Running-related injuries in recreational athletes

Incidence, risk factors and effectiveness of an injury-prevention programme

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UNIVERSITY OF GOTHENBURG
Gothenburg 2021
To my family
Running as a form of physical activity continues to grow in popularity and is accompanied by a number of health benefits, but one of the greatest threats that challenge these benefits is running-related injuries. The overall aim of this thesis is to identify the proportion of runners who sustain a running-related injury (incidence), possible reasons as to why they sustain these injuries (risk factors) and, finally, whether general injury-prevention guidelines can be effective in reducing the number of running-related injuries in recreational runners. This thesis comprises four studies.

Studies I and II of this thesis are prospective cohort studies comprising more than 200 recreational runners from the Gothenburg Half Marathon. Baseline testing prior to study start included range of motion and flexibility tests, a running analysis and isometric strength tests. Weekly training and injury information was collected during a 52-week period. The cumulative incidence proportion of running-related injuries after 52 weeks was 46%. The results revealed that runners with a late timing of maximal eversion, or low hip abductor strength compared with hip adductor strength, sustained more injuries compared with their counterpart runners (Study I). Additionally, runners with a previous injury were found to be almost twice as likely to sustain a new injury compared with runners with no previous injury (Study II).

Studies III and IV of this thesis are prospective, observational, comparative studies comprising 433 male and female recreational runners recruited from the Gothenburg Half Marathon. Participants were allocated to either an intervention group (n=228) or a control group (n=205) and submitted weekly information on their training habits and any running-related injury/pain for 18 weeks. The intervention group performed an injury-prevention programme consisting of neuromuscular control and foam-rolling exercises, twice a week for the duration of the study. No significant differences were found when investigating exposure states of weekly running distance and running-related injuries. However, increasing the weekly running distance by more than 30% appeared to be accompanied by a higher risk of injury, compared with keeping within a 10% increase or decrease, despite these findings lacking statistical significance (Study III). When exploring the effects of the intervention programme, we found that runners with high compliance with the intervention were 85% less likely to sustain an injury compared with the control group (Study IV).

Keywords: Running-related injuries, Neuromuscular control, Injury prevention
Abstract

Running as a form of physical activity continues to grow in popularity and is accompanied by a number of health benefits, but one of the greatest threats that challenge these benefits is running-related injuries. The overall aim of this thesis is to identify the proportion of runners who sustain a running-related injury (incidence), possible reasons as to why they sustain these injuries (risk factors) and, finally, whether general injury-prevention guidelines can be effective in reducing the number of running-related injuries in recreational runners. This thesis comprises four studies.

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Löpning, som en form av fysisk aktivitet, fortsätter att växa i sin popularitet och har flera positiva fysiologiska effekter, men ett av de största hoten som utmanar de positiva effekter är löprelaterade skador. Det övergripande syftet med denna avhandling var att försöka identifiera antalet löpare som får en löprelaterad skada, utforska möjliga anledningar till varför de blir skadade och om generella skadeförebyggande åtgärder är effektiva för att minska antalet löprelaterade skador bland motionärer.

Avhandlingen bygger på fyra artiklar.

Studie I och II är prospektiva kohortstudier med drygt 200 löpare som rekryterades via Göteborgsvarvets register. Innan studiens start genomförde löparna kliniska (rörlighet, triggerpunkter, flexibilitet) och biomekaniska (löpstil, stryka) undersökningar. Under studiens 52 veckor skickade alla löpare in veckorapporter innehållande information om sin träning samt smärta eller skada. Andelen nya skador i förhållande till träningsdagarna som observerades (kumulativ skadeincidensen) blev 46%. Löpare med relativt sen timing av maximal eversion (pronation), och löpare med svagare höftabduktorer i förhållande till höftadduktorer, drabbades av fler skador i jämförelse med referensgrupperna (Studie I). Dessutom visade resultaten att sannolikheten att få en ny skada var nästa dubbelt så stor för löpare med en tidigare skada, som löpare utan en tidigare skada (Studie II).

Studie III och IV är prospektiva jämförelsestudier med 433 skadefria löpare rekryterade från Göteborgsvarvets register. Löparna delades in i en interventionsgrupp (n=228) och en kontrollgrupp (n=205) och skickade in veckorapporter om sin träning och eventuell smärta eller skada, under 18 veckor. Interventionsgruppen fick ett skadeförebyggande träningsprogram innehållande neuromuskulär kontroll- och 'foam-rolling' övningar, att utföra 2 gånger i veckan under studiens gång. Ingen signifikant skillnad kunde påvisas när man undersökte sambandet mellan träningsbelastning och skador. Däremot kunde man notera att löpare som ökar sin veckoliga löpdistans med mer än 30% visade en ökad risk för skada, jämfört med att öka (eller minska) under 10%. Detta resultat var dock inte statistiskt signifikant (Studie III).

Därutöver såg man att löpare med hög följsamhet till interventionen hade 85% mindre sannolikhet att bli skadad, jämfört med löparna i kontrollgruppen (Studie IV).

