Running-related injuries among recreational runners

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Running-related injuries among recreational runners

How many, who, and why?

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Abstract

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Background. It is important for improving and maintaining general health to engage in regular physical activity. A major barrier to retain in regular physical activity is quitting because of an injury. In running, one of the most practiced leisure-time physical activities on a global scale, injuries are unfortunately common. The purpose of this dissertation was to explore questions related to *how many*, *which types of* and *why do* recreational runners sustain injuries. Specifically, how many runners sustain an injury over one year, and which are the most common anatomical locations of running-related injuries? More, are injuries more frequent in runners who have certain characteristics compared with runners having different characteristics? Finally, can exploring changes in training load help us understand why running-related injuries occur?

Methods. The dissertation builds on five papers, all based on data from a prospective cohort study named SPRING. Data were collected from 2016 to 2018. In addition, one paper (paper II) includes data from three other prospective cohort studies. One paper (paper I) is a study protocol presenting the design and methods. More than 200 injury-free male and female recreational runners between the ages of 18 to 55 years were recruited from the Gothenburg Half Marathon. The runners underwent a baseline examination consisting of tests for clinical/anthropometrical factors (such as range of motion, flexibility and trigger points), running style and isometric strength. Their training and injury status were then monitored for one year, or until

the runners were injured or censored (leaving the study due to other reasons than injury). A sports medicine doctor diagnosed the runners with injuries. The 1-year follow-up included training data from more than 17 000 running sessions, from all participants.

How many injuries occur? We found a cumulative proportion of new running-related injuries among recreational runners to be 46% over one year. Across the four studies in paper II, the difference between cumulative incidence proportions calculated with and without censoring ranged between 4% and 22%. In the SPRING-study, the difference was 13%-points, increasing from 33% without censoring to 46% with censoring. The most common anatomical locations were the knee (accounted for 27% of all injuries) and the Achilles tendon/calf area (25% of all injuries).

Who sustains an injury? It was found that runners with a previous injury were almost twice as likely to sustain a running-related injury as runners with no previous injury (Hazard ratio= 1.9, 95% confidence interval (95%CI) = 1.2–3.2). Moreover, the results suggest no associations at all between excessive or restricted joint range of motion, excessive or restricted muscle flexibility or having painful trigger points, and running-related injury, meaning that none of these variables served as strong predictors for running-related injury. However, runners having late timing of maximal eversion or a low ratio between hip abductor strength and hip adductor strength (i.e. relatively weak hip abductors) sustained 17%-point (95%CI= 1–34) and 21%-point (95%CI= 1–40) more injuries, respectively, compared with runners in the corresponding reference groups.

Why does injury occur? The data presented in this dissertation could not reveal the answer to the question of why running-related injuries occur. Although no strong causal relationship between changes in training load and running-related injury was found, the attempt to move closer to causal conclusions is novel in the running-related injury literature. Future studies will need thousands of more runners, and injuries, to reveal potential causal relationships.

Svensk sammanfattning

Bakgrund. Löpning är en av de populäraste motionsformerna i Sverige och i världen. Vi vet att fysisk aktivitet, så som löpning, förebygger flera våra vanligaste livsstilsbaserade sjukdomar, och därför är det ur folkhälsosynpunkt viktigt att minimera de risker som kan medföra att människor slutar att vara fysiskt aktiva. Inom motionslöpning kan en skada ofta leda till ett ofrivilligt träningsuppehåll. Syftet med denna avhandling var därför att utforska frågor kopplade till *hur många*, *vilka* och *varför* motionslöpare drabbas av löprelaterade skador. Mer specifikt, hur stor andel samt vilken typ av löprelaterade skador uppkommer under ett år i en population bestående av motionslöpare? Vidare, vilken typ av löpare har högre eller lägre risk att drabbas av en skada? Slutligen, kan vi med hjälp av förändringar i träningsbelastning förklara uppkomsten av skador?

Metod. Avhandlingen är en sammanläggning som bygger på fem artiklar, där samtliga är baserade på data från SPRING, en prospektiv kohortstudie med datainsamling mellan 2016 och 2018. Dessutom innehåller en av artiklarna (artikel II) data från tre andra prospektiva kohortstudier. Artikel I i avhandlingen beskriver studiens design och metodval. Drygt 200 skadefria män och kvinnor mellan 18 och 55 år rekryterades med hjälp av Göteborgsvarvets register. Motionärerna genomförde en undersökning gällande deras rörlighet, flexibilitet, triggerpunkter, löpstil och styrka och blev sedan ombedda att logga sin träning samt sin skadestatus under ett års tid, eller tills en skada uppstod eller att de censurerades (lämnade studien av andra skäl än skada). Deltagare som under studiens gång drabbades av löprelaterad smärta fick genomgå en medicinsk undersökning för att om möjligt fastställa diagnos. Den ett år långa uppföljningen inkluderade träningsdata från totalt mer än 17 000 träningstillfällen.

Hur många drabbas av en skada? Den kumulativa skadeincidensen, det vill säga andelen nya skador i relation till antalet observerade träningsdagar, uppgick till 46%. Utan att ta hänsyn till löpare som av olika anledningar inte fullföljde sin träningsrapportering under hela studietiden så var andelen skadade löpare 33%. Det betyder att andelen nya skador under ett år underskattades med 13 procentenheter om inte censurering togs i beaktan. Skillnaderna mellan andelen uppkomna skador beräknad med och utan censurering i de fyra studierna i artikel II varierade mellan 4 och 22 procentenheter. Vidare beskrevs vilken typ av skador som uppkom, där den vanligaste typen var knäskador (27% av alla skador) och skador i området kring hälsenan och vadmuskeln (25% av alla skador).

Vilken typ av löpare skadas? Löpare som haft en tidigare skada som läkt (för mer än 6 månader sedan) var nästan dubbelt så benägna att drabbas av en ny löparelaterad skada jämfört med löpare utan tidigare skada (Hazardkvot = 1.9 (95% konfidensintervall (95%KI)= 1.2–3.2). Vi kunde inte identifiera några starka samband mellan överrörlighet eller begränsad ledrörlighet, överdriven eller begränsad muskelflexibilitet eller smärtsamma triggerpunkter och löprelaterad skada. Däremot visade resultaten att löpare med svaga höftabduktorer i relation till höftadduktorer drabbades av 17 procentenheter (95%KI= 1–34) fler skador jämfört med den relativt starkare referensgruppen. Även löpare med en relativt sen timing av maximal pronation drabbades av 21 procentenheter (95%KI= 1–40) fler skador jämfört med löpare med senare timing av maximal pronation.

Varför uppkommer skador? Data som presenterades i avhandlingen kunde inte på ett tillförlitligt sätt svara på frågan varför löprelaterade skador uppkommer. Även om inga orsakssamband mellan förändring i träningsbelastning och skador identifierades, så är avhandlingens ansats ett viktigt steg i jakten efter svaret på varför löprelaterade skador uppkommer. Framtida studier kommer att behöva tusentals fler löpare, och skador, för att upptäcka möjliga kausala samband.

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II **Jungmalm,** J., Bertelsen, M. L. & Nielsen, R. Ø. (2020). What proportion of athletes sustained an injury during a prospective study? Censored observations matter. *British Journal of Sports Medicine*, 54(2):70-71. doi: 10.1136/bjsports-2018-100440

III Desai, P., **Jungmalm, J**., Börjesson, M., Karlsson, J. & Grau, S. (2021). Recreational runners with a history of injury are twice as likely to sustain a running-related injury as runners with no history of injury: a 1-year prospective cohort study. *Journal of Orthopaedic & Sports Physical Therapy*, 51(3), 144-150. doi: 10.2519/jospt.2021.9673

IV **Jungmalm, J.**, Nielsen, R. Ø., Desai, P., Karlsson, J., Hein, T. & Grau, S. (2020). Associations between biomechanical and clinical/anthropometrical factors and running-related injuries among recreational runners: a 52-week prospective cohort study. *Injury epidemiology*, 7(10):1-9. doi: 10.1186/s40621-020-00237-2

V **Jungmalm J.**, et al. Exploring training load and running-related injuries using ratio-based measures.
In manuscript

Abbreviations

ACWR	Acute: chronic workload ratio
AL	Acute load (acute training load)
Au	Arbitrary unit
BMI	Body mass index
CL	Chronic load (chronic training load)
DNR	Diary number
et al.	And others
EVA	Ethylene vinyl acetate
h	Hour
GPS	Global positioning system
IKD	Isokinetic dynamometry
IOC	International olympic committee
IQR	Interquartile range
ISB	International society of biomechanics
kg	Kilogram
km	Kilometre
m.	Muscle
mACWR	Modified acute: chronic workload ratio
n	Number of
N	Time in days
Nm	Newton metre
OR	Odds ratio
QTM	Qualisys track manager
RCT	Randomised controlled trial
RD	Risk difference
ROM	Range of motion
rpe	Rate of perceived exertion (Borg 6-20)
RR	Relative risk
RRI	Running-related injury
v	Version
95%CI	95% confidence interval

Introduction

Despite experiencing a slight decrease in popularity during the last four to five years, running is still one of the most practiced physical activities around the globe (Hulteen, 2017; Pedisic, 2020). Characterised by its accessibility and low cost, running is easy to engage in for many types of runners, including beginners, novice and recreational runners. Given its popularity, running offers great potential for improving and maintaining general health at a population level (Hespanhol Junior, 2015). For the individual runner, a major threat to reaching those health benefits is quitting running because of an injury (Bueno, 2018; Fokkema, 2019; Menheere, 2020). This thesis is focusing on running-related injuries, a common obstacle for persistent running among recreational runners.

Chapter 1: Background

Defining recreational running

Recreational running is not easily defined, and to the best of my knowledge, there was until very recently no accepted definition in the scientific literature (Yamato, 2015). From a semantic aspect, recreational activity is done for enjoyment outlining recreational running as running for fun. This definition has however several limitations. For example, it does not account for running experience, regularity, types of motivation or training volume. Researchers therefore commonly use other definitions of the term *recreational running* than just running for enjoyment.

Browsing through common definitions in the literature reveals several alternative definitions of this type of runner. For example, the RunClever study by Ramskov (2016) defined a recreational runner as a person who had been running between one and three sessions per week for at least 6 months. Other definitions of a recreational runner are "a person who has been running for at least six months" (Hespanhol Junior, 2013), "a runner participating in non-elite races" (Lopes, 2011), "an amateur or a non-competitive marathon runner" (van Middelkoop, 2008a) or "a runner that runs for enjoyment, with a running volume of at least 10 km per week" (Dingenen, 2019).

The lack of a clear nomenclature or definition of different types of runners calls for attention when comparing recreational runners between different studies. However, the majority of the different definitions include a certain period of running experience (e.g. 6 or 12 months), and/or running volume (e.g. 10 or 15 km per week) to exclude complete beginners. Further, competitive top-class runners are also often excluded or defined as another type of runner. Compared with other types of runners such as beginners or novice runners and top-class or elite runners, recreational runners are concerning training experience and volume usually "in-between" these groups. In the summer of 2020, Honert and colleagues presented a consensus statement for three different running levels including novice, recreational and high-calibre runners through a Delphi study based on 24 experts (Honert, 2020). According to this study, the training habits of a recreational runner are 1-5 sessions and 15-50 km per week, and the running experience exceeds 6 months of regular running.

The popularity of recreational running

For the past 50 years, people have used the concept of jogging, or recreational running, as a leisure-time physical fitness activity. The booklet *A Jogger's Manual* published in 1963 by William "Bill" Bowerman is by many seen as the birth of jogging as a public movement, at least in Northern America. In the 1970s people were running not only if they were competitive athletes or in a hurry, but also for recreational purposes. At the time, countries in Europe experienced a similar *recreational (r)evolution* where running became more accepted to perform in a non-sportive, deinstitutionalised and informal manner (Scheerder, 2015). Today, running is one of the most popular forms of leisure-time physical activity among adults on a global scale, and the top-three choice for physical activity regardless of worldwide geographic location (Hulteen, 2017).

Running is also the preferred physical activity by people in many countries across Europe (Scheerder, 2015). To highlight some countries, proportions of people that run regularly are reported to be 31% in Austria (Spectra, 2017), 29% in Denmark (Pilgaard, 2016), 25% in Germany (Preuß, 2012), 19% in Belgium (Scheerder, 2015), 17% in Sweden (Svenska Friidrottsförbundet, 2017), 15% in Finland (Scheerder, 2015) and 12% in the Netherlands (ibid). Even if the studies behind these numbers did not use the same definition on regularity, there is no doubt that millions of people are exposed to regular running (Hulteen, 2017; Andersen, 2020).

Participation in running events

The number of runners participating in events, such as the marathon and half-marathon, has increased extensively during the last decade. Globally, the number of race results indicates an approximate increase of 60% comparing 2008 with 2018 (Andersen, 2020). Since the peak in 2016, the total number of results has decreased slightly but still, almost 8 million finishing results were documented worldwide in 2018.

From a national perspective, the number of entrants in Swedish 10-42 km races increased by 126% between 2007 and 2014 according to data provided by the Swedish Athletics Organisation (Nilson, 2018). In 2019, more than 60 000 people participated in Gothenburg Half Marathon, making it the largest half marathon event in the world. The inhabitants in the western region of Sweden (Västra Götalandsregionen) are overrepresented when it comes to people who have planned to participate in a running event in the upcoming year (Svenska Friidrottsförbundet, 2017).

Health benefits from running

The positive impact on the cardiovascular, metabolic and immune systems as well as improvement of fitness and biological markers (such as improved insulin sensitivity) is scientifically well documented (Lee, 2014; Oja, 2015; Pedisic, 2020). Compared with sedentary behaviour, runners are at reduced risk of several health-related diseases and disorders, including diabetes mellitus type 2, breast and colon cancer, osteoporosis, fractures and depression (Pedersen, 2015). A few benefits emerge immediately after a running session, but the major part is dependent on the regularity of running (Hespanhol Junior, 2015). One of the most effective approaches for enhancing health is to keep up with running, or other similar physical activities, for the entire life (Lee, 2017). Therefore, to maintain the short- and long-term health benefits of running, it is of importance to minimise the factors forcing people to quit running.

Common reasons to quit running

For many years, a running-related injury (RRI) has been one of the major reasons to quit running (Koplan, 1995). Further reasons exist, such as sustaining other injuries, illness, lack of motivation or interest, insufficient time, age, engagement in other social or physical activities, pregnancy or childcare; however, RRI still seems to be the primary reason (Menheere, 2020). In a recent paper, Fokkema and colleagues (2019) found that 48% of the runners who stopped pointed out an RRI as the main reason for quitting running within 6 months after the start of a 6-week running program. Further, in a Danish study where novice runners took up running, 73% were still running after 270 days. Of those who discontinued, 23% had sustained an RRI (Bertelsen, 2017a).

In theory, people who quit running have the possibility to transit to other types of physical exercise and still be able to get health benefits from that activity. However, a study on 49 recreational runners found that runners engaged in less amount of physical activity during weeks in which they reported an injury compared with uninjured weeks (Davis, 2019). Thus, the achievable health effects from physical activity are challenged by the risk of sustaining a running-related injury. Further, a systematic review concluded that physical inactivity is a substantial economic cost for society (Ding, 2016). Hespanhol Junior and colleagues (2016a) quantified the economic burden of RRI to be more than 170 € per injury. Naturally, it is of great importance to promote physical exercise and get as many as possible to start exercise, however, it should not be underestimated to also make sure that physically active people can continue exercising. This includes a detailed understanding of injury aetiology and the development of preventive interventions.

Running-related injury definition

As running-related injuries are such an important barrier to overcome for reaching health benefits on a population level, it might be problematic to use different injury definitions. A systematic review from 2012 revealed that among the 30 studies included in the review (published between 1977 and 2008), more than 20 different definitions were used (Nielsen, 2012). Although the majority of these definitions could be categorised as one of the following three types of definitions, 1) time-loss 2) medical attention or 3) physical complaint, symptoms or pain, the possibility to make between-study comparisons is limited. In 2016, Kluitenberg et al. (2016a) showed that during a 6-week running program for novice runners, the RRI incidence ranged between 7.5% and 58%, depending on the RRI definition used.

To overcome this problem partly, Yamato and colleagues presented a consensus definition on RRI for recreational running (2015). This definition allows researchers to compare the incidence and prevalence of running-related injuries among different populations using the definition, which reads:

> "A running-related (training or competition) musculoskeletal pain in the lower limbs that causes a restriction on or stoppage of running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional"

Albeit a consensus definition strengthens the comparability between studies using it, a few more barriers need to be broken through before we can accurately compare measures of running-related injuries between different studies. What is not considered in the paper by Yamato et al., is the fact that injury measures in prospective studies (observational and randomised controlled trials) are also highly dependent on the compliance of runners during follow-up to accurately report the incidence and/or prevalence of RRI (Nielsen, 2020a). Kluitenberg and colleagues (2015b) also concluded that injury definitions and duration of follow-up affect the injury proportion, and stated: "*Future prospective studies of injury surveillance are highly recommended to take running exposure and censoring into account*". Censoring is an analytical technique that considers runners who, by any reason, are no longer under observation (e.g. quit sending in training monitoring information) (Cleves, 2016). Thus, if runners leave the study during follow-up the incidence proportion will be more accurate if censoring is applied (Nielsen, 2019a). However, injury surveillance studies cannot alone adequately advance the running-related injury thematic. Notwithstanding such studies include one important research goal – describing sports injury – other equally important research goals exist.

Three types of research goals

Many researchers have followed the sequences for injury prevention proposed by Willem van Mechelen in 1992 and later refined by Caroline Finch in 2006. The first two steps of these famous frameworks include 1) injury surveillance (reporting the extent of the problem) and 2) injury mechanisms (identification of risk factors) (van Mechelen, 1992a; Finch, 2006). These steps may result in studies having different research goals, which can be organised into *description*, *prediction* and *causal inference* (Hernán, 2019). Simplified, the different types of goals target different research approaches, designs operationalisation and evaluation. Specifically, description target questions of *how many*, prediction target questions of *who* and causal inference target questions of *why* (Hernán, 2019).

