score (descending) and the athletic level (elite, mixed group, amateur and unclear).

**= The only study with sample size calculation.

a= mean ± standard deviation (range); b= the rates and 95% confidence interval (values in the parentheses) were calculated by current authors for most studie; c= pooled data calculated by current authors; d= resulting values were estimated based on percentages in the original paper; e= mean age was reported only for senior group and age range only for junior group; f= the data was reported in the original article;.g= the prevalence rate was zero.

2

Four studies presented the number of injuries in percentage [72,82,120,121], and for these studies calculations were performed based on number estimation by the authors of the current paper. In addition incidence rates were year-adjusted for seven studies [24,26,72,82,102,108,116]. The highest incidence of ankle and foot injury, expressed per 1000 athletes per season, were reported for sports dance (ballet), 338.5 (95% CI: 283.2 to 401.4); running, 250.0 (95% CI: 100.5 to 515.1); and gymnastics, 188.7 (95% CI: 90.5 to 347.0). The highest incidence of ankle and foot injury, expressed per 1000 athletes per year, were reported for orienteering, 381 (95% CI: 217.7 to 618.6); gymnastics, 380.0 (95% CI: 228.8 to 593.4); and dance (theatrical), 261.5 (95% CI: 198.0 to 338.8).

The highest incidence, expressed per 1000 athlete per hour exposure, were reported for soccer, 2.7 (95% CI: 0.7 to 6.9); and rugby, 1.3 (95% CI: 0.8 to 1.9 game). The overall 1-year prevalence rate was reported in three sports: dance, 0.5% (95% CI: 0.2 to 1); rowing, 1.3% (95% CI: 0.5 to 2.9); and two studies of triathlon with 18.5% (95% CI: 1.1 to 2.7) and 61% (95% CI could not be calculated due to lack of data). Two studies reported an overall prevalence for 5 years in dance (Morris), 2.2% (95% CI: 1.4 to 3.2) and volleyball 7.9% (95% CI: 4.2 to 14.3).

In total 54,851 athletes were investigated with an age range of 8 to 94 years. The mean age was 29.2. The minimum and maximum of sample sizes were 17 and 14,691 athletes respectively. Participation rates varied from 3% to 100%. Different overuse case definitions were used; gradual or insidious onset of symptoms (18 studies), injury without a known trauma (12 studies), injury caused by repetitive micro-trauma or movements (5 studies) and chronic overload or pain (4 studies). Definitions for some studies were unique and study-specific.

In some studies only the overall number of injuries was reported without specifying a diagnosis (28 studies for ankle and foot, four studies only for ankle and two studies only for foot). Specific diagnosis was reported in 31 (35%) studies. In 24 (27%) studies both the overall number of injuries (ankle and/or foot) and the diagnosis (one or more) were presented. Achilles tendinopathy was the most frequently investigated injury in 39 (44%) studies (15 sports, mostly running and soccer). Tendinopathy of other ankle and foot muscles were also investigated commonly: toe extensors and flexors (7 studies), tibialis anterior and posterior (5 studies) and peroneals (5 studies). Stress fracture and plantar fasciitis were the next commonly studied injuries in 16 and 14 sports respectively, stress fracture mostly in basketball and plantar fasciitis in running. Due to heterogeneity across studies in terms of population characteristics, overuse definitions, assessment tools and sampling methods, data pooling and a meta-analysis were not possible.

DISCUSSION

Meta-analysis and meaningful comparisons within and between sports were not possible because of heterogeneity in definitions, assessment tools and various exposure expressions. Incidence and prevalence rates ranged considerably across studies. In three studies on gymnastics [18,19,77], incidence rates of the ankle and foot overuse injuries per 1000 athlete-year ranged from 17.4 to 380.0 meaning 22-fold difference in values. Since the exposure time period is the same for mentioned studies, such big differences in injury rates can only be explained by the influence of different clinical and methodological factors. For example, the investigation method was interview for the study with the highest incidence rate while for the other studies the method was unclear. Clinically, the study population in the study with the highest incidence rate was young, elite female gymnasts. In the study with the lowest incidence rate, the population consisted of mixed group of male and female gymnasts with higher mean age and of both elite and amateur level. Likewise, incidence rates per 1000 athlete-season for two other studies on gymnastics [75,76] varied with 8-fold difference from 23.8 to 188.7. The method of investigation for the higher incidence rate was unclear and for the lower rate orthopedic physical examination and auxiliary methods were used. Thus, bias due to unknown method of assessment should be considered. The broad range in rate estimation was also present in prevalence studies with the same study period. For instance in two studies on triathlon [7,143], with one year study period, the prevalence was 18% in one study and 61% in the other. For these two studies investigation method, skill level, age and gender of population were similar but overuse definition was unclear. Thus, bias due to the unclear definition of overuse should be considered. In short comparing and interpreting data is meaningless, without considering the uniformity in definitions or method of data collection.

In this review Achilles tendinopathy, plantar fasciitis and stress fracture were the most commonly reported injuries. Soccer (19 studies), running (10 studies), gymnastics (6 studies) and dancing (6 studies) made up almost half of the studies on ankle and foot overuse injuries. These findings are not surprising because ankle and foot overuse injuries are more likely to happen in sports which have a repetitive component of the lower extremity, running, or sports with complex movements, soccer and gymnastics. Overuse injuries usually have a chronic nature. Thus, to quantify the impact of overuse injuries (disease burden), prevalence is more suitable than incidence [9]. In this review only 26 studies reported prevalence and from these studies only two reported the point prevalence which is less prone to recall bias, than period prevalence especially for the longer periods.

2

When comparing injury incidence, format of the athlete exposure time is an important factor because different conclusions can be drawn from different formats [144]. Rate expressions in years or seasons do not provide detail about the actual amount of time that athlete has been exposed. The most appropriate method to express the incidence rate is to report exposure per hour or minute [41,145]. However, since these reporting methods might not be appropriate in all sports, it is recommended to report rates using multiple denominators [146]. Reporting rates using multiple denominators will allow for greater inter- and intra-sport comparisons and study of the exposure as a risk factor for sports injuries.

In this review 24 (27%) studies (mostly soccer and rugby) reported the rates per athlete-hour exposure. This promising trend in studies on soccer and rugby indicates the feasibility of collecting exposure data in hour despite its difficulties. We encourage researchers in other sports areas to use the same approach.

Forty two percent of studies focused on elite athletes. Only four papers (4%) focused on amateur groups, thus data on amateur groups is very scarce. Insufficient information on level of amateur sports does not allow comparing injury rates between amateur and professional groups to assess sports level as a factor in developing overuse injuries.

Methodological information was missing or provided poorly in most studies. Lack of adequate description of population characteristics, sampling method and participation rate makes it impossible to generalize results to relevant populations. Furthermore, since the internal validity of the data is strictly related to the method of investigation and definitions, any variation in these factors can affect the outcomes considerably. For example, using MRI in detecting stress fractures is more sensitive than using plain radiographs. Consequently, incidence rate of stress fracture detected with these two different tools can be different [147]. If the aim of science is to share the knowledge, poor and ambiguous reporting should be avoided. Adequate information about the exact procedure should be provided, and words such as examination or assessment without further details should be avoided. In this review some studies were excluded because the number of injuries was presented only in graphs without presenting the actual numbers. For some studies the authors of this review had to calculate incidence, prevalence and corresponding confidence intervals based on number estimation, because in the paper the percentage of injuries was reported and not the actual numbers. Classification of lower extremity parts was not consistent across studies. We recommend authors to use the Orchard Sports Injury Classification System for body classifications[148]. According to consensus statements, for soccer [149] and rugby [150], overuse injury is defined as "one caused by repeated micro-trauma without a single, identifiable event responsible for the injury". Despite this consensus, none of the included studies on rugby or soccer (published after consensus meetings) used the consensus definition. This definition was only used in rock-climbing and track & field [87,119]. However, the consensus definition is not sufficient to address all overuse injuries. In case of stress fracture, it is possible that one athlete/ researcher considers an identifiable event, one step or jump, responsible for the injury [9]. Although the term "chronic" has been widely used to address overuse injuries, it is in fact a broader term than "overuse" only. This term includes also long lasting conditions such as chronic ankle instability which is primary due to an acute traumatic incident. A consensus should be reached to avoid more confusion and diversity in definition and terminology concerning overuse injuries.

In this review the term "recurrent" was not used as a search term because it usually describes acute injuries that occur multiple times [151]. Studies with only military as research population were excluded because this population is exposed to various training programs and not restricted to sports activities only.

To our knowledge this is the first systematic review which assessed methodology of studies reporting incidence and prevalence of overuse injuries of ankle and foot in different sports. An extensive search was performed in four databases and two observers were involved in all selection and quality assessment procedures. For all stages a substantial or perfect agreement was achieved (Kappa= 0.62 to 0.90) [152]. Due to language barrier we were not able to review articles with a language other than English, Dutch and German, and hence our review is prone to selection bias. However, only 3% of the studies identified in the database search (89/3004) were included in this review. If from the papers excluded because of language barrier (21 papers) a similar percentage could be included in this review, only one study (3% of 21 papers) would be added. This additional study cannot change the overall results of this systematic review. The appraisal checklist for quality assessment was developed specifically for our research question, with an unknown validity. The criteria used were based on performing sound research, preventing selection bias, information bias, and inadequate reporting. In conclusion, meta-analysis and meaningful comparisons within and between sports with regard to ankle and foot overuse injuries are not possible at the moment. The main reasons include heterogeneity in definitions, assessment tools and exposure expressions.

PERSPECTIVE

Overuse injuries of the ankle and foot are common in athletic population. In this systematic review, we summarized available epidemiological data to provide an overview of the extent of the problem. Due to heterogeneity in methodology and study population, meaningful comparisons and robust conclusions were not possible. Moreover, reporting methods of most studies are insufficient. The methodology and data reporting methods need to be standardized in future research in this area of sports medicine.

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APPENDICES

Appendix 1: Search strategy in four databases; Medline, Embase, CINAHL and SPORTDiscus.

Appendix 2: Checklist to identify relevant information related to quality items.

Appendix 3: Overview of characteristics of the 89 included studies.

2

Appendix 1: Search strategy in for databases; Medline, Embase, CINAHL and SPORTDiscus

Database Search steps	Medline (pubmed)	Embase	CINAHL & SPORTDiscus
1	"Sports"[Mesh] OR "Athletes"[Mesh]	'sports and sport related phenomena'/exp OR 'athlete'/exp	(MH "Sports+") OR (MH "Athletes+")
2	sport OR sports OR athlete* OR runn* OR jogging OR marathon OR "track and field" OR triathlon OR dancing OR ballet OR skating OR skiing OR gymnastics OR badminton OR squash OR tennis OR basketball OR soccer OR football OR softball OR volleyball OR rugby OR baseball OR swim* OR martial arts OR aerobics	sport* OR athlete* OR runn* OR jogging OR marathon OR 'track and field' OR triathlon OR dancing OR ballet OR skating OR skiing OR gymnastics OR badminton OR squash OR tennis OR basketball OR soccer OR football OR softball OR volleyball OR rugby OR baseball OR swim* OR martial arts OR aerobics	sport* OR athlete* OR runn* OR jogging OR marathon OR 'track and field' OR triathlon OR dancing OR ballet OR skating OR skiing OR gymnastics OR badminton OR squash OR tennis OR basketball OR soccer OR football OR softball OR volleyball OR rugby OR baseball OR swim* OR martial arts OR aerobics
3	1 OR 2	1 OR 2	1 OR 2
4	"Athletic Injuries"[Mesh] OR "Ankle Injuries"[Mesh] OR "Foot Injuries"[Mesh] OR "Foot Diseases"[Mesh] OR "Sprains and Strains"[Mesh] OR "Fractures, Stress"[Mesh] OR "Bursitis"[Mesh] OR "Tendinopathy"[Mesh] OR "Compartment Syndromes"[Mesh] OR "Foot Deformities"[Mesh] OR "Nerve Compression Syndromes"[Mesh] OR "Joint Instability"[Mesh] OR Pain[Mesh]	'sport injury'/exp OR 'ankle injury'/exp OR 'foot injury'/exp OR 'foot disease'/exp OR 'sprain'/exp OR 'repetitive strain injury'/exp OR 'stress fracture'/exp OR 'bursitis'/exp OR 'tendinitis'/exp OR 'compartment syndrome'/exp OR 'foot malformation'/exp OR 'nerve compression'/exp OR 'joint instability'/exp OR 'pain'/exp	(MH "Athletic Injuries") OR (MH "Ankle Injuries+") OR (MH "Foot Injuries+") OR (MH "Foot Diseases+") OR (MH "Sprains and Strains+") OR (MH "Fractures, Stress") OR (MH "Bursitis+") OR (MH "Tendinopathy+") OR (MH "Compartment Syndromes+") OR (MH "Foot Deformities+") OR (MH "Nerve Compression Syndromes") OR (MH "Joint Instability") OR (MH "Pain+")
5	injur* OR "cumulative trauma disorders" OR overuse OR chronic OR "repetitive trauma" OR "plantar fasciitis" OR "heel pain" OR "heel sP" OR metatarsalgia OR sprain OR strain OR "stress fracture" OR bursitis OR tendinopathy or tendinitis OR tendonitis OR "compartment syndrome" OR "foot deformity" OR impingement OR " nerve entrapment" OR "morton neuroma" OR "neuropath*" OR instability OR pain OR sesamoiditis	injur* OR 'cumulative trauma disorders' OR 'overuse' OR 'chronic' OR 'repetitive trauma' OR 'plantar fasciitis' OR 'heel pain' OR 'heel sP' OR 'metatarsalgia' OR 'sprain' OR 'strain' OR 'stress fracture' OR 'bursitis' OR 'tendinopathy' OR 'tendinitis' OR 'tendonitis' OR 'compartment syndrome' OR 'foot deformity' OR 'impingement' OR 'nerve entrapment' OR 'morton neuroma' OR neuropath* OR 'instability' OR 'pain' OR 'sesamoiditis'	injur* OR 'cumulative trauma disorders' OR overuse OR chronic OR 'repetitive trauma' OR 'plantar fasciitis' OR 'heel pain' OR 'heel sP' OR metatarsalgia OR sprain OR strain OR 'stress fracture' OR bursitis OR tendinopathy OR tendinitis OR tendonitis OR 'Compartment Syndrome' OR 'foot deformity' OR impingement OR 'nerve entrapment' OR " morton's neuroma" OR neuropath* OR instability OR pain OR sesamoiditis
6	4 OR 5	4 OR 5	4 OR 5
7	"Foot Joints"[Mesh] OR "Foot"[Mesh] OR "Foot Bones"[Mesh] OR "Achilles Tendon"[Mesh]	'ankle'/exp OR 'foot'/exp OR 'achilles tendon'/exp	(MH "Foot+") OR (MH "Foot Bones") OR (MH "Achilles Tendon")
8	ankle OR foot OR feet OR heel OR metatars* OR tars* OR calcan* OR talus OR forefoot OR hindfoot OR midfoot OR toe* OR plantar OR hallux	'ankle' OR 'foot' OR 'feet' OR 'heel' OR metatars* OR tars* OR calcan* OR 'talus' OR 'forefoot' OR 'hindfoot' OR 'midfoot' OR toe* OR 'plantar' OR 'hallux'	ankle OR foot OR feet OR heel OR metatars* OR tars* OR calcan* OR talus OR forefoot OR hindfoot OR midfoot OR toe* OR plantar OR hallux
9	7 OR 8	7 OR 8	7 OR 8
10	"Epidemiology"[Mesh] OR "Epidemiology"[Subheading] OR "Morbidity"[Mesh]	'epidemiology'/exp	(MH "Epidemiology")
11	epidemiolog* OR prevalence OR incidence OR morbidity OR frequency OR survey OR pattern OR statistics	epidemiolog* OR 'prevalence' OR 'incidence' OR 'morbidity' OR 'frequency' OR 'survey' OR 'pattern' OR 'statistics'	epidemiolog* OR prevalence OR incidence OR morbidity OR frequency OR survey OR pattern OR statistics
12	10 OR 11	10 OR 11	10 OR 11
13	3 AND 6 AND 9 AND 12	3 AND 6 AND 9 AND 12	3 AND 6 AND 9 AND 12
14	Editorial[ptyp] OR Letter[ptyp] OR Review[ptyp] OR Comment[ptyp] OR Interview[ptyp]	13 AND [embase]/lim	Lim 13 to (Publication Type: Anecdote, Commentary, Editorial, Interview, Letter, Review)
15	13 NOT 14	14 NOT ([editorial]/lim OR [letter]/lim OR [note]/lim OR [review]/lim)	13 NOT 14

Mesh/MH=medical subject heading, /exp=explode, *=word truncation, lim=limit, ptyp=publication type

Appendix 2: Checklist to identify relevant information related to quality items

Research question: what is the incidence or prevalence of overuse injuries of ankle or foot in different sports?
Assessor: ………………...
Article number:
Title (first 3 words):
First author: Publication year

** To answer the questions, please draw a circle around the selected item.*

1) Which epidemiological measure is presented or can be calculated? (specifically for ankle and/or foot) a. Incidence b. Prevalence c. Both d. None (if article has been wrongly included, please specify the reason at the last row of this table)
2) What is the research design: a. Prospective Cohort b. Cross-Sectional c. Retrospective /chart review or medical record check d. Unclear
3) What is the sampling method? a. Whole population of interest b. Convenience sampling c. Random sampling d. Systematic sampling e. Cluster sampling f. Stratified sampling g. Unclear h. Other, please specify………………………..………
4) Is there a definition for overuse (Chronic) injury? a. Yes b. No
5) Is the explicit medical diagnosis of an overuse injury of ankle or foot presented? (at least one injury) a. Yes b. No
6) In what way the injuries have been investigated? (more than one answer is possible) a. Orthopaedic physical examination b. Auxiliary method: X-Ray, MRI, CT, US and Bone Scan c. Interview d. Questionnaire e. Unclear f. Other, please specify……………………….…………

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7) Is participation rate of the study reported or can be calculated? a. Yes b. No
8) Is sample size calculation has been performed? a. Yes b. No
The article should be excluded because…………………………….

Appendix 3: Overview of characteristics of the 89 included studies

Item		%*	N	Item		%*	N
Sport				Sample characteristics**			
	Soccer	21	19		Complete reporting	10	9
	Running	12	11		Incomplete reporting	90	80
	Gymnastics	8	7	Sample size			
	Dancing	7	6		<100	30	27
	Track and Field	6	5		100-500	46	41
	Basketball	5	4		>500	16	14
	Volleyball	5	4		Unclear	8	7
	Orienteering	5	4	Sample size calculation			
	Triathlon	5	4		Reported	1	1
	Other (studies with a frequency less than 4)	26	25		Unclear	99	88
Rates				Gender			
	Incidence	69	61		Both	42	38
	Prevalence	25	22		Female	15	13
	Incidence and prevalence	7	6		Male	11	10
Prevalence type					Unclear	32	28
	Point	14	4	Age mean			
	Period	86	24		Reported	44	39
	1 year	38	9		Unclear	56	50
	5 years	17	4	Age SD			
	Sports career	17	4		Reported	26	23
	2 years	8	2		Unclear	74	66
	6 years	8	2	Age range			
	6 months	4	1		Complete age range	37	33
	1.5 years	4	1		Incomplete age range	3	3
	4 years	4	1		Unclear	60	53
Incidence expression				Athletic level			
	Exposure time per 1000 athletes				Elite	42	37
	-hour	36	24		Mixed	25	22
	-year	22	15		Amateur	4	4
	-season	16	11		Unclear	29	26
	-exposure	12	8	Participation rate			
	-event (race/championship)	7	5		≥ 70%	21	19
	-week	3	2		< 70%	13	12
	-kilometre/mile	3	2		Unclear	65	58
Study design				Overuse definition			
	Prospective	54	48		Studies with a definition	37	33
	Cross-Sectional	32	28		Studies without a definition	63	56
	Retrospective	12	11	Main assessment tool			
	Ambispective	1	1		Questionnaire	35	31
	Unclear	1	1		Orthopaedic physical examination (with or without auxiliary methods)	12	11
Sampling method					Interview	5	4
	Whole population of interest	30	27		Unclear	48	43
	Convenience	20	18	Quality score			
	Random	7	6		≥ 5	19	17
	Purposive	2	2		< 5	81	72
	Unclear	40	36				

N= number of studies; *= percentage of studies, numbers may not add up to 100 per cent due to rounding; **= including size, gender and age (mean, standard deviation and range)

CHAPTER 3

Biomechanics of slow running and walking with a rocker shoe

Gait Posture. 2013;38:998-1004

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ABSTRACT

Evidence suggests a link between the loading of the Achilles tendon and the magnitude of the ankle internal plantarflexion moment during late stance of gait, which is clinically relevant in the management of Achilles tendinopathy. Some studies showed that rocker shoes can reduce the ankle internal plantarflexion moment. However, the existing evidence is not conclusive and focused on walking and scarce in running. Sixteen healthy runners participated in this study. Lower extremity kinetics, kinematics and electromyographic (EMG) signals of triceps surae and tibialis anterior were quantified for two types of shoes during running and walking. The peak ankle plantar flexion moment was reduced significantly in late stance of running (0.27 Nm/kg; $p<0.001$) and walking (0.24 Nm/kg; $p<0.001$) with the rocker shoe compared to standard shoe. The ankle power generation and plantar flexion moment impulse were also reduced significantly when running and walking with the rocker shoe ($p<0.001$). No significant changes in the knee and hip moments were found in running and walking. A significant delay of the EMG peak, approximately 2% ($p<0.001$), was present in the triceps surae when walking with rocker shoes. There were no significant changes in the EMG peak amplitude of triceps surae in running and walking. The peak amplitude of tibialis anterior was significantly increased (64.7 μV, $p<0.001$) when walking with rocker shoes. The findings show that rocker shoes reduce the ankle plantar flexion moment during the late stance phase of running and walking in healthy people.

1. INTRODUCTION

Achilles tendinopathy is common in both the general and athletic population[1, 2]. A possible explanation for this problem is that the Achilles tendon is subject to repetitive high magnitude of loads during locomotion, making it highly vulnerable to overuse tendinopathy[3].

Load management, in order to control the pain and allow tendon adaptation, plays a central role in the treatment of (Achilles) tendinopathy[4]. It has been shown that loading of the Achilles tendon is related to the magnitude of the ankle "internal plantar flexion moment" (PFM)[5]. For the sake of simplicity, if we assume terminal stance of gait as a static condition (Figure 1), the external dorsiflexion moment (ground reaction force × external moment arm) is equal to PFM (muscle force × internal moment arm). Footwear modifications such as rocker profiles (rocker shoes) affect the joint moments[6]. Biomechanically, rocker shoes with the apex proximal to metatarsophalangeal joint (Figure 2A) cause a decrease in external dorsiflexion moment arm of the ground reaction force around the ankle joint[7]. This alteration reduces the external dorsiflexion moment, and consequently results in smaller PFM around the ankle, which is mainly generated by the triceps surae (attached to the Achilles tendon)[7].