Nyckelord: Löprelaterade skador, Neuromuskulär kontroll, skadeförebyggande åtgärder

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### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ACL</td>
<td>Anterior cruciate ligament</td>
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<tr>
<td>AT</td>
<td>Achilles tendon</td>
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<td>BMI</td>
<td>Body mass index</td>
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<tr>
<td>CIP</td>
<td>Cumulative incidence proportion</td>
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<tr>
<td>HAB:HAD</td>
<td>Ratio between hip abductor and hip adductor strength</td>
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<tr>
<td>IQR</td>
<td>Interquartile range (Q1-Q3 range)</td>
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<tr>
<td>ITBS</td>
<td>Iliotibial band syndrome</td>
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<tr>
<td>Kg</td>
<td>Kilogram</td>
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<tr>
<td>Km</td>
<td>Kilometre</td>
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<tr>
<td>n</td>
<td>Number of</td>
</tr>
<tr>
<td>PA</td>
<td>Physical activity</td>
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<td>PAP</td>
<td>Physical activity on prescription</td>
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<tr>
<td>RD</td>
<td>Risk difference</td>
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<td>ROM</td>
<td>Range of motion</td>
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<tr>
<td>RRI</td>
<td>Running-related injury</td>
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<tr>
<td>SD</td>
<td>Standard deviation</td>
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<tr>
<td>SMR</td>
<td>Self-myofascial release</td>
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<td>95% CI</td>
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Censoring
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Cumulative injury incidence proportion
The proportion of athletes at risk that suffer an injury during a specified period of time, expressed as a percentage. Can be calculated with/without censoring.

Injury incidence rate
The rapidity with which new injuries occur in the population at risk, during a specified period of exposure time (e.g. injuries/hours of running).

Prevalence proportion
The proportion of athletes that suffer an injury in a certain time period (e.g. end of the study).

Recreational runner
A runner with more than six months’ running experience, who performs one to five sessions and 15 to 50 km of running a week.

Running-related injury
A running-related musculoskeletal pain in the lower limbs or back that causes a restriction 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.

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1.1 Physical activity for health

The lack of regular physical activity (PA) has been associated with several health consequences and is reported to be the fourth leading risk factor for non-communicable diseases and mortality globally. 1 Regular PA has been shown to be effective in the treatment and prevention of multiple diseases including coronary heart disease, diabetes type 2, depression and osteoporosis.2–4 Although the minimum recommended PA level for adults worldwide is 150-300 minutes of moderate-intensity, or 75 minutes of vigorous-intensity aerobic PA a week, an estimated one in three adults still remains physically inactive globally. 3,5,6 Continuous efforts are being made to promote PA in society to minimise the health consequences associated with a sedentary lifestyle. One such effort includes a model implemented, to varying degrees, in the healthcare system in Sweden, known as Physical Activity on Prescription (PAP).7 All licensed healthcare professionals in Sweden, with sufficient knowledge in the area, are able to prescribe PAP, using individualised exercise regimens and encouraging patient-oriented treatment plans. Strong evidence exists when it comes to the positive effects of PAP in increasing PA levels amongst adults, where key elements in the success of the prescribed treatment involve a patient-centred approach, with the support of a medical professional.8,9 The recommended levels of aerobic PA and strength training, maintained through activities such as walking, cycling, running and resistance training, promote an active lifestyle, while also improving metabolic and cardiorespiratory health, as well as health-related quality of life.

1.2 Running for health

1.2.1 Benefits associated with running

Running is one of the most popular forms of PA globally. 10 The simplistic nature of running, combined with the low costs, high availability and accessibility, makes it an engaging form of PA for both the beginner and the experienced runner. It is also a low-impact form of exercise that can be adapted to suit all fitness levels, making it accessible to people of all ages and abilities. Regular running can improve cardiovascular health, increase bone density, enhance mood and reduce the risk of chronic diseases such as diabetes and obesity. It can also improve sleep quality, boost immune function, and enhance cognitive function. Additionally, running can be a social activity, allowing individuals to connect with others and form a sense of community. The endorphin release that occurs during running can have a positive impact on mental health, reducing anxiety and depression. Running is a sport that can be enjoyed for its own sake, without the pressures of competition or performance, making it a satisfying and rewarding activity for many people.
Introduction

1.1 Physical activity for health
The lack of regular physical activity (PA) has been associated with several health consequences and is reported to be the fourth leading risk factor for non-communicable diseases and mortality globally. Regular PA has been shown to be effective in the treatment and prevention of multiple diseases including coronary heart disease, diabetes type 2, depression and osteoporosis. Although the minimum recommended PA level for adults worldwide is 150-300 minutes of moderate-intensity, or 75 minutes of vigorous-intensity aerobic PA a week, an estimated one in three adults still remains physically inactive globally. Continuous efforts are being made to promote PA in society to minimise the health consequences associated with a sedentary lifestyle. One such effort includes a model implemented, to varying degrees, in the healthcare system in Sweden, known as Physical Activity on Prescription (PAP). All licensed healthcare professionals in Sweden, with sufficient knowledge in the area, are able to prescribe PAP, using individualised exercise regimens and encouraging patient-oriented treatment plans. Strong evidence exists when it comes to the positive effects of PAP in increasing PA levels amongst adults, where key elements in the success of the prescribed treatment involve a patient-centred approach, with the support of a medical professional. The recommended levels of aerobic PA and strength training, maintained through activities such as walking, cycling, running and resistance training, promote an active lifestyle, while also improving metabolic and cardiorespiratory health, as well as health-related quality of life.