Researchers have not always been explicit with their goal of the research (Hernán, 2018; Nielsen, 2020b). Many of the hundreds of papers that have cited one of the framework studies seem to have targeted injury prevention and causality, although the approaches for drawing causal conclusions may not always have been appropriate (Nielsen, 2020c). The following sections aim to unfold this statement and clarify the differences and similarities between the three types of research goals.

Description

Describing sports injuries can be done using prevalence- or incidence-based measures, such as prevalent cases, prevalence proportion, incident cases, incidence proportion and incidence rate. Depending on the study question, aim and design, researchers have naturally been reporting different measures in previous research on running-related injuries (Videbæk, 2015). As the difference between these measures sometimes can be difficult to grasp for the reader, perhaps especially the difference between incidence proportion and incidence rate, it is important to accurately report the measure used. Unfortunately, in previous research on running-related injuries, there are many examples of when researchers fail to be specific about what measure they have used which can lead to confusion. One example is a paper from the study of the Vancouver Sun Run (Taunton, 2002). Here, the authors present an overall injury incidence rate of 29.5% over 13 weeks, based on 249 recorded injuries for 844 runners ((249/844)*100= 29.5%). However, this number represents the proportion of runners with new injuries during a period of 13 weeks expressed as a percentage – which is the same as the incidence proportion, and not the incidence rate. The incidence rate would have described the rapidity of which new injuries develop, that is, the number of new injuries divided by the total exposure time (e.g. injuries/hours of running).

One further source of confusion might be that prevalence and prevalence proportion are commonly used interchangeably, whereas incidence rate is commonly shortened to incidence (Nielsen, 2019a). Thus, it is not always clear for the reader if a proportion or a rate is presented.

In addition, as highlighted by a recent systematic review on lower limb running injuries by Francis et al. (2019), there is a lack of clarity and consistency regarding injury reporting in descriptive studies. In 19 out of the 36 included studies in this review the authors found unclear reporting of a) the total number of runners, b) the total number of injured runners c) the total number of injuries, and d) the number of new injuries versus recurrent injuries. This is very important as these numbers in combination with a specified time point or time period are used to calculate measures of prevalence and incidence adequately.

Other inaccuracies when describing the incidence proportion of sports injuries in prospective cohort studies exist. Specifically, authors sometimes present the incidence proportion as if all runners were at risk of sustaining an injury throughout the follow-up period. This is only true if the compliance is 100%, which very rarely is the case (Nielsen, 2020a). If runners drop out of the study without experiencing the outcome (injury), the time that runners are not under observation needs to be taken into consideration. A recent example of this is a study that presented the injury incidence proportion in a cohort of 706 recreational runners with a follow-up time of 3 months before, and 3 days after, a running event (approximately 95 days) (Dallinga, 2019). In total, 142 of 706 participants ((142/706)*100= 20.1%) reported an injury during preparation for the event. However, the authors chose to present the incidence proportion as if all 706 runners were at risk of sustaining an RRI over the 3 months, which they were not due to dropouts or missing information. Calculating the incidence proportion can be done by dividing the runners with new injuries by all runners at risk at the start of follow-up. Calculating a more accurate incidence proportion is however done by dividing the number of new injuries by runners at risk during the same time period. If a runner drops out of the study, he or she is not considered at risk anymore, and the denominator (number of exposed runners) should be adjusted accordingly. This consideration, or analytical technique as written in the previous section, is called right-censoring or only *censoring*. Table 1 summarises the incidence proportion (without considering censoring) from a few studies that included recreational runners. The goal of this table is not to outline all studies that have reported descriptive information on running-related injuries, but instead, highlight the large variety in incidence proportions (from 20.1 to 92.4%) and follow-up time (from 1 week to 12 months) throughout several decades (from the 1980s to today). Importantly, all studies (also those not listed in Table 1) have generated much knowledge about running-related injuries. However, it is also likely that the incidence proportions they have presented are underestimated. In summary, prospective studies having the goal to describe injury incidence or prevalence should consider 1) being more precise in the reporting of injury data and 2) the use of censoring.

Table 1. Injury incidence proportion in prospective cohort studies

Study (year)	Sample size (n)	Injuries (n)	Follow-up time	Incidence proportion (%)
Macera (1989)	583	300	12 months	51.3
Walter (1989)	1281	620	12 months	48.4
Satterthwaite (1996)	916	846	1 week	92.4
Taunton (2003)	844	249	13 weeks	29.5
Lun (2004)	87	69	6 months	79.3
Theisen (2014)	247	69	22 weeks	27.9
Dallinga (2019)	706	142	3 months	20.1
Winter (2020)	76	39	12 months	51.3

Prediction

In research on running-related injuries, prediction relates to the investigation of who is more likely to sustain an injury. Prediction studies aim to determine individual, or subgroup, risks compared with other individuals, or subgroups. The closely related term *predictor* has been widely used in sports injury research, as it is a common term to describe the independent factors in regression models. (Hulme, 2017). Others use *risk factor,* which is synonymous with predictor in many articles. Importantly, prediction is not always outlined as the research goal in risk factor-studies or studies using regression models. Nevertheless, I would argue that the majority of the studies included in recent systematic reviews (e.g. Hulme, 2017 and van Poppel, 2020) are related to prediction. Consequently, the majority of the current literature can assist in identifying who (or what type of runner) is more or less likely to sustain RRIs, by quantifying the risk of injury.

The risk of sustaining a running-related injury can be presented in both relative and absolute terms, where relative measures, such as relative risk (RR) or odds ratio (OR), are more common than for instance the risk difference (RD) which is an absolute measure of association. As in the previous section, I will again use a study by Taunton and colleagues (2003), this time to give an example where a relative measure of association is presented. Here, the authors revealed males with a BMI higher than 26 kg/m^2 were less likely (RR= 0.4, 95%CI= 0.2 ; 0.8) to sustain a running-related injury compared with males having a BMI lower than 26 kg/m^2. Having this information, a coach can identify this sub-group of low-BMI runners to whom particular attention can be paid, as they may be more likely to commit a training error that causes an RRI. Importantly, the coach cannot intervene on BMI in this case, but only closely observe the group as they have a higher risk of injury. However, this is only relevant if one group (the low-BMI runners) has more injures than the other group (the high-BMI runners). Having a quantitative measure of how many more runners are of increased risk is essential to be able to identify a potential clinical relevant difference between the groups. In this example, it could be that male runners with a BMI higher than 26 kg/m^2 have a 0.7% risk of sustaining RRI during the course of the study, and male runners with a BMI lower than 26 kg/m^2 have a 1.7% risk (RR= 0.7%/1.7%= 0.4). It could also be that the risk for high-BMI runners is 20%, and the risk for low-BMI runners is 50% (RR= 20%/50%= 0.4). Table 2 and Figure 1 visualises this fictive example (see also Nielsen, 2017). The absolute risk difference of 1%-point (RD= 1.7% – 0.7%) may not be clinically relevant, whereas an absolute risk difference of 30%-point (RD= 50% – 20%) may be. Despite having equal relative risks, the coach for groups A and B in Figure 1 can likely ignore any associations between BMI and RRI, simply as the fraction of influenced runners is very small whereas the coach for groups C and D might benefit from the same knowledge. By comparing these two fictive scenarios, it is clear that relative risks can be similar even if the risk differences are vastly different.

Table 2. Associations between BMI and RRI using a fictive example.

Group (BMI)	Runners (n)	Injuries (n)	Absolute risk (%)	Relative risk	Risk difference
A (>26 kg/m^2)	290	2	0.7	0.4	-1
B (<26 kg/m^2)	290	5	1.7	1 (ref)	0 (ref)
C (>26 kg/m^2)	20	4	20	0.4	-30
D (<26 kg/m^2)	20	10	50	1 (ref)	0 (ref)

Table 2. BMI= Body mass index. Relative risk is the ratio in absolute risk between groups A/B and C/D.

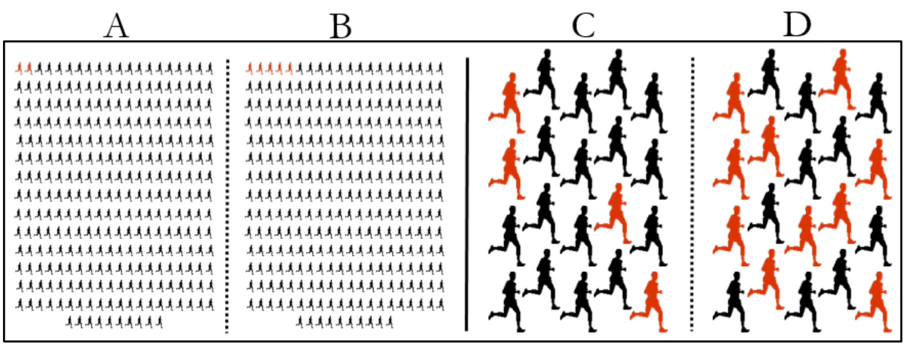

Figure 1. Four fictive groups of runners as an illustration of the equal relative risk between groups A/B and C/D. The red colour indicates an injured runner.

Research presenting associations between one or several predictors and an outcome is important as it can reveal interesting correlation coefficients, odds ratios or risk differences. However, the vast majority of the studies included in recent systematic reviews (Hulme, 2017; van Poppel, 2020) have used relative measures of association. Table 3 displays a summary of the used measures of association derived from these reviews. As previously discussed, presenting absolute measures of associations might increase the practical usefulness for runners, coaches and clinicians. Further, a relative measure, such as an odds ratio, may be misleading if it is used to exaggerate a trivial difference (as for group A/B in Table 2). When the absolute risk difference is presented, the number of affected people is considered, and the reader can form an idea of the total impact.

Table 3. Measures of association used in studies included in the reviews by Hulme (2017) and/or van Poppel (2020).

Measure of association	Study (year)
Relative measures of association	
Relative risk	McQuade (1986), Walter (1989), Taunton (2003), Kelsey (2007), Reinking (2007), Lopes (2011), Rasmussen (2013), Ryan (2014), Malisoux (2015a), Messier (2018)
Relative rate	van Mechelen (1993), Wen (1998)
Odds ratio	Macera (1989), Satterthwaite (1996, 1999), Wen (1997), Hootman (2002), Taunton (2002, 2003), McKean (2006), van Middelkoop (2007, 2008a), Buist (2008), Knobloch (2008), Thijs (2008), Ghani Zadah Hesar (2009), van Ginckel (2009), Parker (2011), Bennett (2012), Chang (2012), Hirschmüller (2012), Hespanhol Junior (2013, 2016b), Messier (2018)
Hazard ratio	Reinking (2006), Cobb (2007), Kelsey (2007), Buist (2010a, 2010b), Bredeweg (2013), Theisen (2014), Nielsen (2014a), Hotta (2015), Kluitenberg (2015a, 2016b), Malisoux (2015a), van der Worp (2016), Napier (2018)
Absolute measures of association	
Risk difference	Nielsen (2013a, 2014b), Ramskov (2015), Brund (2017)

Table 3. Studies in the table are presented solely with the first author and publication year.

As visualised in Table 3, the majority of previous studies used a ratio-based measure of association, and only four considered using an absolute measure of association.

Finally, the example presented above indicates that runners with a high BMI have a 60% lower risk of sustaining RRI than individuals with a low BMI, but it does not indicate that increasing the BMI will lower the risk of RRI by 60%. It only says something about *who* is more or less likely to sustain an injury, not *why*. To be able to draw causal conclusions, and explain if and why manipulating BMI changes the risk of RRI, prediction research is not helpful (Hernán, 2018). As we move on to the section on causal inference, it is important to mention that some risk factors can be both predictors and causal factors for running-related injury (Schooling, 2018).

Causal inference

Causal research questions help us understand *why* running-related injury occurs. In this dissertation, I assume that training load is a *necessary cause* for running-related injuries (Rothman, 1976). Although several definitions exist (Udby, 2020), training load can be defined as the sum of all physical stresses on a certain structure during running (Impellizzeri, 2019). To explain briefly, in this case, a necessary cause means that physical stress during running is needed to cause an RRI. Consequently, it is not possible to sustain an RRI without running (Malisoux, 2015b).

In the scientific literature, running-related injuries are often described to have a multifactorial nature, which means, an RRI is considered to be caused by multiple factors (Meeuwisse, 2007; Bertelsen, 2017b). Indeed, many factors may have a causal effect on RRI, although training load is the only necessary factor. More specifically, RRI is believed to occur if the load applied to a certain structure in the body is higher than the capacity to tolerate load for that specific structure is (Hreljac, 2005; Bertelsen, 2017b). Other factors, such as running style or strength capacity, may influence both the applied training load and the capacity to withstand load, but cannot alone cause injury.

Recent frameworks have been developed to visualise the relationship between training load, load capacity and influencing factors (Bertelsen, 2017b; Edwards, 2018; Nielsen, 2018a). As described in the framework on the aetiology of RRI by Bertelsen and colleagues (2017b), the effect of training load on RRI most likely differs across runners having different characteristics (Figure 2). This implies that the susceptibility to injury likely varies within and among runners. In other words, different runners will have different characteristics and tolerate different amounts of training load. The International Olympic Committee (IOC) is supporting this statement and has declared it very unlikely that a universal training programme to reduce injuries exists (Soligard, 2016). As discussed in the previous section, the majority of the existing RRI-literature can reveal who is more likely to sustain an injury, and how different characteristics or factors might increase or decrease the risk of RRI have been researched extensively in the last decades (Hulme, 2017; van Poppel, 2020). Unfortunately, researchers have sometimes also – at least to some extent – disseminated potential prevention guidelines. One example of this is from a study by van Middelkoop and colleagues (2008b) among male marathon runners, where smokers sustained fewer injuries than non-smokers. Even if smoking was found to be significantly protective against RRI, it is biologically unlikely to believe that non-smokers would sustain fewer running-related injuries if they started smoking. The authors are fully aware of this and do critically discuss this result as implausible, and that smoking is likely a proxy for a non-measured variable. On the other hand, the authors also write: "this study indicates that daily smoking helps to prevent running injuries", which I interpret as a causal statement. However, to be able to draw causal conclusions and make informed decisions regarding injury prevention, it is important to align the rationale and analytical approach with one of the training load-frameworks (Nielsen, 2020c). Injury prevention advice should be based on information provided from such studies. As none of the studies included in the reviews by Hulme (2017) and van Poppel (2020) have this alignment clarified, we are based on the current literature not able to explain why RRI occurs. Importantly, much of the literature is very valuable and can help us in understanding who is more likely to sustain an RRI.

Perhaps is it not enough to include only training load as the primary exposure to be able to draw causal conclusions on why running-related injury occurs. It might be necessary also to include other influencing factors. However, according to the training load theories, if the goal is to explore why running-related injury occurs, monitor training load is an essential step.

Moreover, if susceptibility to injury varies across populations, as the IOC and others seem to agree on (Soligard, 2016), researchers need to move away from giving generalised population-based prevention guidelines and towards personalised prevention strategies (Nielsen, 2020d; Stovitz, 2019). Personalised in the sense that an advice or prevention strategy is communicated to sub-groups of runners, and not to all runners.

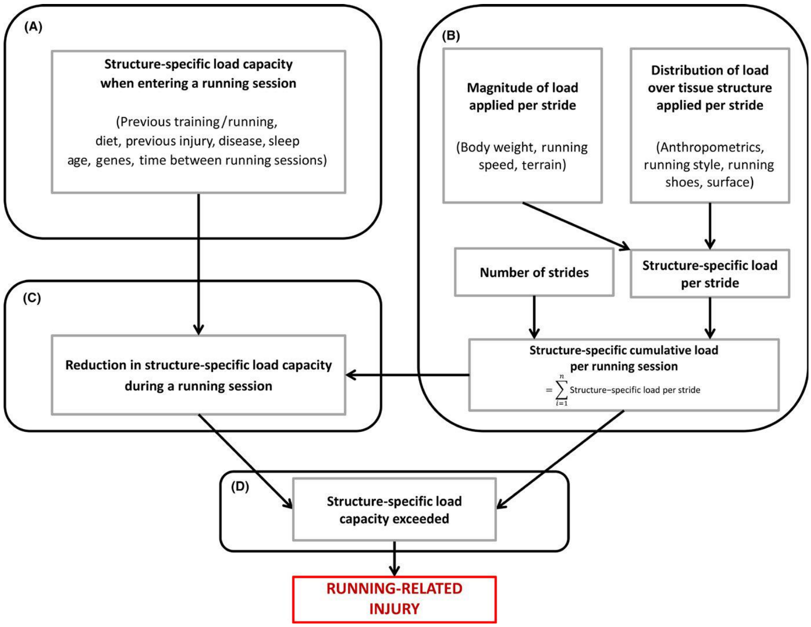

Figure 2. A causal framework for RRI, by Bertelsen et al. (2017b). The cornerstone in this framework is that an injury occurs if the cumulative load of a running session exceeds the capacity of a structure in the body (e.g. a muscle or a ligament). The risk of injury can increase or decrease if the load capacity (e.g. recovery or nutrition), the magnitude of the load (e.g. running speed) or the distribution of the load (e.g. new shoes) changes.

Training load monitoring

In research on running injuries, different expressions for the variables related to training load and load capacity exist. For instance distance, workload, stress, running participation (related to training load) and sleep, soreness and fitness level (related to capacity) have been used (Udby, 2020). This dissertation will mainly use the term *training load* to describe the variables contributing to physical stresses (loads) that a certain musculoskeletal structure is exposed to during a training session.

Monitoring training load in running has mainly been done using external measures of training load such as distance (km or miles) and duration (Paquette, 2020). Recently, attention has been brought to monitor training beyond these metrics, for example by including measures of internal training load, such as intensity (Napier, 2020; Ryan, 2020).