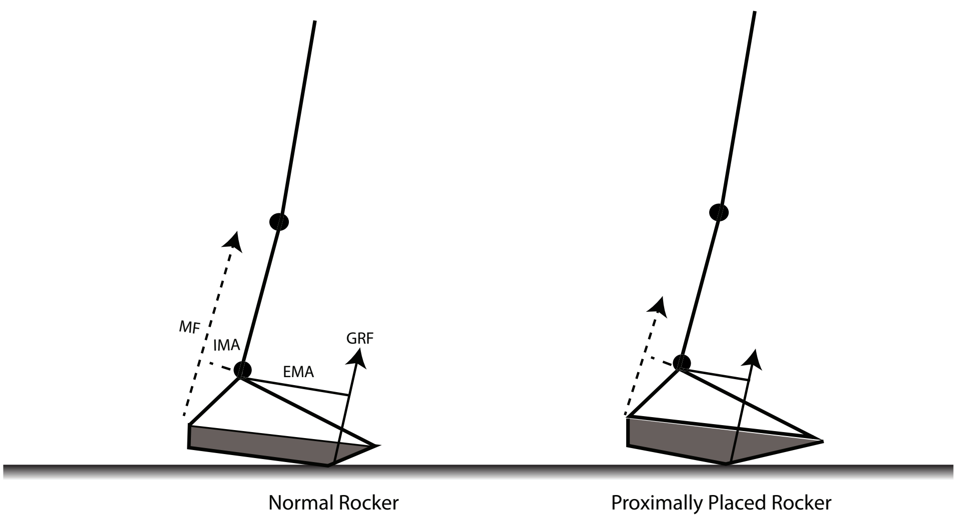

Figure 1: The effect of proximally placed rocker profile on external and internal moments around the ankle joint during terminal stance of gait. GRF = ground reaction force; EMA = external moment arm; MF = muscle force generated by triceps surae; IMA = internal moment arm.

In both running and walking as dynamic situations, the same effect (reduction in PFM during terminal stance) should be expected when using the rocker shoe. Although theoretically plausible, the body of evidence for such an effect is not sufficient to make concrete conclusions, especially considering running. In the only published study so far in slow running, the ankle PFM during terminal stance was reported to be lower for a rocker shoe (Masai Barefoot Technology, MBT®) compared to standard running shoes[8]. In walking, some studies found significant reduction in ankle PFM during terminal stance for rocker shoes compared to standard shoes[9-12], other studies found no significant differences or, at the most, small changes which were not considered clinically significant[13, 14].

The aim of this study was to further investigate the biomechanics of a custom-made special rocker shoe design (proximally placed stiffened rocker profile) in both slow running and walking, with special attention to the ankle joint moments. Firstly, we hypothesized that this type of rocker shoe would significantly reduce the ankle PFM during terminal stance. Secondly, we hypothesized that the knee and hip joint moments would increase to compensate for changes in the ankle joint moment. The primary outcome was the peak PFM during terminal stance of walking and slow running (shortly referred to as running). The secondary outcome measures included ankle PFM impulse, ankle power, ankle angles, knee and hip joint moments, and EMG (timing and amplitude) of the main ankle plantar- and dorsiflexors.

2. METHODS

2.1 Participants

For the current study we considered 10% reduction in ankle PFM as a clinically significant change for both walking and slow running. In walking this percentage change results in an amount of reduction of about 0.1 Nm/kg when using the data of Riley et al.[15]. For slow running no studies have been reported on normative data for ankle kinetics, but we expected that the relative standard deviation would not be substantially larger than in walking. Based on the power analysis,[16] a minimum of 13 subjects was necessary to provide a statistical power of 80% to detect 0.1 Nm/kg decrease in peak PFM.

To be included, runners needed to be healthy with no injury in the back, trunk or lower extremities in the 12 months preceding the study and running at least twice a week for 5km each time. A convenience sample of 16 heel-toe runners (8 females and 8 males) in the age of 20 to 50 years was recruited. The demographic information (mean ± standard deviation) was as follows: age=29±9 years, height=177.1±9.3cm, weight=69.8±11kg, body-mass index=22.1±2kg/m2 and shoe size=41±2. The experimental protocol was approved by the local Medical Ethical Committee and each subject read and signed a consent form.

2.2 Shoe condition

Twenty two pairs of standard running shoes in 11 European sizes (36 to 46) were purchased for this study. Eleven pairs remained in their original state for the baseline measurements (standard shoe, Figure 2B). The others were modified with a stiffened rocker profile (rocker shoe, Figure. 2A) by a certified orthopaedic shoe technician. The apex (rolling point) of the rocker shoes and baseline shoes were at 53% (proximal to metatarsal region)[17] and 65% of the shoe length from the heel respectively. The rocker profile thickness was 2.2±0.1cm at the apex and under the heel. Due to extra weight of rocker profiles, a pair of modified shoes was heavier than a pair of baseline shoes (depending on shoe sizes, the mass of the baseline shoes was on average 467±87g, and the mass of the rocker shoes was on average 805±157g)

Figure 2: (A) Shoe with a proximally placed rocker profile and (B) standard shoe. The black arrow indicates the apex (rolling point) of the shoe.

2.3 Study design

The design used in this study was similar to a cross-over design. Participants were asked to walk and run slowly with both the rocker shoe and the standard shoe overground in the 10-meter long gait lab. For each subject all testing procedures were completed in one session consisting of two parts. Half of the participants started with the standard shoe in the first part and continued with the rocker shoe, while for the other participants this order was reversed. The order of running and walking changed with subjects within each part, and were balanced across the order in shoes. The patients were randomly assigned to one of the eight combinations in order of shoes and tasks.

2.4 Experimental protocol

After receiving the shoes with an appropriate size, each subject was given approximately 15 minutes to walk and run to get used to the first pair of shoes (either standard or rocker). Additional familiarization was permitted, if desirable.

Subsequently, sixteen reflective markers were placed bilaterally on the following anatomical landmarks (lower body Plug-in-Gait model): the anterior superior iliac spine, posterior superior iliac spine, lateral thigh, lateral femoral epicondyle, lateral shank, lateral malleolus, second metatarsal head, and calcaneus. The markers were tracked by an eight-camera motion capture system (Vicon, Oxford, UK, f_s=100Hz) to measure the kinematics. Analog force data were measured by two force plates (AMTI; Watertown, Massachusetts, f_s=1000Hz). A wireless EMG system (Zero-wire EMG, Aurion, Italy, f_s=1000Hz) was used simultaneously to record the muscle activity from tibialis anterior (TA), lateral gastrocnemius (LG), medial gastrocnemius (MG) and soleus of both legs. Subject preparation and the position of the electrodes were according to the SENIAM guidelines for surface EMG[18]. The EMG electrodes were not removed during the entire measurement session. Before each task, subjects performed six trials at their comfortable speed, to determine their preferred average speed. To minimize the effect of speed variability on biomechanical parameters, all actual trials were required to be within ±5% of the determined average speed.[19] Speed was monitored with an iPad positioned 1.5m from the force plates using a video radar application (SpeedClock, Sten Kaiser©, version 3.1). This application was pilot tested for three subjects during slow running and walking. The calculated speed from Vicon kinematic data confirmed successful speed control for both tasks.

Subjects had to perform 7 acceptable trials for each task. Acceptable trials were those in which subjects completely hit the force plate with the preferred leg without targeting and with the appropriate speed. The preferred leg was defined as the leg that the subject would select to kick a ball with.

2.5 Data processing

Joint kinematics and kinetics were computed using VICON Nexus® software and together with EMG data exported to MatLab™ software (R2010a) to be further processed. Using MatLab, time-distance parameters were calculated. Electrode artefacts were removed from raw EMG data, with a 20 Hz high-pass filter (Butterworth, 4th order), and then rectified and smoothed with a 24 Hz low-pass filter (Butterworth, 4th order)[20]. Then, kinetics, kinematics and EMG data were scaled as a percentage of a stride (heel contact of one foot to heel contact of the same foot). All kinetic outcomes were normalized for body mass (kg).

2.6 Parameters

Calculated time-distance parameters included speed (m/s), step length (m), cadence (steps/min) and stance phase (as % of the gait cycle). For analysis, only the late stance phase of running and walking (where the peak PFM is expected) was considered Late stance was defined as 20-40% of the gait cycle for running (propulsion phase)[21] and 30-60% of the gait cycle (combined phases of terminal stance and pre-swing) for walking[22].

Evaluated kinetic parameters in the sagittal plane were ankle, knee and hip internal net joint moments (peak values during late stance) and ankle joint power (the peak positive values in late stance (generation)). We also calculated the ankle PFM “impulse” as the area under the PFM time graph (moment over time) in stance phase. The kinematic parameters included ankle peak angles in late stance and range of motion (RoM) in sagittal plane during the total gait cycle. For each muscle, the peak and time of peak occurrence (% gait cycle), were calculated from enveloped EMG signals.

2.7 Statistical Analysis

Kinetics, kinematics and EMG graphs of a representative subject as well as descriptive statistics for characteristics of the participants are provided. The results for the parameters of the seven trials were first averaged for each subject under each testing condition, leading to four average responses (running and walking with both shoe conditions) per subject. A marginal linear mixed model, using an unstructured four-dimensional variance-covariance matrix (describing the variation and correlations between the four repeated observations per subject), was fitted with SAS software, version 9.2, to the four average values per subject for each parameter separately. Type III t-tests, using Kenward-Rogers degrees of freedom, were used to determine the effect of type of shoe for running and walking separately. To correct for multiplicity, these tests were considered significant at the level of 0.025. Furthermore, the effects of type of shoe were all corrected for effects due to the part of the session (i.e. period effect in cross-over), the order in shoes, and the order of movement nested within the part of the session.

3. RESULTS

The mean and 95% confidence interval of all outcome measures, differences and statistical comparisons between two shoe conditions are presented in table 1 (running) and table 2 (walking). The ankle, knee and hip joint moments in running and walking, collected from one representative subject, are presented in figure 3. Joint angles, powers and EMG plots are presented in figures 4-6 as supplementary files (see appendices).

The linear mixed model demonstrated an order effect of shoe only for the medial gastrocnemius peak ($p=0.001$) during walking. This implies that a change in peak for the rocker shoe after wearing the standard shoe is different when the order in wearing shoes changes. Therefore, the effect of 1.08 (μV) in table 2 should be interpreted with care.

No significant differences were observed for speed, step length, cadence, and stance for running and walking ($p= 0.025$) (supplementary files). Below, the main results will be presented separately for running and walking.

3.1 Running

At the ankle joint, running with the rocker shoes caused a significant ($p<0.001$) decrease in PFM peak (0.27 Nm/kg), PFM impulse (0.04 Nms/kg) and power generation (2.28 W/kg). No significant changes in the knee and hip moments were found between two shoe conditions. The results of EMG parameters showed no change in EMG peak amplitude of triceps surae and TA between two shoe conditions. However, a significant delay was present in time of peak of MG muscle ($p=0.012$). In this study, only the ankle kinematics were assessed statistically. The results showed that while the maximum dorsiflexion was reduced significantly when wearing the rocker shoes (2.38º; $p<0.001$), the total RoM was not changed ($p=0.33$).

3.2 Walking

At the ankle joint, walking with the rocker shoes caused a significant ($p<0.001$) decrease in PFM peak (0.24 Nm/kg), PFM impulse (0.05 Nms/kg) and power generation (1.14 W/kg). The knee and hip moments were not significantly affected by the rocker shoes. While EMG peak amplitude of triceps surae muscles were not changed, a significant delay of more than 2% was present in time of peak of these muscles for the rocker shoes. Further, walking with the rocker shoes increased the peak activity of TA muscle by 20% ($p<0.001$). There were significant changes in kinematics, both maximum dorsiflexion (2.63º; $p<0.001$) and total RoM (2.64º; $p=0.011$) of the ankle were reduced when using the rocker shoes.

Table 1. Comparison of kinetics, kinematics and EMG between standard and rocker shoes during slow running

Variables	*Standard Shoe[a] [95% CI]*	*Rocker Shoe[a] [95% CI]*	*Difference [95% CI]*	*p-value[b]*
Ankle				
Moment (Nm/kg)				
Max plantarflexion	2.58 [2.35 ; 2.82]	2.31 [2.07 ; 2.54]	0.27 [0.17 ; 0.38]	**<0.001**
Moment impulse (Nms/kg)				
Plantarflexion	0.34 [0.30 ; 0.37]	0.30 [0.27 ; 0.34]	0.04 [0.02 ; 0.05]	**<0.001**
Power (W/kg)				
Max power generation	10.6 [9.09 ; 12.0]	8.29 [6.82 ; 9.77]	2.28 [1.40 ; 3.15]	**<0.001**
Angle (°)				
Max dorsiflexion	28.9 [26.9 ; 30.9]	26.5 [24.5 ; 28.5]	2.38 [1.10 ; 3.67]	**0.001**
RoM (GC)	46.7 [43.5 ; 49.9]	45.2 [42.0 ; 48.4]	1.51 [-1.75 ; 4.79]	0.333
Knee				
Moment (Nm/kg)				
Max	0.19 [0.13 ; 0.24]	0.26 [0.20 ; 0.31]	-0.07 [-0.13 ; 0.01]	0.030
Hip				
Moment (Nm/kg)				
Max	0.66 [0.55 ; 0.77]	0.65 [0.54 ; 0.76]	0.01 [-0.02 ; 0.05]	0.488
EMG				
Medial gastrocnemius				
Peak (μV)	381.7 [338.8 ; 424.5]	367.3 [324.4; 410.1]	14.3 [-6.13 ; 34.9]	0.153
Time of peak (% GC)	19.0 [17.1 ; `20.9]	20.9 [19.0 ; 22.8]	-1.89 [-3.28 ; -0.50]	**0.012**
Lateral gastrocnemius				
Peak (μV)	466.7 [358.7 ; 574.7]	468.1 [360.1 ; 576.1]	-1.40 [-71.7 ; 68.9]	0.967
Time of peak (% GC)	17.2 [15.3 ; 19.0]	18.3 [16.4 ; 20.2]	-1.12 [-2.73 ; 0.48]	0.154
Soleus				
Peak (μV)	393.6 [307.3 ; 479.8]	351.8 [265.5 ; 438.1]	41.7 [5.77 ; 77.7]	0.027
Time of peak (% GC)	17.2 [15.9 ; 18.5]	17.8 [16.5 ; 19.1]	-0.63 [-1.70 ; 0.45]	0.230
Tibialis anterior				
Peak (μV)	302.0 [229.3 ; 374.7]	329.7 [257.0 ; 402.4]	-27.7 [-60.0 ; 4.63]	0.087
Time of peak (% GC)	5.57 [1.75 ; 9.40]	4.22 [0.39 ; 8.04]	1.36 [-2.67 ; 5.39]	0.483

GC: complete gait cycle, Max: maximum, RoM: range of motion.
a Values include mean [95% confidence interval].
b The statistical significance level is set at $p < 0.025$ (marked in bold).

Table 2. Comparison of kinetics, kinematics and EMG variables between standard and rocker shoes during walking

Variables	*Standard Shoe[a][95% CI]*	*Rocker Shoe[a] [95% CI]*	*Difference [95% CI]*	*p-value[b]*
Ankle				
Moment (Nm/kg)				
Max plantarflexion	1.73 [1.63 ; 1.82]	1.49 [1.39 ; 1.58]	0.24 [0.18 ; 0.31]	**<0.001**
Moment impulse (Nms/kg)				
Plantarflexion	0.29 [0.26 ; 0.32]	0.24 [0.21 ; 0.27]	0.05 [0.03 ; 0.07]	**<0.001**
Power (W/kg)				
Max power generation	4.41 [3.95 ; 4.87]	3.31 (0.71)	1.14 [0.80 ; 1.48]	**<0.001**
Angle (°)				
Max dorsiflexion	15.9 [14.1 ; 17.7]	13.3 [11.5 ; 15.1]	2.63 [1.53 ; 3.72]	**<0.001**
RoM (GC)	27.0 [24.8 ; 29.2]	24.3 [22.1 ; 26.6]	2.64 [0.72 ; 4.55]	**0.011**
Knee				
Moment (Nm/kg)				
Max	0.28 [0.18 ; 0.37]	0.22 [0.13 ; 0.32]	0.05 [-0.01 ; 0.11]	0.085
Hip				
Moment (Nm/kg)				
Max	1.18 [1.02 ; 1.34]	1.12 [0.95 ; 1.28]	0.07 [0.00 ; -0.13]	0.042
EMG				
Medial gastrocnemius				
Peak (µV)	241.3 [206.2 ; 276.3]	240.2 [205.1 ; 275.2]	1.08 [-36.7 ; 38.8]	0.952
Time of peak (% GC)	42.0 [40.7 ; 43.3]	44.8 [43.4 ; 46.1]	-2.78 [-3.86 ; -1.71]	**<0.001**
Lateral gastrocnemius				
Peak (µV)	230.7 [170.3 ; 291.1]	221.9 [161.5 ; 282.3]	8.82 [-19.6 ; 37.2]	0.510
Time of peak (% GC)	43.5 [42.1 ; 44.9]	45.7 [44.3 ; 47.1]	-2.18 [-3.67 ; -0.69]	**0.008**
Soleus				
Peak (µV)	219.3 [166.5 ; 272.1]	222.8 [170.0 ; 275.6]	-3.57 [-21.2 ; 14.0]	0.667
Time of peak (% GC)	40.3 [35.5 ; 45.2]	42.8 [38.0 ; 47.6]	-2.46 [-4.36 ; -0.56]	**0.015**
Tibialis anterior				
Peak (µV)	326.4 [267.4 ; 385.3]	391.1 [332.1 ; 450.0]	-64.7 [-88.2 ; -41.2]	**<0.001**
Time of peak (% GC)	4.49 [3.81 ; 5.18]	5.01 [4.32 ; 5.70]	-0.52 [-1.43 ; 0.40]	0.242

GC: complete gait cycle, Max: maximum, RoM: range of motion.
a Values include mean [95% confidence interval].
b The statistical significance level is set at $p < 0.025$ (marked in bold).

3

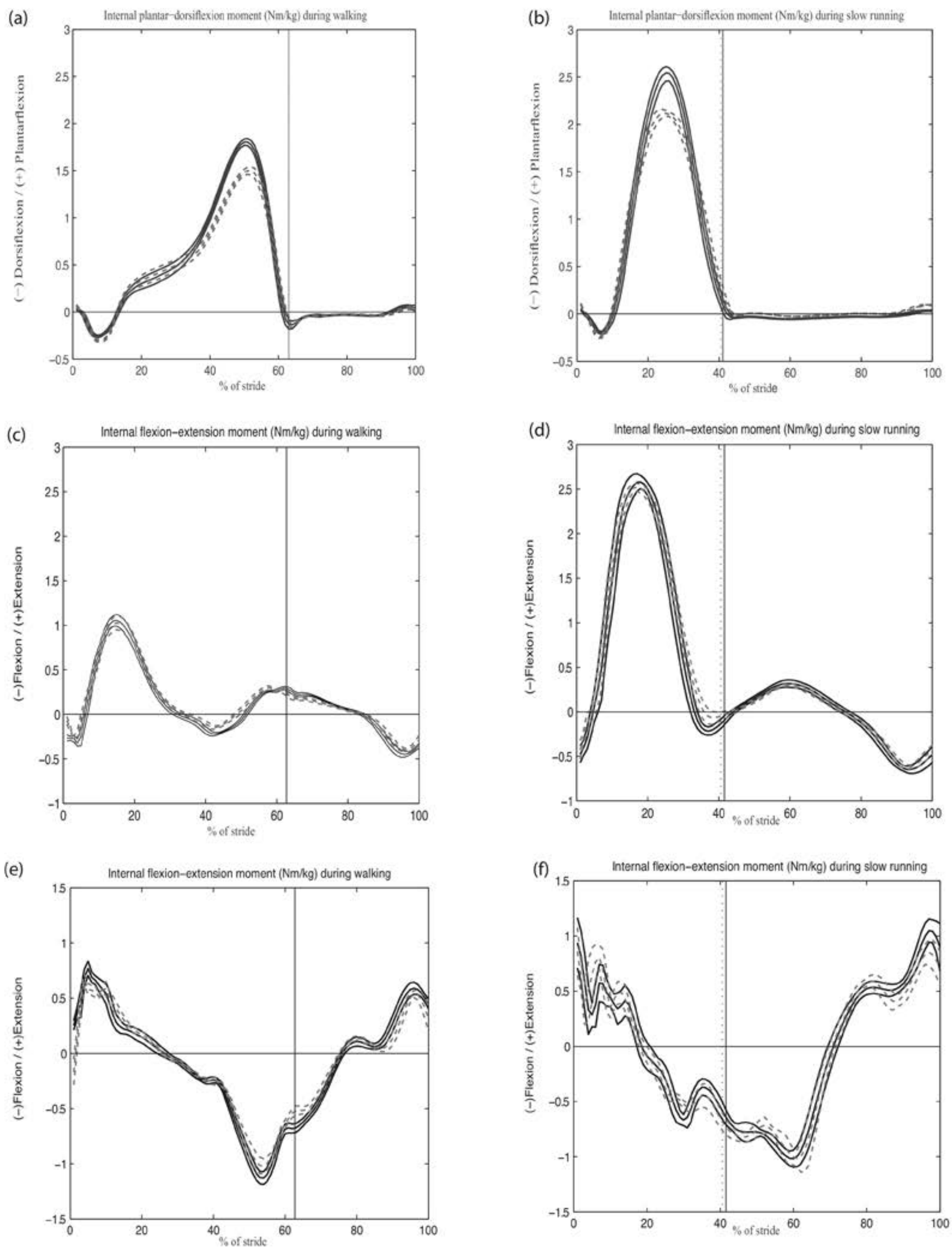

Figure 3. Sagittal plane internal joint moments of the ankle (a and b), knee (c and d) and hip (e and f) for a representative subject during walking (left graphs) and slow running (right graphs) with standard (—) and rocker shoe (- - -). Curves are mean and standard deviation of seven trials. The vertical lines indicate the toe-off. Please note that for this subject, toe-off in running with the rocker shoe occurs earlier in the gait cycle.

4. DISCUSSION

4.1 Running

This is one of the first studies investigating the effect of a rocker shoe design during slow running on lower extremity biomechanics. As hypothesized, compared to standard shoes running with rocker shoes caused a considerable reduction in the ankle PFM during terminal stance phase of running. The ankle PFM peak and impulse were respectively reduced by 0.27 Nm/kg and 0.04 Nms/kg, which means more than 10% reduction in these parameters. These findings are similar to a previous study on MBT shoe, where 12% decrease in ankle peak PFM was found in running[8].

During the propulsive phase of running the Achilles tendon is exposed to the highest loads that can exceed eight times body weight per step[3, 23, 24]. According to the Cook and Purdam pathology continuum model, tendon pathology can roughly be divided into two stages: reactive tendinopathy/early tendon dysrepair and late tendon dysrepair/degeneration[4]. Especially in the reactive tendinopathy, treatment should be focused on load reduction which allows tendon adaptation and also helps in pain reduction[4]. Moreover, early load management in at-risk athletes can limit the progression of overuse tendinopathy[4]. Considering the direct relationship between ankle PFM and the load on Achilles tendon[25, 26], 10% reduction in ankle PFM peak and impulse in response to rocker shoes can be clinically important in the load management of Achilles tendinopathy.

Since the speed was maintained constant throughout the measurements for two shoe conditions, the propulsion force was expected to change in more proximal joints to compensate for significant decrease in ankle PFM. However, changes in the knee and hip moments were not statistically significant, and our second hypothesis could therefore not be supported. Boyer and Andriacchi[8] found similar results regarding knee and hip moments for MBT shoes in slow running. It is likely that changes occurred in joint moments and powers at the hips and knees, yet the sample size was not sufficient to detect various alterations in movement strategies. It is also possible that the timing of any compensation at the knee and hip joints may not correspond exactly with late stance intervals defined in our study. Further research is necessary to verify these possibilities.