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Running is one of the most popular forms of PA globally. The simplistic nature of running, combined with the low costs, high availability and accessibility, makes it an engaging form of PA for both the beginner and the
more experienced runner to maintain, not only as a hobby, but also as a lifestyle. The health benefits associated with running are vast and even a low dose of leisurely running (5-10 minutes a day at a slow pace) has been shown to be sufficient to reduce mortality from cardiovascular disease, compared with sedentary individuals. Increased social interaction and general well-being, as well as enhanced performance, are additional advantages of running, making it a form of PA that should be encouraged in the sedentary population, or sustained among those that are already active.

1.2.2 Risks associated with running

Even though running has many positive benefits, there are some accompanying risks that are yet to be reduced. The continuously growing interest in taking part in the many running events available means that medical encounters of both a life-threatening and a moderately severe nature are inevitable. In these events, infrequent cardiovascular and respiratory complications, as well as even more frequent sudden death, cannot be ignored. However, even runners outside the realm of running events are faced with a major burden, namely musculoskeletal injuries. Running-related injuries (RRIs) remain one of the main reasons why runners are forced to hang up their shoes for good. In a study of novice runners taking part in a six-week running programme, almost one-third of the participants had stopped running within six months after the start and 48% stopped due to an RRI. With the growing importance of maintaining a physically active lifestyle, it is vital to overcome the hurdles, such as RRIs. More research related to injury prevention is therefore needed, but, in order to achieve this, the extent of the burden of RRIs and the mechanisms behind the development of RRIs need to be better understood.

1.3 Running-related injuries

1.3.1 Reporting the incidence of running-related injuries

Running-related injuries are common in recreational runners, but the incidence reports vary greatly across studies. The wide range of reports can be attributed to a number of reasons, one of which is the choice of measures authors use to describe the occurrence of injuries in their studies. Injury prevalence (cases and proportions) and incidence (proportions and rates) are often used as measures to describe injuries in studies, but these terms have been inconsistently or even incorrectly used in several research reports, making the interpretation and comparisons of injury incidence and prevalence difficult. Francis et al. (2019) highlighted the lack of consistent injury reporting across studies, where 19 of the 36 studies included in the systematic review lacked sufficient information on the number of runners studied and the number of injured runners and injuries, as well as the number of new vs. recurrent injuries in order to report injury incidence or prevalence in a satisfactory manner.
Other methodological aspects that affect the reporting of injuries include the inconsistent definitions of a running-related injury. A systematic review comprising 30 studies from 1977 to 2008 found that more than two-thirds of the studies used different definitions to classify an RRI. Importantly, in a study by Kluitenberg et al. (2016), the use of different injury definitions affected the incidence of RRIs in novice runners during a six-week period, with numbers ranging from 7.5% to 58%. A consensus definition of RRIs has been presented to overcome problems of this kind and to enable comparisons between studies, as well as uniting researchers in the field with a 'common language'. Yamato et al. presented the definition of a running-related injury as:

“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.”

Although a consensus statement may make it easier to compare studies, certain aspects of the definition above may not be applicable to runners of all types; for example, the scheduling of training sessions for novice or recreational runners. Additionally, the compliance of participants in a prospective observational study or RCT will influence the reporting of injury incidence and prevalence, as the duration of follow-up will be affected. In order to report incidence proportions more accurately, it is necessary to take account of censoring. Censoring occurs when participants are no longer under observation, for example, if they stop reporting training data, fall ill or lose the motivation to continue with the study, before the event of interest (e.g. injury) has occurred. This method does not assume that all participants are included in the study for the same amount of time, nor that they run the same risk of sustaining an injury, and it is therefore a more accurate means of reporting incidence proportions. In addition, ways in which injuries are classified (even when a clear definition is used) may also affect injury reports, for example, if injuries are examined by a medical professional, or self-reported by the runners.

Moreover, the different running populations used in studies make comparisons of injury incidence difficult. Studies of different running populations such as novice, recreational, marathon and ultramarathon, and track runners (sprint or middle-distance) are difficult to compare due to the differences in experience, training habits and level of running. Although many definitions of recreational running have been used across the literature, a recent consensus statement was presented by Honert et al. (2020), with definitions of three types of runners, in order to make studies more comparable, similar to the injury definitions. Here, recreational runners are defined as having more than six months’ running experience, with one to five running days and 15 to 50 km running distance a week.
Finally, the design of a study can also affect the reporting of injury incidence. Prospective studies are favourable compared with retrospective studies as they observe participants forward in time and risk factors can be observed before an injury occurs.\textsuperscript{28} Retrospective studies, on the other hand, look back in time at what could have caused an injury after it occurred. This study design is often accompanied by recall bias, making reports of injury less accurate.\textsuperscript{16,28} Uniform reporting across studies is vital in order to acquire an adequate understanding of the burden of RRIs, which can then serve as a foundation for establishing why and how these injuries occur.