Changes in training load

Changes (progression and regression) in training load can be calculated in several ways, for instance by using bi-weekly changes, which have been done in a few previous RRI-studies (Buist, 2010b; Nielsen 2014a; Winter, 2020). In the majority of these studies, external training load measures such as distance have been the only measures included to calculate weekly changes. Another tool developed for calculating changes in training load is the acute to chronic workload ratio (ACWR) proposed by Hulin and colleagues (2014). ACWR consists of two measures of load, the acute load that represents the "short-term" (usually one week) training load and chronic load that represents the "long-term" (usually three or four weeks) training load (Gabbett, 2016). Then a simple ratio can be calculated by dividing the acute load by the chronic load. Here, the intensity is commonly included in the acute and chronic load parameters, represented by the rate of perceived exertion (Borg rpe or session rpe) (Borg, 1982). ACWR has mainly been used in team sports such as rugby, football and cricket. Of twelve included studies in a systematic review on the associations between training load and musculoskeletal injury, none reported measures of internal training load or ACWR, and only one study analysed changes in training load (Johnston, 2018). Another systematic review including four original articles investigating the association between changes in training load and RRI was published by Damsted and colleagues (2018). Here, three studies reported sudden or recent increases in training load to be associated with increased injury risk. Again, no study reported or included any measures of internal training load. To the best of my knowledge, only one study has used the ACWR in a running population, where the researchers studied 23 competitive runners over two years and could not find any association between ACWR and injury (Dijkhuis, 2020).

Many ways of altering the ACWR exist, for instance by using different time-windows (Carey, 2017), weighting techniques (Murray, 2017) or coupling methods (Windt, 2019; Gabbett, 2019). In a study on the associations between ACWR and health problems in youth football players, the authors concluded that 108 different "analysis methods" (i.e. alterations or versions) of the ACWR can be performed (Dalen-Lorentsen, 2021). The fact that no uniform version of the ACWR is agreed upon, and that many of the alterations have surfaced due to different inherent limitations with the ratio is problematic. Several researchers have expressed their concerns about the (mis)use of ACWR (Impellizzeri, 2020; Wang, 2020) and for instance the Australian Institute of Sports is recommending to not use the metric, although the value of monitoring training load remains fully supported (https://www.ais.gov.au). Others promote further research and collaboration to generate a more robust metric (Andrade, 2020; Maupin, 2020; Wang, 2021), and the IOC has not updated its position about the use of ACWR since the endorsement in 2016 (Soligard, 2016). In addition, several commercially available tools for training monitoring, such as Training Peaks ®, use ACWR to inform their users about the training load for a training session.

In summary, change in training load is indeed an important and rather unexplored area of study, especially if both physiological (e.g. internal) and biomechanical (e.g. external) measures to monitor training load are considered. However, the use of ratio-based measures in RRI-research is controversial.

Population-based prevention

One example of population-based injury prevention advice in running-related injury research is the 10%-rule. The 10%-rule says that the increase in weekly training volume should not exceed ten percent. This advice is known for decades (Paty Jr, 1984), and has surfaced in the literature many times over the years (Johnston, 2003; Buist, 2008). Maybe a bit surprisingly, the supportive scientific evidence of this advice is close to non-existent (Damsted, 2018), and the rule should therefore not be used as a guide for *all* runners. However, it might be reasonable to give to certain runners. For example, one study found an increased rate of sustaining injury among novice runners who increased the weekly distance by 30% compared with novice runners who increased the weekly distance by less than 10% (HR= 1.59) (Nielsen, 2014a). But what happens if we give the same advice, to not increase the weekly training volume more than 10%, to all runners? Most likely, some runners who tolerate more than a 10% increase in training load will lose potential training effects. For other runners, even smaller increases than 10% will be excessive (Nielsen, 2020d). Therefore, contemporary frameworks recommend a more "individualised" approach, in the sense of exploring sub-group differences. Thus, giving population-based prevention advice on training load does not align with current training load theories and frameworks, or with the IOC who does not believe in one universal training programme for different types of athletes. If the goal is to examine training load-related research questions, and for instance explore how much running that is *too much* or *too soon* (Soligard, 2016; Schwellnus, 2016), personalised prevention is more suitable.

Personalised prevention

If the research goal is causal inference and researchers aim to generate personalised prevention strategies, there is a major difference in appropriate analytical approach compared with if the goal is population-based prevention, namely the inclusion of confounders or effect-measure modifiers. Confounding is related to potential bias when estimating the direct, in-direct or total causal effects, and produces one adjusted estimate (Christenfeld, 2004; Mansournia, 2017). Effect-measure modification can be used to produce one estimate for each sub-group analysed, and therefore reveal sub-group differences in a sample. Thus, if the research goal is to explore some effect across different characteristics or types of runners, these sub-groups can be included in the analyses as effect-measure modifiers (Knol, 2012). Consequently, it is possible to inform if for instance a progression in training load is more or less injurious among runners with different characteristics.

The concept of effect-measure modification is not new but has been sparsely used within research on sports injuries. For instance, Nielsen, (2014a) and Malisoux, (2015b) have used effect-measure modification with hazard rate ratio as the measure of association. Two other studies by Nielsen (2014b and 2014c) used cumulative risk difference as the measure of association.

Many variables might serve as effect-measure modifiers on the association between training load and running-related injury. To visualise both the measured and unmeasured variables/factors in the present study, a graph was created (Figure 3). This was also an approach to visualise the relationship between structure-specific load, structure-specific load capacity and running-related injury, guided by the previously mentioned framework on the aetiology of RRI. Detailed quantification of structure-specific load and structure-specific load capacity is close-to impossible in epidemiological studies, however, many of the proxy variables in Figure 3 are possible to quantify.

The idea behind Figure 3 was to display how different factors might increase or decrease the risk of sustaining a running-related injury, and simultaneously embrace the importance that exceeding the load-capacity (by running an excessive distance) is the fundamental causal assumption behind all running-related injuries. Importantly, the graph does not reveal whether a variable should be included as an effect-measure modifier or not, and it is not considered to represent a directed acyclic graph.

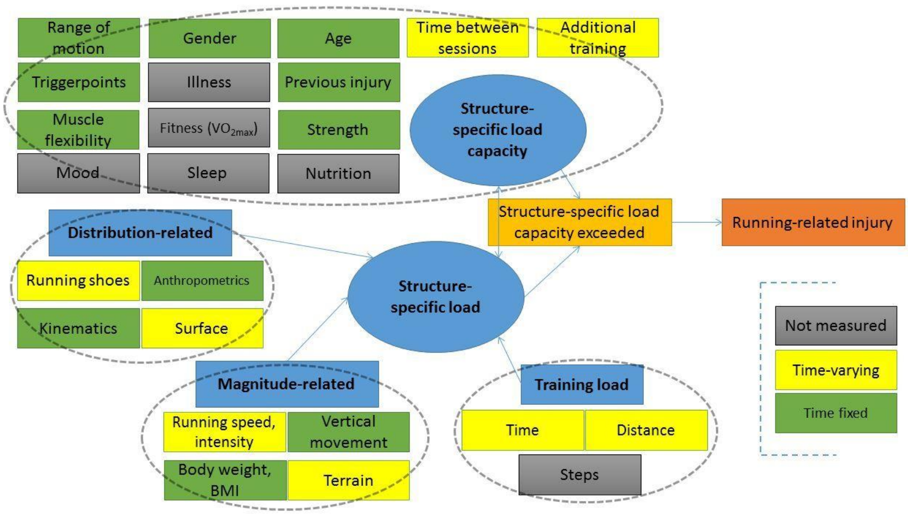

Figure 3. A graph to visualise the relationship between structure-specific load and structure-specific load capacity, and running-related injury. Variables in green are considered time-fixed, yellow variables are considered time-varying and grey represent variables not measured.

Finally, if no training load exposure is included in the calculations of different measures of association, an underlying assumption must be that running exposure is similar in the compared groups (Nielsen, 2016). Therefore, it is important to present data on distance, time, steps, or other values of training load also when investigating the associations between non-training load-related characteristics and RRI.

Magnitude-related variables

The magnitude-related variables in Figure 3 represent factors that may influence the size of the applied load, such as running speed and body weight. As an example of previous research on magnitude-related variables, one study found that slower running speeds decrease the load per stride at the knee joint and, for faster running, the cumulative load for a given distance increases compared with slower speeds (Petersen, 2015). Moreover, running with an additional load applied (Silder, 2015) or running with a high BMI compared with a low BMI (Vincent, 2020) alters the load magnitude of one stride.

Distribution-related variables

The distribution-related variables, such as shoe-wear or running style (kinematics), refer to factors that may influence how the applied load is distributed within and between structures in a body. For example, the degree of foot movements, such as pronation or rear foot eversion, has been discussed as factors affecting how the load is distributed during running (Behling, 2020). Other examples of factors that influence how loads are distributed include minimalist shoes (increases load at the ankle joint) and stride length, where shorter strides decrease the loads at the ankle and knee (Firminger, 2016).

Summary of background

Based on knowledge from the available literature on running-related injuries among recreational runners, it appears that prospective studies that do not account for censoring cannot answer the question of *how many* runners sustain an injury over time with sufficient accuracy. There is also a need to investigate what type of runners have a higher or lower risk of RRI using absolute measures of association, answering the question of *who* is sustaining running-related injuries. Finally, few studies have explored *why* running-related injuries occur by using time-varying training load-exposures and ratio-based measures.

Purpose of the dissertation

The purpose of this dissertation was to explore running-related injuries among recreational runners, targeting three types of research goals, description, prediction and causal inference.

First, *how many* (targeting description): to describe the cumulative incidence proportion (CIP) over the course of one year, and describe the most common anatomical locations of running-related injuries among recreational runners.

Second, *who* (targeting prediction): to identify who is more likely to sustain a running-related injury depending on certain clinical/anthropometrical and biomechanical characteristics.

Third, *why* (targeting causal inference): to explore if changes in training load can explain why running-related injuries occur using ratio-based measures.

Aims and research goals of dissertation papers

Paper I: Study protocol

This paper aimed to present the design of a prospective cohort study to add comprehensive information on the aetiology of running-related injuries and present a new approach for investigating changes in training load in recreational running. The paper outlined five hypotheses, of which two (#1 and #5) are included in this dissertation.

Paper II: Educational editorial (description)

The aim was to compare the analytical approaches for cross-sectional studies and prospective cohort studies (i.e., without censoring and with censoring, respectively) to help the reader accurately estimate incidence proportion in prospective studies.

Paper III: Original research (description, prediction)

This paper aimed to estimate the incidence proportion of running-related injuries over one year, describe the anatomical locations of RRI, and to investigate the associations between running-related injuries and previous injury, running experience, weekly running distance, age, sex and body mass index.

Paper IV: Original research (prediction)

The aim of this paper was to investigate whether runners with certain biomechanical or clinical/anthropometrical characteristics sustain more running-related injuries than runners with other biomechanical or clinical/anthropometrical characteristics.

Paper V: Original research (causal inference)

The aim was to explore changes in training load and incidence of running-related injuries using ratio-based measures.

Chapter 2: Methods

The planning of a prospective cohort study on running-related injuries among recreational runners started in 2015. The application to the funding agency Sten A Olssons' foundation for Research and Culture with SG as the principal investigator was approved later the same year (project approval title: *Health promotion with focus on physical activity and injury prevention*).

Data sources, ethical approval and consent

One prospective cohort study, named SPRING, served as the main data source for papers III, IV and V in this dissertation. No data needed to be collected for paper I, as it was a study protocol. For paper II, the educational editorial, data from four prospective cohort studies were used: *the Danish novice runner study, Dano-Run* (Nielsen, 2011), *the RunClever study* (Ramskov, 2016), *the Project Run21 study* (Damsted, 2017), and finally *SPRING* (Jungmalm, 2018). Importantly, I did not take part at all in any of the three former studies and they are therefore not further described in this dissertation.

The Gothenburg regional ethical review board approved the SPRING-study (approval numbers: 712-15 and 713-15), and the study was compliant with the General Data Protection Regulation. The Danish studies (Dano-Run, RunClever and Project Run21) followed Danish law regarding data protection and ethical approval. Two studies, Dano-Run (request number: M-20110114) and Project Run21 (request number: 187/2015) required no ethical approval according to the Ethics committee of the Central Denmark Region. The Ethics committee of the North Denmark Region approved the Run Clever study (approval number: N-20140069). All participants in each of the studies provided written informed consent before their inclusion.

Study design, setting and participants for the SPRING study

The study was designed as a prospective, observational cohort study with 52 weeks of follow-up. The study took place in Gothenburg, Sweden and the runners were recruited from e-mail records administered by the organiser of the Gothenburg half marathon, which is the Gothenburg Athletic Association. The records contained approximately 60 000 e-mail addresses and the organiser managed the distribution of invitation e-mails. All persons who received an e-mail with an invitation to, and information about the study, were allowed to invite other people they assumed to have interest in participating in the study. People who showed interest in participating in the study by responding to the e-mail or making contact with the test leader (n=294), were initially screened for eligibility. After the screening, 227 participants scheduled a time for baseline examination. Two male runners were excluded at baseline, one who did not show up and one who showed up with a very recent knee injury. One male runner reported pain, which later was classified as an injury, after the end of follow-up (at day 367), and was therefore included in the baseline information but excluded from the analyses as the injury occurred after the 1-year follow-up. A flow chart of the recruitment and eligibility procedure is presented in Figure 4. Participant recruitment started in February 2016 and ended in January 2017, and data were collected from March 2016 to March 2018.

Consequently, 225 healthy recreational runners completed the baseline examination and participated in the study. Healthy was defined as a person free from any musculoskeletal injury to the lower extremities during the past six months. A recreational runner was defined as a runner with an average weekly running volume of at least 15 km during the preceding year (e.g. from March 2015 to March 2016 for the first registered participant). Fulfilling the inclusion criteria of being a healthy recreational runner, according to these definitions, was required to participate in the study. All runners who participated in the study provided written consent prior to baseline examination.

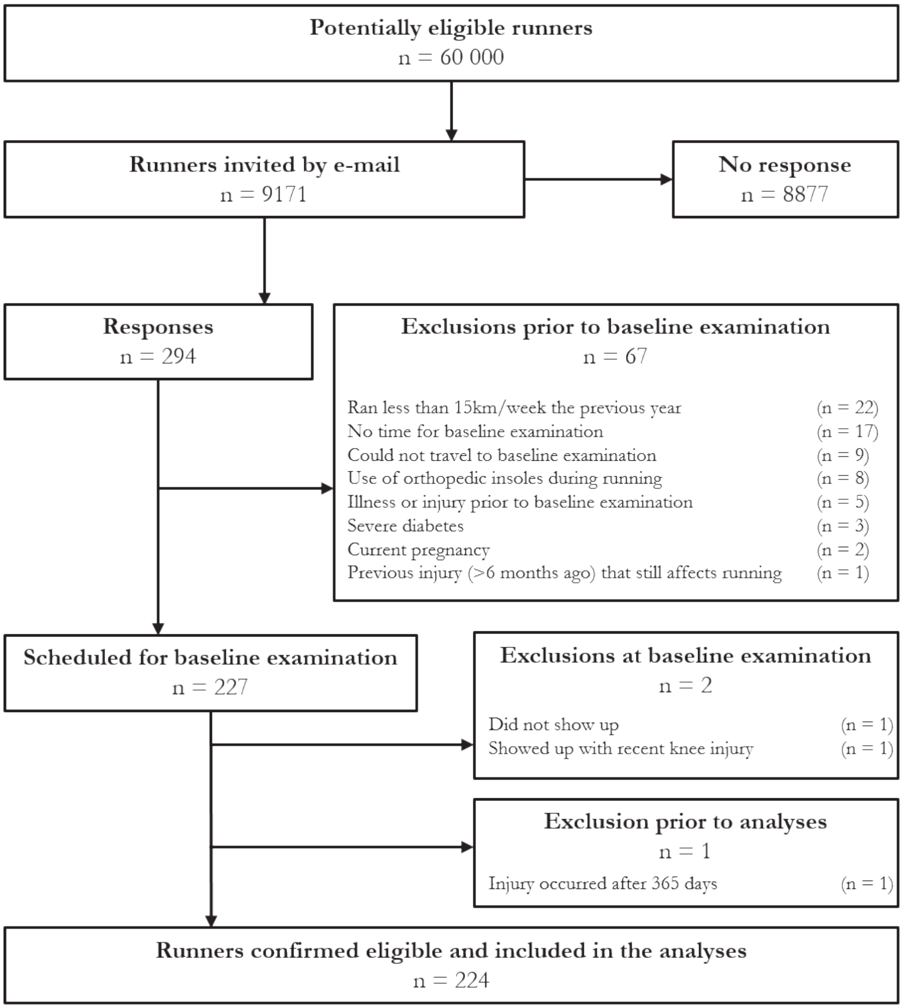

Figure 4. Recruitment procedure and the inclusion and exclusion of participants.

Baseline examination

At the baseline examination, participants self-reported information about running experience, training habits, personal bests and equipment by filling out a questionnaire. They were then informed about the training diary and how to use it. The diary was a two-page Excel sheet where the first page consisted of running-specific information on distance (km), duration (min), intensity (Borg rpe), type of training (easy/medium/fast/interval/competition), running shoes (brand and model), surface (soft/medium/hard), terrain (elevation), stretching and pain, for each day in the week. The second page included a summary of the total training volume for that week as well as an open text box where participants could comment about pain, illness, new shoes, or anything that they believed could be of importance for the study. The second page also explained the Borg rpe scale for intensity and the Visual analogue pain scale. Importantly, all participants were explicitly told not to change anything in their running regimen because of the participation in the study.

The second part of the baseline examination included a physical examination, consisting of a clinical/anthropometrical assessment, a biomechanical running analysis and isometric strength tests, all following a standardised protocol performed by the test leader. A summary of characteristics obtained from the baseline examination can be seen in Table 4.