Despite decreases in joint moments, increase in muscle activity (e.g. co-contraction) can increase the total joint loading during locomotion[14]. This study, however, showed that the reduced PFM did not coincide with systematic changes in the activity pattern of plantar and dorsiflexors with rocker shoes during running.

The apex position of the stiffened rocker sole influences the start of roll-off. The more proximal the apex is positioned, the earlier roll-off would be expected resulting in less dorsiflexion demand. This factor might have led to the reduced dorsiflexion peak angle observed for the rocker shoes in running. Based on this effect, the rocker shoe can be applied when the ankle dorsiflexion is restricted or when reduced motion is required.

4.2 Walking

Walking with rocker shoes resulted in a reduction of 13% in PFM peak and 17% in PFM impulse. Our findings (0.24 Nm/kg reduction in PFM) supported previous works in which significant reduction in peak PFM, 0.11 to 0.32 Nm/kg[9, 12, 13], was reported during late stance of walking. The differences in the amount of changes probably rely on the characteristics of the toe rocker profiles (e.g. apex position, and rocker radius) and methodology (e.g. gait speed and order of the shoes). It should be emphasized that while previously investigated shoes were different in design, all had a rocker profile in forefoot region (e.g. MBT shoes have rounded heel as well as a toe rocker), which makes the comparison reasonable.

In walking, we observed delayed peak activation for triceps surae. The same pattern was previously reported for LG when walking with MBT shoes[27]. An explanation given for this delay was the forward propulsion facilitation due to rounded sole[27]. However, since no time shift was observed in ankle moment graphs, the exact mechanism for this delay remains unknown. Moreover, there was an increase in peak activity of TA (at about 5% of the gait cycle) when walking with the rocker shoes. This possible side-effect of rocker shoes warrants further investigation.

4.3 Strength and limitations

In the current study, seven trials were obtained from each subject, as it is recommend for running[28], to increase the reliability of kinetics and kinematics measurements within subject. In the previous study only three trials were obtained[8].

Since variability in running and walking speed can significantly influence the kinetics parameters such as joint moments[19], we controlled the running and walking speed. This issue was not considered in any of previous studies reporting kinetic data of running and walking with rocker shoes. The results of current study rules out strong carry-over effects for studied parameters (except medial gastrocnemius EMG) when comparing the rocker shoes to standard shoes in a single session (not investigated by previous studies)[8-10, 12, 13, 29]. A limitation of this study was the extra mass of the rocker shoes compared to standard shoes. In this study we only focused on the stance phase of gait. Compared to swing phase, the effect of extra mass of the foot segment on gait dynamics is minimal in stance[30]. If the swing phase of gait is investigated in future research, this issue should be considered. Another limitation was the short adaptation time the participants had with the rocker shoes. The current study only assessed the short-term effects of rocker shoes. The long term effects and faster running speeds should be investigated in future studies. Runners in this study were heel striker, so the results do not account for midfoot/toe runners.

4.4 CONCLUSION

Shoes with a toe rocker profile cause a significant reduction in PFM in late stance of both slow running and walking, without systematic changes in the knee and hip joint moments. This biomechanical effect of rocker shoes might play a role in the management of Achilles tendinopathy. Further studies are warranted to assess the biomechanical and clinical effectiveness of rocker shoes in patients with Achilles tendinopathy.

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CONFLICT OF INTEREST

No sources of funding were used in the preparation of this article, and the authors have no conflicts of interest in this work.

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Appendices

Appendix 1:

Figure 4. Sagittal plane joint angles of the ankle, knee and hip

Appendix 2:

Figure 5. Sagittal plane joint powers of the ankle, knee and hip

Appendix 3:

Figure 6. EMG profiles of medial gastrocnemius, lateral gastrocnemius, soleus and tibialis anterior

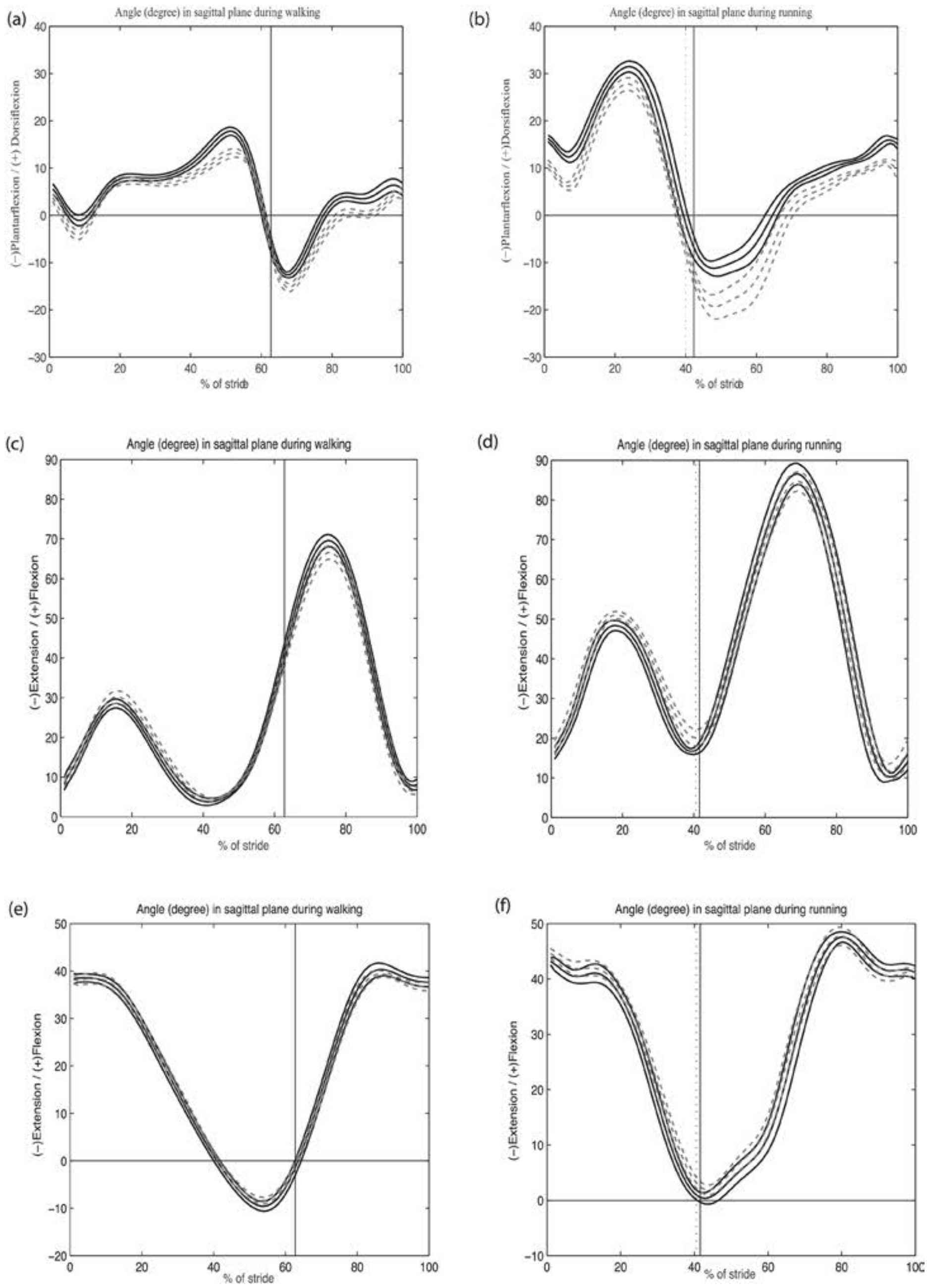

Figure 4. Sagittal plane joint angles of the ankle (a and b), knee (c and d) and hip (e and f) for a representative subject during walking (left graphs) and slow running (right graphs) with standard (—) and rocker shoe (- - -). Curves are mean and standard deviation of seven trials. The vertical lines indicate the toe-off. Please note that for this subject, toe-off in running with the rocker shoe occurs earlier in the gait cycle.

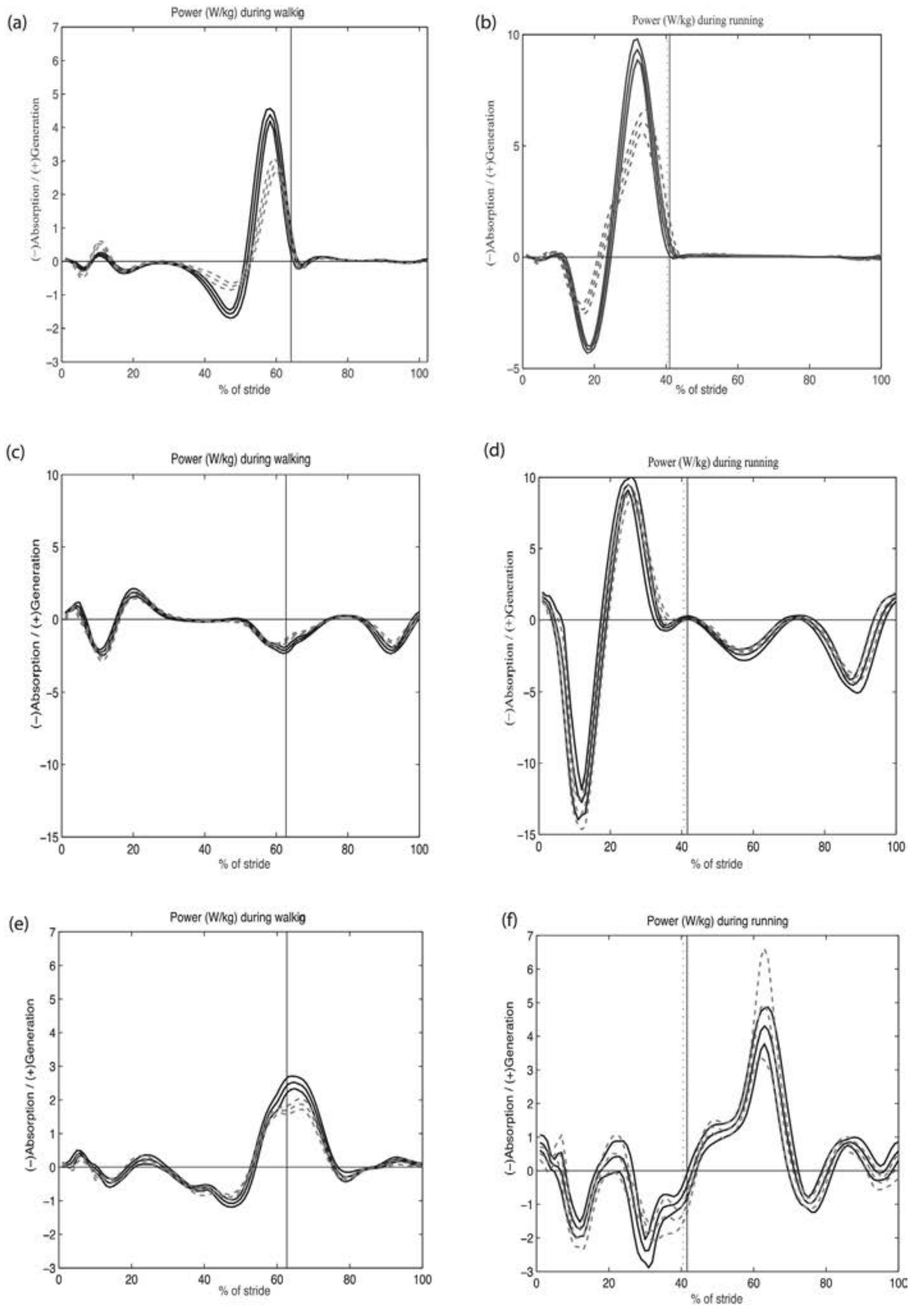

Figure 5. Sagittal plane joint powers of the ankle (a and b), knee (c and d) and hip (e and f) for a representative subject during walking (left graphs) and slow running (right graphs) with standard (—) and rocker shoe (- - - -). Curves are mean and standard deviation of seven trials. The vertical lines indicate the toe-off. Please note that for this subject, toe-off in running with the rocker shoe occurs earlier in the gait cycle.

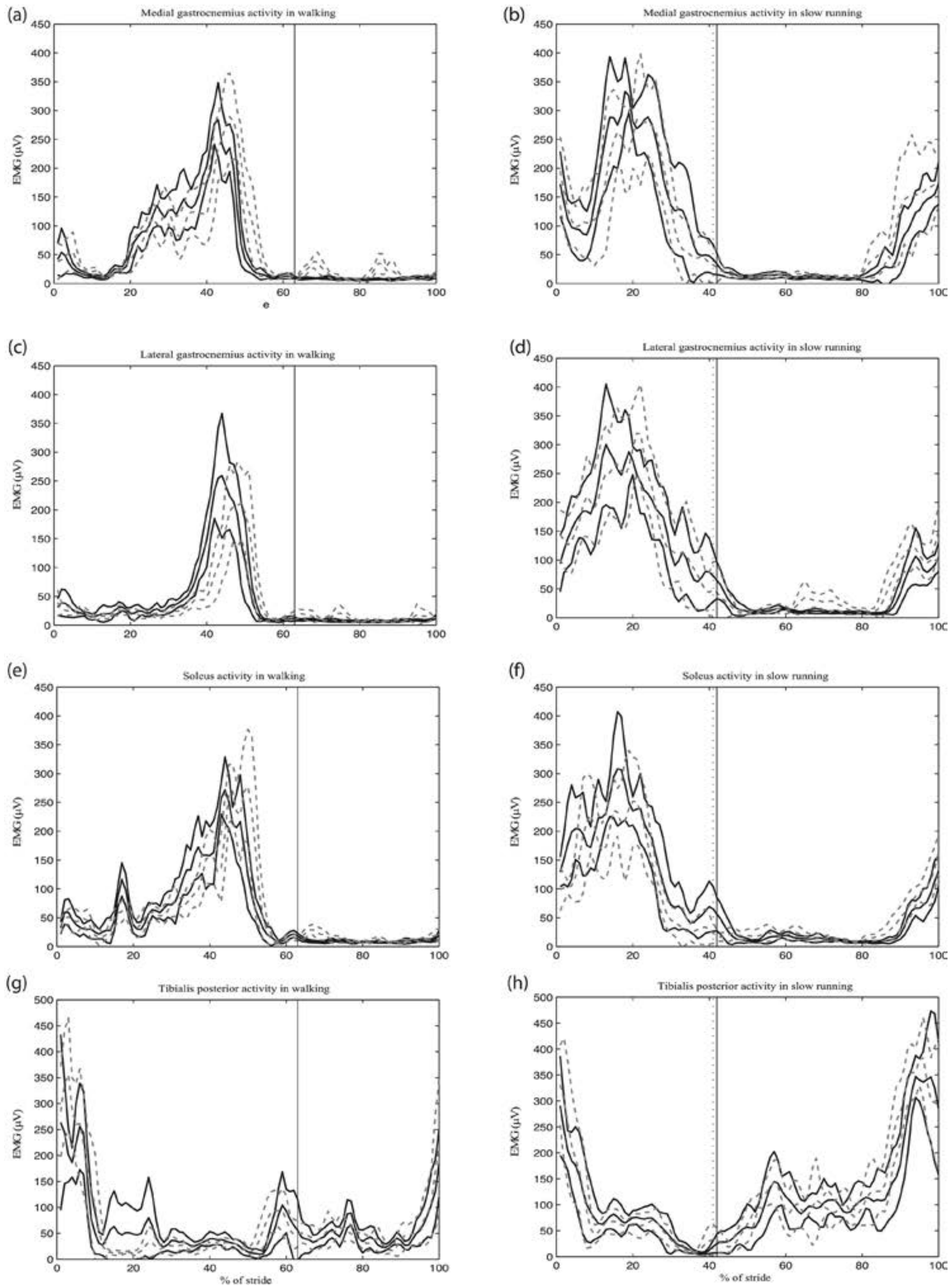

Figure 6. EMG profiles of medial gastrocnemius (a and b), lateral gastrocnemius (c and d), soleus (e and f) and tibialis anterior (g and h) for a representative subject during walking (left graphs) and slow running (right graphs) with standard (—) and rocker shoe (- - - -). Curves are mean and standard deviation of seven trials. The vertical lines indicate the toe-off. Please note that for this subject, toe-off in running with the rocker shoe occurs earlier in the gait cycle.

CHAPTER 4

Biomechanics of running and walking with a rocker profile shoe in chronic symptomatic Achilles tendinopathy

Submitted.

Sobhan Sobhani, Johannes Zwerver, Edwin van den Heuvel, Klaas Postema, Rienk Dekker and Juha Hijmans

ABSTRACT

Background: Relative rest and pain relief play an important role in the management of symptomatic Achilles tendinopathy, and might be achieved by reducing the load on the Achilles tendon. Previous studies have provided evidence that rocker shoes are able to decrease the peak ankle internal plantar flexion moment during the terminal stance phase of running and walking. Since this ankle moment is related to the Achilles tendon loading, rocker shoes might be considered in the conservative management of Achilles tendinopathy. So far, no studies have been published investigating the biomechanics of running and walking in patients with Achilles tendinopathy wearing a rocker shoe. *Purpose:* To investigate the differences in biomechanics of running and walking of Achilles tendinopathy patients wearing normal vs. rocker shoes. *Study Design*: Cross-over. *Methods:* Thirteen patients (mean age 48±14.5 years) underwent three-dimensional gait analysis wearing standard running shoes and rocker shoes during running and walking. Surface electromyography (EMG) of triceps surae and tibialis anterior was recorded simultaneously. The level of pain during the test procedure was also assessed using a 10-point scale. A linear mixed model was used to analyze data. *Results:* Patients had symptoms for an average of 22.5 months and VISA-A scores were on average 54 .With the rocker shoes, plantar flexion moment was reduced by 13% in both running ($p<0.001$) and walking ($p<0.001$). The peak hip flexion moment was significantly ($p=0.019$) lower with the rocker shoe in walking (8%). The peak activity of tibialis anterior was increased by 35% ($p=0.015$) for the rocker shoes in walking. Neither EMG peak amplitudes of triceps surae nor the Achilles tendon pain significantly differed between two shoe sessions in both activities. *Conclusions:* When used by patients with chronic Achilles tendinopathy, rocker shoes cause a significant reduction in peak plantar flexion moment in the late stance phase of running and walking without substantial adaptations in knee and hip moments and lower leg muscular activity. *Clinical Relevance:* The findings of this study suggest that rocker shoes reduce the load to the Achilles tendon in chronic AT patients, and could therefore play a role in the management of symptomatic Achilles tendinopathy.

INTRODCUTION

Achilles tendinopathy (AT) is one of the most common overuse injuries among athletic populations.[13, 22] AT is not limited to sports activities but it is observed in the general population as well.[3] Although the multifactorial and complex etiology of AT has not been fully elucidated yet, excessive and/or repetitive load are believed to be important etiological factors.[9, 15] In line with the continuum model of tendon pathology,[2] load management plays an important role in conservative treatment of AT.

This load reduction might be achieved by wearing rocker shoes, which are proven to be effective in reducing the *ankle internal plantar flexion moment* (shortly referred to PFM hereafter) in both running and walking activities in healthy people.[1, 12, 14, 21, 23, 24] However, it is still unknown if similar results can be expected for AT patients.[1, 21]

To our knowledge, no studies have been published investigating the biomechanics of running and walking in patients with AT wearing a rocker shoe. Therefore, the purpose of this study was to extend previous research by investigating the biomechanics of slow running (referred to as running hereafter) and walking in response to a rocker shoe in AT patients, with the ultimate goal to obtain more insight into the possible role of rocker shoes in the conservative management of AT.

MATERIALS AND METHODS

Participants

Patients were recruited by one experienced sports physician (JZ) at the Sports Medicine Department at University Medical Center Groningen, the Netherlands. Physically active patients who met the following criteria were recruited: (a) unilateral tendinopathy located 2 to 6 cm proximal to the insertion of the Achilles tendon on the calcaneus, (b) pain for at least 3 months, (c) Achilles tendon abnormality objectified in ultrasound imaging, (d) VISA-A<80 [18, 19], (e) experiencing no other medical problem or pain over the last year that could interfere with normal running and walking patterns.

Eligible patients were informed about the research project by the sports medicine physician. Those who were interested were contacted afterwards by the principal investigator, received all information about the study in detail, and were invited to the lab. After informed consent patients were included. The study protocol received the approval of local medical ethical committee.

Shoe Conditions

A pair of standard running shoes was used as the baseline shoe (Figure 1-A). Another pair of the same model of shoes was modified with a stiffened rocker profile by a certified orthopaedic shoe technician (Figure 1-B). The shoes were available for patients in different sizes. The apex (rolling point) of the standard and rocker shoes were respectively at 65% and 53% (proximal to metatarsal region)[25] of the shoe length from the heel. The rocker profile thickness for different sizes was 2.2±0.1cm at the apex and under the heel. Depending on shoe sizes, the mass of a pair of standard shoes was on average 467±87g, and the mass of a pair of rocker shoes was 805±157g.

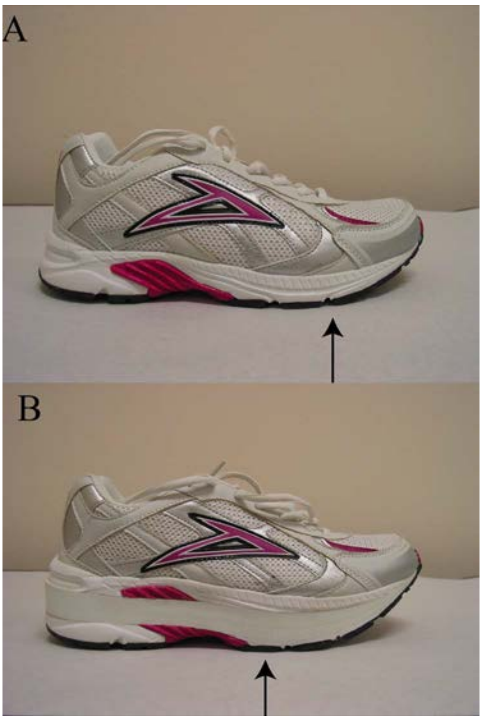

Figure 1. Investigated shoes in this study: (A) standard running shoes, and (B) rocker shoes. The black arrows indicate the shoe apex (rolling-point).

Measurement instruments

An eight-camera motion capture system (Vicon, Oxford, UK, f_s =100Hz) was used to measure the kinematics by tracking sixteen reflective markers placed bilaterally on the following anatomical landmarks (lower body Plug-in-Gait model): the posterior superior iliac spine, anterior superior iliac spine, lateral thigh, lateral femoral epicondyle, lateral shank, lateral malleolus, calcaneus and second metatarsal head. Analogue force data were measured by two force plates (AMTI; Watertown, Massachusetts, f_s =1000Hz). A wireless electromyography (EMG) system (Zero-wire EMG, Aurion, Italy, f_s =1000Hz) was used simultaneously to record the muscle activity. EMG measurements were conducted according to the SENIAM guidelines for surface EMG.[8] EMG electrodes were placed bilaterally on lateral gastrocnemius, medial gastrocnemius, soleus and tibialis anterior muscles, and they were not removed during the entire measurement session.

Experimental Protocol

The experimental procedures were conducted in a 10-meter long gait lab and lasted about two hours for each patient. The design used in this study was a type of cross-over design. For each patient all measurements, consisting of two parts (standard and rocker shoes), were completed in one session. Patients were asked to run and walk overground with the standard shoes in one part, and run and walk with the rocker shoes in another part. The order of activities (running and walking) and shoes (standard and rocker) were randomly assigned to patients trying to maintain a balance in the number of patients for the eight different orders.