### 1.3.2 Anatomical locations of running-related injuries

Repeated stress on a specific musculoskeletal structure that exceeds the load capacity of the structure will result in an injury.\textsuperscript{29,30} Although runners may also sustain acute injuries such as sprains and fractures, the majority of RRIs are so-called overuse injuries, which develop over time. The lower extremities are more commonly affected with regard to injuries in runners, with the knee, lower leg and foot/ankle facing the majority of injuries.\textsuperscript{31} A recent review by Francis et al.\textsuperscript{18} compiled results from 36 studies, where the specific pathology of injuries could be obtained from 11 studies, and found that the knee (28%), foot/ankle (26%) and lower leg/shank (16%) sustained the most injuries.\textsuperscript{18} Differences were observed between sexes, where females tended to sustain more knee injuries than males (40% vs. 31% respectively) and males sustained more injuries to the foot/ankle (26% vs. 19%) and lower leg/shank (21% vs. 16%). Patellofemoral pain syndrome, Achilles tendinopathy and medial tibial stress syndrome accounted for the most common injuries.

### 1.3.3 Aetiology of running-related injuries

Although a large amount of research exists on the aetiology of RRI, reports remain ambiguous and continuous efforts are being made to unearth the underlying mechanisms. The mechanisms behind the development of RRIs are complex and multifactorial, influenced by both intrinsic factors (e.g. age, gender, BMI, running experience) and extrinsic factors (e.g. training load, running surface).\textsuperscript{32} Many studies have investigated only single variables or mechanisms with regard to injury rather than investigating their interactions and combined effects. A system-based approach taking account of several factors, such as biomechanical, anthropometric and training-related variables, rather than adhering to the mono-disciplinary approach, has been suggested when researching injury risk.\textsuperscript{32}

Previous injury,\textsuperscript{33,34} is a known factor consistently reported to be one of the strongest risk factors for RRIs.\textsuperscript{32,35} Although the reason is not fully understood, the fact that that runners with a previous injury may return to running prior to full recovery and therefore exacerbate an ongoing injury has been discussed. It may also be the case that the anatomy at the injury site is altered or weakened after an injury and if the recovery time is also insufficient, the structures may be stressed beyond their
capacity and subsequently be reinjured. Moreover, it is speculated that a change in running style may be adopted as a result of a previous injury, where compensatory and protective mechanisms cause a shift in loading and predispose the runners to new injuries. Another factor highlighted when identifying the risks of RRIs is running experience, where reports in the literature are conflicting. Some studies show that more experienced runners have a higher risk of injury, whereas other studies report that novice or less experienced runners sustain more injuries. In addition to these contradictory reports, another systematic review concluded that there is no association between running experience and RRI risk. Factors such as age, sex, and BMI have been reported to be associated with RRI, but, even here, with inconsistencies in the literature. Higher age, higher BMI and sex (male) have been suggested to increase the risk of sustaining an RRI, but these reports have been contrasted, leaving it still unclear as to the extent to which these variables affect the development of RRIs.

Training-related variables are also highlighted as important factors influencing RRI risk. Training load, often monitored through measures of distance (km or miles) and/or duration, is one such variable. Sudden or recent changes (progression or regression) in weekly training load, often monitored in a bi-weekly manner, have shown associations with RRI risk. A recent review by Damsted et al. (2018) revealed that a progression of more than 30% in weekly running distance increased the risk of injury compared with a progression of less than 10%. Additionally, weekly running volumes exceeding two hours, and running more than twice a week have also been shown to increase the risk of injuries in recreational runners. Though research exists in this area, the results reported lack consistency, leaving questions still unanswered. Continued efforts are needed to unravel the extent to which training load affects RRI risk.

To summarise, reports of running-related injury incidences across the literature vary greatly due to reasons such as the definition of injury used in studies, the populations of runners that are studied (e.g. novice, recreational, ultramarathon) and methodological aspects such as the study design (e.g. prospective or retrospective) and analytical approach (e.g. the use of censoring). There is a consensus that RRIs occur most commonly in the lower extremities, affecting mainly the knee, lower leg and foot/ankle. It is also known that a previous injury is a strong risk factor for RRIs, however, running experience, age, sex and BMI are inconsistently reported with regards to RRI, and it remains unclear how, and to what extent they contribute to the development of RRIs. Identifying the risks of RRIs is vital in order to be able to implement effective injury-prevention strategies. If the underlying mechanisms of injury are unclear, developing injury-prevention strategies will be challenging. However, even if it may be vital for coaches and clinicians to know the runners who are at a higher risk of injury, only factors that are modifiable can serve as a basis for injury-prevention strategies. Nevertheless, it must be noted that, as RRIs are multifacto-
rial and complex, the interaction between modifiable and non-modifiable variables in the development of RRIs must not be overlooked. It is apparent that we need more research to shed light on the unanswered questions regarding RRIs.