Table 4. Baseline characteristics

	Women (n=89)	**Men (n=136)**	**Range (n=225)**	**All group (n=225)**
Age (years)	40.0 (± 8.5)	40.5 (± 7.8)	22 – 55	40.3 (± 8.1)
Height (cm)	168 (± 6)	180 (± 6)	152 – 196	175 (± 9)
Mass (kg)	61.3 (± 7.2)	76.0 (± 8.4)	44.2 – 98.4	70.2 (± 10.7)
BMI (kg/m²)	21.8 (± 2.0)	23.3 (± 1.9)	17.4 – 30.2	22.7 (± 2.1)
Previous injury (% yes)	50.6	65.4		59.6
Running experience (years)	10 (6 – 16)	10 (5 – 20)	1 – 45	10 (5 – 17)
Weekly distance (km)	25 (20 – 35)	27.5 (22.5 – 40)	15 – 100	25 (20 – 39)
Weekly running frequency	3.3 (± 0.9)	3.4 (± 1.4)	1.5 – 12	3.4 (± 1.2)
PB half marathon (min)	108 (± 13.9)	93 (± 6.3)	75 – 142	99 (± 12.7)

Table 4. Participant baseline characteristics presented as mean and standard deviation (±SD) for age, height, mass, body mass index (BMI), weekly running frequency and personal best (PB) at the half marathon, and median with interquartile range (IQR) for running experience and weekly distance. Weekly distance equals the average weekly distance during the preceding year, frequency indicate the average number of running sessions per week during the preceding year.

As the participants were recruited from the Gothenburg half marathon, thus some of these characteristics can be compared with data extracted from the Gothenburg half marathon. In 2016, the median age was 41 years for men and 38 for women and the female proportion of runners completing the half marathon has been 34%-

35% over the last four years (https://www.goteborgsvarvet.se). Unfortunately, no comparisons between the half marathon population and the study sample regarding BMI, running experience, weekly distance and average running frequency were possible.

Clinical/anthropometrical assessment

First, the height and body mass of each participant was measured with a ruler and a calibrated personal scale (Kern MPB300K100; Balingen, Germany), to enable calculations of body mass index (BMI). The test leader then asked the participants to describe any previous sports-related injury they experienced, which has affected their running. Importantly, all participants were again informed about the need of being injury-free the past 6 months.

Further, passive joint range of motion (ROM) for the hip, knee and ankle joints was tested for the left and right sides. One test leader examined flexion, extension, abduction, adduction, internal and external rotation of the hip joint, flexion and extension of the knee joint and dorsiflexion, plantarflexion, eversion and inversion of the ankle joint (Table 5). All tests were done with the participants in a supine position, except the hip extension test which was done with the participant lying on the side. ROM was categorised as *restricted* or *excessive* when there was a visual difference of at least ±10° compared with the average *normal* ROM.

Table 5. Normative values of passive range of motion tests.

Joint motion	Restricted	Normal	Excessive
Hip flexion	<125°	130° – 140°	>145°
Hip extension	<5°	10° – 20°	>25°
Hip abduction	<45°	50° – 80°	>85°
Hip adduction	<15°	20° – 30°	>35°
Hip internal rotation	<25°	30° – 40°	>45°
Hip external rotation	<35°	40° – 50°	>55°
Knee flexion	<115°	120° – 150°	>155°
Knee extension	<0°	0° – 10°	>10°
Ankle dorsiflexion	<5°	10° – 20°	>25°
Ankle plantarflexion	<35°	40° – 50°	>55°
Foot eversion	<20°	25° – 35°	>40°
Foot inversion	<40°	45° – 55°	>60°

Table 5. Cut-off values for range of motion, categorised into normal, restricted, and excessive.

Moreover, muscle flexibility was assessed unilaterally for the hamstrings with the straight leg raise test and for m. iliopsoas and m. rectus femoris with the Thomas test. Muscle flexibility was categorised as *normal* or *restricted*. For hamstrings and rectus femoris, values below 90° were considered as *restricted*, and above 90° considered as *normal*. For m. iliopsoas, a value above 0° was considered as *restricted*, and below 0° considered as *normal*. The neutral zero method was used as a reference for the clinical/anthropometrical assessments and the corresponding normative values (Ryf, 1995).

Lastly, the test leader assessed the occurrence of trigger points in lower leg muscles. Trigger points were defined as *a tender area in a muscle or tissue that reproduces pain during palpation* (Nix, 2017). Participants simply informed the test leader whether they experienced pain when the current muscle or tissue was palpated. Trigger points were assessed at the tractus iliotibialis, m. gastrocnemius, m. soleus, m. piriformis, m. gluteus medius, m. tibialis posterior and m. tibialis anterior. All clinical/anthropometrical measures of joint range of motion, muscle flexibility and trigger points were measured on categorical scales.

Biomechanical running analysis

The biomechanical laboratory was set up with 12 pieces of 1.1 m long, 72 cm wide, and 24 mm thick ethylene vinyl acetate (EVA) mats, creating a diagonal foam runway on the lab floor. The running speed was controlled by two light beam photocells (Alge-timing, Lustenau, Austria) and placed halfway through the runway, 2.0 m apart from each other. A 3D motion-capture system (Qualisys AB, Gothenburg, Sweden) with 16 cameras aimed at the centre of the runway created a motion-capture volume of approximately 16-20 m^3 (Figure 5). Cameras had a sampling frequency of 400 Hz.

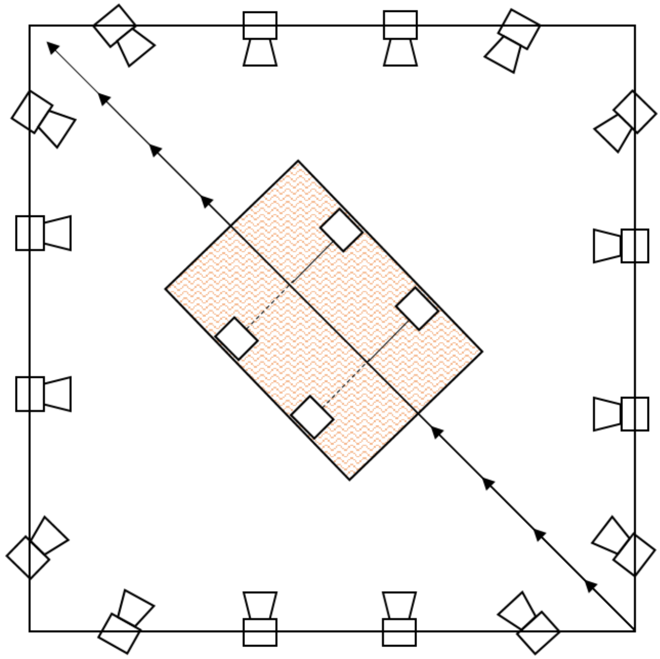

Figure 5. Sketch of the laboratory setup seen from above, including 16 motion-capture cameras and two light beam photocells. The coloured area shows the estimated capture volume. Participants ran diagonally across the laboratory, both directions, and arrows indicate the running direction for motion capture.

To collect motion, the cameras use infrared technology to detect the position of reflective markers. Therefore, participants were equipped with 32 spherical reflective markers placed at anatomical landmarks (Figure 6), according to the recommendations by the International Society of Biomechanics (ISB) (Wu, 2002). Six markers at the hip (2x anterior and 2x posterior superior iliac spine, and 2x trochanter major). Five markers at each knee (medial and lateral epicondyle of the femur, medial and tibial plateau, and tuberositas tibiae). One marker was placed at each tibia. Seven markers at each foot (medial, lateral and posterior side of the calcaneus, lateral and medial malleolus, and first and fifth metatarsal head).

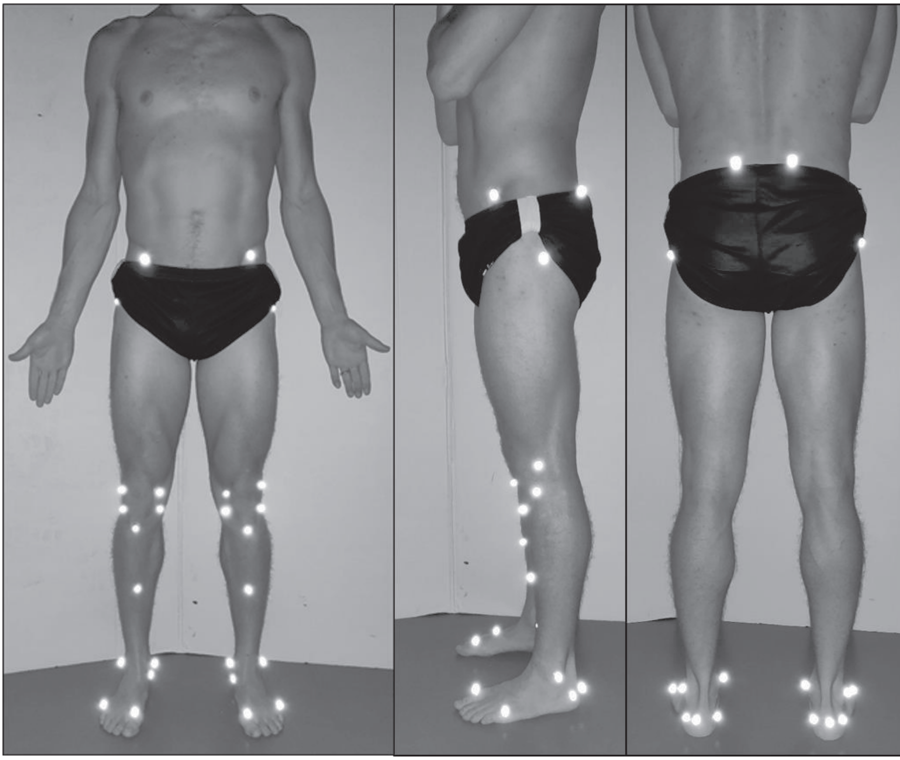

Figure 6. Marker placement.

After the marker setup, participants started running back and forth in the laboratory to warm up and get familiar with the testing situation. During these 5-10 minutes, they also learned to keep a speed of approximately 12 $km \cdot h^{-1}$. Following the warm-up, a static trial was captured with the participant facing the forward running direction in a neutral anatomical static position. All markers were re-checked before the participant ran barefoot on the runway for 25 trials within the given speed range of 11.4 – 12.6 $km \cdot h^{-1}$. The foam mats were then removed, and the participants repeated the procedure using his or her own running shoes, running directly on the floor. The reflective areas of the shoes were taped in advance to avoid unwanted reflections/ghost markers in the Qualisys Track Manager (QTM) software. For each of the conditions, one or two full strides were collected per running trial, depending on the individual running style, stride length and timing. To calculate average joint angle curves relative to the static neutral trial, ten successful dynamic trials per leg were needed.

Isometric strength tests

The final part of the baseline examination consisted of tests of maximal voluntary strength using isometric devices (David Health Solutions Ltd., Helsinki, Finland). The gold standard measuring equipment for muscle strength assessment is isokinetic dynamometry (IKD). However, isometric devices have been reported to have high reliability and validity, and a faster testing procedure compared with IKD (Kienbacher, 2014; Ruschel, 2015).

Participants were tested for trunk extension, trunk flexion, left and right trunk rotation, bilateral hip abduction and adduction, and unilateral knee flexion and extension strength (Figure 7). The test order was randomised to avoid potential and unwanted fatiguing effects. The participants performed all tests in a sitting position with a seatbelt around the waist. Trunk flexion was tested at 0°, trunk extension at a forward incline of 30°, and trunk rotation at ±30° (for left and right side). Hip abduction and adduction were tested at a hip abduction angle of 30°. Knee flexion and extension strength were tested with 30° and 60° of knee flexion, respectively.

Participants were allowed to become accustomed to the testing devices by first performing some dynamic movements against increasing resistance, and then by performing one or two sub-maximal isometric contractions. After familiarisation, two maximal voluntary contractions were done with a 30-second resting period in-between. If the difference between the first and the second trial was >10% or if the participant explicitly said that it was not a maximal effort, a third measurement was conducted. Participants were verbally encouraged to increase the likelihood of reaching the maximal strength potential. Only the highest torque value for each trial was noted and used in the analyses.

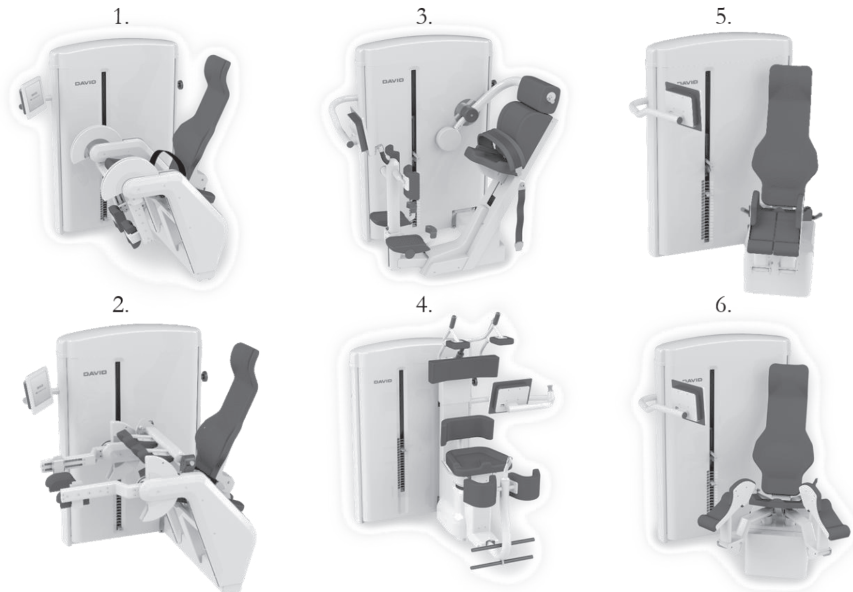

Figure 7. Isometric strength devices.

1) Knee extension, 2) Knee flexion, 3) Trunk flexion and extension, 4) Trunk rotation, 5) Hip abduction, 6) Hip adduction. Pictures obtained from https://www.davidhealth.com/products.

To enable comparisons between differently sized persons, maximal voluntary strength measurements were normalised by dividing the maximal torque by body mass (Harbo, 2011). We did not adjust for the person's height by normalisation, but instead adjusted each device according to the height of the participant. Further, strength balance values (ratios) were calculated for the trunk (flexion/extension), the hip (abduction/adduction) and the knee (flexion/extension). All strength values were measured on continuous scales.

Summary baseline examination

The typical baseline examination lasted for about 1 hour and 50 minutes. Runners were scheduled at 8 am, 10 am, 1 pm, 3 pm and 5 pm, but usually not more than three runners per day. The majority of baseline examinations were done in July (n=41), May (n=39) and

April/November (both n=28) 2016. The remaining baseline examinations were equally distributed among the other months between March 2016 and March 2017, except from September 2016 and March 2017 that only contained one baseline examination each. Electronic supplementary material concerning the baseline examination is published together with the study protocol, found at http://dx.doi.org/10.1136/bmjsem-2018-000394.

Overall, the final sample consisted of 89 women (39.6%) and 136 men (60.4%).

Follow-up

The training information was collected prospectively during the follow-up through the Excel training diary. Runners did not receive any running program and were not required to run a certain distance or with a certain frequency, but were instead told not to change anything in their training regimen due to the inclusion in the present study. Training diaries were sent in via e-mail and the study leader monitored each training diary every week. Runners who did not send in any training diary for the current week received a daily reminder until they sent in a report. In case of missing or unreasonable training information (such as missing rpe or extreme running speed), runners were contacted to verify or revise the data. Participants were told that they would receive a summary of their baseline examination and their training information after the end of follow-up, or after completing an injury examination if they would sustain an injury.

Outcome

The primary outcome measure was any running-related injury sustained during the 1-year follow-up. The definition of RRI was almost, but not completely, consistent with the consensus statement by Yamato and colleagues (2015) as a minor modification was made. The original definition was agreed upon by an international group of experts in the field of running-related injuries using a modified Delphi approach including three rounds of questionnaires. The agreement was 81% among the 26 participants in the final round. The definition covers two components of typical injury definitions, time-loss and medical attention. Although the definition was created specifically for recreational runners, the authors highlight that no definition for this type of runner existed in the literature at the time. As the definition assumes recreational runners to schedule training sessions in advance, the decision to use a slight modification of the consensus definition was made. The adjustments excluded the part targeting scheduled training sessions and replaced it with a certain percentage of running sessions, adopted from a previous study by Hein and colleagues (2014). The modification was adopted into the original definition, resulting in the following definition of RRI:

> "A running-related musculoskeletal pain in the lower limbs or back that causes a restriction on or stoppage of running (distance, speed, duration or training) in more than 66% of all training sessions in two consecutive weeks or in more than 50% of all training sessions in four consecutive weeks, or that requires the runner to consult a physician or other health professional."

If a runner fulfilled the definition of being injured, he or she was asked to attend a medical examination. An experienced sports medicine doctor carried out all medical examinations according to a standardised protocol. For the purpose of paper III, injuries were also classified into one of seven anatomical locations, namely foot/ankle, Achilles tendon/calf, lower leg, knee, thigh, hip/pelvis and lumbar spine region.

Exposures

No exposure was defined for the design paper (I) or the educational editorial (II). In paper III, the main exposure variables were previous injury, running experience, weekly running distance, age, sex and BMI. Previous injury was dichotomised as yes or no, running experience was the number of years of regular running participation, on a continuous scale. Weekly running distance represented the average weekly distance run during the year prior to baseline examination and was based on a self-reported number. Age and BMI were both on continuous scales whereas sex was dichotomised as male and female.

The main exposure variables in paper IV were obtained from the baseline examination and consisted of biomechanical and clinical/anthropometrical variables. In this paper, both kinematic (joint motion) and isometric strength data were included as biomechanical variables. The clinical/anthropometrical variables consisted of measures of passive joint range of motion, muscle flexibility and trigger points. Each biomechanical exposure variable was categorised using two cut-offs based on the normal distribution, creating three exposure groups. The reference category was defined as all values ±1 standard deviation (SD) around the mean, whereas the two other groups were all values above or below this range, respectively. As an example, Figure 8 illustrates the distribution and cut-off values for knee extension strength, where the darker blue indicates the reference group (±1 SD around the mean) and the lighter blue represents the low (<1SD) and high (>1SD) group, respectively.