Patients were given 15 minutes to get accustomed to each kind of shoes. Additional familiarization was permitted, if desirable. After instrumentation, each patient was asked to perform six running and walking trials at their comfortable speed to determine the average speeds. To minimize the effect of speed on biomechanical parameters, all actual trials were required to be within ±5% of the determined average self-selected speed.[17] Speed was monitored with an iPad positioned 1.5m from the force plates using a video radar application (SpeedClock, Sten Kaiser© Kaiser&Kaiser, version 3.1). Seven acceptable trials were required (for each shoe and activity) and were defined as those in which patients completely contacted the force plate with the injured leg with the appropriate speed and without targeting. The Achilles tendon pain were also assessed using a 10 points scale (0 no pain, 10 extreme pain) immediately after each activity. The exact same procedures were followed for the second part of the session with the other shoes.

Data processing

VICON Nexus® software (Plug-in-Gait model) was used to compute joint kinematics and kinetics, and together with EMG data were exported to MatLab™ software (R2010a) for further processing. The time-distance parameters were calculated using MatLab. Moreover, electrode artefacts were removed from raw EMG data, with a 20Hz high-pass filter (Butterworth, 4th order), and then rectified and smoothed with a 24 Hz low-pass filter (Butterworth, 4th order).[6] Then, kinetics, kinematics and EMG data were scaled as a percentage of a stride (heel contact of one foot to heel contact of the same foot). Kinetic variables were all normalized for body mass.

Outcome variables

Sagittal plane kinetic and kinematic variables were assessed in the late stance (LS) phase of running and walking. LS was defined as 20-40% of the gait cycle for running (propulsion phase),[4, 11] and 30-60% of the gait cycle (combined phases of terminal stance and pre-swing) for walking.[16]

The primary outcome was peak PFM, and all other variables were secondary. PFM impulse (the area under the PFM time graph), ankle power generation (the peak positive values in late stance), and peak knee and hip flexion moments were other kinetic variables. The kinematic data were only assessed for the ankle joint and included peak angle (in late stance) and total range of motion (RoM) during the total gait cycle. For each muscle, the peak and time of peak occurrence (% gait cycle), were calculated from enveloped EMG signals. Calculated time-distance variables included speed (m/s), step length (m), cadence (steps/min) and stance phase (as % of the gait cycle). In addition, pain in the Achilles tendon region was assessed using a 10 point scale.

Statistical analysis

Descriptive statistics are presented for some of the characteristics of the study patients (PASW Statistics 18.0, SPSS, Chicago). For the biomechanical variables the results of the seven trials were first averaged for each patient under each testing condition, leading to four responses (two shoes and two activities) per patient. A marginal linear mixed model, using an unstructured four-dimensional variance-covariance matrix, was fitted with SAS software, version 9.3 (SAS Institute, Inc., Cary, North Carolina), to the four average values per patient for each parameter separately. The same statistical model was used to analyze the pain scores. Type III tests, using Kenward-Rogers degrees of freedom, were used to determine the effect of type of shoes for slow running and walking separately. To correct for multiplicity, these tests were considered significant at the level of 0.025. Furthermore, the effects of type of shoe were all corrected for effects due to the part of the session (i.e. period effect in cross-over terminology), the order in shoes, and the order of movement nested within the part of the session. A post-hoc power analysis was performed to determine the power of the observed effect sizes of the main outcome.

RESULTS

During the recruitment period, 14 patients were eligible for this study. One patient refused to participate because of time constraints, and therefore in total 13 patients (11 females and 2 males) were included. The population's characteristics (mean ± standard deviation) were as follows: age 48±14.5 years, height 172±7 cm and weight=77±14 kg. Duration of the AT ranged from 4 months to 9 years (mean 22.5 months, median 11.5 months) and VISA-A scores were 54 ± 16. For 8 patients AT was diagnosed on the right side and for 5 patients on the left side. Patients developed a symptomatic AT while participating in different sports activities: running (5 patients), body fitness (4 patients), gymnastics (1 patient), golf (1 patient), and yoga (1 patient). One patient was physically active without doing any specific sports. During slow running a heel to toe running pattern was observed for all patients.

The linear mixed model demonstrated no order effects for the shoes and activities. The mean and 95% confidence interval of all outcome variables, differences and statistical comparisons between two shoe conditions are presented in table 1 (running) and table 2 (walking). The ankle, knee and hip joint moments during running and walking, collected from one patient, are presented in figure 2. Below the main findings are presented separately for running and walking.

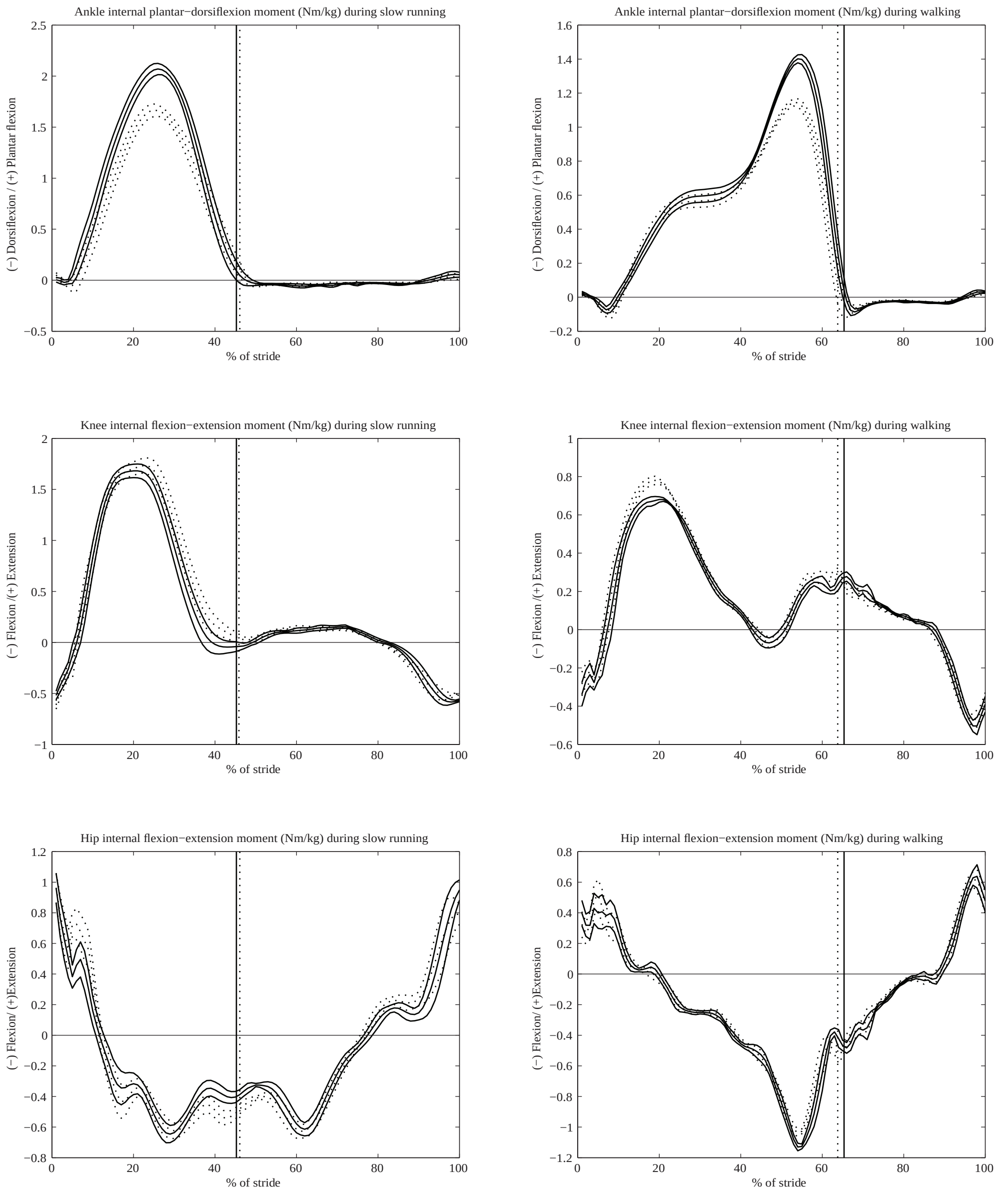

Figure 2. Sagittal plane internal joint moments of the ankle (top), knee (middle) and hip (bottom) for a male patient during slow running (left graphs) and walking (right graphs) with standard (—) and rocker shoe (---). Curves are mean and standard deviation of seven trials. The vertical lines indicate the toe-off.

Running

Running with the rocker shoes caused a significant ($p<0.001$) reduction in PFM (0.28 Nm/kg, 13%), PFM impulse (0.05 Nms/kg, 15%) and peak power generation (1.80 W/kg, 23%). The post-hoc power analysis for PFM indicated a power of 99.7%. While the ankle RoM was not affected by the rocker shoes, the dorsiflexion peak angle in LS was reduced significantly ($p<0.001$) (3.21º, 11%). No significant differences were observed in the peak knee and hip flexion moments between rocker and standard shoes in LS. The only significant changes in EMG variables in response to the rocker shoes was a delay of about 4% of the gait cycle in time of peak activity of lateral gastrocnemius ($p=0.001$).

The time-distance parameters did not differ significantly between rocker and standard shoes. There was no difference between the Achilles tendon pain between the two shoes ($p=0.845$).

Walking

Walking with the rocker shoes caused a significant ($p<0.001$) reduction in the peak PFM (0.20 Nm/kg, 13%), PFM impulse (0.06 Nms/kg, 19%) and peak power generation (0.80 W/kg, 21%). The post-hoc power analysis for PFM indicated a power of 99.9%. Walking with the rocker shoes reduced significantly ($p<0.001$) both the dorsiflexion peak angle (3.23º; 20%) and RoM (3.75º, 14%) when compared with the standard shoes.

Walking with the rocker shoes did not change the knee flexion moments in LS. The hip flexion moments however, were reduced significantly (0.09 Nm/kg, $P=0.019$). While EMG peak amplitude of triceps surae were not changed, the peak activity of tibialis anterior was increased by 35% ($p=0.015$) for the rocker shoes. The time-distance parameters did not significantly differ between rocker and standard shoes. There was no difference between, the Achilles tendon pain between the two shoes ($p=0.982$).

Table 1. Comparison of all outcome variables between standard and rocker shoes during slow running

Variables	Standard Shoe[a] [95% CI]	Rocker Shoe[a] [95% CI]	Difference [95% CI]	p-value[b]
Ankle				
Plantarflexion moment				
Peak (Nm/kg)	2.12 [1.95 ; 2.28]	1.84 [1.67 ; 2.02]	0.28 [0.16 ; 0.32]	**<0.001**
Impulse (Nms/kg)	0.32 [0.27 ; 0.35]	0.27 [0.23 ; 0.31]	0.05 [0.03 ; 0.06]	**<0.001**
Power				
Peak power generation (W/kg)	7.67 [6.75 ; 8.59]	5.87 [4.92 ;6.82]	1.80 [1.22 ; 2.38]	**<0.001**
Angle				
Max dorsiflexion (°)	28.40 [26.34 ; 30.47]	25.20 [23.10 ; 27.34]	3.21 [1.79 ; 4.64]	**<0.001**
Range of motion (°)(GC)	41.86 [37.44 ; 46.27]	41.01 [36.53 ; 45.49]	0.84 [-0.20 ;1.89]	0.100
Knee flexion moment				
Peak (Nm/kg)	0.18 [0.09 ; 0.27]	0.19 [0.11 ; 0.28]	-0.02 [-0.10 ; 0.13]	0.753
Hip flexion moment				
Peak (Nm/kg)	0.72 [0.65 ; 0.80]	0.71 [0.65; 0.78]	0.01 [-0.06 ; 0.07]	0.778
EMG				
Medial gastrocnemius				
Peak (µV)	251.10 [185.35 ; 316.86]	255.81 [190.43 ; 321.18]	-4.70 [-28.10 ;18.70]	0.670
Time of peak (% GC)	21.51 [18.90 ; 24.13]	24.08 [21.63 ; 26.54]	-2.57 [-5.68 ; 0.54]	0.094
Lateral gastrocnemius				
Peak (µV)	215.65 [155.95 ; 275.36]	237.24 [181.87 ; 292.61]	-21.59 [-90.95 ;47.77]	0.509
Time of peak (% GC)	20.51 [17.47 ; 23.56]	24.45 [21.61 ; 27.30]	-3.94 [-5.80 ; -2.09]	**0.001**
Soleus				
Peak (µV)	224.94[140.05; 309.83]	247.50 [166.92 ; 328.08]	-22.56 [-87.01; 41.90]	0.449
Time of peak (% GC)	19.52 [15.10; 23.95]	21.15 [16.98; 25.32]	-1.63 [-6.20 ; 2.94]	0.424
Tibialis anterior				
Peak (µV)	198.56 [142.57; 254.55]	228.23 [170.87; 285.59]	-29.67 [-79.96; 20.62]	0.211
Time of peak (% GC)	8.51[4.88; 12.14]	4.72 [0.69; 8.75]	3.79 [-1.46; 9.04]	0.139
Speed (m/s)	2.11 [2.00 ; 2.24]	2.08 [1.97 ; 2.20]	-0.03 [-0.04 ; 0.10]	0.387
Step Length (m)	0.86 [0.81 ; 0.91]	0.84 [0.79 ; 0.89]	0.02 [-0.03 ; 0.07]	0.349
Cadence (steps/min)	140.60 [131.27 ; 149.86]	145.31 [137.00 ; 154.00]	-4.74 [-12.30 ;2.83]	0.193
Stance (%GC)	45.6 0[43.9 ; 47.3]	44.24 [42.50 ;46.02]	1.35 [0.03 ; 2.67]	0.046
Pain (0-10)	2.83 [1.57 ; 4.09]	2.97 [1.58 ; 4.36]	0.14 [-1.82 ; 1.55]	0.845

GC: complete gait cycle, LS: late stance

[a]Values include mean [95% confidence interval]

[b]The statistical significance level is set at p< 0.025

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Table 2. Comparison of all outcome variables between standard and rocker shoes during walking

Variables	**Standard Shoe[a] [95% CI]**	**Rocker Shoe[a] [95% CI]**	**Difference [95% CI]**	**p-value[b]**
Ankle				
Plantarflexion moment				
Peak (Nm/kg)	1.55 [1.47 ; 1.63]	1.35 [1.26 ; 1.44]	0.20 [0.14 ; 0.27]	**<0.001**
Impulse (Nms/kg)	0.32 [0.29 ; 0.36]	0.27 [0.23 ; 0.30]	0.06 [0.03 ; 0.08]	**<0.001**
Power				
Peak power generation (W/kg)	3.86 [3.51 ; 4.21]	3.06 [2.68 ; 3.44]	0.80 [0.52 ; 1.08]	**<0.001**
Angle				
Max dorsiflexion (°)	15.96 [13.74 ; 18.18]	12.72 [10.42 ; 15.03]	3.23 [1.43 ; 5.04]	**<0.001**
Range of motion (°)(GC)	27.94 [25.89 ; 29.98]	24.18 [22.09 ; 26.27]	3.75 [2.06 ; 5.44]	**<0.001**
Knee flexion moment				
Peak (Nm/kg)	0.21 [0.10 ; 0.31]	0.17 [0.07 ; 0.27]	0.04 [-0.01 ; 0.08]	0.111
Hip flexion moment				
Peak (Nm/kg)	1.09 [0.96 ; 1.22]	1.00 [0.87 ; 1.13]	0.09 [0.02 ; 0.16]	**0.019**
EMG				
Medial gastrocnemius				
Peak (µV)	145.18 [99.43 ;190.94]	141.18 [94.92 ;187.44]	4.00 [-12.73 ;20.73]	0.606
Time of peak (% GC)	40.85 [39.70 ; 42.63]	40.81 [39.14 ; 42.47]	0.05 [-1.74 ; 1.83]	0.956
Lateral gastrocnemius				
Peak (µV)	120.18 [78.79 ; 161.57]	150.09 [108.50 ; 191.69]	-29.92 [-81.32 ; 21.49]	0.226
Time of peak (% GC)	41.89 [38.99 ; 44.79]	44.22 [41.54 ; 46.91]	-2.34 [-5.12 ; -0.45]	0.092
Soleus				
Peak (µV)	98.38 [36.61 ; 328.08]	143.33 [88.50 ; 198.15]	-44.95 [-132.72 ; 42.82]	0.276
Time of peak (% GC)	45.16 [40.39 ; 49.93]	45.07 [40.56 ; 49.58]	0.09 [-3.75 ; 3.93]	0.957
Tibialis anterior				
Peak (µV)	173.63[135.54 ; 211.72]	235.40 [194.87 ; 275.93]	-61.77 [-106.38 ; -17.16]	**0.015**
Time of peak (% GC)	5.25[2.83 ; 7.67]	4.16 [0.96 ; 7.37]	1.94 [-2.67 ; 3.79]	0.591
Speed (m/s)	1.41 [1.33 ; 1.49]	1.40 [1.32 ; 1.49]	0.00 [-0.05 ; 0.06]	0.920
Step Length (m)	0.75 [0.72 ; 0.78]	0.75 [0.72 ; 0.78]	0.00 [-0.01 ; 0.01]	0.715
Cadence (steps/min)	115.30 [111.11 ; 119.40]	114.10 [119.71 ; 118.40]	1.19 [-2.88 ;5.27]	0.522
Stance (%GC)	62.66 [61.77 ; 63.54]	61.92 [61.06 ;62.78]	0.74 [0.09 ; 1.39]	0.030
Pain (0-10)	2.49 [1.47 ; 3.51]	2.50 [1.40 ; 3.60]	0.01 [-1.17 ; 1.15]	0.982

GC: complete gait cycle, LS: late stance
[a]Values include mean [95% confidence interval]
[b]The statistical significance level is set at $p < 0.025$

4

DISCUSSION

To our knowledge, this is the first study that demonstrated that rocker shoes can effectively decrease PFM during running and walking in AT patients. Our findings confirm previous work in healthy people and provide additional biomechanical information to support the possible role of rocker shoe in the conservative management of patients with chronic AT.

Running

Our results showed that ankle kinetics in the sagittal plane were considerably reduced by the rocker shoes compared with the standard running shoes. Peak PFM and PFM impulse were reduced by 13% and 15% respectively, and peak power generation was 23% lower for the rocker shoes. These findings are very similar to our previous work in healthy group where peak PFM, PFM impulse and peak power generation were all reduced by more than 10% with the rocker shoes.[21] In another study with a healthy group, Boyer and Andriacchi reported a reduction of 12% in ankle peak PFM in late stance of running with MBT™ rocker shoes relative to the standard shoes.[1]

The reduced peak PFM was coincided with smaller dorsiflexion angle in late stance which was also observed in previous research.[21] These changes in ankle kinetics and kinematics were not accompanied with significant changes in knee and hip moments. Regarding EMG data, the only significant change was a delay in the peak activation of lateral gastrocnemius. Interestingly, this pattern was observed for medial gastrocnemius for healthy people.[21] Based on these initial observations, it seems that when using the rocker shoes for AT patients, biomechanical adaptations in the lower extremity are similar to the healthy population in running.

Walking

The amount of reduction in peak PFM, PFM impulse and peak power generation were respectively 13%, 19% and 21% when using the rocker shoes. These changes were very similar to what previously was observed in healthy participants (10%, 12% and 22% reduction respectively).[21]

Lack of change in knee moment and reduced ankle angle in late stance were other biomechanical observations in response to the rocker shoes which were also reported in healthy populations.[1, 21] Triceps surae were previously found to have a delay in the peak activation when healthy subjects used the rocker shoes.[21] This pattern was not observed in our patient group.

Clinical application

Load management plays an important role in conservative management of overuse tendinopaties. Load reduction might help to relieve pain and allows for tendon adaptation.[2] The Achilles tendon is highly vulnerable to overuse injuries because of the repetitive overload to which it is subjected during running and walking activities. In the propulsion phase of running, the load to the Achilles tendon (which is directly related to ankle PFM.[5, 20]) can exceed eight times body weight per step.[7, 10]

Our findings show that peak PFM can be reduced on average by more than 10% during running and walking with the rocker shoes. Considering the repetitive load on the Achilles tendon in each step of running and walking activities, this decrease in peak PFM can considerably reduce load on the Achilles tendon. Therefore, wearing rocker shoes might be useful in the management of pain in AT patients during both the early and recovery phases.

In this study, the pain was assessed to provide an initial insight into a possibly immediate effect of the rocker shoes on chronic Achilles tendon pain. Neither positive nor negative effects on pain were evident in running and walking when comparing pain levels immediately after use of the rocker shoes and standard shoes. The chronicity of the Achilles tendon pain (on average 22.5 months) might be a reason for the lack of immediate change in the pain level. Based on clinical experience, one might expect a more prominent pain relief in patients with acute reactive Achilles tendinopathy, or after prolonged use of rocker shoes in patients with more chronic degenerative tendinopathy. Future research should point out if pain will really be reduced and how long people have to use the rocker shoes before this will happen.

Although this study had enough power to detect substantial changes in ankle kinetics and kinematics, we were limited by sample size in the analysis of some of the secondary outcome measures. The current study only assessed the biomechanical adaptation to a specific rocker shoe design, and the results might differ for other rocker bottom shoe designs. In addition, the biomechanical changes in response to the rocker shoes were assessed for the sagittal plane. Because of extra height of rocker shoes and reduced sole compliance (due to rigidity) some adaptations might have occurred in the frontal plane and needs further investigations.

CONCLUSION

When used by patients with chronic Achilles tendinopathy, shoes with a proximally placed rocker profile cause a significant reduction in internal ankle peak plantar flexion moment in late stance of both slow running and walking without major adaptations in knee and hip joints moments and lower leg muscular activity. These findings suggest that rocker shoes might be useful in unloading the Achilles tendon, and therefore might play a role in the management of symptomatic Achilles tendinopathy. No immediate effect on the pain was found in a group of patients with chronic symptomatic tendinopathy. A randomized controlled trial, with pain as clinical outcome, is needed to assess the efficacy of rocker shoes in reducing pain in patients with symptomatic Achilles tendinopathy.

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CHAPTER 5

Effect of rocker shoes on plantar pressure pattern in healthy female runners

Submitted.

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ABSTRACT

Rocker profile shoes (rocker shoes) are one of the treatment options of metatarsalgia and forefoot stress fractures. The efficacy of rocker shoes in unloading the forefoot pressure has been shown in walking. In running, however, the effect of rocker shoes on forefoot pressure is unknown. Eighteen healthy female runners participated in this study. In-shoe plantar pressures were recorded during running with the standard running shoes and rocker shoes. Shoe comfort was assessed after each shoe measurement. Peak pressure (PP), maximum mean pressure (MMP) and force-time integral (FTI) were determined for seven foot areas. The effects of shoes on the different outcome variables were statistically analyzed using a linear mixed model. Running with the rocker shoes caused a significant reduction ($p<0.001$) in all pressure parameters in the central and lateral forefoot. FTI and MMP were also reduced by 11% and 12% in the medial forefoot while running with rocker shoes. Running with rocker shoes resulted in a significant increase in all pressure parameters at the heel region ($p<0.001$). Running with rocker shoes received a significant ($p<0.01$) lower comfort rate than running with standard running shoes. Rocker shoes might be beneficial for runners who are recovering from metatarsalgia or stress fractures of the forefoot region, as it reduces plantar pressure in the forefoot region.