1.4 Injury prevention

In order to effectively implement injury-prevention guidelines, it is vital to understand the extent of the problem you are aiming to solve and why it occurs. A sports injury-prevention model first proposed by van Mechelen et al. (1992) was later expanded upon and presented as a new framework for sports injury research by Finch (2006). This framework, known as the Translating Research Into Prevention Practice (TRIPP) framework, highlights the six vital steps in building a solid foundation for injury prevention. The initial step, which serves as a crucial base for the rest of the steps, entails injury surveillance, using established injury definitions, and appropriate analysis methods to establish the extent of the problem. Once an outline of the injury picture has been drawn, the question of why injuries occur needs to be answered. Step two dives into the aetiology of injuries, knowledge without which prevention measures cannot be created. Step three and four focus on the development of possible solutions to the injury problem and implementing these approaches in a controlled setting. The final two steps of the loop involve implementing the prevention strategies in a real-world context where they can actually be effective in their purpose and, finally, evaluating the true effectiveness of the implemented strategies, continuously using feedback from steps 1 and 5. This thesis focuses primarily on steps 1-4, with the aim of contributing to the foundation for future research to continue to steps 5 and 6. Figure 1 below depicts the stages in the TRIPP model.
1. Injury surveillance
Describing the extent of the problem using valid and reliable methodology to ensure routine monitoring and reporting

2. Establishing aetiology & mechanisms of injury
Understanding why injuries occur in order to build a base for prevention measures, using multidisciplinary approaches

3. Development of preventive measures
Identifying possible solutions to the problem and developing appropriate preventive measures, strongly guided by stage 2. Again using multidisciplinary approaches

4. Apply to ideal conditions (experimental)
Assessment of intervention efficacy in e.g. a laboratory setting on small groups and ideal, controlled conditions. Contributing to the evidence base and uncovering what works and what does not (recruitment, compliance, drop-outs, adverse effects)

5. Implementation strategies in relevant context
Exploring how efficacy outcomes (stage 4) can be translated and adopted into a 'real-world' setting. Understanding the target group, sporting activity, infrastructure and resources available and needed for the intervention

6. Evaluate effectiveness in relevant contexts*
Final stage where implementation and evaluation of the intervention takes place in a 'real-world' setting. Evaluating the evidence from stage 4 and taking account of the considerations in stage 5

*Feedback loop includes evidence from stage 4 and concurrent feedback from stage 1 and stage 5.

Figure 1. Diagram showing the Translating Research into Prevention Practice (TRIPP) framework for injury prevention in sports.50

1.4.1 Injury-prevention strategies in sport
The effects of prevention interventions to lower the risk of injury in team-sport contexts have been examined previously, producing mixed results.51,52 It has been suggested that insoles, external braces and multi-component training programmes, including proprioceptive balance training and neuromuscular control exercises, are effective in lowering the risk of injury,51,52 whereas interventions such as stretching, injury-prevention videos and footwear have so far failed to show any positive effect on sports injuries.51

More recently, a systematic review from 2018, including studies of military recruits and elite adult and young football players, showed positive effects of strength training on the risk of injuries.53 Here, it was reported that an increase of 10% in the volume of strength training, significantly reduced the risk of injury across all six studies included, where both acute (hamstring and anterior cruciate ligament (ACL)) and overuse (anterior knee pain) injuries were reduced.
The prevention of injuries in football has been researched in detail and several studies have investigated approaches to reduce the number of injuries. An injury-prevention programme focusing on core stability, balance and knee alignment, known as Knee Control (Knäkontroll, SISU Idrottsböcker, Sverige 2005), has been shown to be effective in reducing the number of ACL injuries in adolescent female football players. This 15-minute warm-up programme reduced the number of ACL injuries by 64% compared with the control group. Moreover, the International Federation of Associated Football (FIFA), together with a team of experts, has developed an injury-prevention programme, FIFA 11+, designed to lower the risk of injuries in male and female football players. The programme consists of running exercises, strength exercises for the lower extremity and core muscles, and plyometric exercises, to improve neuromuscular control and overall readiness and awareness during static and dynamic movements. The implementation of this programme has been shown to significantly improve lower limb strength and reduce the number of both ACL injuries and overall injuries in football. Further research will strengthen the positive effects of neuromuscular control exercises on lowering injury risk among football players, however, little research exists on the effect of knee control exercises on RRIs, and this must be addressed.

Self-myofascial release (SMR) techniques, commonly using a foam-roller or roller massage tool, are a popular method used in rehabilitation and fitness contexts with the aim of improving myofascial mobility. So far, however, the results in terms of the effects of SMR have been ambiguous in the literature and research is still emerging. Improvements after foam-rolling with regard to fatigue-induced impairments in muscles and exercise-induced muscle soreness have been reported, where both regenerative effects (post-exercise foam-rolling) and preventive effects (pre-exercise foam-rolling) are seen. Moreover, the acute effects of foam-rolling on ankle dorsiflexion ROM were observed in a study, following three bouts of 30-second foam-rolling sessions. Although no differences were found between the foam-rolling group and the control group that did not foam-roll, within-group differences were found, where increased ankle dorsiflexion compared with a baseline measurement was observed for up to 20 minutes after the intervention. Foam-rolling remains a debated topic in the literature with inconsistent reports, and though some studies show positive effects, these tend to be acute effects lasting only a short time after the bout of foam-rolling. More studies investigating the optimal dosage and long-term effects of foam-rolling, particularly in endurance athletes, may contribute with valuable information to this field.