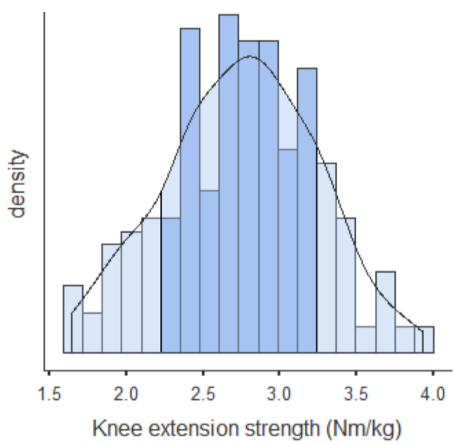

Figure 8. Example of how exposure categories were defined using a 68% prediction limit, according to the normal distribution.

The clinical/anthropometrical variables were also divided in groups using cut-offs. Joint range of motion was trichotomised into hypermobile, hypomobile and normal (reference group), whereas muscle flexibility was dichotomised into restricted and not restricted (reference). The grouping for trigger points was *pain* or *no pain*, where *no pain* was considered as the reference. Bahr and Holme (2003) were early in suggesting using a 68% prediction limit, as done for the biomechanical variables, although few previous studies have used it (Nilsson, 2012). Further, each runner had the possibility to be categorised differently across the two legs (e.g. *reference* for right side and *restricted* for left side). Thus, biomechanical and clinical/ anthropometrical factors were assumed to represent the characteristic of one leg.

The primary exposure for paper V was a modified version of the acute: chronic workload ratio (mACWR). The acute load was calculated for each training day by multiplying the distance in km by the intensity on a scale from 6-20, which resulted in a measure with an arbitrary unit (au). The sum of the present and most previous six days (n=7 days) acute loads was later used in the numerator. Chronic loads were similarly calculated but for the seventh to 28th days away from the present day (n=21 days), and used in the denominator. A ratio (mACWR) was then calculated by dividing the acute load values in the numerator with chronic load values in the denominator.

The ratio was modified with regard to weighting and moving averages. The weighting was exponential, as described by Williams et al. (2017), meaning that the load closest to the "present" day was given a higher weight than loads further away from the present day. The weighting was calculated by 2/(N+1), where N was the time difference in days from the present training day. Moving averages were considered by continuously calculating a new ratio for each individual training day. The first day possible to calculate a ratio was the first training day that occurred at least 28 days after inclusion. Four exposure states (low: <0.8, reference: 0.8-1.3, high: 1.3-1.7, very high: >1.7) were created based on the cut-off values of 0.8, 1.3, and 1.7 available in the previous literature (Blanch, 2016; Soligard, 2016). Further, as the specified original cut-off values for the ACWR turned out not to be sensitive enough (63% of all training session were categorized within the "very high" exposure state), an additional analysis was performed using cut-off values based on the median mACWR across all training sessions in this study. Here, five exposure states were created: "low" and "very high, representing the 5% of the total number of sessions with the lowest ratio and highest ratio, respectively. The reference state and the "high" state covered 20% of the sessions each (between 5%-25%, and between 75%-95%, respectively). Finally, the last exposure state, "medium", covers 50% of the total number of sessions closest to the median number.

A secondary exposure for paper V was added after the publications by Impellizzeri (2020) and Wang (2020) and is therefore not presented in paper I, the study protocol. The secondary exposure was the ratio between two weekly training load measures expressed as a percentage of change (progression or regression). The week in the numerator was represented by the sum of the distance multiplied by the intensity for the present and most previous six days. The week in the denominator was similarly calculated but for the seventh to the thirteenth day away from the present training day. Five exposure states were created based on the progression or regression from week to week: regression >30%, regression 10% to 30%, <10% regression to <10% progression (reference state), 10% to 30% progression and >30% progression, as seen in one previous study (Nielsen, 2014a).

Data organisation and cleaning

Training data were sent in individually from each participant throughout the follow-up time and was continuously organised in one Excel spreadsheet. Most data collected at baseline (questionnaire, clinical/anthropometrical measures and isometric strength values) were directly put in one Excel spreadsheet. Raw data from the running analysis was processed in Qualisys Track Manager (QTM) v.2018.1 (or later) and MATLAB v. r2018b (or later) before entered into the baseline spreadsheet. Consequently, all data were gathered in two spreadsheets, one containing baseline information and one containing training data. Data were structured and organised using the statistical software STATA v.15. (StataCorp. College Station, TX), in the sense that not all the collected information was needed for each analysis. One STATA do-file was created for each paper which only included the necessary data for that paper. A do-file explains the code/syntax and reveals the commands that were used for each analysis.

A custom-written MATLAB (Matworks, Natick MA) code was used to process the raw kinematic QTM data and calculate joint motions. The joint motion analysis was restricted to the stance phase, defined as the time from the touchdown of any part of the foot until no part of the foot was no longer in contact with the ground. Touchdown and toe-off were identified manually. Stance phase was normalised to 100 data points, to enable comparison between subjects with different stance times. Frontal motion of the hip, sagittal motion of the knee, and sagittal and frontal motion of the ankle were calculated relative to the neutral anatomical static position. The MATLAB computation generated three, four and six discrete variables for each of the three joint motions (hip, knee and ankle) respectively, resulting in a total of 13 discrete variables. Examples and visualisation of joint motions are found in Figures 9a-d. All joint motion values were measured on continuous scales.

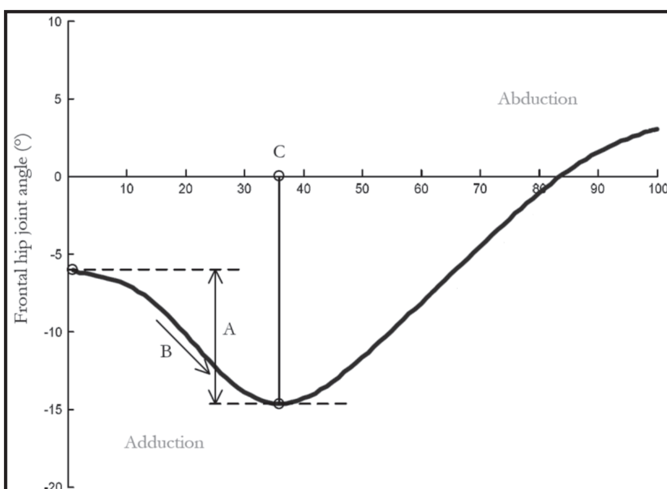

Figure 9a. Hip adduction range of motion (A), hip adduction maximal velocity (B) and timing of maximal hip adduction (C).

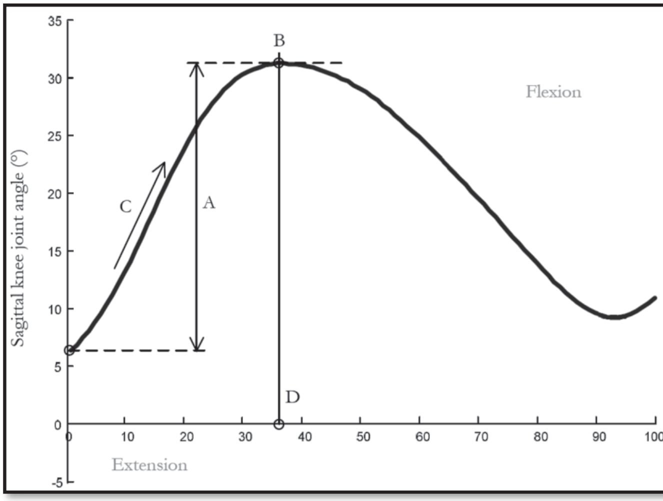

Figure 9b. Knee flexion range of motion (A), maximal knee flexion (B), maximal knee flexion velocity (C) and timing of maximal knee flexion (D).

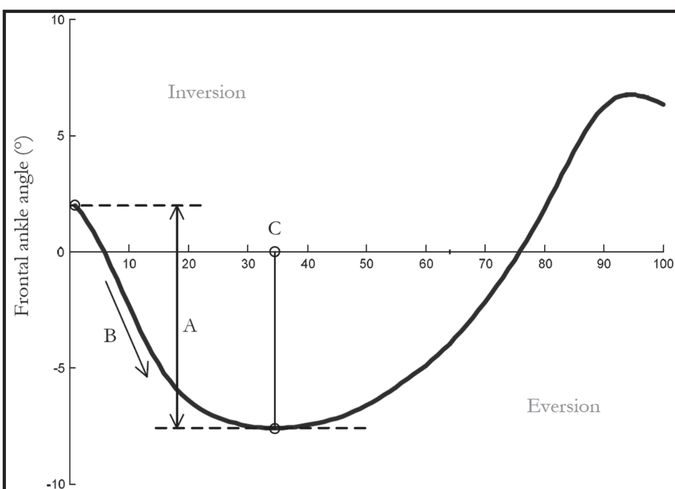

Figure 9c. Rear foot eversion range of motion (A), maximal rear foot eversion velocity (B), timing of maximal rear foot eversion (C)

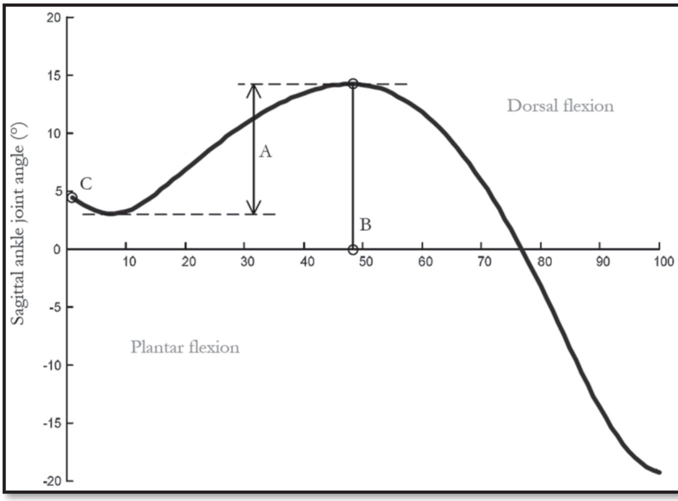

Figure 9d. Ankle dorsal flexion range of motion (A), timing of maximal ankle dorsal flexion (B) and ankle touch down angle (C)

Statistical analyses and sample size

In papers II-V, time-to-injury with days as the time-scale was used. The Kaplan-Meier estimator was used to calculate the cumulative incidence proportion in papers II, III and IV. The way of reporting the CIP in paper IV differed from the two other papers (II and III) as it was reported with legs being the unit of interest, instead of participants.

In paper III, cox proportional hazards regression was used to assess the association between independent (exposure) variables (previous injury, running experience, weekly running distance, age, sex and BMI), and the outcome (RRI). The log-rank test was used to assess the assumption of proportional hazards.

In papers IV and V, generalised linear regression using the pseudo-observation method was used to assess the cumulative risk difference (in %-point) in injury survival between the exposure groups or exposure states. The primary analysis was done after 365 days.

In all analyses, runners were censored in case of not reporting any training information (e.g. due to time constraints, lack of motivation or issues with the training log), disease, illness or injuries not related to running, pregnancy, unwillingness to attend the clinical examination, other personal concerns hindering further participation, or completing follow-up at one year, whichever came first. In addition, legs opposite to an injured leg were censored in the analysis in paper IV. For the primary analyses in paper V, runners who sustained an injury during the first 28 days were censored, due to no primary exposure could be calculated until the 29th day of inclusion. Finally, for the secondary analysis in paper V, runners who sustained an injury during the first two weeks were censored because of the same reason.

Descriptive data were reported as means and SDs if the requirement of normal distribution was met, otherwise reported with median and interquartile range (IQR). Data were presented with 95% confidence interval (95%CI). Statistical analyses and analytical graphs were performed and created using STATA v.15. Descriptive graphs were created using Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA) and Jamovi v. 1.2 (The Jamovi Project).

No a priori sample size calculation was performed. Instead, the aim was to include at least five or ten injuries in each of the exposure groups or exposure states, depending on the statistical analysis used (Peduzzi, 1996; Hansen, 2014; Nielsen, 2019b).

Chapter 3: Results

Results are presented relating to the different types of research goals. In the description section, information on training (total and average distance, frequency, intensity, progression and load) and injury (incidence and anatomical locations) parameters are included. Results from paper III and paper IV are presented in the prediction section. Finally, the preliminary results from paper V are found in the section on causal inference.

Description

Training data

During the 1-year follow-up, all included participants (n=224) ran a total of 182 904 kilometres in 17 039 running sessions with a median intensity of 13 (IQR 11–15). Tuesdays, Saturdays and Sundays were the most frequent training days, and there was no major difference in intensity based on weekday (Table 6, Figures 10 and 11).

Table 6. Total distance, number of sessions and number of injuries by weekday.

Weekday	km	sessions	km/session	injuries	injuries/1,000km
Mondays	20 366	2 107	9.67	9	0.44
Tuesdays	26 585	2 823	9.42	10	0.38
Wednesdays	22 005	2 347	9.38	8	0.36
Thursdays	23 112	2 432	9.50	7	0.30
Fridays	19 486	1 945	10.01	12	0.62
Saturdays	36 388	2 657	13.70	12	0.33
Sundays	34 962	2 728	12.82	17	0.49
Total	**182 904**	**17 039**	**10.74**	**75**	**0.41**

Table 6. Total distance (km) and total number of running session covered by all included participants, average distance per session, number of injuries and injuries per 1,000 km displayed by weekday.

Further, Figure 10 reveals 31 ultra-long running sessions where runners covered more than 50 km in one session. In five of these, the distance exceeded 100 km. Interestingly, two injuries occurred during the ultra-long sessions (categorised as "other knee injury" and Achilles tendinopathy, respectively).

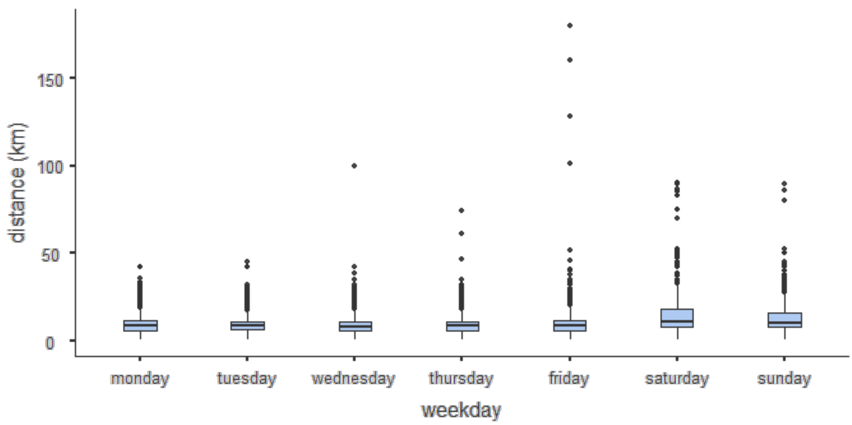

Figure 10. Distance (km) displayed by weekday.

Figure 11 displays the average intensity by weekday. Here, four injuries occurred at the two highest intensities (Borg rpe 19 (n=115 sessions) and 20 (n=2 sessions)), categorised as one triceps surae injury, one hamstring injury and two plantar fasciitis.

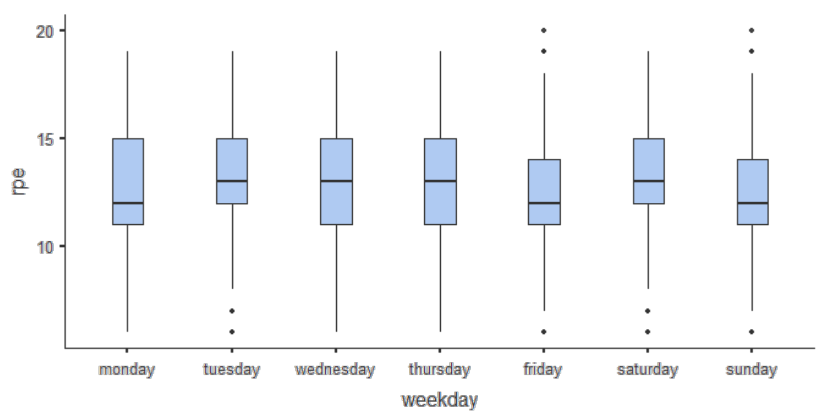

Figure 11. Intensity (Borg rpe) displayed by weekday.

Figure 12 visualises the average daily distance during follow-up (mean= 3.99 km, SD= 1.16). Runners did not increase or decrease the average distance during follow-up (r^2= -0.01). The average distance per running session for runners who sustained an injury was 10.96 km (SD= 3.67), which was similar to the average distance per running session of 10.74 km (SD= 2.95) among the runners who remained injury-free throughout the follow-up period.

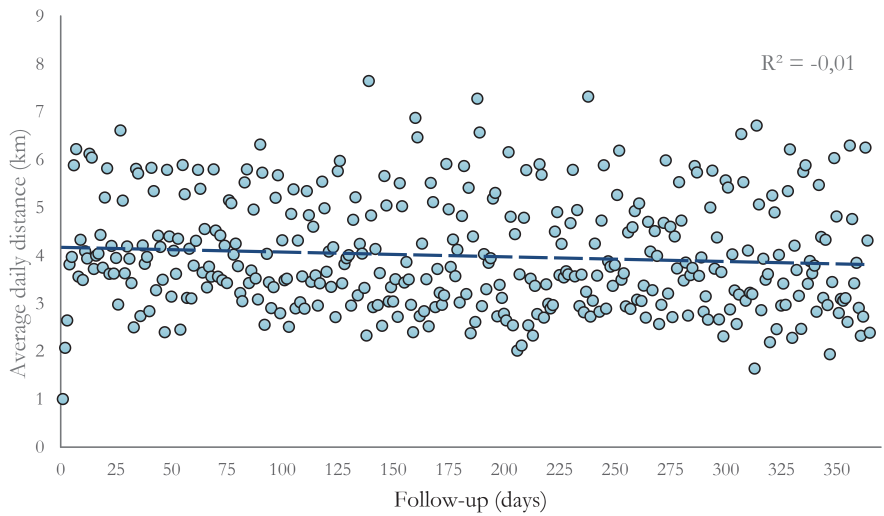

Figure 12. Average daily distance and the coefficient of determination (R^2) during the 365 days follow-up period.