1. INTRODUCTION

Forefoot overuse injuries such as metatarsal stress fractures and metatarsalgia are fairly common in the athletic population, especially in runners [1-3]. A potential cause of these injuries is excessive plantar pressure in the forefoot region,[4, 5] and reducing plantar pressure in this region might be an effective treatment[6-9]. This treatment goal may be achieved with shoes having a stiffened rocker profile (further called: rocker shoes) with the apex positioned proximal to the metatarsal heads[10] (Figure 1). The unloading mechanism of the forefoot region due to rocker shoes is not fully understood. Factors such as the restricted motion at the metatarsophalangeal joint and the shorter loading time at the forefoot during the propulsion phase of gait are thought to be the main mechanisms [7, 11, 12].

Figure 1. (A) Standard shoe and (B) shoe with a proximally placed rocker profile. The black arrows indicate the apex (rolling point) of the shoe.

The efficacy of rocker shoes in reducing plantar pressure loading in the forefoot region has been well documented in walking for both healthy individuals and patients with forefoot problems such as metatarsalgia [7, 11, 13-16]. So far, two studies have investigated the effects of rocker shoes on running biomechanics. The focus of these studies has been on the kinetics, kinematics and lower limb muscular activity in response to rocker shoes [17, 18]. To date, there have been no studies that have investigated the effects of rocker shoes on

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the plantar pressure pattern during running. More information in this regard gives a better understanding of the capability of rocker shoes to reduce forefoot plantar loading during running which might give direction to alternative prevention and treatment options for foot overuse injuries.

Therefore, the purpose of the current study was to examine the effect of rocker shoes on the foot plantar pressure in running. A sample of healthy female runners was chosen because a higher incidence rate of overuse injuries is reported for females [19-21]. We hypothesized that during running, the rocker shoes would significantly reduce forefoot plantar pressure when compared with standard running shoes. Secondary outcome of this research was shoe comfort, since this factor might influence the regular use of footwear.

2. METHODS

2.1 Participants

In this study, female runners were recruited from local running clubs. To be eligible, female runners needed to be between 18 to 50 years old, run at least twice per week and at least five km per run, and be healthy with no history of injuries to the back or lower limb. The experimental protocol of this research was approved by the local Medical Ethics Committee (METc 2012.014).

2.2 Shoe conditions

In this study a standard running shoe was used as the baseline condition (Figure 1-A). Another pair of these shoes (same brand and model) was modified with a stiffened rocker profile by a certified orthopaedic shoe technician to be used as the rocker shoe condition (Figure 1-B). The apex (rolling point) of the rocker shoes and baseline shoes were respectively positioned at 53% (proximal to metatarsal region),[22] and 65% of the shoe length from the heel. The rocker profile thickness for different sizes was 2.2±0.1cm at the apex and under the heel. Due to extra weight of the rocker profiles, a pair of rocker shoes was heavier than a pair of standard shoes. Depending on shoe size a pair of standard running shoes weighed on average 541±44g, and a pair of rocker shoes weighed 858±96g.

2.3 Plantar loading assessment

In-shoe plantar pressure was measured using flexible Pedar® insoles (Pedar-X system; Novel Inc; Munich, Germany). Each insole was 1.8 mm thick and consisted of 99 pressure sensors. All insoles were calibrated by the manufacturer. The data were collected from both feet with a sampling frequency of 100 Hz and sent to a computer via Bluetooth® wireless communication.

Using the Pedar® medical professional software, the foot area was divided into seven anatomical regions (masks): heel, midfoot, medial forefoot, central forefoot, lateral forefoot, first toe, and small toes (Figure 2).

For each mask the following parameters were determined: peak pressure (PP), maximum mean pressure (MMP), and force-time integral (FTI). PP was the maximum pressure over all individual sensors within a mask and all time frames of each step. While PP takes only one value into account, MMP represents the highest average loading of all sensors within one mask during one step. MMP was calculated for each mask as follows: for each time frame the mean pressure of all sensors within a mask was calculated, and then the maximum value over frames was selected as the MMP (for each step). While the repetitive high amount of load during running is a critical factor in overuse injury development, the duration of the high loading is an important parameter too, and cannot be understood from PP and MMP. Therefore, we also included FTI, calculated as the area under the force-time curve within each mask and also for the entire foot. The reason for including FTI for the entire foot was to check whether the observed changes in the plantar pressure were caused by the footwear itself and not by other factors which can affect the total force

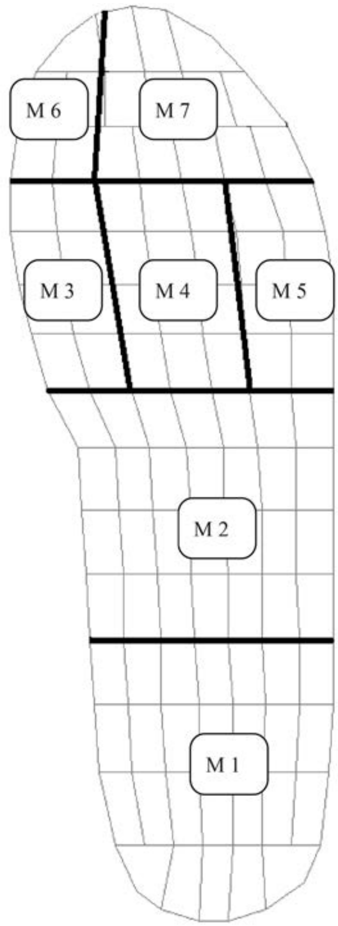

Figure 2. Seven anatomical foot regions (masks) defined in this study: M1 (heel), M2 (midfoot), M3 (medial forefoot), M4 (central forefoot), M5 (lateral forefoot), M6 (first toe), and M7 (small toes).

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during locomotion [23] (e.g. different running technique or fatigue with one shoe condition). Considering the high correlation between PP and the pressure-time integral, reporting both parameters has been suggested to be redundant [24, 25]. Hence, the pressure-time integral is not reported in the current study.

2.4 Shoe comfort assessment

After over-ground running, shoe comfort was assessed for both shoes via a Visual Analog Scale (VAS). The left endpoint of a 100 mm line was labeled as "not comfortable at all" and the right endpoint was labeled as "most comfortable imaginable". Subjects rated the overall comfort of standard and rocker shoes in running by placing a single vertical line on the scale. This method has been shown to be reliable in assessing footwear comfort during running [26].

2.5 Strike pattern and foot type classification

Since the plantar loading pattern of the foot might differ for different strike patterns and foot types, these two factors were also determined for their possible effects on the main outcome. Foot strike pattern was determined by the Strike Index (SI) [27]. This was done by assessing the location of the in-shoe center of pressure at initial contact along the longitudinal axis of the foot. The location between 33% and 67% of the foot length indicates a midfoot strike; the location proximal to 33% indicates as rearfoot strike; and the location distal to 67% indicates a forefoot strike (Figure 3). The strike pattern was assessed for both shoes. In case of variability in runners` strike pattern, after checking all steps, we considered the dominant pattern as their strike pattern. To classify the foot type (neutral, pronated, and supinated), all dominant feet were visually examined by two examiners, a physiatrist and a sports physician.

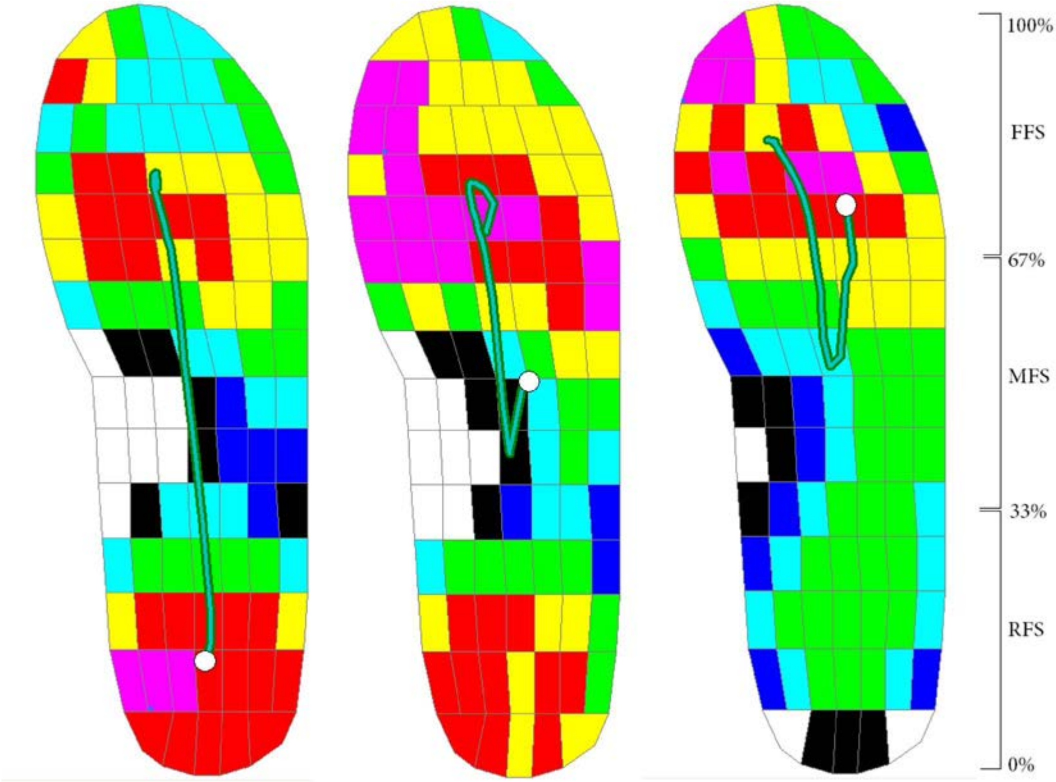

Figure 3. Center of pressure trajectory pictures obtained from the Pedar-x system. The white circles indicate the location of the center of pressure at initial contact. The picture on the right belongs to a forefoot striker (FFS), the picture in the middle belongs to a midfoot striker (MFS), and the picture on the left belongs to a rearfoot striker (RFS) They were all running with the standard shoe.

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2.6 Experimental procedure

Study design was of the crossover type. The procedures were described in detail for all participants, and each subject read and signed a consent form. First, height and weight were recorded, and subjects had 20 minutes of running on a treadmill (Valiant; Lode, B.V., Groningen, The Netherlands), to accommodate to both pair of shoes (10 minutes per shoe). Then, subjects were instrumented with the Pedar system according to the manufacturer's instructions and fitted with the first pair of assigned shoes.

Prior to the data collection, subjects performed five running trials along a 22-m runway at their comfortable speed to determine their preferred running speed. Then, during the actual trials with both shoes, running speed had to be maintained within ±5% of the determined self-selected speed to minimize the effect of speed variability on plantar loading [28, 29]. Speed was monitored using two photo-cells placed 4 meters apart in the middle of the runway. For each subject, 5 acceptable trials (within allocated speed range) were obtained for the first pair of shoes. The data were recorded for 18 meters of the runway. The shoe comfort was assessed immediately after the measurements. The same procedure was conducted for the second pair of shoes. The time between the two measurements was approximately 10 minutes, and the subjects were randomly allocated to the two sequences (standard shoe-rocker shoe; rocker shoe-standard shoe) such that the design was balanced.

2.7 Data analysis

For the analysis, only the data of the dominant foot was taken into account. The dominant foot was defined as the foot that the subject uses to kick a ball. After counting the number of recorded footfalls in each trial, the first 25% of steps (acceleration) and the last 25% of steps (deceleration) were excluded from analysis and only the steps belonging to the middle 50% of each trial (ranged from 3 to 6 steps) were considered. Values of PP, MMP and FTI were calculated for each step, and then averaged over included steps in each trial. Then the data were averaged over 5 trials of each shoe condition. The shoe comfort scores were also averaged across subjects for both shoe conditions.

Descriptive statistics were used to describe the characteristics of the population. The outcome variables were analyzed separately using a linear mixed model as the main analysis of estimating the shoe effect. Subjects were treated as random effects nested within the order of wearing shoes, and the effect of shoes was estimated when corrected for the order of wearing shoes. Type III tests were used to determine the effects of shoe and order of shoe.

As an exploratory analysis, the effects of different strike types (forefoot, midfoot or rearfoot) on the main effects of the shoes were examined. For this analysis the runners were grouped in two categories based on their running pattern with standard shoes: rearfoot strikers and forefoot/midfoot strikers. This binary factor was added to the mixed model including an interaction term with shoe type. All statistical analyses were performed using SAS software, version 9.2. The level of significance was set at $p<0.05$.

3. RESULTS

Eighteen female endurance runners between 19 and 31 years participated in this study. The demographic information (mean ± standard deviation) was as follows: age =23.6±3 years, height =171.5±6 cm, and weight=61.7±7 kg.

The mean and 95% confidence intervals for each outcome measure and the result of statistical comparisons between the two shoe conditions are presented in table 1. The analyses showed no significant order effects for any of the parameters. There was no difference between two shoe conditions for running speed (p=0.79) and FTI of the entire foot (p=0.74). The Lack of significant changes in these two later parameters indicates that the observed changes in pressure parameters are most likely due to footwear intervention than other influencing factors.

For medial, central and lateral forefoot regions, running with rocker shoes caused a significant reduction in MMP (respectively 11, 17 and 23%) and FTI (respectively 12, 17 and 28%), compared with standard shoes. The PP values were significantly reduced by 24 and 27% at the central and lateral forefoot (P<0.01), and by 11% at the midfoot region (p=0.02). Compared with standard shoes PP, MMP and FTI increased in the heel region when running with rocker shoes by 47, 22 and 52% (p<0.01) respectively. While analysis showed no changes in any parameters for the first toe region between two shoe conditions, in other toes PP was increased by 11% (p=0.03) and MMP was reduced by 14% (p<0.01) when running with rocker shoes. Running with rocker shoes received a significant (p<0.01) lower comfort rate (33.3 on VAS) than the standard shoe (76.1 on VAS).

The assessment of strike pattern showed rearfoot strike for 12 runners, and forefoot/midfoot strike for 6 runners (5 midfoot and 1 forefoot) with the standard shoes. For the rocker shoes, 13 runners had a rearfoot strike and 5 runners a midfoot strike. Exploratory analyses on strike type showed that the main effects of the rocker shoe were present in both strike types (forefoot/midfoot and rearfoot strike). The complete results of these analyses are provided in figures 4-6 (see appendices).

Of the 18 feet examined 15 feet were classified as neutral, 2 feet as slightly pronated and 1 foot as slightly supinated. There was no disagreement between examiners regarding the foot type classifications.

Table 1. Mean [95% confidence interval] results for all outcome variables

Variable	Standard shoe	Rocker shoe	*p*-value
Peak pressure (kPa)			
Heel	221.63 [179.13;264.13]	325.46 [282.96;367.95]	**<0.001**
Midfoot	160.30 [140.04;180.56]	143.13 [122.87163.38]	**0.02**
Medial forefoot	355.14 [303.47; 406.81]	325.03 [273.36;376.70]	0.09
Central forefoot	291.00 [261.15;320.85]	220.8 [190.95;250.64]	**<0.001**
Lateral forefoot	254.66 [229.40;279.91]	186.81 [161.56;212.06]	**<0.001**
First toe	324.52 [258.65;390.39]	324.93 [259.06;390.80]	0.98
Other toes	221.48 [182.27;260.69]	245.28 [206.07;284.49]	**0.03**
Maximum mean pressure (KPa)			
Heel	150.59 [126.04;175.15]	183.77 [159.22;208.32]	**<0.001**
Midfoot	83.21 [73.14;93.27]	84.66 [74.59;94.72]	0.66
Medial forefoot	226.37 [208.19;244.55]	199.53 [181.35;217.71]	**<0.001**
Central forefoot	205.40 [188.16;222.64]	154.63 [137.39;171.86]	**<0.001**
Lateral forefoot	169.99 [151.92;188.07]	121.87 [103.79;139.95]	**<0.001**
First toe	221.44 [185.37;257.52]	208.39 [172.31;244.47]	0.20
Other toes	109.79 [98.64;120.95]	94.51 [83.35;105.66]	**<0.001**
Force time integral (N.s)			
Heel	41.97 [35.41;48.52]	63.69 [57.13;70.24]	**<0.001**
Midfoot	30.34 [23.66;37.03]	33.17 [26.49;39.86]	0.14
Medial forefoot	34.00 [30.29;37.71]	30.42 [26.70;34.13]	**0.006**
Central forefoot	44.14 [39.66;48.62]	36.59 [32.12;41.07]	**0.001**
Lateral forefoot	28.51 [25.47;31.54]	22.03 [19.00;25.06]	**<0.001**
First toe	20.01 [16.51;23.51]	19.37 [15.87;22.87]	0.52
Other toes	24.78 [9.14;40.43]	31.57 [15.92;47.21]	0.52
Total foot	227.58 [210.25;244.92]	228.81 [211.47;246.14]	0.74
Shoe comfort (mm VAS)	76.11 [68.86;83.37]	33.28 [26.02;40.53]	**0.001**
Running speed (m/s)	3.40 [3.15;3.65]	3.41 [3.16;3.66]	0.79

The statistical significance level is set at $p < 0.05$ (marked in **bold**)

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4. DISCUSSION

To our knowledge, this is the first study that examined the plantar loading patterns in response to a rocker shoe design in running. As hypothesized, the plantar loading in the forefoot region was reduced considerably by the rocker shoes. PP, MMP, and FTI were significantly reduced in the central and lateral forefoot during running with rocker shoes. MMP and FTI were also reduced significantly in the medial forefoot when running with rocker shoes. The reduction in PP in the forefoot when using rocker shoes is similar to those found in walking studies (ranges 20-30%) [11-14]. PP in the medial forefoot was the only parameter not considerably affected by rocker shoes. This parameter tended to decrease, though not significantly (p=0.09). Two previous studies in walking found similar results [7, 16].

The observed effect of rocker shoes in offloading the forefoot area might be clinically important especially for runners who are recovering from metatarsalgia or a stress fracture of the forefoot region. Rocker shoes might also be helpful to reduce the risk of overuse injuries such as metatarsal stress fractures in endurance runners. Nagel et al. measured the plantar pressure of 200 marathon runners before and after a race [5]. They found a significant increase in plantar pressure at metatarsal region after the race which might explain the risk for stress fractures of metatarsals in long distance runners [5]. The findings of our study show that rocker shoes are able to decrease the load on the metatarsal region during running. Further studies in both healthy and patient groups can provide more information on the capability of rocker shoes in reducing plantar loading. A future randomized controlled trial might examine the effect of rocker shoes on overuse injuries such as metatarsalgia or metatarsal stress fractures in endurance runners.

The assessment of plantar loading in other foot regions indicated a large load transfer to the heel region, where PP, MMP and FTI were respectively increased by 47%, 22% and 52% for rocker shoes. Two studies in walking reported similar results for FTI and PP in the heel region. In these studies authors reported that compared with the standard shoes FTI values were increased by 15% [14] and 42% [11] and PP increased by 18% [11] when subjects walked with a rocker shoe. However, the exact mechanism for this load transfer to the heel region is not clear. Less cushioning caused by the stiffened sole of the rocker shoe might results in higher impact forces at initial phase of running and thereby increase load at the heel region. Two forefoot/midfoot runners changed their strike pattern towards a more posterior strike when running with the rocker shoes. This can also explain a part of elevated pressure at the heel region. In short, while the studied rocker shoes are able to reduce the forefoot pressure during running, the chance of an injury to the hindfoot might increase when using them. Further studies on the other rocker shoe designs can provide more insight into this issue.

There were also some changes in the small toes region where PP and MMP were changed in different directions; PP was increased by 10% and MMP was reduced by 14%. The increase in PP in the small toes can be a compensation for the limited propulsion force which normally provided by metatarsophalangeal joints. The reason for the decrease in MMP in this region, however, remains unclear.

Shoe comfort is one of the factors that might affect the regular use of therapeutic footwear. In this study, running with the rocker shoes received a low comfort rate compared with the standard running shoes. Some participants mentioned the mass of the shoe as a negative factor. Therefore, this factor should be taken into consideration in fabricating the rocker shoes. It is also possible that decreasing the pain of the metatarsal region by the rocker shoes outweigh the general discomfort of the shoe.

We preformed a separate exploratory analysis on strike pattern to check for possible interaction between strike type and the shoe main effects. The changes in pressure parameters for both groups (forefoot/midfoot strikers and rearfoot strikers) were similar to the findings of the primary analysis; the plantar loading at the forefoot region was significantly reduced, and at the heel region was increased irrespective of strike pattern. The increase in pressure at the heel was larger in forefoot/midfoot strikers than in rearfoot strikers when using the rocker shoe. The rocker component in the forefoot region might have changed a forefoot/midfoot striker to a rearfoot striker leading to more pressure at the heel.

The foot type of three runners deviated from neutral, two had slightly pronated feet and one had slightly supinated feet. The individual data of these participants revealed that the changes in pressure parameters in response to rocker shoes were in line with the main findings.

This study has some limitations. The results of this study are limited to the investigated rocker shoe, and should not be generalized to other rocker-bottom shoe designs. Further work on rocker shoes, with different mass and sole stiffness, will enhance the understanding of the observed drawbacks of rocker shoes such as the increase in loading of the heel and also the low comfort level during running with these shoes. In this research participants were pain-free female runners, so generalizability to other populations is unknown and needs further assessment.

5. CONCLUSION

In conclusion, the current study provide initial evidence that the shoes with a stiffened rocker profile, with the apex positioned proximal to the metatarsal region, significantly reduce the forefoot loading in running. Therefore, rocker shoes might be beneficial for runners who are recovering from metatarsalgia or stress fractures of the forefoot region. However, a load transfer to the heel region may be present as a side-effect. Moreover, running with rocker shoes was less comfortable than running with standard shoes which might affect the rate of regular use of this type of footwear.

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CONFLICT OF INTEREST

No sources of funding were used in the preparation of this article, and the authors have no conflicts of interest in this work.

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APPENDICES

Appendix 1:

Figure 4. The force-time integral (N.s) for two strike types (forefoot/midfoot and rearfoot strike).

Appendix 2:

Figure 5. The peak pressure (kPa) for two strike types (forefoot/midfoot and rearfoot strike).

Appendix 3:

Figure 6. The maximum mean pressure (kPa) for two strike types (forefoot/midfoot and rearfoot strike).