1.4.2 Injury-prevention strategies in running

Neuromuscular control and strength exercises

Neuromuscular control refers to the production of a desired movement as a result of the interaction between the musculoskeletal and nervous systems. During running, hip adduction occurs after foot-strike, resulting in the eccentric activa-
tion of the hip abductors to resist or control the motion. It has been shown that runners with iliotibial band syndrome (ITBS) exhibit weaker hip abduction strength and greater knee adduction angles, but the question of whether hip muscle strength is an influential factor in the development of ITBS, is a subject of debate in the literature. Hip-focused neuromuscular training, targeting muscle activation and the eccentric strength of the hip abductors, may help to minimise lower-leg valgus during dynamic movements, but assessments of interventions have produced conflicting results in the literature. Taddei et al. (2020) recently reported the effects of a foot core strengthening intervention on recreational runners taking part in a randomised controlled trial (RCT). Here, runners allocated to the intervention group performed foot and ankle exercises supervised either remotely or in person by a physiotherapist, for a duration of 12 months. The study showed that recreational runners who performed the intervention were 2.42 times less likely to sustain an RRI during the 12 months, compared with the control group. In contrast to this, a recent study of first-time marathon runners was conducted, with the aim of reducing the number of RRIs. Participants were instructed to perform a strengthening programme consisting of exercises targeting the hip abductor, quadriceps and core muscle groups, three times a week for a duration of twelve weeks. The results of this study showed that the intervention had no effect on RRIs.

It is apparent that neuromuscular control and strength training have some effect on RRI, but not enough evidence exists to be able to draw concrete conclusions on the matter. In particular, neuromuscular control remains an interesting subject to explore further in the field of running, especially when it has shown to be effective in reducing the risk of injury in other sports contexts.

**Training load**

The general rule that has been accepted over the decades and is still applied as a recommendation today, is the so-called 10% rule, which states that increases in weekly running volume should stay within 10%. Buist et al. (2008) performed a study to test this rule, comparing two intervention groups- a 10% average increase in weekly running volume over 12 weeks and a 24% average increase in weekly running volume over eight weeks. No differences were found between the groups with regard to RRI risk. It may be that progressions over 8 or 12 weeks are not sudden enough and changes over two-week periods, or excessive progressions in training load, may be more likely to make runners susceptible to RRIs.

Coaches, clinicians and runners alike have used this rule as a guideline for optimal training progression, to minimise the risk of RRI, but there is minimal evidence to support this guideline. Further research is therefore needed in order to establish the relationship between sudden changes in weekly running volume and the risk of RRI, and consequently, develop sound prevention guidelines.
Equipment

Equipment, such as shoe insoles and orthoses, as well as knee braces has been researched with regard to RRRIs. Although commonly used by runners and recommended by manufacturers, evidence on the true effect this equipment has on RRI risk still diverges. Running footwear is another example of equipment largely discussed with regard to load distribution in and between the structures of the body. Pronation and rear-foot eversion are types of foot movement that are thought to affect load distribution in running and an excessive degree of these movements are known risk factors for RRRIs. Footwear designed to control the amount of movement in the ankle-foot complex, specifically pronation and rear-foot eversion, is often in the spotlight when it comes to running equipment or gear. Malisoux et al. (2016) found that, among runners with an excessive amount of pronation, motion-control shoes were effective in lowering the risk of RRRIs, compared with standard running shoes. Similar findings were reported more recently by Willems et al. (2021), who concluded that the risk of specific pronation-related injuries (Achilles tendinopathy and plantar fasciitis) was reduced by motion-control shoes, but the risk of other types of RRI was not affected.

1.4.3 Methodological aspects

Conducting intervention studies can encounter several factors that can influence the outcome of the intervention, as well as assessments of effectiveness. The use of a prospective study design when conducting studies collecting information regarding injuries or pain related to running is highly recommended. Retrospective study designs are often accompanied by a degree of recall bias, making them unsuitable for injury surveillance, particularly when pain or injury is self-reported by the participants. Although RCTs are most favourable in terms of scientific strength, they can also be expensive and difficult to conduct in a real-world setting, such as sports. Observational studies (such as prospective cohort studies) may overcome some of these barriers and be effective in providing a structured means by which authors can be transparent in interpreting and reporting results. The prospective collection of training data may also help to increase compliance by the participants, as well as to more accurately report data, as the element of recall bias is eliminated.