Training load (acute and chronic loads) was calculated using original and median cut-off values. Using the original mACWR, the average acute load (AL) for each exposure state was 85 au (low), 134 au (reference), 159 au (high) and 188 au (very high). The average chronic loads were 138 au for the low state, 125 au for the reference state, 106 au for the high state and 65 au for the very high state.

Using the median cut-offs, the average acute load was found to be lowest in the low state (92 au), 140 au in the reference state, 171 au in the median state, 205 au in the high state and highest in the very high state (232 au). For chronic loads, the relationship was the opposite.

The low state had the highest average chronic load of 139 au, the reference state had 121 au on average, the median state had 85 au on average and the high state had 51 au on average, and the lowest value of 22 au was found in the very high state. The arbitrary units represent the distance in kilometres multiplied by the intensity on Borg's 6-20 rpe scale.

Injury data

A total of 75 of the 224 recreational runners included in the study sustained a running-related injury over the course of one year. Of the 75 injuries, 27 injuries occurred only at the left side, 38 injuries occurred only at the right side, and the remaining 10 injuries were bilateral injuries or low back pain. Descriptive data regarding the types of running-related injuries are presented in Table 7, Figure 13 and Figure 14. The two most common anatomical locations were the knee (accounted for 20 of 75 injuries, 26.7%) and Achilles tendon/calf (19 of 75, 25.3%). Next followed the foot/ankle (n=15, 20.0%), the hip/pelvis (n=11, 14.7%), the lower leg (n=5, 6.7%), the lumbar spine region (n=3, 4.0%) and finally the thigh (n=2, 2.7%).

Table 7. Number of injuries by injury type, median number of days and sessions to injury.

Injury type	Injuries (♂|♀)	Days to injury ♂ | ♀	Sessions to injury ♂ | ♀
Triceps surae injuries	11 (7|4)	137 | 224	61 | 79.5
Meniscal injuries	6 (3|3)	76 | 168	44 | 49
Other knee injuries*	6 (4|2)	86 | 78	65.5 | 32.5
Achilles tendinopathy	6 (3|3)	75 | 90	27 | 44
Gluteal injuries	5 (2|3)	150 | 168	81.5 | 25
Plantar fasciitis	4 (3|1)	82 | 225	52 | 63
Retrocalcaneal bursitis	4 (4|0)	265 | n/a	123 | n/a
Low back pain	3 (2|1)	64 | 281	28.5 | 54
Trochanterit	3 (0|3)	n/a | 153	n/a | 81
Patellar tendonitis	3 (3|0)	243 | n/a	122 | n/a
Medial tibial stress syndrome	3 (3|0)	226 | n/a	70 | n/a
Hallux injuries	3 (1|2)	68 | 226	20 | 83.5
Hamstring injuries	2 (2|0)	166 | n/a	66 | n/a
Knee capsule	2 (2|0)	207 | n/a	69.5 | n/a
Tibial stress fracture	2 (1|1)	120 | 191	77 | 70
Greater trochanteric bursitis	1 (1|0)	182 | n/a	52 | n/a
Hip abductor injuries	1 (1|0)	91 | n/a	26 | n/a
Iliopsoas injuries	1 (0|1)	n/a | 315	n/a | 121
Iliotibial band syndrome	1 (1|0)	27 | n/a	14 | n/a
Chondromalacia patellae	1 (1|0)	80 | n/a	29 | n/a
Knee osteoarthritis	1 (0|1)	n/a | 153	n/a | 94
Tibialis posterior tendinopathy	1 (1|0)	22 | n/a	11 | n/a
Peroneal tendinopathy	1 (0|1)	n/a | 230	n/a |120
Calcaneal apophysitis	1 (0|1)	n/a | 71	n/a | 17
Ankle synovitis	1 (0|1)	n/a | 175	n/a | 74
Heel fat pad atrophy	1 (1|0)	112 | n/a	22 | n/a
Other foot/ankle injuries*	1 (0|1)	n/a | 255	n/a | 96
Total	**75**	**126**	**52**
♂ | ♀	46 | 29	131.5 | 120.5	52 | 50

Table 7. Number of days and sessions are reported as median time-to-injury for males (♂) and females (♀). n/a= not applicable (no injuries). "Other injuries" refer to injures without a clear diagnosis. Color corresponds to anatomical location (light blue: foot/ankle, grey: Achilles tendon/calf, yellow: lower leg, light green: knee, dark green: thigh, red: hip/pelvis and dark blue: lumbar spine region.

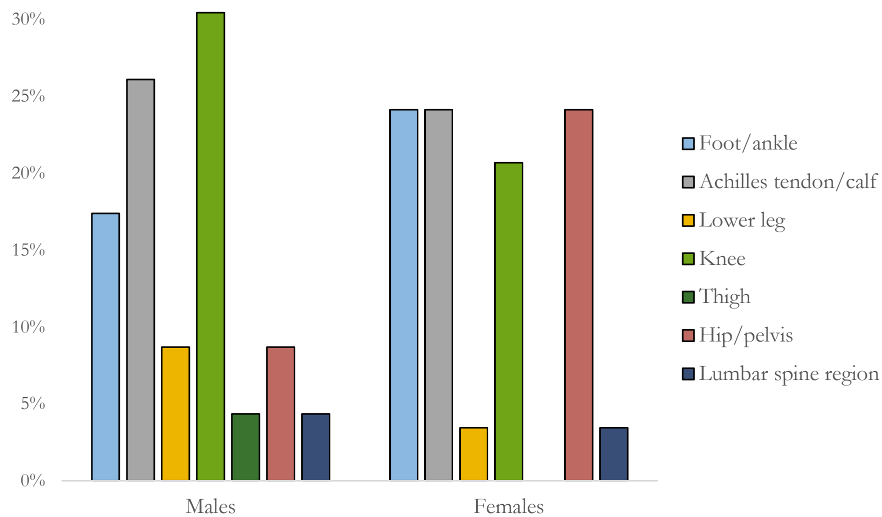

Figure 13. Percentages of injury location category, by sex.

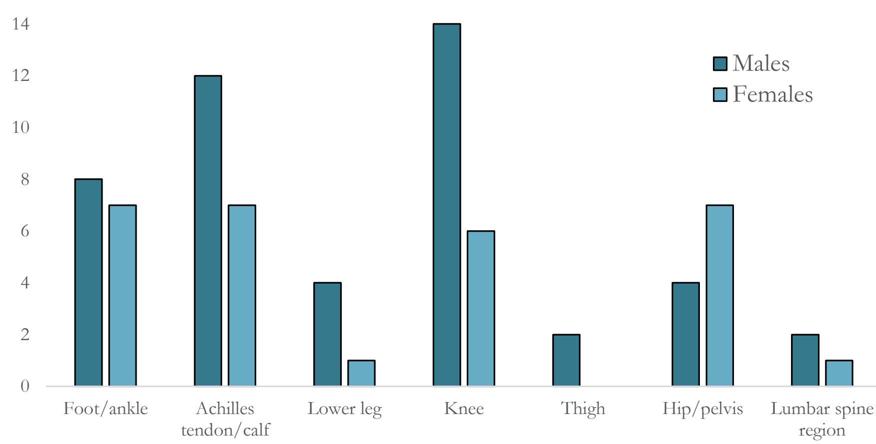

Figure 14. Frequencies of injury location category, by sex.

The overall cumulative incidence proportion was 45.9% (95%CI= 38.4 ; 54.2). There was no difference between the sexes. More specifically, the cumulative incidence proportion for women was 46.0% (95%CI= 34.3 ; 59.5) and for men 45.8% (95%CI= 36.4 ; 56.5). Women sustained an equal proportion of injuries to the foot/ankle, Achilles tendon/calf and hip/pelvis areas (24% each) whereas the most frequently injured anatomical location for men was the knee (30.4%). The cumulative incidence proportions per anatomical location are presented in Figure 15, which adds up to 45.9%.

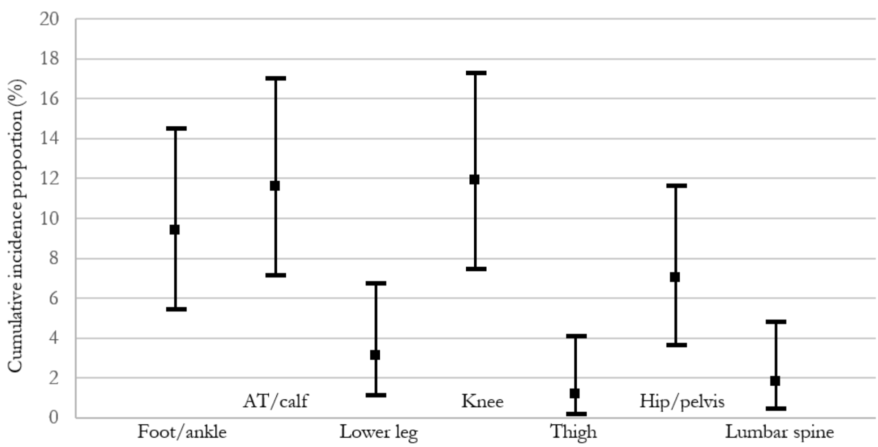

Figure 15. Cumulative incidence proportions (%) by injury location, with 95% confidence intervals.

The median number of days from the day a participant reported pain until the injury examination was 22.5 days (IQR= 14.5 to 41). The median number of days and training sessions are presented for each injury type in Table 7 (page 63). As the majority of the number of individual types and/or diagnoses of injuries was low, Figure 16 presents the median number of training sessions until injury for each group of anatomical location. In the table, the whiskers for the lower leg are not visible due to two of the five observations (injuries) being close to the median, meaning that both the upper and lower quartiles are within the box.

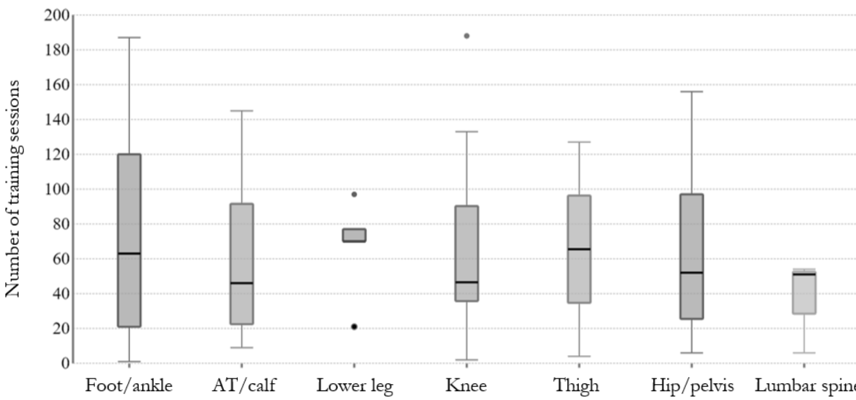

Figure 16. Median number of training sessions until injury (y-axis) per anatomical location.

Two incidence rates can be presented. First, the number of injuries per 1,000 kilometres of running was 0.41 (95%CI= 0.31 ; 0.51) and second, the number of injuries per 1,000 hours of running was 4.4 (95%CI= 3.8 ; 5.0).

The median time-to-injury from inclusion was 126 days (IQR= 75 to 243), which can be compared with the overall median inclusion time of 192.5 days (IQR= 69.5 to 363) for all runners and 265 days (IQR= 69 to 363) for the non-injured runners.

In the analysis for paper II, a total of 2798 runners (1441 male; 1357 female) and 645 injuries were used to calculate the cumulative incidence proportions without and with censoring across four studies (Table 8).

The difference in CIP across the four studies ranged between 4- and 22%-points. In the Project Run21 study, the CIP doubled from 22% to 44% with censoring compared to without censoring.

Table 8. Cumulative incidence proportions from four RRI-studies presented without and with censoring.

Study	Days	Runners (n)	Injuries (n)	Cumulative incidence proportion: Without censoring (95%CI)	With censoring (95%CI)	Difference (%-point)
Dano-Run	365	931	252	27% (24-30)	31% (28–34)	4
Pr. Run21	98	804	178	22% (19-25)	44% (39–50)	22
RunClever	168	839	140	17% (14-19)	29% (25–34)	12
SPRING	365	224	75	33% (27-40)	46% (38–54)	13

Table 8. Pr. Run21= Project Run21, 95%CI= 95% confidence interval. Difference= difference in cumulative incidence proportion between cumulative incidence proportion with and without censoring expressed in percetage points.

Prediction

One of the objectives in paper III was to investigate the associations between running-related injuries and previous injury, running experience, weekly running distance, age, sex and body mass index (BMI). We found that previous injury was associated with a higher injury rate (HR= 1.9, 95%CI= 1.2 ; 3.2), while the 95% CI for all other parameters crossed 1 (Table 9). The characteristics of group age, height, mass, BMI and weekly running frequency are presented in Table 4 (Chapter 2, page 42).

Table 9. Associations between baseline parameters and RRI

Parameter	Hazard rate ratio	95%CI	p-value
Previous injury	1.91	1.15–3.16	0.01
Running experience	0.99	0.97–1.02	0.47
Weekly distance	1.00	0.99–1.02	0.64
Age	1.00	0.97–1.03	0.87
Sex	0.91	0.55–1.51	0.72
Body mass index	0.94	0.84–1.06	0.32

Table 9. Having had a previous injury and male sex was used as reference groups. 95%CI= 95% confidence interval.

Further, in paper IV, we investigated if runners with certain characteristics (related to range of motion, strength and running style) sustain more injuries than runners having other characteristics. The average absolute values for strength and movement characteristics are presented in Table 12 and Table 13. For strength measures, the mean and SDs are plotted in Figures 17a and 17b. The data from this study suggest no associations at all between an excessive or restricted joint range of motion or an excessive or restricted muscle flexibility, and running-related injury. For joint range of motion, only 10 out of 24 of the *restricted* and *excessive* exposure groups included five or more injured legs. An average of 396 of the 448 legs (88%) across the twelve measures of range of motion was categorised within the reference group. For muscle flexibility, there was a sufficient number of legs with injuries in all three groups; however, the risk differences were small and ranged between –0.1% and –4.5%, with large confidence intervals. Although not significant, and with large confidence intervals, some data appear to suggest that runners with painful trigger points sustain more RRI compared with runners without painful trigger points (Table 10).

Table 10. Associations between clinical/anthropometrical (trigger points) factors and RRI

Exposure	**Reference (no pain)**		**Pain**	
	Injuries (Total)	Risk (%)	Injuries (Total)	Risk difference (95%CI)
Gastrocnemius	24 (167)	24.8	61 (281)	7.0 (−4.3 ; 18.4)
Soleus	46 (295)	25.6	39 (153)	10.6 (−2.4 ; 23.5)
Tibialis anterior	71 (391)	27.7	14 (57)	11.5 (−4.8 ; 27.9)

Table 10. Injuries= number of injured legs, total= number of legs, 95%CI= 95% confidence intervval.

However, we could identify that runners having late timing of maximal eversion or low ratio between hip abductor strength and hip adductor strength (i.e. relatively weak hip abductors) sustained more injuries compared with runners in the corresponding reference group

(Table 11). More specifically, runners having a late timing of ankle eversion sustained 20.7% (95%CI= 1.3; 40.0) more injuries compared with runners having an earlier timing of ankle eversion. Further, runners having a low ratio between hip abduction strength and hip adduction strength sustained 17.3% (95%CI= 0.8; 33.7) more injuries compared with runners in the reference group, having relatively stronger hip abductors.

Table 11. Associations between biomechanical (movement and strength) factors and RRI

Exposure	**Reference**		**−1SD**		**+1SD**	
	Injuries (Total)	Risk (%)	Injuries (Total)	RD (95%CI)	Injuries. (Total)	RD (95%CI)
Timing ankle eversion	55 (316)	25.7	9 (52)	2.4 (−15.2 ; 20.0)	21 (74)	20.7 (1.3 ; 40.0)
HAB:HAD	57 (320)	26.3	17 (62)	17.3 (0.8 ; 33.7)	11 (66)	2.4 (−14.0 ; 18.8)

Table 11. Injuries= number of injured legs, total= number of legs, SD= standard deviation, RD= risk difference in percentage, 95%CI= 95% confidence intervval, HAB:HAD= ratio between hip abduction strength and hip adduction strength.

Table 12. Average normalised values for strength characteristics

	Knee flexion	*Knee extension*	*Hip abduction*	*Hip adduction*	*Trunk flexion*	*Trunk extension*	*Trunk rotation*	*H:Q ratio*	*HAB:HAD ratio*	*Trunk ratio*
♂	2.1 (0.3)	2.9 (0.4)	3.5 (0.4)	5.4 (0.7)	2.2 (0.4)	4.2 (0.7)	2.3 (0.4)	0.7 (0.1)	0.7 (0.1)	0.5 (0.1)
♀	1.7 (0.3)	2.4 (0.4)	3.2 (0.5)	4.3 (0.6)	1.7 (0.3)	3.7 (0.7)	1.7 (0.4)	0.7 (0.1)	0.7 (0.1)	0.5 (0.1)

Table 12. Strength (unit: Nm/kg) and strength ratios presented as mean and (standard deviation) for males (♂) and females (♀). H:Q ratio= Hamstring:quadriceps strength ratio, HAB:HAD ratio= hip abduction:hip adduction strength ratio.

Table 13. Average absolute values for movement characteristics.

	HAD ROM (°)	HAD v (°/s)	HAD tim (%)	Knee flexion ROM (°)	Knee flexion max (°)	Knee flexion v (°/s)	Knee flexion tim (%)	Eversion ROM (°)	Eversion v (°/s)	Eversion tim (%)	Ankle flexion ROM (°)	Ankle flexion tim (%)	Ankle touch down angle (°)
♂	5.9 (1.9)	137 (43)	33.1 (4.7)	25.6 (4.6)	40.2 (5.2)	447 (85)	37.4 (4.1)	5.8 (2.4)	228 (74)	21.7 (8.0)	9.1 (3.0)	50.0 (4.0)	-0.5 (3.8)
♀	6.4 (2.7)	154 (53)	36.6 (6.0)	25.1 (6.1)	41.8 (6.0)	452 (72)	37.4 (6.3)	7.1 (2.5)	267 (72)	23.8 (7.1)	9.6 (4.0)	50.1 (5.9)	-1.5 (4.7)

Table 13. Movement variables presented as mean and (standard deviation) for males (♂) and females (♀) during stance. Data is average of 10 left and 10 right trials. HAD= hip adduction; ROM= range of motion in degrees; v= velocity in degrees per second; tim= timing in percent of stance phase.