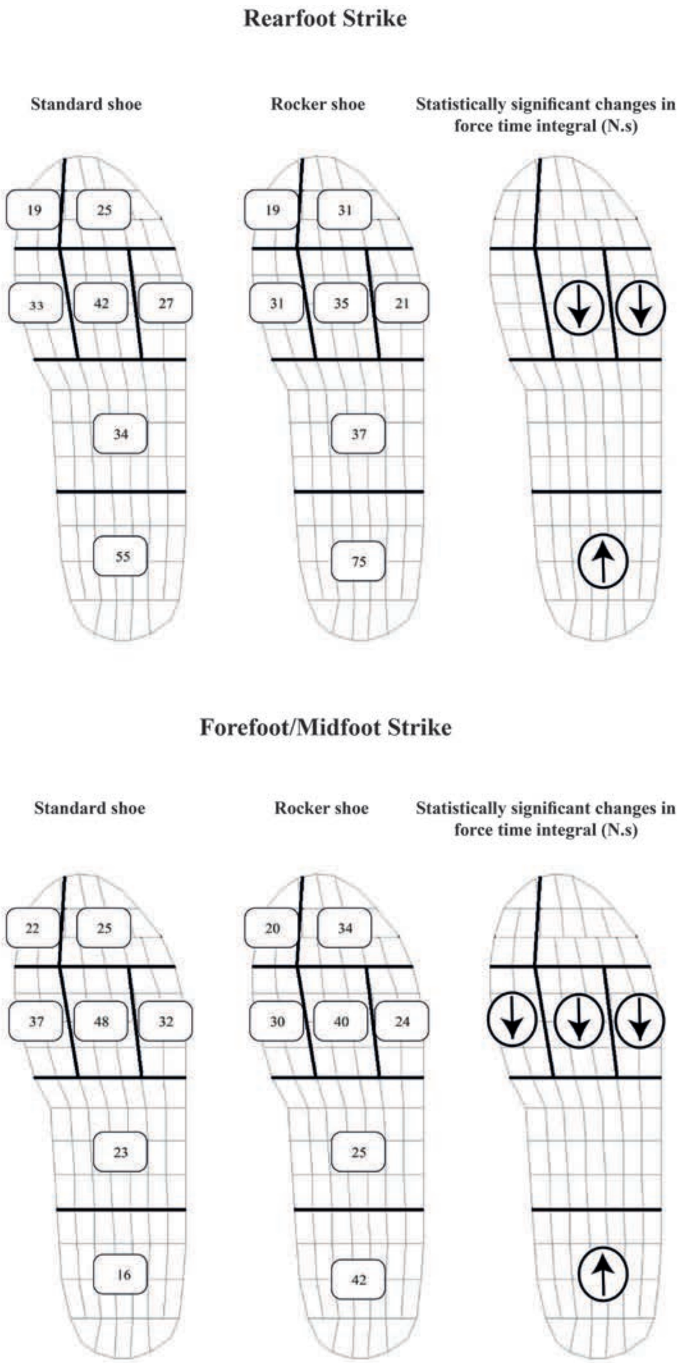

Figure 4. The separate analysis of two strike groups for the force-time integral (N.s). The numbers are average values. The arrows indicate the locations with statistically significant changes and also the direction of change.

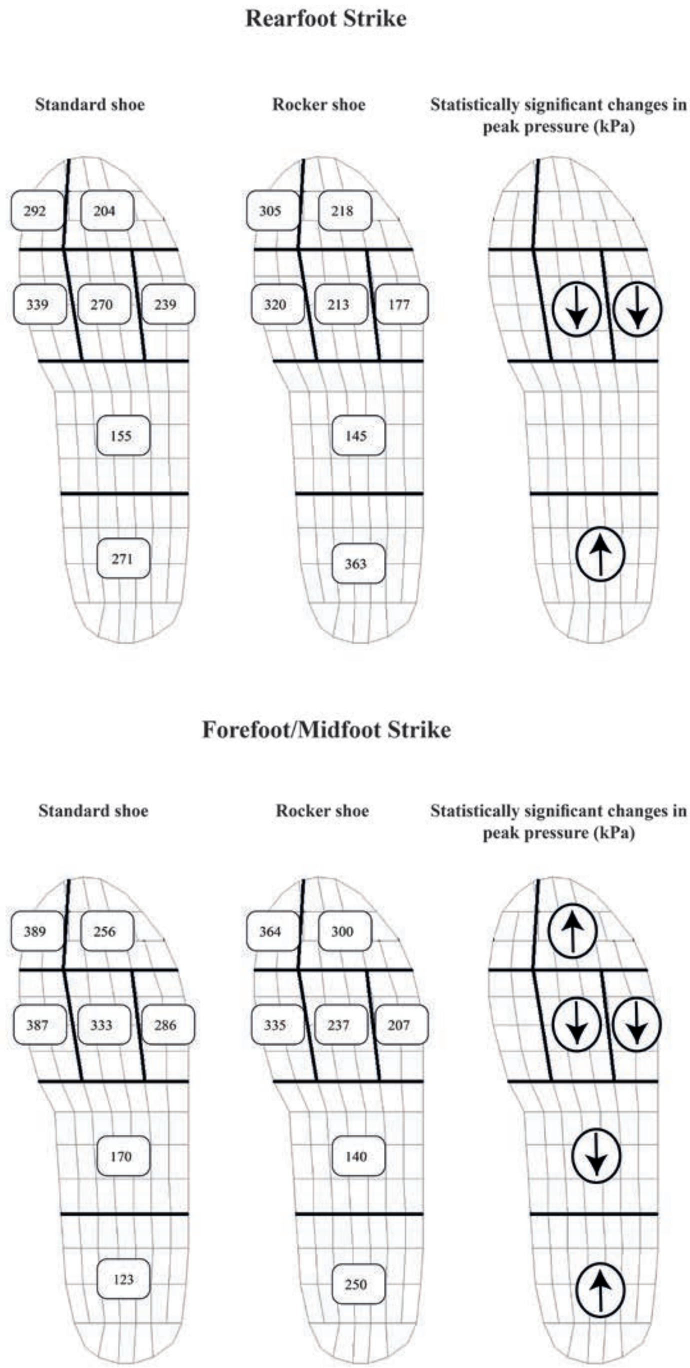

Figure 5. The separate analysis of two strike groups for the peak pressure (kPa). The numbers are average values. The arrows indicate the locations with statistically significant changes and also the direction of change.

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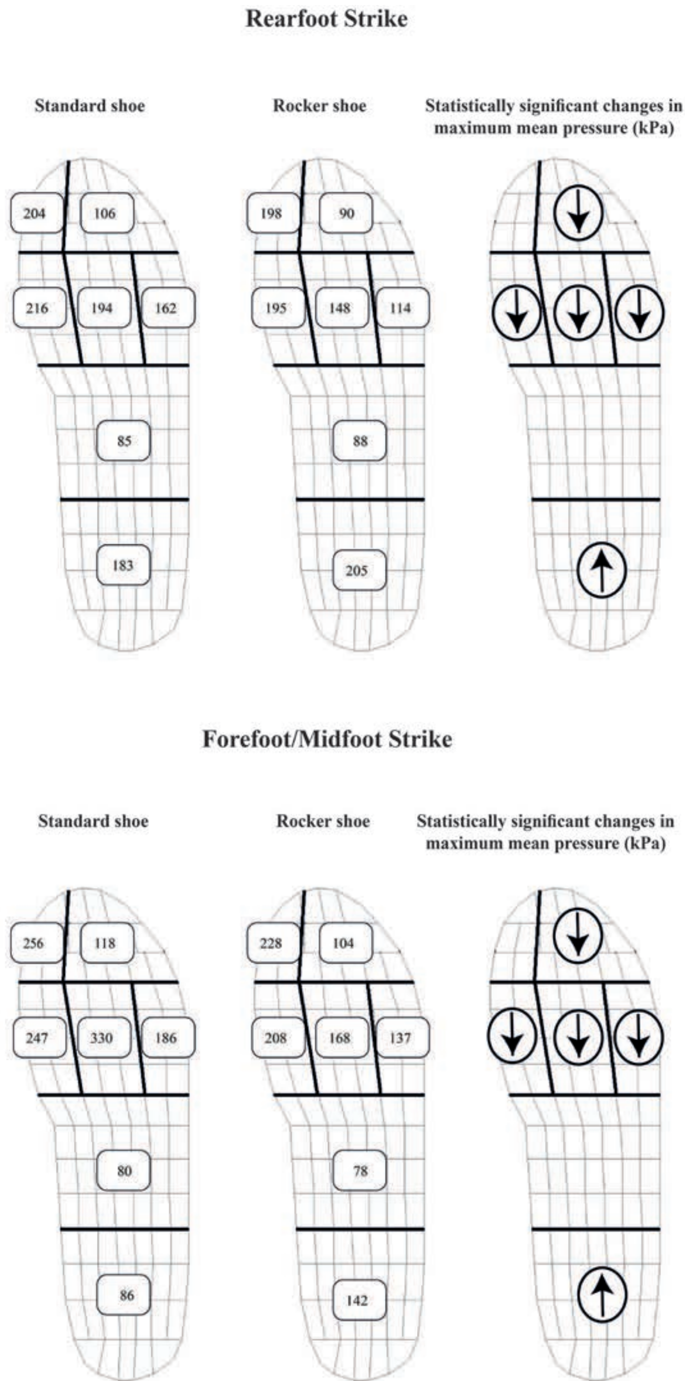

Figure 6. The separate analysis of two strike groups for the maximum mean pressure (kPa). The numbers are average values. The arrows indicate the locations with statistically significant changes and also the direction of change.

CHAPTER 6

Rocker shoe, minimalist shoe, and standard running shoe: a comparison of running economy

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ABSTRACT

Objectives: Running with rocker shoes is believed to prevent lower limb injuries. However, it is not clear how running in these shoes affects the energy expenditure. The purpose of this study was, therefore, to assess the effects of rocker shoes on running economy in comparison with standard and minimalist running shoes. *Design:* Cross-over design *Method:* Eighteen endurance female runners (age =23.6±3 yrs), who were inexperienced in running with rocker shoes and with minimalist/barefoot running, participated in this study. Oxygen consumption, carbon dioxide production, heart rate and rate of perceived exertion were measured while participants completed a 6-min sub-maximal treadmill running test for each footwear condition. The data of the last 2 min of each shoe condition were averaged for analysis. A linear mixed model was used to compare differences among three footwear conditions. *Results:* Oxygen consumption during running with rocker shoes was on average 4.5% higher than with the standard shoes ($p<0.001$) and 5.6% higher than with the minimalist shoe ($p<0.001$). No significant differences were found in heart rate and rate of perceived exertion across three shoe conditions. *Conclusions:* Female runners, who are not experienced in running with the rocker shoes and minimalist shoes, show more energy expenditure during running with the rocker shoes compared with the standard and minimalist shoes. As the studied shoes were of different masses, part of the effect of increased energy expenditure with the rocker shoe is likely to be due to its larger mass as compared with standard running shoes and minimalist shoes.

1. INTRODUCTION

The high amount of load at the forefoot region during the push-off phase in walking and running, makes this region susceptible to different overuse injuries such as metatarsal stress fractures and metatarsalgia.[1] Rocker bottom shoes (hereafter referred to as rocker shoe) have been shown to be able to reduce the excessive plantar pressure in the forefoot region during walking.[2,3] Moreover, rocker shoes can reduce the peak plantar flexion moment (related to the force on the Achilles tendon) during propulsion phase of run-ning, and therefore they might be beneficial for runners who are inthe recovery phase of Achilles tendinopathy.[4] For these reasons, rocker shoes might play a role in the prevention and treatment of overuse injuries during running.

While the biomechanical effects of rocker shoes in relation with lower limb injuries have been subject to a number of studies,[5] no attention has been made to the possible side-effects such as the energy expenditure during running with these shoes. Some work, however, has been done in walking activities, and conflicting results have been reported. In one study[6] no changes in metabolic cost between rocker bottom shoes and standard shoes were observed. One study reported an increase in energy expenditure during walking with rocker shoes compared with standard shoes,[7] and the opposite was found in another study.[8]

The minimalist shoe is a rather new type of footwear, gaining popularity among runners. Minimalist shoes are presumed to simulate barefoot running and may therefore reduce running injuries.[9] For instance, minimalist shoe running is believed to promote a forefoot strike which reduces the impact force and impact loading rate during running.[10,11] Since these factors are related to running injuries, minimalist shoes are used by runners to prevent overuse injuries.[9,10] Apart from injury prevention, running with minimalist shoes is shown to be more economic than running with standard running shoes.[11,12] However, to date no comparison has been made between minimalist shoes and rocker bottom shoes regarding the running economy (RE).

RE can be an important factor for runners, and might affect the choice of footwear for their regular running activities. Therefore, the purpose of present study was to determine how rocker shoes affect RE, and compare it with minimalist and standard running shoes.

2. METHODS

The experimental protocol of this research was approved by the Medical Ethics Committee of the University Medical Center Groningen (METc 2012.014). This study was part of a bigger research project focusing on running overuse injuries and shoe biomechanics with only the female sample population. The selection of females as the sample for the whole project was based on the higher incidence rate of overuse injuries reported for this gender.[13]

To be included, female runners needed to be between 18 to 55 years old, and be healthy with no history of cardiovascular and musculoskeletal (back and lower limb) problems. Participants had to have experience of running at least twice per week and at least five km per run in the past year. In addition, the runners needed to be familiar with treadmill running, and had the ability (self-reported) to run for approximately 30 minutes at sub-maximal pace on treadmill.

The investigated shoes in this research (European sizes 37 to 42) were as follows: rocker shoe (average mass per pair: 858±96 g, Figure 1-A), standard running shoe (Dutchy™, average mass per pair: 541±44 g, Figure 1-B), and minimalist shoes (Merrell™ Pace Glove, average mass per pair 321±25 g, Figure 1-C). Rocker shoes were modified from standard shoes with a stiffened rocker sole by a certified orthopedic shoe technician. The apex (rolling-point) of the rocker shoes and baseline shoes were respectively positioned at 53% (proximal to metatarsal region), and 65% of the shoe length from the heel. The rocker profile thickness for different sizes was 2.2±0.1cm at the apex and under the heel.

Figure 1. Three investigated shoe conditions: (A) Rocker, (B) Standard, and (C) Minimalist

Oxygen consumption (VO_2) and, carbon dioxide production (VCO_2) were recorded and monitored continuously via face mask using an open circuit breath-by-breath gas analysis system (Cortex Metalyzer 3B, Leipzig Germany) and its dedicated software (MetaSoft 3.9.5, Germany). Prior to data collection, the gas analysis system was calibrated according to manufacture's instructions using ambient air and known gas concentrations. The volume calibration was performed using a 3-litre syringe. Heart rate (HR) was measured using a wireless chest strap telemetry system (Polar Electro T31, Kempele, Finland).

Rating of Perceived Exertion (RPE) of running was determined using 15 points (6 to 20) Borg scale[14] for each shoe condition. This scale was used to subjectively measure the overall effort when running with three different shoes for the first time. The Borg scale has been shown to be a reliable method for rating perceived exertion in treadmill running.[15]

The experimental procedure was as follows: Each participant visited the exercise laboratory once, and all testing procedures were conducted under similar conditions. Prior to data collection, the procedures were described in detail for participants and each participant read and signed a consent form. Then, body weight and height were recorded without shoes. After preparation, each participant ran on a treadmill (Valiant; Lode, B.V., Groningen, The Netherlands) with all three shoe conditions. Participants were randomly assigned to the six different orders in running with the shoes, but with the restriction that the design would be balanced. The treadmill grade was set at 1% incline to compensate for lack of air resistance.[16] The sub-maximal running tests for each shoe condition included two running bouts: 1) running for 3 min at the speed of 7 $km.h^{-1}$ to help the participants to get familiar with experimental condition (e.g. face mask and shoes), 2) running for 6 min at the speed of 9 $km.h^{-1}$ to allow the runners to reach the steady state. The running pace for the economy test (9 $km.h^{-1}$ for 6 min) was assumed to be moderate enough as a sub-maximal test for our sample group who were experienced endurance runners. There was a 2 min rest between each measurement, which allowed participants to rate the perceived exertion, and change the shoes. In total a RE test for each participant took 31 minutes.

Descriptive statistics were used to describe the characteristics of the population. The data of the last 2 min of each shoe condition were averaged to calculate the mean VO_2 ($ml.kg^{-1}.min^{-1}$), respiratory exchange ratio (RER), and HR (bpm) for analysis. VO_2 and VCO_2 values were normalized to the participant's body mass (kg) while not wearing shoes. For two persons, HR could not be measured for technical reasons, and thus for this parameter data analysis was performed using the data of 16 participants. The data were analyzed using a linear mixed model. Participants were treated as random effect nested within the order of wearing shoes, and the effect of shoes was estimated when corrected for the order of wearing shoes and for “period” effects. Type III tests were used to determine the effects of shoe, order of shoe and period. An α level <0.05 was taken as significant. All analyses were conducted using SPSS software (version 20). Two plots were created by MatLab™ software (R2012a) to visualize the individual values of RE when wearing the rocker shoe and the percentage difference to the other two shoe types (figure 2).

3. RESULTS

Characteristics of the eighteen participants were as follows (mean±SD): age =23.6±3 years, height=171.5±6 cm, weight=61.7±7 kg and self reported 10-km race time=49.6±5.8 min. Type III tests revealed no shoe order effect for any of the response variables (VO_2, p=0.91; RER, p= 0.38; HR, p=0.96; RPE, p=0.11). Compared with rocker shoes, VO_2 was significantly lower during running with standard (p<0.001) and minimalist shoes (p<0.001). There was no significant difference between VO_2 of minimalist shoe compared with the standard shoe (p=0.186).

No significant differences were found concerning in RER, HR, and rate of perceived exertion across three shoe conditions. The mean values with their 95% confidence intervals for the outcome measures were determined with the linear model and they are provided in Table 1. This table also contains the p-values for the comparisons between shoes.

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Table 1. Mean values [95% confidence interval] of experimental variables (N=18)

Variables	Rocker Shoe (RS)	Standard Shoe (SS)	Minimalist Shoe (MS)	p-Value[a]	Significant Differences in Pairwise Comparison
VO_2 (ml.kg^{-1}.min^{-1})	34.59 [33.03 ; 36.15]	33.02 [31.46; 34.58]	32.65 [31.09 ; 34.21]	<0.001	RS>SS, RS>MS
RER (VCO_2/VO_2)	0.96 [0.93 ; 0.98]	0.94 [0.92 ; 0.97]	0.95 [0.93 ; 0.98]	0.07	NA
HR[b] (bpm)	151.97 [141.35 ; 162.59]	150.84 [140.21 ; 161.46]	152.55 [141.93; 163.17]	0.47	NA
RPE (6-20)	11.31 [10.53 ; 12.09]	11.05 [10.27 ; 11.83]	11.00 [10.22 ; 11.78]	054	NA

HR: heart rate; RER: respiratory exchange ratio; RPE: rate of perceived exertion; VCO_2: rate of carbon dioxide production; VO_2: rate of oxygen consumption.
[a] The statistical significance level is set at p< 0.05.
[b] The values are the mean of 16 participants

The individual differences in VO_2 between the rocker shoes and the other two shoes, expressed in percentages, are provided in figure 2.

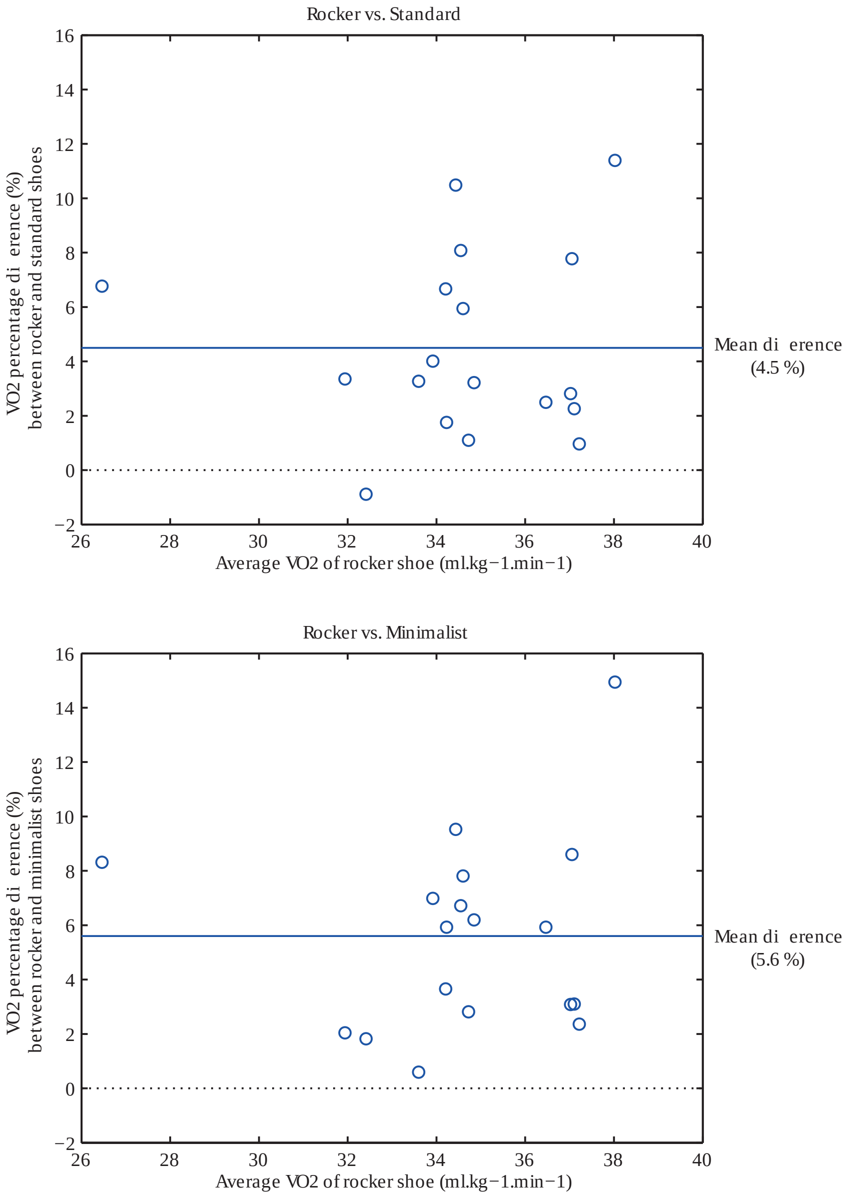

Figure 2. A comparison of oxygen consumption between the rocker shoe and the other shoe types: the standard (top plot) and the minimalist (bottom plot). The X axis in both plots shows the oxygen consumption of each individual while running with the rocker shoe, and the Y axis shows the percentage difference to the standard shoe [(VO2 rocker- VO2 standard)/ VO2 rocker] x 100 (top), and to the minimalist shoe [(VO2 rocker- VO2 minimalist)/ VO2 minimalist] x 100 (bottom). Values above zero indicate runners who had a worse running economy with the rocker shoe in comparison with the other shoes.

4. DISCUSSION

The current study is the first that has evaluated RE for a rocker shoe design in comparison with other running shoes. Running with rocker shoes caused a significant increase in VO_2 compared with the standard shoe (on average 4.5%). In this study the rocker shoe was modified by adding a stiffened rocker profile to the forefoot region of the standard shoe. The added rocker profile not only changed the structure of the rocker shoe, which could potentially have affected the running mechanics, but also led to a shoe mass difference of 317 g (on average) compared with the standard shoe.

Previous studies have shown that adding 100 g mass to the shoes/feet would result in approximately 1% increase in VO_2.[17-19] Thus, based on the extra shoe mass, an average increase of 3.1% in VO_2 was expected while running with the rocker shoe in comparison with the standard shoe. Our findings however, showed an average increase of 4.5% in VO_2. This result supports the hypothesis that factors other than the shoe mass might play a role in RE.[11] The participants in the current study were not experienced in running with rocker bottom shoes. This factor might have led to higher energy expenditure during running with the rocker shoe. Moreover, rocker shoes have different biomechanical characteristics than the standard shoes. In the only biomechanical study on rocker shoes in running[4], Boyer and Andriacchi reported that the MBT™ rocker shoe could substantially change the lower extremity kinetics and kinematics especially in the ankle region. Considering the common features between our rocker shoe design and the MBT™ shoe in above mentioned study (e.g. the rocker component in the forefoot region), similar changes in running biomechanics could be expected and might have negatively affected the running energetic with the rocker shoe. In addition, the correlation between RE and some spatiotemporal variables such as stride length and stride frequency has been previously reported previously.[20,21] These variables could have been influenced by the rocker shoe, leading to more energy consumption while running with this shoe. The present study was not aimed however, to assess the mechanisms underlying these differences, but rather to provide initial insight into physiological characteristics when running with a rocker shoe design. Further studies are warranted to systematically assess the effects of aforementioned factors on RE when using rocker shoes. In brief, running with the rocker shoes caused higher energy expenditure compared with standard running shoes. While this effect is not desirable for the competitive runners, it might have values in physical fitness and body weight management programs.