Designs of intervention studies vary greatly in the literature, in terms of the type, goals, duration, frequency, intensity, and the feasibility of the interventions. It is important to consider the target group or subgroup of runners who receive an injury-prevention intervention. We know that previous injury is a strong risk factor for RRRIs, and that this subgroup of runners may have a higher risk of injury than their counterpart peers. However, these runners may also be more inclined to accept injury-prevention advice due to their history of injury, thereby increasing their willingness to comply with the intervention. In the case of novice runners, or runners with no previous injury, on the other hand, a disruption or change in routine training hab-
its may well lead to an increased risk of injury and should therefore be considered carefully.76,86 Additionally, different durations and doses of intervention programmes have been used across the literature, with periods of 12-13 weeks,74,76 six months86 and 12 months.73 Participant compliance during the intervention, regardless of the duration, is vital in order to evaluate the effects of the intervention. Hägglund et al. (2013) revealed that football players who were highly compliant with a neuromuscular training programme, sustained significantly fewer ACL injuries compared with low compliance players.87 The use of visual (pictures or videos) or written guidelines for participants to follow throughout the study, with unlimited online access to the exercises,74,85,86 or, even better, supervised training sessions (on-site or remote),73 may greatly affect the motivation for participants to comply with the prescribed intervention.86,88

Moreover, the optimal duration, dose and frequency of intervention studies are yet to be clarified, but it is important to consider ways in which compliance can be increased among participants. Randomised controlled trials have reported compliance of 0% to 21% and 68% to 90% depending on the type of intervention,24 highlighting the vast differences between studies. When implementing an injury-prevention programme, the feasibility of the guidelines is fundamental; duration and dose, requirement for equipment and where the programme can be performed (at home, gym, etc.). Additionally, the reporting of compliance in a study is vital to enable the authors to correctly evaluate the effectiveness of their interventions.24

To summarise, understanding the problem at hand is an important initial step towards preventing it in the first place. In this case, why and how RRI’s occur must be clear before injury-prevention strategies can be developed and implemented. Injury-prevention approaches have previously been studied including the use of equipment (such as external braces, footwear and insoles), neuromuscular control exercises (such as knee control), multi-component programmes (including proprioceptive balance training and stretching, for instance) and running schedules (such as graded training programmes). The literature is divided when it comes to reporting of effective injury-prevention approaches, where specific foot core strengthening or pronation-control shoes are shown to be effective in reducing the risk of sustaining a RRI, whereas other approaches such as stretching, foam-rolling and prescribed running schedules produce unclear results. Neuromuscular control has shown to be effective in reducing the risk of ACL injuries in football players, but not enough research exists on this in the field of running. In addition to the specific types of interventions used, other aspects such as the study design, feasibility of the intervention and importantly, participant compliance with the intervention, also contributes to the overall effectiveness. A prospective study design with an intervention that is easily understood and performed by the participants, will ultimately lead to better compliance, and in turn, a more accurate interpretation of the effectiveness of the intervention.
For many people, running has become more of a lifestyle, rather than just a sport or a hobby. Maintaining an active lifestyle is vital in order to minimise the health risks that accompany a sedentary lifestyle and recreational running remains one of the most popular forms of physical activity. There remain vast discrepancies in the reports of annual injury incidence proportions in the existing literature seemingly due to the lack of uniformity across articles, in terms of injury definition, study designs used (e.g. retrospective, prospective) and running populations studied (novice, recreational or elite runners). Although some risk factors have been suggested to contribute to the development of RRIs, additional knowledge is needed to fully understand how and why runners sustain injuries in order to ultimately get ahead of the race and prevent these from occurring in the first place. So far, various attempts at implementing injury prevention guidelines in sports, and running, have yielded mixed results. The overall effectiveness of injury prevention interventions has been shown to be largely influenced by the type and feasibility of, and compliance with the intervention. In order to implement successful prevention strategies, we must have an understanding of what is it we are trying to prevent, and how we best can achieve this. Solid, multifaceted approaches are vital to tackle the multifactorial nature of RRIs.

The overall goal of this research is to identify and understand the possible mechanisms responsible for the development of RRIs, which runners have an increased risk of injury and how these risks can be alleviated. Using prospective study designs, a well-established injury definition, as well as targeted injury prevention guidelines, this research aims to pave the way forward within the scope of RRIs; adding a piece to the complex puzzle, and enabling an active and, more importantly, injury-free lifestyle.
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The overall aim of this thesis is to present injury incidence proportions in recreational runners followed prospectively over a 52-week period. Subsequently, this research aims to evaluate whether an 18-week general injury-prevention programme consisting of neuromuscular and foam-rolling exercises, is effective in preventing running-related injuries in recreational runners.

STUDY I:
The purpose of this study was to explore whether recreational runners with certain characteristics related to biomechanical and anthropometric variables sustained more running-related injuries compared with runners with different characteristics of this kind.

STUDY II:
This study primarily aimed to present the cumulative incidence proportion (with censoring taken into account) and the location of running-related injuries in recreational runners in one year. The secondary aim was to explore whether previous injury, running experience and intrinsic factors including age, gender and BMI, were associated with running-related injuries.

STUDY III:
The purpose of this study was to evaluate whether weekly changes in running volume were associated with an increased risk of running-related injuries in recreational runners included in a prospective observational comparative study.