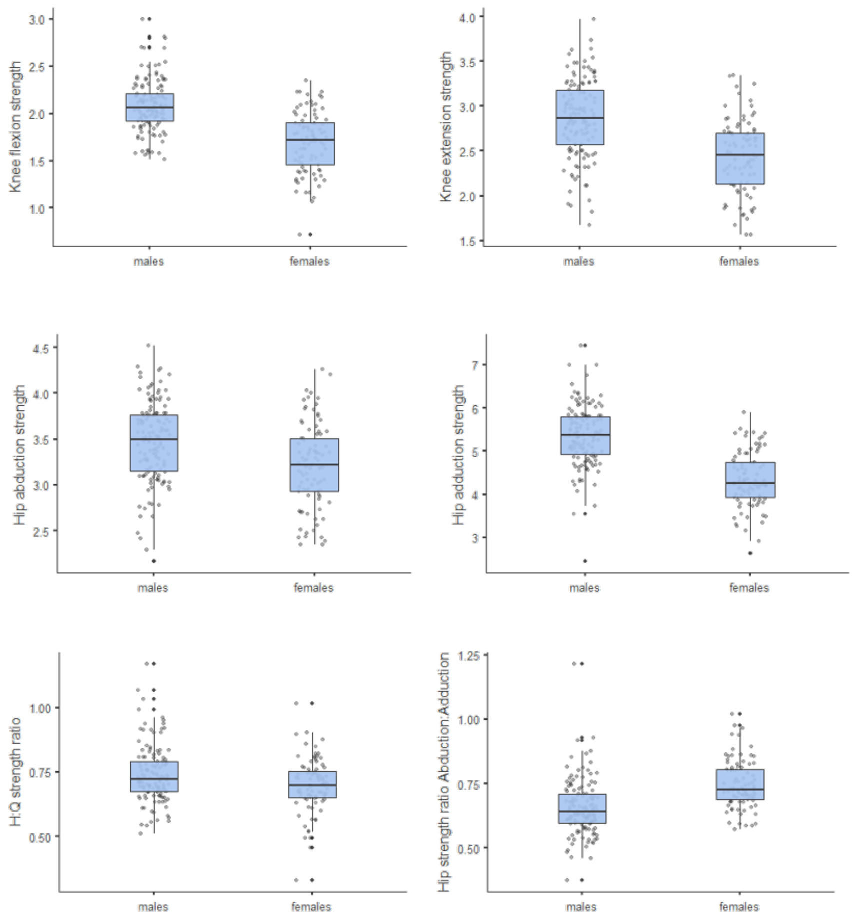

Figure 17a. Normalised (Nm/kg) average lower body strength values plotted for males and females. H:Q= Hamstring: quadriceps.

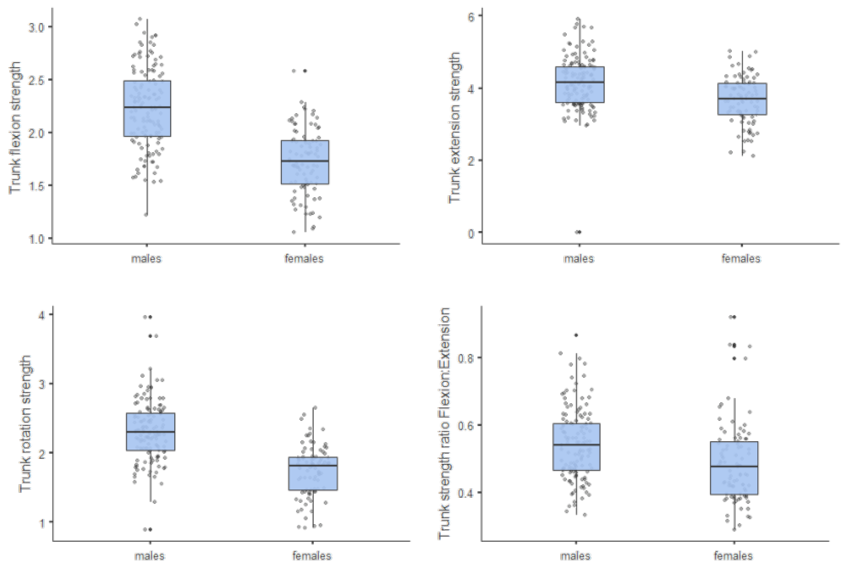

Figure 17b. Normalised (Nm/kg) average upper body strength values plotted for males and females.

Causal inference

The section is split with regard to three analyses that use different exposure states. First, mACWR using the original cut-offs is presented, then mACWR using the median cut-offs, and finally, the analysis of bi-weekly changes is presented.

mACWR using original cut-offs

Nine injuries occurred during the first 28 days and were therefore not included in the analyses, as no ratio (primary exposure) could be calculated for these participants. Using the original cut-off values, a vast majority (n=50 or 75.8%) of the injuries were sustained during a training session categorised in the very high state (mACWR>1.7). The reference state (mACWR 0.8-1.3) included 2379 sessions, of which five were sessions where an injury occurred. The cumulative incidence proportion for the reference state was 33.7% (95%CI= 20.5 ; 46.9). In only two of the 573 sessions categorised in the low state (mACWR <0.8), an injury occurred. In the high state, mACWR >1.3-1.7, nine injuries occurred in 2543 sessions (RD= 13.3% (95%CI= -10.8 ; 37.5). In the very high state, mACWR >1.7, 50 injuries occurred in 9370 sessions (RD= 12.5% (95%CI= -4.7 ; 29.7) (Table 14). The hypothesis of equal median time to injury across exposure states was tested with a log-rank test. The p-value of 0.29 revealed that this hypothesis could not be rejected.

Table 14. Modified acute to chronic workload ratio using original cut-offs

Exposure state	Sessions (n)	Injuries (n)	Expected injuries (n)	Risk difference (95%CI)	p
mACWR <0.8 low	571	2	2.4	9.5% (-33.5 ; 52.6)	0.66
mACWR 0-8-1.3 reference*	2374	5	7.8	-	-
mACWR >1.3-1.7 high	2534	9	9.3	13.3% (-10.8 ; 37.5)	0.28
mACWR >1.7 very high	9320	50	46.5	12.5% (-4.7 ; 29.7)	0.15
			Trend of survivor functions		0.29

*Table 14. mACWR: modified acute to chronic workload ratio. "Sessions" column shows the number of sessions categorised into each exposure state. "Injuries" column shows the number of sessions where an injury occurred. The risk difference in each exposure state is with regard to the reference risk. *Reference risk= 33.7% (95%CI= 20.5 ; 46.9). 95%CI= 95% confidence interval.*

mACWR using median cut-offs

As a vast majority of the injuries were sustained during a training session categorised as very high (using the original cut-off values), a secondary analysis using five exposure states based on median cut-off values was also explored. The median mACWR was 2.03, and the percentile values creating the median cut-offs were p5=0.86, p25=1.43, p75=3.00 and p95=6.87. The reference state (mACWR= 0.86<1.43) included 2973 sessions, of which at five sessions an RRI occurred. The cumulative incidence proportion for the reference state (mACWR= 0.86-1.43) was 30.7% (95%CI= 19.5 ; 41.9). Runners with a high (mACWR= 3.0-6.87) and very-high (mACWR= >6.87) training load progression sustained 24.1%-point (95%CI= -1.8 ; 50.1) and 13.0%-point (95%CI= -36.9 ; 62.8) more injuries than runners who had training load progressions between 0.86 to 1.43 (reference state). Table 15 displays each of the exposure states for the analysis of mACWR using median cut-offs.

The hypothesis of equal median time to injury across exposure states was tested with a log-rank test. The p-value of 0.11 revealed that this hypothesis could not be rejected.

Table 15. Modified acute to chronic workload ratio using median cut-offs

Exposure state	Sessions (n)	Injuries (n)	Expected injuries (n)	Risk difference (95%CI)	p
mACWR < 0.86 low	741	3	3.0	15.3% (-22.2 ; 52.8)	0.42
mACWR 0.86 < 1.43 reference*	2968	5	10.2	-	-
mACWR 1.43 < 3.0 medium	7401	30	30.3	14.5% (-1.3 ; 30.3)	0.07
mACWR 3.0 – 6.87 high	2954	20	16.2	24.1% (-1.8 ; 50.1)	0.07
mACWR > 6.87 very high	735	8	6.3	13.0% (-36.9 ; 62.8)	0.61
				Trend of survivor functions	0.11

*Table 15. mACWR: modified acute to chronic workload ratio. "Sessions" column shows the number of sessions categorised into each exposure state. "Injuries" column shows the number of sessions where an injury occurred. The risk difference in each exposure state is with regard to the reference risk. *Reference risk= 30.7% (95%CI= 19.5 ; 41.9). 95%CI= 95% confidence interval.*

Bi-weekly changes

The secondary exposure was the ratio between two weekly training load measures expressed as a percentage of change (progression or regression). Here, changes could be calculated after 14 days, meaning that the four injuries occurring during this time were excluded as no ratio could be calculated. A total of 15 209 training sessions (including 71 sessions with an injury) were categorised, as seen in Table 16. No ratio seems to be more injurious than another is, as all confidence intervals are crossing zero. Nevertheless, the highest number of injuries (n=32) occurred when the training session was categorised as more than 30% progression. The hypothesis of equal median time to injury across exposure states was tested with a log-rank test. The p-value of 0.17 revealed that this hypothesis could not be rejected.

Table 16. Bi-weekly changes

Exposure state	Sessions (n)	Injuries (n)	Expected injuries (n)	Risk difference (95%CI)	p
>30% ↓	2626	10	16.8	-18.7% (-46.3 ; 8.9)	0.18
>10% ↓ to 30% ↓	2196	12	9.1	3.3% (-25.6 ; 32.1)	0.83
Reference* 10% ↓ to 10% ↑	2828	13	11.3	-	-
>10% ↑ to 30% ↑	1974	4	7.5	-17.6% (-41.3 ; 6.1)	0.20
>30% ↑	5524	32	26.3	2.4% (-21.6 ; 26.4)	0.84
			Trend of survivor functions		0.17

*Table 16. "Sessions" column shows the number of sessions categorised into each exposure state. "Injuries" column shows the number of sessions where an injury occurred. Arrow ↓ indicates a regression, and arrow ↑ indiactes a progression. *Reference risk= 50.2% (95%CI= 31.5 ; 69.0). 95%CI= 95% confidence intervval.*

Chapter 4: Discussion

Description

One of the aims of this dissertation was to describe how many runners sustain an injury over one year. Further, we described the difference in incidence proportion with and without censoring.

The importance of estimating the injury incidence proportion with censoring seems to be large, as the difference between the two analytical methods ranged between 4%-points and 22%-points across four prospective cohort studies. The difference was largest in Project Run21, where the incidence proportion doubled from 22% to 44%. The main reason is likely that in this study, about 13% of the runners completed follow-up compared with beyond 50% of the runners in the Dano-Run study, which had the lowest difference in incidence proportion among the included studies. The take-home message is therefore that the lower the number of participants who complete the follow-up in a study, the greater the risk for a large difference in incidence proportions calculated with and without censoring.

The proportion of runners who dropped out during follow-up in the prospective studies included in van Gent (2007) were 23% on average (excluding studies shorter than 7 days). In randomised controlled trials, the proportion of runners compliant at the end of the follow-up ranged from 0% to 21% and from 68% to 90% depending on the intervention used (Nielsen, 2020a). Studies with perfect compliance are extremely rare, and therefore it is important to consider the time participant is not under observation, which can be done by applying censoring.

Exploring the 95% confidence intervals in the four studies included in paper II, the cumulative incidence proportions range from 25% to 54%. This can be compared with previous reports presented in the background ranging from 20% to 92% (without 95%CI).
Moreover, the proportion of injuries by anatomical location found in this study was as follows, the knee (27%), Achilles tendon/calf (25%),

foot/ankle (20%), hip/pelvis (15%), lower leg (7%), lumbar spine region (4%) and thigh (2%). These results are comparable with the most affected anatomical sites reported in previous literature. Commonly the knee (28-41%) and the lower leg (24-40%) constitute the most injurious anatomical locations (Buist, 2008; Bredeweg, 2012; Nielsen, 2014d). Note that injuries to the Achilles tendon/calf are included in the lower leg-category in the first two of those studies. In this study, injuries to triceps surae (n=11), meniscal injuries (n=6) and undiagnosed (other) knee injuries (n=6) were the most frequent types of injuries, whereas Achilles tendinopathy was the most frequent diagnosis. In slight contrast, Lopes (2012) found that the three most common diagnoses were medial tibial stress syndrome (lower leg injury), Achilles tendinopathy (Achilles tendon/calf injury) and plantar fasciitis (foot/ankle injury). As a majority of previous literature has reported, the present study found most running-related injuries to affect anatomical locations at or below the knee.

The two participants who sustained injuries in one of the sessions above 50 km (Achilles tendinopathy and undiagnosed knee injury), can be compared with the most frequently reported injuries in ultra-marathon races which are Achilles tendinopathy and patellofemoral pain syndrome (Lopes, 2012). In addition, all four injuries (one triceps surae injury, one hamstring injury, two plantar fasciitis injuries) that occurred during a session rated with the highest intensity (Borg rpe= 19 or 20) are injuries that typically are classified as pace-related injuries (Nielsen, 2013b). Pace-related injuries are assumed to be more frequent at the posterior parts of the leg, an assumption that likely can be supported by the findings in the present study, even though pace and intensity is not defined equally. Research investigating the association between intensity and running-related injury is sparse, however, one study by Kluitenberg and colleagues (2016b) found that higher intensity was associated with injury occurrence (HR= 1.28, 95%CI= 1.18 ; 1.40).

Prediction

The part of this dissertation focusing on prediction aimed to identify who is more likely to sustain a running-related injury depending on certain clinical/anthropometrical and biomechanical characteristics using absolute measures of association. We identified runners with late timing of maximal eversion, and runners with a low strength ratio between hip abductors and hip adductors to sustain more injuries than their corresponding reference groups. Foot motion, especially rear foot eversion or pronation has received massive attention throughout the decades (Ferber 2009; Behling, 2020). Nielsen (2014b) found no difference in injury incidence proportions based on foot posture index, whereas Malisoux (2016) found that among overpronators, runners wearing motion control shoes had reduced injury risk compared with runners using neutral shoes. Data from the same study were later re-analysed using competing risks, which could then reveal that runners wearing the motion-control shoe had a lower risk of injuries related to pronation (such as Achilles tendinopathy and plantar fasciitis) compared with runners wearing a neutral shoe (Willems, 2021). Ceyssens (2019) conducted a systematic review investigating biomechanical risk factors for RRI and concluded that the evidence regarding maximal rear foot eversion is conflicting or inconsistent. In the light of this knowledge, runners with late timing of maximal eversion may be a group of runners that coaches and clinicians can devote careful attention to, as the association indicates those runners to be more susceptible to RRI. The association between hip abduction and/or adduction strength and RRI is not consistently reported in previous literature (Christopher, 2019). However, two high-quality studies reported weak hip abductors to increase the risk of injury, especially knee-related pain (Luedke, 2015; Ramskov, 2015). The finding in the present study adds to this knowledge, that more injuries occur in runners with relatively weak hip abductors compared with runners having relatively stronger hip abductors, and suggests this group of runners to be more susceptible to RRI.

Further, we investigated the associations between other baseline characteristics, such as previous injury, running experience, weekly running distance, age, sex and BMI, and running-related injuries using a relative measure of association. As reported in previous research, a previous injury seems to make runners more susceptible to new RRIs (Saragiotto, 2014a; Hulme, 2017). Despite having a rather strict inclusion criterion of being injury-free for at least six months prior to inclusion, there is a possibility that injured participants were not fully recovered from the previous injury. However, we cannot exclude any other possible reason for this association.

Further, a recent meta-analysis concluded male or female sex does not seem to be associated with the occurrence of running-related injuries, among recreational, elite, novice and competitive runners (Hollander, 2021). The authors noted females to be more represented to bone stress injuries and males to Achilles tendinopathies. In this study, we did not find any association between sex and RRI, nor any specific type of injury that was highly overrepresented among one of the sexes.

BMI is most likely an important factor to consider, as the distribution of injuries in normal-weight, overweight and obese runners seem to differ (Nielsen, 2014c; Juhler, 2020). However, in this study, we could not identify any strong association between BMI and running-related injury, perhaps explained by the lack of variety, as the vast majority, 78%, of the runners had a BMI between 20 and 25.

Causal inference

In paper V, we analysed time-varying training load exposures using two versions of a modified acute to chronic workload ratio, and bi-weekly changes.

First, hypothesis number five in the study protocol intended to investigate whether a U-shaped pattern existed for the association between mACWR and running-related injury. Runners having a mACWR between 0.8 and 1.3 had the lowest injury risk, and it could be possible that a U-shaped pattern exists, similar to what Blanch (2016) and Gabbett (2016a) have suggested. However, caution is needed as a low number of injuries were present in all states except in the very high state (where 50 sessions with injuries occurred), and the risk difference confidence intervals were large. Therefore, the expected U-shaped curve cannot be supported by the findings in this study.

As the original cut-off values categorised 63% of the sessions into mACWR >1.7 (very high state), perhaps due to the weighting of acute and chronic loads (Murray, 2017) another way of categorising the ratio was explored using five states based on the median. The training session distribution using the new cut-offs changed, as an equal number of sessions were categorised as below or above the median (medium state). The medium state (mACWR= 1.43<3.0) contained the most number of injuries. The high state (mACWR= 3.0-6.87) seems to be more vulnerable to RRI than the reference state (mACWR= 0.86<1.43) as the risk difference equals 24.1%-point (95%CI= -1.8 ; 50.1). The scientific evidence for this possible relationship is close to non-existent, as only one study has acknowledged large progressions to be associated with increased injury risk (Nielsen, 2014a), and one other study investigated if increases in training occurred prior to injury (Winter, 2020). Further, an older study on triathletes found no association between an increase in training loads and the onset of injury, however, the training load progression in this study was "only" 37%, on average, over 6-weeks (Korkia, 1994).