The other shoe condition which was compared with our rocker shoe was the minimalist shoe which is gaining popularity in runners. By simulating barefoot running, lightweight minimalist shoes are presumed to prevent running injuries and also reduce energy expenditure during running.[9,11,12] However, little information is still available on RE with this type of shoe. In this study running with the minimalist shoe was more economic, and required on average 5.6% less VO_2 compared with the rocker shoe. As mentioned before, every 100 g extra shoe mass results in 1% increase in energy cost. Considering the fact that rocker shoes were on average 537 g heavier than minimalist shoe, an increase of 5.6% in VO_2 can be explained by the difference in shoe mass. However, the rocker shoe was considerably different in design from minimalist shoes (e.g. different sole height and flexibility), which is highly likely to cause dissimilarity in running biomechanics between these shoes.

As seen in the bottom plot of figure 2, a large variation in RE (ranging from 0.6% to 15% increase in VO_2) existed when comparing rocker and minimalist shoes. Therefore, it is premature to conclude based on this finding that the shoe mass is the only contributor to observed differences in RE between rocker and minimalist shoe. It would be interesting in future studies to compare RE while two shoe conditions are matched for weight as it was done in walking.[6] In addition, some biomechanical comparison studies can provide more information about differences or similarities when running with these shoes.

Our experiment gave us also the opportunity to compare RE when running with minimalist and standard shoes. The results showed that although not significant, running with minimalist shoes was 1.1% more economic than running with standard shoes. Sqaudrone and Gallozzi reported 2.8% improvement in RE for minimalist shoes compared with standard shoes in a group of barefoot runners.[12] In a recent study after controlling the shoe mass, strike type, and strike frequency, running with minimalist shoes reported to be on average 2.4%-3.2% more economic than running with standard shoes.[11] The observed difference in our study was smaller than what was previously reported. One explanation can be the difference in the population examined. In our study we recruited runners who were not experienced in barefoot/minimalist running, while in previous studies participants were habitually barefoot/minimally runners. Additionally, RE in our study were assessed in female runners at speed of 9 Km/h, while in previous works RE were evaluated mainly in male runners at higher speeds of 10.8 Km/h and 12 Km/h.[11,12] Another explanation might rely on different models of minimalist shoe used in present study (Merrell™ Pace Glove) and the model previously used (Vibram™ Fivefingers).

In the present study, the mean RER was less than 1 and validated the sub-maximal intensity which is necessary in RE evaluation. Further, the mean rate of perceived exertion was about 11 for all three footwear conditions, which corresponds to ‘‘light’’ intensity on the Borg scale. It is a limitation of this study that the shoe weight was not controlled for as a potential confounder. Unlike previous research, we were unable to find significant differences between minimalist and standard shoes concerning RE. This study was under-powered to detect small differences between these two shoe conditions. Our sample included female runners who were inexperienced in running with minimalist and rocker shoes, and therefore, the generalizability of the findings to other populations is limited. Additionally, the findings might only be valid for the shoe designs experimented in this research.

5. CONCLUSION

In conclusion, the findings showed that running with the studied rocker shoe design is less energy efficient than running with minimalist and standard shoes. Although not totally clear from the findings of this study, it seems that the mass of the rocker shoe is the main contributor to the increased energy consumption during running with this type of shoe. Therefore, to be used by runners, this factor should be considered when fabricating rocker shoes.

6. PRACTICAL IMPLICATIONS

- In this study the energy expenditure while running with the rocker shoe was compared with minimalist and standard running shoes.
- More energy expenditure should be expected when running with the rocker shoe (studied in the present research) compared with standard running shoes.
- Running with the studied rocker shoe is less efficient than running with minimalist shoe.

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CHAPTER 7

General Discussion

7. DISCUSSION

The aim of this thesis was to enhance our understanding of the potential of rocker shoes with a proximally placed rocker as a possible treatment/prevention option for Achilles tendinopathy and forefoot problems. Therefore, several biomechanical and physiological aspects of these shoes were studied in running and walking activities.

7.1 Main findings of this thesis

In chapter 2 a systematic review was performed to understand the extent of ankle and foot overuse injuries in different sports activities. Unfortunately, a meta-analysis was not possible due to heterogeneity in case definitions, assessment tools, and exposure expressions. The estimates of incidence and prevalence rates (within and between sports) varied considerably across included studies. However, this review did show that Achilles tendinopathy was the most commonly reported injury in different sports activities with the high incidence and prevalence rates in runners. For example, three studies reported the high incidence rates of 83.3 (per 1000 athlete-year)[1], 107.1 (per 1000 athlete-season) [2] and 411.8 (per 1000 athlete-race)[3], and one study reported a point prevalence of 33% for Achilles tendinopathy in runners[4] (chapter 2). Likewise, forefoot problems such as metatarsalgia were mainly observed in runners with fairly high incidence rates (16.7 per 1000 athlete-year)[1], 35.7 (per 1000 athlete-season) [2] and 117.6 (per 1000 athlete-race)[3]).

In chapter 3 and 4 we examined the effect of rocker shoes in reducing the load on the Achilles tendon during (slow) running and walking. The peak ankle plantar flexion moment was determined as the primary parameter related to the load on the Achilles tendon during locomotion. First a group of healthy runners was tested (chapter 3), revealing that the peak plantar flexion moment with rocker shoes was reduced with more than 10% both in running and walking compared with standard shoes. A similar change was present also for plantar flexion moment impulse and peak power generation. Although these findings were promising, it was still unclear if the same results could be observed in the target population as they might have adapted gait patterns due to pain. Thus, another biomechanical study (chapter 4) examined the effects of rocker shoes in a group of patients with chronic symptomatic Achilles tendinopathy. Peak and impulse of plantar flexion moment and also power generation all turned out to be significantly reduced (≥13%) during both running and walking with the rocker shoe compared with standard shoe. This was similar to the earlier findings made in the healthy group (chapter 3). Another chapter of this thesis (chapter 5) looked at load reduction in the forefoot region while wearing rocker shoes. We found that rocker shoes were also able to decrease plantar pressure in the forefoot region during running when compared with standard shoes.

These chapters (3-5) also looked for biomechanical side-effects accompanied with reduced plantar flexion moment and the forefoot plantar pressure. The increased EMG activity of tibialis anterior in walking (chapter 3 and 4) and the increased plantar pressure in the heel in running (chapter 5) were two important biomechanical side-effects of rocker shoes. Physiologically, rocker shoes had a worse running economy when compared with standard running shoes and minimalist shoes (chapter 6).

7.2 Rocker shoes, potentials and limitations

It is important to mention a comment that we received from a reviewer on one of the papers of this thesis: "*It seems that rocker shoes are meant more for walking than running.*" From a historical point of view, I could agree with this comment. Most of our knowledge about rocker shoes has come from studies that investigated walking activities, and there is lack of evidence on this topic in running. At the time we were designing the first study on rocker shoes (2010), searching the words "rocker" AND "running" in PubMed yielded 1 relevant result.[5] Thus, it seems that the biomechanical efficacy of rocker shoes in prevention and treatment of running injuries is rather neglected. In this thesis it was tried to shed some light on the potential of rocker shoes in running. Maybe based on our results, we could rephrase the reviewer's comment as follows: "*It seems that rocker shoes* ***were*** *meant more for walking than running* ***but not anymore****.*"

7.2.1 Potentials of rocker shoes

The Achilles tendon and metatarsal joints are subject to high loadings during locomotion. In the propulsion phase of running the peak force on the Achilles tendon can reach 8 times body weight[6] and force on metatarsal joints can reach up to 2.3 times body weight.[7] Reducing these high loads might play an important role in prevention and treatment of Achilles tendinopathy and forefoot overuse problems like metatarsal stress fractures. We believed that rocker shoes would have potential to decrease the internal ankle moment by decreasing the external ankle moment arm and also to decrease the pressure on the metatarsal joints by shifting the rolling point of the third rocker more proximal. Our findings have demonstrated this.

The internal ankle plantar flexion moment is used as a measure of the forces on the Achilles tendon as the prime mover for plantar flexion.[6] In running, the peak force on the Achilles tendon occurs at the same time as the peak plantar flexion moment.[6] Thus, peak plantar flexion is considered as the biomechanical outcome that is directly related to the peak Achilles tendon force. These biomechanical parameters were previously tried to be decreased in running by means of heel lifts.[8-10] However, no significant changes in peak plantar flexion moment and Achilles tendon force (50-55% of stance phase) were observed using heel lifts. One study even reported an increase in Achilles tendon force in some runners by using heel lift and caution was advised in the routine use of this intervention for Achilles tendinopathy.[8] Beyond these studies, little effort has been made to influence Achilles tendon loading. Chapter 3 and 4 of this thesis are further steps in this direction by investigating the ability of rocker shoes (as a new intervention) in reducing peak plantar flexion moment and therefore Achilles tendon loading.

The findings in both healthy (chapter 3) and patient groups (chapter 4) were promising from a clinical standpoint, as they indicated that rocker shoes significantly reduced the peak plantar flexion moment for about 10-13% in running and walking. However, we do not know if this change will be clinically relevant. One of the advantages of using rocker shoes over current treatment options is the ease of use during both athletic trainings and daily activities. Therefore, if continuously used, 10% decrease in the peak plantar flexion moment can cumulatively contribute to a considerable reduction of the loads imposed to the Achilles tendon during running and walking activities.

While rocker shoes significantly influence the biomechanics of ankle joint, it seemed that no major changes occurred in knee and hip joint moments in response to the use of rocker shoes (chapter 3and 4). This observation is in line with previous reports in running and walking activities.[5, 11-13] Therefore, despite different design and sole geometry from standard running shoes, rocker shoes seem to influence the ankle joint in the way we expected without substantial risk to the knee and hip joints. In saying this, however, it needs to be emphasised that all these studies, including ours, have investigated the immediate effect of rocker shoes on gait dynamics. Long-term effects are still unknown and need further investigation. In addition, it should be noted that in chapter 3 and 4, plantar flexion moment was used as a surrogate outcome which may be related to clinical measures such as pain, although this relation has not been established yet. In the study with the patient group (chapter 4), level of pain was assessed as a clinical outcome using a point scale to provide an initial insight into a possibly immediate effect of the rocker shoes on chronic Achilles tendon pain but an immediate effect could not be demonstrated as a result. Probably we could have expected this, because the pain is supposed to be caused by the tendinopathy and this will not be changed immediately after using the rocker shoe. Thus, it is essential to determine how long a rocker shoe should be used before its real effectiveness becomes apparent.

Two other domains that are also clinically relevant to patients with Achilles tendinopathy include function in daily living and sports activity. These two domains can be measured by the Victorian Institute of Sports Assessment-Achilles (VISA-A) questionnaire, a validated tool for assessing clinical outcome and including questions on pain, activity, and function.[14] The VISA-A has been successfully used to monitor clinical progress of Achilles tendinopathy in response to eccentric exercises.[15] A phase III clinical trial is necessary to evaluate the effectiveness of rocker shoes in treatment of Achilles tendinopathy possibly with VISA-A score as the clinical outcome rather than pain alone. The feasibility of such a phase III trial, needs to be assessed first using a pilot study. This pilot study will generate data for sample size calculations for the main study and also provide useful information about recruitment potentials, multicenter collaboration, study design and so on.[16] After the pilot study, a number of patients can be randomly assigned to two (or more) treatment groups: one group receives rocker shoes and the other group(s) receives current treatment methods (e.g. eccentric exercises or shockwave therapy). Patients then can be monitored and followed up every two weeks for a period of 2-3 months. It is essential to stratify patients to different groups depending on their level of activity. It must be clear whether due to pain they have stopped running activities (use of rocker shoe only for walking) or they still run in spite of pain (use of rocker shoe for walking and running).

From a *primary prevention perspective*, it would be desirable to perform a prospective controlled trial to study the role of rocker shoes in preventing Achilles tendinopathy in comparison with standard shoes or minimalist shoes. This study, however, seems to be difficult to perform owing to the large sample size required for each group. For example, a total of 656 runners (2 × 328) would be required to demonstrate a 30% reduction in Achilles tendinopathy rate in the rocker shoe group compared with standard shoes using a two-tailed alpha of 0.05, a power of 80%, and assuming an incidence rate of 10% for Achilles tendinopathy.[1, 2] This number must be even larger if we consider 10-15% attrition rate. Assuming a higher incidence rate of Achilles tendinopathy in recovered patients, an alternative could be to study the role of rocker shoes in recurrence of Achilles tendinopathy (*secondary prevention*). However, one study reported a recurrence rate of only 15% for Achilles tendinopathy at 5-year follow-up.[17] If other studies also confirm this result, then investigating recovered patients will not offer any advantages in terms of sample size. To summarize, the overall contribution of chapter 3 and 4 to the current knowledge is presented in figure 1.

The efficacy of rocker shoes in reducing plantar pressure is already well documented in walking activities. Our findings show the same effect also in running (chapter 5). Running with the rocker shoes caused a significant reduction in peak pressure, maximum mean pressure, and force-time integral in the central and lateral forefoot. Force time integral and maximum mean pressure were also reduced by 11% and 12% in the medial forefoot while running with rocker shoes. This highlights the biomechanical value of rocker shoes for those runners who are recovering from metatarsalgia or a stress fracture of the forefoot region. Rocker shoes might also be helpful to reduce the risk of overuse injuries such as metatarsal stress fractures in endurance runners.

Since this study is the first of its kind dealing with running activities, it is premature to make general conclusions based on its findings. Yet, this study opens up the possibility for future investigations in this area. As our study only studied female runners, more studies are needed to evaluate the plantar pressure in male runners while wearing rocker shoes.

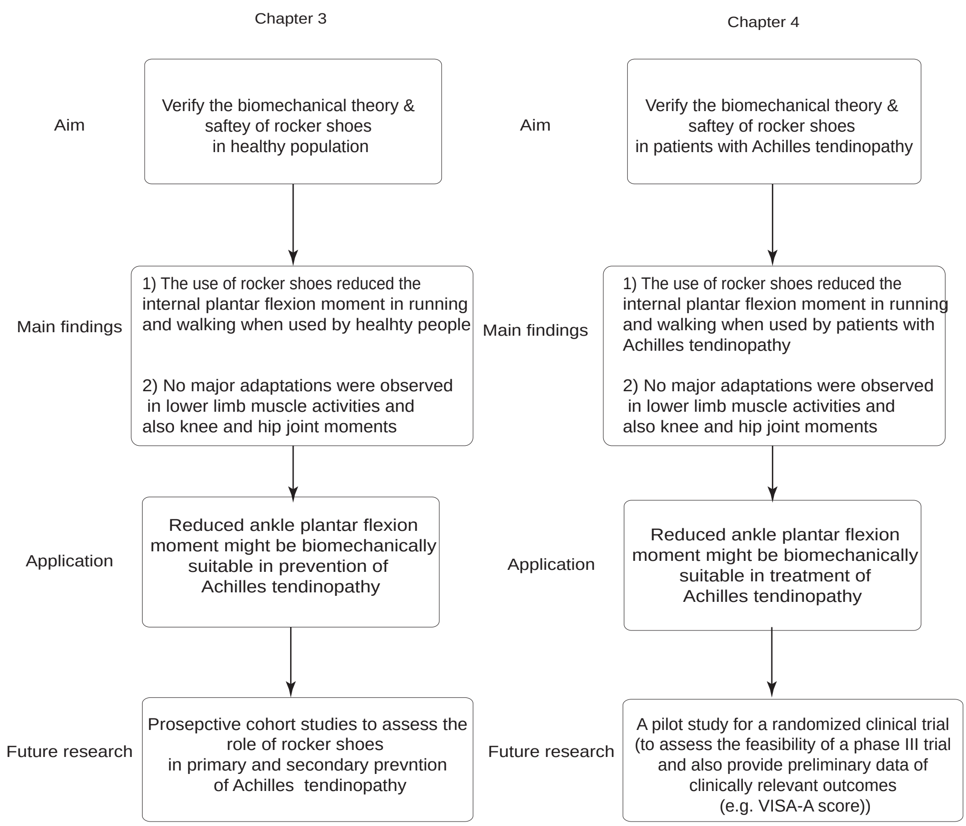

Figure 1. Contribution of chapter 3 and 4 to the current knowledge concerning biomechanics of rocker shoes and the possible clinical applications

7.2.2 Limitations of rocker shoes

There are some limitations related to rocker shoes that should be considered. One issue is the increased activity of tibialis anterior at early stance phase of walking while walking with rocker shoes (chapter 3 and 4). In previous research, the opposite (decreased activity of tibialis anterior) was observed for non-heeled and rounded heel rocker shoes.[18, 19] Thus, thickness or shape of the heel seems to be the possible reasons for this observation. This effect coincided with an increase in external plantar flexion moment of the ankle joint at early stance (this information has not been reported in chapter 3 and 4 because early stance was not the focus of these chapters).The explanation could be a posterior shift in the point of application of the ground reaction force, leading to a longer external moment arm for the ankle joint. Rocker shoes could be designed with a rounded heel. This can be an interesting subject for future research. The stiffness of the sole might be another reason for increased activity of tibialis anterior. With a hard sole, subjects might need more plantar flexion control to avoid foot slap during loading response.

If consistently used, inserts or orthotics might negatively influence the musculoskeletal function.[20] By reducing the plantar flexion moment, the use of rocker shoes biomechanically result in less activity of calf muscles. We do not know if without additional trainings, this muscle group might become less trained in long-term which eventually reduce the propulsive power of running.

The rocker shoe studied in this thesis had certain characteristics to ensure that it would be reasonably suitable for running and walking. The apex location of the rocker shoe was placed proximally enough (53%) to efficiently shorten the moment arm of external dorsal flexion moment (see figure 1 in the introduction), and yet not too much proximal that could lead to instability of the shoe. In addition, a curved type of rocker profile was used to achieve a smoother rolling-off rather than an abrupt heel raise motion that usually occurs by traditional angle rocker soles. Our findings, however, revealed a poor running economy, low comfort and increased pressure at the heel region for rocker shoes. These factors can decrease the chance of use of rocker shoes by runners.

Our rocker shoes were significantly heavier than standard shoes due to rocker profiles added to them. This factor could have negatively affected both running economy and overall shoe comfort (chapter 5 and 6). It is unclear whether poorer running economy with rocker shoes is due to its extra weight or different running mechanics. Future studies may answer this question. Using lighter materials or creating a number of cavities inside rocker profiles could be possible ways to keep the weight of rocker shoes down.

Running with our rocker shoes resulted in a large load transfer to the heel region. In a recent study[21], the plantar pressure patterns of 12 rocker shoe designs (different apex angle, apex position and rocker angle) was assessed during walking. They found that peak pressure at the heel was increased in 8 out of 12 designs. This observation was for proximally placed rockers (50-60% of shoe length) and higher angle designs (20 degree and more).[21] The authors have not provided any explanation for the increased pressure at the heel region. The stiffness of the rocker sole might be a reason for the increased peak pressure at the heel region with rocker shoes (higher impact at the moment of heel contact). Therefore, this problem might be less severe by using shoes with adequate cushioning.

7.3 Strength and limitations of this thesis

With regard to the study design, there are notable strengths. A cross-over design was used in experimental studies of this thesis (chapter 3-6). The advantages of cross-over designs are already mentioned in the introduction of the thesis. In our studies, participants were randomly assigned to different orders of intervention. The randomization procedure assured a balanced design for 3 experiments (chapter 3, 5 and 6) and a partially balanced design for 1 experiment (chapter 4). In addition, some statistical tests were performed at the analysis stage to examine the possibility of order and/or period effects having occurred. To our knowledge, such methodological considerations have been ignored in previous studies on similar topic,[5, 12, 13, 18, 22, 23] which makes them less reliable than our studies.

In chapter 3 and 4, the analysis of kinetic and kinematic variables was limited to discrete time points during stance phase (e.g. peak moment in the terminal stance). Evaluating the entire gait curves during the complete gait cycle could have provided a better picture of the overall biomechanical adaptations in response to rocker shoes. Further, in chapter 6 the shoe weight was not controlled for as a potential confounder when comparing running economy with different shoe conditions. Short adaptation time to the shoes and also short wash-out period between shoe sessions were the other limitations (chapter 3-6).

7.4 Overuse running injuries, the role of footwear in prevention/treatment

The main finding of the present work is that use of rocker shoes resulted in reduced ankle and forefoot loads during the propulsion phase of running. Does this effect of rocker shoes make them different from other running shoes (e.g. heavily cushioned shoes, or minimalist shoes)? In one of the first studies on running kinetics, D. Winter (1983)[24] emphasized the importance of mechanical loads of propulsion phase of running in the development of running overuse injuries He states that "*About 75% of the chronic injuries resulting from jogging (tendinitis, shin splints, stress fractures, plantar fasciitis and chondromalacia) appear to be related to the high forces and powers that occur at push-off when the knee is flexing and the ankle is plantarflexing* ." This idea, however, did not become the dominant concept regarding running injuries. Instead, researchers related overuse running injuries to other biomechanical variables.

Impact forces and excessive pronation are the two variables frequently proposed as the main cause of overuse running injuries.[25-29] Therefore to minimize impact forces and limit excessive pronation, well-cushioned shoes and motion control shoes have been advocated by researchers and shoe companies with a promise of reducing overuse running injuries.[20, 28, 30-32]

Barefoot/minimalist running is another concept that has gained popularity among scientific community and runners. It is believed that barefoot runners are more likely to land on the forefoot region than on the heel.[33] This will reduce impact forces/loading rate and eventually rate of running injuries.[33] So again, barefoot/minimalist concept concerns impact forces/loading rate and strategies to reduce them. Although reducing impact loads and rearfoot motion control are the concepts predominantly focussed on (in literature, clinics, trainers and runners) to prevent and treat running injuries, there is no strong evidence to support these notions.[20, 32, 34, 35]

Obviously, too much focus on "impact loadings" and strategies to control them has distracted us from "active phase" of running. Dr. Benno Nigg ,as a leading researcher in the field of shoe biomechanics, in his recent book[20] has summarized the most influential body of evidence with regard to running injuries and prevention/treatment strategies over the last decades. Here we mention some of his statements: "*(1) There is currently no conclusive evidence that impact forces during heel-toe running are responsible for the development of running related injuries, (2) Internal loading in the joints and muscle-tendon units of the lower extremities during impact is relatively small compared to loading in the same structures during active phase of ground contact, (3) If excessive forces are the reason for the development of injuries, one would expect more injures for active phase of ground contact than for the impact phase, and (4) If reducing internal loading is the goal of a shoe construction, one should concentrate on the active phase of the ground contact*".

These statements encourage a new way of thinking in relation to overuse injuries and running shoes which we already incorporated in our research. Our findings showed that rocker shoes can reduce ankle and foot loading during active phase of running. This finding can be a step forward in the development of shoes that might be beneficial in prevention and treatment of overuse injuries that are related to propulsive phase of running. In saying this, it should be emphasized that not all overuse injuries can be prevented or treated by a specific type of shoe or running strategy.