Importantly, all states had wide confidence intervals and none of the states had clearly a greater risk difference compared with the reference. In fact, the lower bound of the 95% confidence interval for the very high state (mACWR>6.87) was estimated to be 6.2%-points below zero, which is not possible, and likely a result of a model that is not robust enough.

In summary, no U-shaped pattern could fully be confirmed, and few injuries occurred in several of the exposure states. Nevertheless, runners having large increases in training load may more vulnerable to injury than runners with smaller training load progressions are. These presumptions would be in line with current believes among runners who often perceive "excessive training" as one major factor in injury occurrence (Saragiotto, 2014b). However, the results must be interpreted with caution due to the questionable robustness of the model because of the low number of events (injuries) in certain states, but also as this is the first study to explore changes in training load among recreational runners using (a modified version of) the acute to chronic workload ratio.

Finally, due to the ongoing debate regarding the use of the acute to chronic workload ratio, a secondary analysis was performed. Here, four injuries occurred while runners progressed between >10% and 30%. This was less than for all other states (>30% regression: 10 injuries, >10% to 30% regression: 12 injuries, 10% regression to 10% progression (reference): 13 injuries and >30% progression: 32 injuries). However, as all confidence intervals crossed zero, no ratio representing bi-weekly changes seems to be more or less injurious than others.

Translating arbitrary units into kilometres

Interestingly, for both mACWR (original and median cut-offs), the average acute training load increased from the lower to the higher exposure states. In contrast, the average chronic training load decreased from the lower to the higher exposure states. If a training session is categorised as a low mACWR state can therefore be a result either of a relatively low acute training load or by having a large chronic training load. The latter seems to be more common in this study. Conversely, if a training session is categorised as a higher mACWR state can be a result either of a relatively high acute training load or by having a (very) low chronic training load. Again, the latter seems to be more common in this study as the average chronic training load for the highest mACWR states was 65 au and 22 au for the original and median cut-offs, respectively. Others have argued that the "journey" of how an athlete is increasing to a certain weekly training load perhaps is more important than how large the weekly training load is in absolute numbers (Gabbett, 2016b). In research on running-related injuries, this assumption remains unknown.

It is also important to remember that in the present study, au was the product of distance (in kilometres) and intensity (Borg's rpe 6-20), and that many other definitions of training load exist (Impellizzeri, 2019; Udby, 2020). Therefore, these values presented may or may not be generalizable for other running populations, partly depending on the constitution of training load.

Further, a training load ratio is not always easy to grasp, especially not if the ratio is altered with regard to time-windows, exponentially weighted moving averages and uncoupling of the numerator and denominator. To visualise the average training loads for each of the five exposure states based on the mACWR median cut-offs, Figure 18 was created. Here, "Low" represents the 5% of the total number of sessions with the lowest ratio (n=744) and "Very high" represents the 5% of the total number of sessions with the highest ratio (n=743). "Reference" (n=2973) and "High" (n=2974) each include 20% of the sessions (between 5%-25%, and 75%-95%, respectively). Finally, "Medium" covers 50% (n=7431) of the total number of sessions closest to the median number (from 25% to 75%).

mACWR Exposure states (Median cut-offs)									
Low < 0.86		Reference 0.86 to < 1.43		Medium 1.43 to < 3.0		High 3.0 to 6.87		Very high > 6.87	
Average Training Load									
AL 92 au	CL 139 au	AL 140 au	CL 121 au	AL 171 au	CL 85 au	AL 205 au	CL 51 au	AL 232 au	CL 22 au

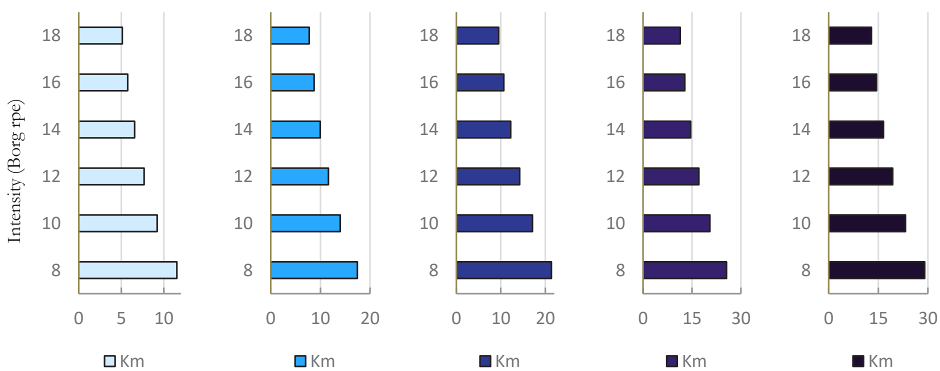

Figure 18. Average training loads (in arbitrary units, au) in each exposure state (modified acute to chronic workload ratio with median cut-offs). AL= Acute training loads, CL= Chronic training loads. mACWR= modified acute to chronic workload ratio. The bars show the number of kilometres (km) corresponding to the average acute training loads at a certain intensity (Borg rpe), given a certain average chronic load.

In an attempt to translate the average acute loads for each exposure state, given a certain average chronic load in that state, six bars representing a distance in kilometres at different intensities (Borg rpe) were created (Figure 18). As an example, if a runner who is in the low state (mACWR <0.86) runs 9.2 km at an average intensity of 10, that represents an acute load of 92 au. An equal training load can be achieved by running a distance of 5 km at an average intensity of 18. Thus, a certain acute load is dependent on the distance and intensity of a training session. The longer-term (chronic) training loads will tell if that certain acute load is low or high in relation to your past training.

Limitations

Unsupported definition of a recreational runner

The project aimed to include recreational runners. As a clear definition did not exist at the time the study was planned or conducted, we used a definition similar to what other studies have used (see e.g. Koplan, 1982; Lun, 2004; Hein 2013). The definition was solely distance-based, and any individual who had a weekly average of 15 km or more during one year met the definition of being a recreational runner. The definition then guided some of the inclusion and exclusion criteria, specifically about running habits (volume) and experience (years of regular running). Most likely, we did not include any beginners or novice runners, as our cut-off for experience (12 months) exceeds the definition in the consensus statement by Honert et al. (2020). However, it is more likely that our study included some runners who were close to high-calibre or (sub)-elite-runners, as the cut-off in this paper was 50 km per week. We did not exclude any runners because of having a high weekly running volume. The fact is that 97 runners (43%) in the present study exceeded a weekly volume of 50 km at least once. A few runners completed excessive running sessions (+50 km in one session). It is possible to argue that those runners are not typical recreational runners. Consequently, the choice of not having an upper (distance) limit in the recruitment procedure might have led to the inclusion of a few high-calibre runners.

Modified injury definition

Despite having access to a recently published consensus statement on running-related injuries for recreational runners (Yamato, 2015), the present study did not fully adopt this definition. Instead, the decision to modify parts of the consensus statement was made. First, we argue that recreational runners do not usually schedule their training sessions in advance. Recreational running is often referred to as a convenient, time-efficient and easily accessed leisure-time physical activity. Scheduling can make the activity slightly less flexible. Thus, the part with "three consecutive scheduled training sessions with pain" was replaced by a percentage of training sessions (≥66% over two weeks or ≥50% over four weeks) with pain. This modification has previously been used in works by Hein (2013, 2014). With this modification, runners who did not experience pain in several consecutive training sessions, but instead in, for instance, every other session, were contacted by the study leader to have the pain investigated. Overall, the definitions are though very similar, and runners had the possibility to ask for a medical examination if they were suspecting an injury. In a broader perspective, recent studies (conducted after the publication by Yamato et al. in 2015) do not always align with the consensus definition. For various reasons, other consensus statements and injury definitions, such as, but not limited to the ones by Bahr, 2020 and Timpka, 2014, are sometimes used, for instance in a study on injuries and health problems in adolescent distance runners (Mann, 2021).

Information problems regarding self-reporting

A further limitation of this study includes the self-reporting of training information. Self-reporting is not as accurate as GPS-based information on distance. Moreover, it might be a socially desirable behaviour to report high training volume, and self-reporting makes it easier to over-report their running distance or physical activity. Previous research indicates that over-reporting mostly applies to retrospective questionnaires, but might also apply to prospective data collections. GPS would probably have been a more reliable way to collect information on running distance and time (Terrier, 2005). However, to provide more than 200 runners with GPS-watches was impossible due to the costs. Providing runners with GPS-watches would perhaps solve the potential problem of over-reporting, however, it would possibly also introduce external motivation to run more – which was not an intention. An alternative could have been to equip participants with an inertial measurement unit to measure vertical acceleration. This would have provided the possibility to get detailed information on the load per step, as vertical acceleration is highly correlated with the vertical force (Willy, 2018).

Not every injured participant in the study was able to attend the medical examination. Despite numerous efforts, four participants declined these requests due to logistical problems such as time constraints or long travel distance. In all of those cases, the participants sought help from other medical professionals (doctors or physiotherapists) and received a diagnosis or injury type of the current injury, which make this information secondary although not self-reported.

In addition, runners self-reported information on pain, which means that the outcome was dependent on honest reporting. If participants are honest or not in their reporting on pain is though difficult to control, regardless of the method used for monitoring pain.

Lack of specific injury-type analysis

The prospective cohort study was of considerable size, with more than 200 participants followed for a maximal time of one year. However, it was not large enough to analyse specific injury types separately as the variety of injuries was too high and the number of injuries were too low. Preferably, competing risk analysis would have been performed, but the number of certain injuries was simply too small. In competing risk analyses, time-to-event data are used from inclusion to the occurrence of a certain injury (e.g. a tendon-related injury) (Finch, 2014; Shrier, 2016). If a participant sustains a tendon-related injury, the same person cannot sustain any other competing events (such as a muscle-related injury). As different injuries likely have slightly or completely different aetiology, the lack of a specific injury type analysis, such as competing risks analysis, is a limitation.

Exclusion of baseline and follow-up variables

The graph in Figure 3 (Chapter 1, page 34) visualised the relationship between structure-specific load and structure-specific load capacity, and running-related injury and showed the included and excluded variables. In the light of this graph, it becomes clear that many highly interesting variables were not part of the data collection. To include for instance a measure of fitness (e.g. maximal aerobic capacity) would have provided a more comprehensive picture of the capacity of the runners. In addition, mood, sleep, nutritional intake and illness are factors that most likely also affect the load capacity of a specific structure (Mousavi, 2021). As for training load variables, we measured distance and time, but not the number of steps. Measuring steps could be important as for a given running distance, the cumulative number of steps increases with decreased running speed (Dorn, 2012). However, the trade-off between including many variables and the cost (monetary, time and labour) of doing that is fine-tuned.

The approach of having one baseline examination did not allow for analysis of change in several variables. For instance, we could not analyse strength, running mechanics, flexibility or trigger points over time but only provide a snapshot in time. As the research goal was to compare if runners with certain characteristics were at higher risk of sustaining an injury compared with runners having different characteristics, there was no need of including multiple examinations, although it would have provided interesting information.

Strengths

Study design

A major strength of the current study was the prospective design. According to the principle of temporality in Hill's criteria for causation, the effect must occur after the cause (Hill, 1965 & 2015). A prospective study design does allow for this, but it is still possible to violate the criteria of temporality in prospective studies. However, in the present study, the outcome (RRI) was always considered to occur because the applied load exceeded the load-capacity of a structure. Importantly, we did not use information from the future (e.g. information on which individuals sustained an injury) to compare the "soon-to-be-injured" with the non-injured (Andersen, 2012;

Nielsen, 2018b). Moreover, a prospective study design increase the likelihood of participants reporting accurate follow-up information, as it is easier to recall than in retrospective studies.

Comprehensive baseline examination

The clinical/anthropometrical and biomechanical assessments included a wide range of collected variables. Many studies have collected data on joint range of motion (Haglund-Åkerlind, 1993), flexibility (van Mechelen, 1992b), trigger points (Liu, 2012), strength (Ferber, 2011), or kinematics (Napier, 2019), but the combination of many variables is rarely seen. As the aetiology of RRI is considered to have a multifactorial nature (Meeuwisse, 2007; Bertelsen, 2017b), including a wide range of variables must be seen as a strength of this study.

Committed participants

The participants were fairly committed to submit training information, and the average follow-up time was >200 days (injured runners are included in this number). In previous prospective cohort studies, it has been common to exclude between 10% and 50% (average 23%) of the number of runners from the analyses due to missing training information (van Gent, 2007).

Aligning research goal and analytical approach

Being explicit about the research goal and the analytical approach are prerequisites for good science (Hernán, 2018). A step towards a more transparent research procedure was taken as we disseminated the study design by publishing the protocol prior to any analyses. In the protocol, we outlined specific hypotheses, explained the data collection procedure and the planned analytical approaches.

Although it should be stated that studying causal inference in running-related injury research is not a simple task, one strength of this study is that we aimed for causal inference.

Finally, the different analytical approaches used, such as accounting for censoring in the calculation of the cumulative incidence proportion and the use of absolute measures of association in some of the predictive analyses, are considered as strengths of the present study.

Ethical considerations

Due to the collection of sensitive data (health information and injury status), this project underwent and was approved ethical vetting prior to its start. The project itself was not particularly questionable from an ethical perspective (no invasive measurements or blood samples, no sensitive personal information except health status, no intervention). Nevertheless, it is important to discuss some of the ethical considerations that have been made within the project. Especially, data treatment (data preparation, organisation, cleaning and storing) was a necessary issue to deal with as the participants sent in their training information via e-mail. Training documents were downloaded, anonymised with ID-numbers and organised in Excel spreadsheets during the course of the study. The list of ID-numbers and corresponding names were kept in a locked cupboard. At the end of the follow-up, all e-mails from participants were deleted from the e-mail server, which effectively means that it is only possible to back-track participants via the list of names and ID-numbers. The anonymised data set is stored at an encrypted server.

A critical part of this study was the medical examinations. As soon as a participant fulfilled any part of the definition of having sustained an injury, a medical examination was offered. For several participants, the examination led to further medical investigations, such as diagnostic imaging. All further medical examinations were done outside of the study meaning that the participants were directed to primary health care services. At this stage, participants were no longer part of the study. However, we (study leader and the medical professional) always aimed at giving each participant the best support possible in his or her way back to pain-free running.

Perspectives

The results from the present study should primarily be applied to recreational runners. Other types of runners might benefit from the results as well, however, the result may differ if a similar study had been conducted in other groups or subgroups or runners. Coaches and clinicians may use the results of the present study to inform runners how many injuries occur and where most RRIs occur (in terms of anatomical location), as well as who, or what type of runners, sustain more or less RRIs.

Further, the results from the present study may hopefully assist in the design of future RRI-studies with research goals targeting description, prediction or causal inference. Concerning description, future studies are highly recommended to use the concept of censoring for a more accurate estimation of injury incidence proportions. With regard to prediction and causal inference, much larger studies are needed if the aim is to explore how much running that is too much for sub-groups of runners having different characteristics. In my judgment, such large studies can be performed either by multi-centre studies (collaboration between many research groups collecting equal data) or by collaboration with companies behind online training platforms, such as Strava. Finally, the present study has outlined, together with theories on structure-specific load and structure-specific load capacity, and may assist in, how to target appropriate systems and proxy-variables. Importantly, many other theories and frameworks exist (see for instance the reviews by Johnson, 2017 or Hausken-Sutter, 2021) that could serve as bases for future research on injuries, also in the running community.

Context

This dissertation is closely related to a project on running-related injuries among recreational runners named SPRING. Figure 19 visualises the relationship between this dissertation and the SPRING-project. SPRING includes five hypotheses (H), of which two (number one and five) are part of the present dissertation.

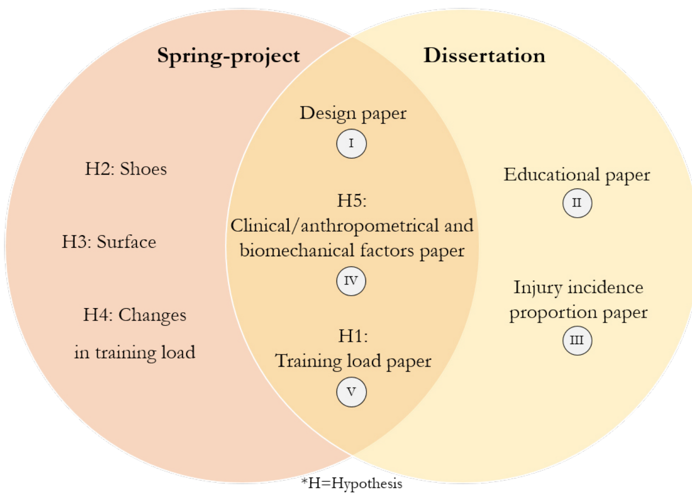

Figure 19. Relationship between dissertation and Spring-project.

Chapter 5: Conclusions

How many injuries occur?

During any given year, a cumulative incidence proportion of 36% to 54% can be expected among a population of recreational runners.

Calculating the cumulative injury incidence proportions using censoring is important, as it otherwise will be underestimated. In the SPRING-study, the cumulative incidence proportion was 13%-points lower if calculated without applying censoring.

The knee and the Achilles tendon/calf are expected to be the most frequently injured sites of the body. In this study, 27% and 25% of all injuries occurred at these anatomical locations, respectively.

Who sustains an injury?

The injury rate was twice as high in recreational runners with a history of injury compared to runners with no history of injury.

Runners having a late timing of maximal eversion or a low strength ratio between hip abductors and adductors sustained more injuries compared with runners in the corresponding reference groups.

Many variables related to load-capacity, such as range of motion, muscle flexibility and trigger points, or variables related to structure-specific load, such as BMI, could not serve as strong predictors for running-related injury.

Why does injury occur?

No causal relationship between training load and running-related injury was found, although the attempt to move closer to causal conclusions by exploring changes in training load was novel in light of the previous RRI-literature. Future studies will need thousands of more runners, and injuries, to reveal potential causal relationships.

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