The structures that are at risk during impact phase of running are different from those at risk during active phase. A well-cushioned shoe can damp impact loads during initial phase of running and thus might prevent tibial stress fractures; however, its role is limited in prevention or treatment of metatarsal stress fractures, and a rocker shoe might then be suitable. This point might seem obvious; however, the majority of studies that have investigated the relationships between biomechanical factors (e.g. impact load) and overuse injuries usually look at overall rate of injuries instead of looking at specific problems. This issue is very likely due to the fact that large sample sizes are needed for reliable data on frequency of specific overuse injuries. This might, however, lead to wrong conclusions about risk factors for running injuries and also effectiveness of different shoe designs in prevention/treatment of overuse running injuries. The recommendation for running footwear is also very general as if one type of shoe or running strategy might solve all the problems (one shoe suits all).

At the end, it is worth mentioning that there are other risk factors for overuse running injuries such as anatomical (e.g. foot type) or training (e.g. frequency or distance) variables. [36] The present work was related to biomechanical variables, and therefore other variables were not discussed.

7.5 Conclusion

Taken together, the studies presented in chapter 3-5, provided strong evidence in the potential of proximally placed rocker shoes in reducing the parameters which are biomechanically related to the load on the Achilles tendon and the forefoot region. Therefore, rocker shoes might be beneficial for prevention and/or treatment of Achilles tendinopathy and forefoot overuse injuries such as metatarsalgia and metatarsal stress fractures.

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SUMMARY

Summary

Overuse injuries of the ankle and foot are common in athletes, especially in runners. The triceps surae propel the body forward by generating a plantar flexion moment about the ankle joint during the terminal phase of stance. This applies a high amount of load to the Achilles tendon, the common tendon of the triceps surae. The metatarsophalangeal (MTP) joints are also prone to high forces during the terminal phase of stance. When the heel rises off the ground, the body weight is transferred forward over the MTP joint, and therefore MTPs provide a base of support which allows the foot to roll over. Reducing the high loads on the Achilles tendon and the MTP joint could be valuable in both prevention and treatment of overuse injuries such as Achilles tendinopathy and forefoot overuse injuries.

Shoes with a proximally placed rocker (rocker shoes) are used in clinical practice to reduce loads on the Achilles tendon and MTP joint. Rocker shoes, presented in this thesis, have a rigid rocker sole with its apex (rolling-point) positioned proximal to the MTP joint. Thus, with this type of shoe, during the roll-off, the application point of the ground reaction force is located at the rocker instead of the MTP joint. This change in the point of application of the ground reaction force (proximal shift) causes a smaller external dorsiflexion moment due to a shorter moment arm. Since internal moments need to be counterbalanced, a smaller external dorsifexion moment indicates a smaller "internal plantar flexion moment" (PFM). Biomechanically, a reduced PFM results in less tension on the Achilles tendon.

Moreover, the proximal position of the apex of rocker shoes can reduce pressure in the MTP joint during roll-off. A shorter loading time at MTPs, reduced forefoot range of motion, and better pressure distribution are believed to be the underlying mechanisms for this effect.

Therefore, based on different mechanisms rocker shoes can be used to reduce loads on both the Achilles tendon and MTP joint. These effects were previously reported for walking activities. In running activities, however, little information was available. Therefore in this thesis we examined these biomechanical effects of rocker shoes primarily for running activities. The ultimate goal of this thesis was to investigate the biomechanical characteristics of rocker shoes that might be valuable for the management/prevention of Achilles tendinopathy and forefoot overuse problems.

As a start, a systematic review was conducted to identify the extent of ankle and foot overuse injuries in different sports activities (*chapter 2*). The estimates of incidence and

prevalence rates (within and between sports) varied considerably across included studies. This review showed that Achilles tendinopathy was the most commonly reported injury in different sports activities with high incidence and prevalence rates in runners. Likewise, high incidence rates of forefoot problems such as metatarsalgia were mainly observed in runners.

In *chapter 3*, lower extremity kinetics and kinematics as well as electromyography (EMG) of the triceps surae and tibialis anterior were measured while using rocker shoes and standard running shoes during slow running and walking in 16 runners (8 ♀, 29± 9 years). The primary outcome of this study was the peak ankle PFM, as this is directly related to Achilles tendon loading. The peak PFM was reduced significantly ($p < 0.001$) in the late phase of stance during slow running (0.27 Nm/kg; 10%) and walking with the rocker shoe (0.24 Nm/kg; 13%) compared to standard running shoe. The PFM impulse and power generation of the ankle joint were also reduced significantly ($p < 0.001$) when running (11% and 21% respectively) and walking (17% and 25% respectively) with the rocker shoe. No significant changes in knee and hip moments were found in slow running and walking during the late phase of stance. There were no significant changes in the EMG peak amplitude of the triceps surae in slow running and walking. The peak amplitude of tibialis anterior was, however, significantly ($p < 0.001$) increased when walking with rocker shoes (64.7 µV, 20%).

It was concluded that the use of rocker shoes would reduce PFM during the late stance phase of slow running and walking in healthy people, without systematic changes in the knee and hip joint moments.

Beforehand it was hypothesized that patients with a painful Achilles tendon might would have an adapted gait pattern and a different biomechanical reaction to rocker shoes than healthy people. Therefore, another study (*chapter 4*) investigated running and walking biomechanics in response to rocker shoes in 13 patients (11 ♀, 48±14.5 years) with chronic Achilles tendinopathy. With the rocker shoes, the peak PFM was reduced by 13% in both slow running (0.28 Nm/kg, $p<0.001$) and walking (0.20 Nm/kg, $p<0.001$). The peak hip flexion moment was significantly lower (8 %, $p=0.019$) with the rocker shoe in walking. In running, no differences were observed in peak hip and knee moments during the late stance. Furthermore, EMG peak amplitudes of the triceps surae were not changed in either activities. The EMG peak activity of the tibialis anterior was increased by 35% ($p=0.015$)

for the rocker shoes only in walking.

These results showed that when used by patients with chronic Achilles tendinopathy, rocker shoes cause a significant reduction in PFM in the late phase of stance of both slow running and walking without major adaptations in knee and hip joints moments. It was concluded that rocker shoes might be useful in unloading the Achilles tendon in chronic AT, and therefore might play a role in the management of symptomatic Achilles tendinopathy.

In *chapter 5,* the objective was to examine the potential of rocker shoes in reducing forefoot plantar pressure in running. Offloading the forefoot area in running is clinically important especially for runners who are recovering from metatarsalgia or a stress fracture of the forefoot region. Eighteen healthy female runners (23.6±3 years) participated in this study. Participants had 20 minutes of running on a treadmill to accommodate to both pair of shoes (10 minutes per pair). In-shoe plantar pressures were recorded during running with the standard running shoes and rocker shoes. Shoe comfort was assessed after each shoe measurement using the Visual Analog Scale (0 mm = "not comfortable at all"; 100 mm = "most comfortable imaginable"). At the medial, central and lateral forefoot regions, running with rocker shoes caused a significant reduction in maximum mean pressure (respectively 11% (P<0.001), 17% (P<0.001) and 23% (P<0.01)) and force-time integral (respectively 12% (P<0.01), 17% (P<0.01) and 28% P<0.001), compared with standard shoes. The peak pressure was significantly reduced by 24% and 27% at the central (P<0.001) and lateral forefoot (P<0.001), and by 11% at the midfoot region (p=0.02). Compared with standard shoes, peak pressure, maximum mean pressure and force-time integral increased at the heel region when running with rocker shoes by 47, 22 and 52% (p<0.01) respectively. On the 100 mm Visual Analog Scale for comfort, running with rocker shoes was rated on average 33.3 mm which was significantly (p<0.01) lower than running comfort of the standard shoe with an average rate of 76.1 mm.

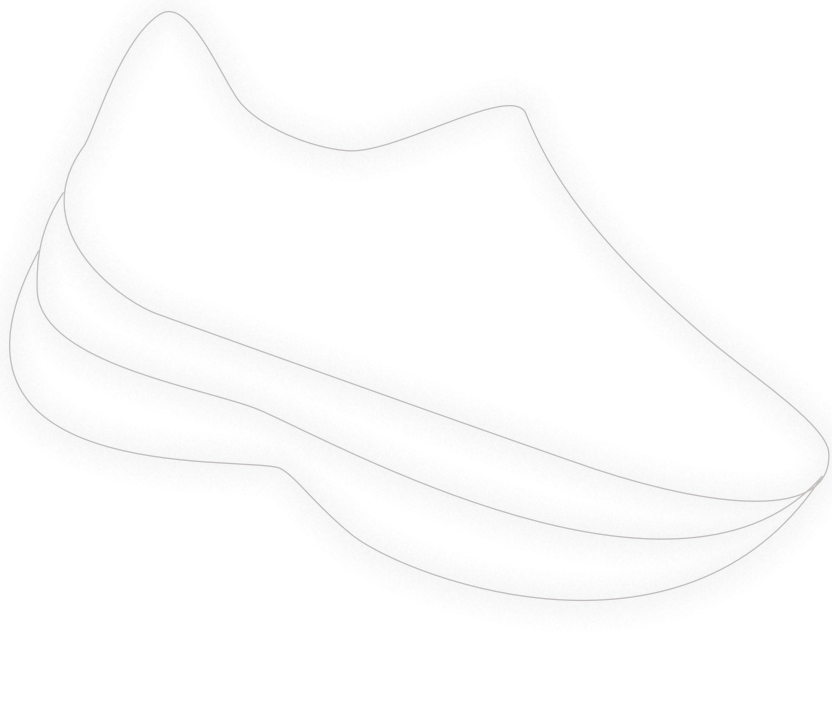
This study provided initial evidence that rocker shoes significantly reduce forefoot pressure in running, and therefore, they might be beneficial for runners who are recovering from forefoot overuse injuries such as metatarsalgia or stress fractures of the forefoot region. However, a load transfer to the heel region was a side-effect. Moreover, running with rocker shoes was less comfortable than running with standard shoes, which might affect the rate of regular use of this type of footwear.

Running economy can be an important factor for runners, and might affect the choice of footwear for their regular running activities. *Chapter 6* described a study on this topic. Oxygen consumption rate was measured while a 18 female endurance runners (23.6±3 years) completed a 6-min steady state sub-maximal treadmill running test with rocker shoes, minimalist shoes and standard running shoes. Runners were not experienced in running either with rocker shoes or with minimalist/barefoot running. Oxygen consumption rate during running with rocker shoes was on average 4.5% higher than with standard shoes ($p < 0.001$) and 5.6% higher than with minimalist shoes ($p < 0.001$).

It was concluded that running with the studied rocker shoes is less efficient than running with minimalist and standard running shoes. As rocker shoes were heavier than standard running shoes and minimalist shoes, part of the effect of increased energy expenditure with rocker shoes is likely to be due to its larger mass as compared with the two other running shoes.

The findings of the research in this thesis were integrated in *chapter 7.* In order to prevent or treat overuse running injures, reducing impact loads has been the dominant focus of most research on running shoes in the last decades and little attention has been paid to manage the high loads during the active (propulsion) phase of running. This thesis is one of the first attempts to investigate this subject. The main findings support the potential of rocker shoes usage in reducing ankle and forefoot loads during the propulsion phase of running. Phase III clinical trials are still necessary to evaluate the effectiveness of rocker shoes in treatment of Achilles tendinopathy and forefoot overuse injuries. Moreover, the side-effects of rocker shoes (e.g. poor running economy) need further attention in future research by optimizing the rocker shoes.

SAMENVATTING



Samenvatting

Overbelastingsblessures van de voet en enkel komen vaak voor bij sporters, voornamelijk bij hardlopers. De triceps surae genereren, in het laatste deel van de standfase, een plantairflexiemoment waardoor het lichaam naar voren wordt bewogen. Dit leidt tot een grote kracht op de Achillespees, als onderdeel van de triceps surae. Daarnaast worden, in het laatste deel van de standfase, ook de metatarsofalangeale (MTP) gewrichten aan grote krachten blootgesteld. Op het moment dat de hiel los komt van de grond, wordt het lichaamsgewicht over de MTP gewrichten naar voren verplaatst. De MTP gewrichtskopjes fungeren daarmee als steunpunt, waarover de voet kan afwikkelen. Vermindering van grote krachten op de Achillespees en de MTP gewrichten kan waardevol zijn ten behoeve van zowel de preventie als de behandeling van overbelastingsblessures van de Achillespees en de voorvoet.

Schoenen met een proximaal geplaatste afwikkelingscorrectie (hierna rockerschoen genoemd) worden in de klinische praktijk gebruikt om krachten op de Achillespees en de MTP gewrichten te verminderen. De rockerschoenen, gebruikt in dit proefschrift, hebben een rigide zool met afwikkelingscorrectie waarbij het draaipunt proximaal van het MTP gewricht geplaatst is. Door het gebruik van dit type schoen, grijpt de grondreactiekracht tijdens het afwikkelen aan op dit, meer proximale, draaipunt in plaats van op de MTP gewrichten. Deze proximale verschuiving van het aangrijpingspunt van de grondreactiekracht zorgt voor een kleiner extern dorsaalflexiemoment, vanwege een kortere momentsarm. Aangezien externe momenten met interne momenten gecompenseerd moeten worden, zal een kleiner extern dorsaalflexiemoment leiden tot een kleiner "intern plantairflexiemoment" (PFM). Een kleiner PFM leidt tot lagere krachten in de Achillespees.

Daarnaast leidt de proximale positie van het draaipunt van de rocker schoen tot vermindering van de druk op de MTP gewrichten tijdens de afzetfase, een kortere duur van de druk op de MTP gewrichten, en een verminderde bewegingsuitslag van de enkel. Rockerschoenen kunnen dan ook, gebaseerd op verschillende mechanismen, gebruikt worden om de kracht op zowel de Achillespees als ook de MTP gewrichten te verminderen. Deze effecten zijn eerder beschreven tijdens lopen. Voor activiteiten zoals hardlopen is echter weinig informatie beschikbaar.

In dit proefschrift zullen we de bovengenoemde biomechanische effecten van rockerschoenen tijdens hardlopen onderzoeken. Het uiteindelijke doel van dit proefschrift

is om de biomechanische eigenschappen van rockerschoenen te onderzoeken die mogelijk waardevol zijn voor de behandeling en/of preventie van overbelastingsblessures van de Achillespees en de voorvoet.

Allereerst is er een systematische review verricht naar de omvang van het aantal overbelastingsblessures van de voet en enkel ten gevolge van het beoefenen van verschillende sportactiviteiten (Hoofdstuk 2). De schattingen van incidentie en prevalentie (binnen en tussen sporten) variëren behoorlijk tussen de geïncludeerde artikelena. Dit review toonde aan dat Achillespeestendinopathie de meest voorkomende blessure was bij verschillende sportactiviteiten, met een hoge incidentie en prevalentie bij hardlopers. Ook voorvoetproblemen zoals metatarsalgia werden, vooral bij hardlopers, met hoge incidentie gerapporteerd.

In Hoofdstuk 3, zijn de kinetica en kinematica gemeten van de onderste extremiteit en het electromyogram (EMG) van de triceps surae en tibialis anterior bij 16 hardlopers (8 ♀, 29±9 jaar) tijdens langzaam hardlopen en lopen met zowel de rockerschoenen als standaard hardloopschoenen. De primaire uitkomstmaat van dit onderzoek was het maximale PFM, aangezien dit direct gerelateerd is aan de kracht op de Achillespees. Het maximale PFM was significant verminderd ($p<0.001$) in de afzetfase tijdens zowel langzaam hardlopen (0.27 Nm/kg; 10%) als lopen (0.24 Nm/kg; 13%) met de rockerschoenen in vergelijking met standaard hardloopschoenen. De plantairflexieimpuls en het enkelgewrichtsvermogen waren met de rockerschoen ook significant verminderd ($p<0.001$) tijdens zowel langzaam hardlopen (respectievelijk 11 en 21%) als lopen (respectievelijk 17 en 25%). Er was geen significant verschil in knie- en heupmoment tijdens langzaam hardlopen en lopen in het laatste deel van de standfase. Er waren ook geen significante verschillen in de maximale amplitude van het EMG van de triceps surae tijdens langzaam hardlopen en lopen. Echter, de maximale amplitude van het EMG van de tibialis anterior was significant ($p<0.001$) verhoogd (64.7 µV, 20%) tijdens het lopen met rockerschoenen.

De conclusie van dit onderzoek was dat rockerschoenen het PFM verminderen tijdens de afzetfase bij zowel langzaam hardlopen als lopen bij gezonde mensen, en dat er daarbij geen systematische veranderingen in het knie- en heupmoment optreden.

De hypothese van het volgende onderzoek was dat patiënten met een pijnlijke Achillespees mogelijk hun looppatroon aanpassen ten gevolge van de pijn en daardoor een andere biomechanische reactie hebben op rockerschoenen dan gezonde mensen.

Daarom is in deze studie (Hoofdstuk 4) de biomechanica van langzaam hardlopen en lopen met rockerschoenen bij 13 patiënten (11 ♀, 48±14.5 jaar) met aangetoonde chronische Achillespeestendinopathie onderzocht. Bij de rockerschoenen was het maximale PFM met 13% verminderd tijdens zowel langzaam hardlopen (0.28 Nm/kg, $p<0.001$) als lopen (0.20 Nm/kg, $p<0.001$).

Het maximale heupflexiemoment was significant lager (8%, $p=0.019$) bij gebruik van de rockerschoenen tijdens lopen. Tijdens langzaam hardlopen waren er geen verschillen te zien in het maximale heup- en kniemoment in het laatste deel van de standfase. De maximale EMG amplitudes van de triceps surae veranderden niet tijdens zowel hardlopen als lopen. De maximale EMG activiteit van de tibialis anterior was verhoogd met 35% ($p=0.015$) bij het gebruik van de rockerschoen tijdens lopen.

Deze resultaten laten zien dat de rockerschoenen een significante vermindering in PFM in het laatste deel van de standfase kunnen bewerkstelligen bij mensen met chronische Achillespeestendinopathie. Dit geldt zowel voor langzaam hardlopen als voor lopen. Daarnaast zijn er geen grote veranderingen te zien in knie- en heupmoment en de spieractiviteit van de onderbeenspieren. Concluderend kan gesteld worden dat rockerschoenen nuttig kunnen zijn in het verminderen van de kracht op de Achillespees bij chronische Achillespeestendinopathie en kunnen rockerschoenen daarmee een rol spelen in de behandeling van symptomatische Achillespeestendinopathie.

In Hoofdstuk 5, is een onderzoek beschreven met als doelstelling te onderzoeken of rockerschoenen de belasting van de voorvoet tijdens hardlopen kunnen verminderen. Het ontlasten van de voorvoet tijdens hardlopen is vooral klinisch belangrijk voor hardlopers die herstellende zijn van metatarsalgie of een stress fractuur in de voorvoet. Achttien gezonde hardloopsters (23.6±3 jaar) namen deel in dit onderzoek. De deelneemsters renden 20 minuten op een loopband om te wennen aan de standaard hardloopschoenen en de rockerschoenen (beide schoenparen 10 minuten). De drukverdeling onder de voet werd in de schoen gemeten tijdens het hardlopen. Het comfort van de schoen werd na afloop van elke schoenmeting vastgesteld met behulp van een Visual Analog Scale (0 mm = “helemaal niet comfortabel”; 100 mm = “meest comfortabel mogelijk”). Hardlopen met rockerschoenen resulteerde, in de mediale, centrale en laterale voorvoet, in een significante vermindering van de maximale gemiddelde druk (respectievelijk 11% ($p<0.001$), 17% ($p<0.001$) and 23% ($p<0.01$)) en krachtimpuls (respectievelijk 12% ($p<0.01$), 17%

($p<0.01$) and 28% ($p<0.001$)) vergeleken met standaard schoenen. De maximale druk was significant verminderd met 24% en 27% in respectievelijk de centrale ($p<0.001$) en laterale ($p<0.001$) voorvoet en met 11% in de middenvoet regio ($p=0.02$). Vergeleken met standaard schoenen was de maximale druk, de maximale gemiddelde druk en krachtimpuls verhoogd rond de hiel tijdens hardlopen met rockerschoenen met respectievelijk 47%, 22% en 52% ($p<0.01$). Op de 100 mm Visual Analog Scale voor comfort, werd hardlopen met rockerschoenen gemiddeld beoordeeld met 33.3 mm, wat significant lager was ($p<0.01$) dan met de standaard schoenen (76.1 mm).

Dit onderzoek geeft het eerste bewijs dat rockerschoenen de kracht op de voorvoet tijdens hardlopen significant verminderden, en daarom bevorderlijk kunnen zijn voor hardlopers die herstellende zijn van een overbelastingsblessure van de voorvoet, zoals metatarsalgie of een stressfractuur in de voorvoet. Echter, een verschuiving van de kracht naar de hiel is een neveneffect. Daarnaast blijkt hardlopen met rockerschoenen, op de korte termijn, minder comfortabel dan hardlopen met standaard schoenen, wat het gebruik van dit type schoen zou kunnen beïnvloeden.

Loopefficiëntie kan een belangrijke factor zijn voor hardlopers en zou de schoenkeuze voor hun reguliere loopactiviteiten kunnen beïnvloeden. Hoofdstuk 6 beschrijft een onderzoek naar dit onderwerp. De zuurstofopname per tijdseenheid werd gemeten bij lange afstandsloopsters (23.6±3 jaar) tijdens een zes minuten durende submaximale loopbandtest met rockerschoenen, minimalistische schoenen en standaard hardloopschoenen. De hardloopsters hadden geen ervaring met hardlopen met rockerschoenen of minimalistische schoenen. De zuurstofopname tijdens hardlopen met rockerschoenen was gemiddeld 4.5% hoger dan met standaardschoenen ($p<0.001$) and 5.6% hoger dan met minimalistische schoenen ($p<0.001$). Concluderend kan gezegd worden dat hardlopen met de onderzochte rockerschoenen minder efficiënt is dan met minimalistische en standaard hardloopschoenen. Aangezien de bij dit onderzoek gebruikte rockerschoenen zwaarder zijn dan standaard hardloopschoenen en minimalistische schoenen, zal een deel van het effect van dit verhoogde energieverbruik met de rockerschoenen te verklaren zijn door de grotere massa vergeleken met de andere twee paar schoenen.

De uitkomsten van het onderzoek in dit proefschrift zijn geïntegreerd in Hoofdstuk 7. Om overbelastingsblessures bij hardlopen te voorkomen of te behandelen, heeft het meeste onderzoek van de afgelopen decennia zich geconcentreerd op het verminderen van de kracht tijdens het initiële voetcontact. Maar weinig aandacht is gegeven aan het omgaan met de grote krachten tijdens de actieve afzetfase bij hardlopen. Dit proefschrift is één van de eerste pogingen dit onderwerp te onderzoeken. De belangrijkste resultaten ondersteunen het potentiële gebruik van rockerschoenen in het verminderen van enkel- en voorvoetbelasting in de afzetfase tijdens hardlopen. Fase drie klinisch onderzoek is nu nodig om de effectiviteit van rockerschoenen bij de behandeling van Achillespeestendinopathie en overbelastingsblessures van de voorvoet te onderzoeken. Daarnaast verdienen de neveneffecten van rockerschoenen (bijvoorbeeld slechtere loopefficiëntie) de aandacht in toekomstig onderzoek om rockerschoenen te kunnen optimaliseren.

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