STUDY IV:
This study aimed to compare the injury incidence proportion of running-related injuries in recreational runners who receive a training intervention consisting of neuromuscular control and foam-rolling exercises with runners who do not receive the training intervention.
Aims

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4.1 Theme 1: Incidence of and risk factors for running-related injuries (Studies I and II)

4.1.1 Study design
This study was a 52-week observational prospective cohort study taking place in Gothenburg Sweden.

4.1.2 Participants
Runners were recruited via the Gothenburg Athletics Association using e-mail records of runners who had previously participated in the Gothenburg Half Marathon event. Approximately 60,000 e-mail addresses were available for use in the recruitment process and the event organiser assisted in distributing invitations to participate in this study. Runners who responded to the e-mail or contacted the test leader expressing an interest in participating in the study were screened for eligibility and were subsequently invited to a baseline examination. Runners were eligible to participate in the study if they were between 18 and 55 years of age and ran a minimum average of 15km/week for the 12 months prior to baseline. Exclusions were made if the runners had sustained a musculoskeletal injury in the lower extremities six months prior to baseline, used orthopaedic insoles in their running shoes, were pregnant and/or suffered from diabetes. A schematic overview of the recruitment process can be seen in Figure 1. Of the 294 runners who responded to the invitation, 227 were eligible for participation in the study and were invited to a baseline examination. Two runners were excluded prior to baseline; one did not show up and the other showed up with a recent injury. One runner was excluded prior to analysis due to an injury sustained after the follow-up period. Subsequently, 225 injury-free recreational runners participated in the study, of which 224 were included in the final analyses. The demographics of the included participants can be seen in Table 1.
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Participants and Methods

Pia Desai – Sahlgrenska Academy, University of Gothenburg

Running-related injuries in recreational athletes

Invitation sent via Gothenburg Half Marathon
(n = 9,171 of 60,000 potentially eligible runners)

Non-responders
(n = 8,877)

Responders
(n = 294)

Excluded prior to baseline measurements
(n = 67)
→ Ran less than 15km/week previous year (n = 22)
→ Time constraints (n = 17)
→ Could not get to location for baseline examination (n = 9)
→ Use of orthopaedic insoles (n = 8)
→ Illness/injury prior to baseline (n = 5)
→ Severe diabetes (n = 3)
→ Pregnancy (n = 2)
→ Prior injury (>6 months) with ongoing symptoms (n = 1)

Invited for baseline measurements
(n = 227)

Excluded prior to baseline measurements
→ No-show (n = 1)
→ Current knee injury (n = 1)

 Eligible for study start
(n = 225)

Excluded prior to analysis
→ Injury after 365 days (n = 1)

Completed study and eligible for analysis
(n = 224)

Figure 2. Schematic overview of the recruitment process

Table 1. Baseline demographics and training information for participants

<table>
<thead>
<tr>
<th></th>
<th>Males (n = 135)</th>
<th>Females (n = 89)</th>
<th>Overall (n = 224)</th>
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<tbody>
<tr>
<td>Agea (years)</td>
<td>40.4 (7.8)</td>
<td>40.0 (8.6)</td>
<td>40.3 (8.1)</td>
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<td>BMIA (kg/m²)</td>
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<td>10.0 (6.0–16.0)</td>
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<td>Weekly running distanceb (km)</td>
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<td>Previous injury n (%)</td>
<td>88 (65.2)</td>
<td>45 (50.6)</td>
<td>133 (59.4)</td>
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a Values are presented as the mean (± SD).
b Values are presented as the median (interquartile range).
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a Values are presented as the mean (± SD).

b Values are presented as the median (interquartile range).

4.1.3 Baseline

Information regarding previous running experience, training habits and any previous injury that had affected their running was self-reported by all runners at baseline. Further, the training diary, through which weekly reports of running habits (distance, intensity, type of training, surface, terrain), shoe type, and running-related pain were submitted by each runner, was explained in detail by the test leader. Further information on the details of the training diary is given in the chapter entitled ‘4.1.4 Data collection’.

Clinical/anthropometric examination

The height (centimetres) and weight (kilograms) of each participant were measured using a wall-mounted ruler and a calibrated weight scale (Kern MPB300K100; Balingen, Germany). Joint range of motion (ROM) was assessed passively in the lower extremity joints, including the hip, knee and ankle, for both legs. All assessments were performed with the participants in the supine position, with the exception of hip extension, which was performed with the participants in a lateral (side-lying) position. The specific movements assessed for each joint, as well as the restricted, normal and excessive ROM values are presented in Table 2.
Table 2. Joint movement and normative values of ROM

<table>
<thead>
<tr>
<th>Joint</th>
<th>Joint movement</th>
<th>Range of motion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(restricted)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>normal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>excessive</td>
</tr>
<tr>
<td>Hip</td>
<td>Flexion</td>
<td>(&lt; 125) 130 - 140</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&gt;) 145</td>
</tr>
<tr>
<td></td>
<td>Extension</td>
<td>(&lt; 5) 10 - 20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&gt;) 25</td>
</tr>
<tr>
<td></td>
<td>Abduction</td>
<td>(&lt; 45) 50 - 80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&gt;) 85</td>
</tr>
<tr>
<td></td>
<td>Adduction</td>
<td>(&lt; 15) 20 - 30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&gt;) 35</td>
</tr>
<tr>
<td></td>
<td>Internal rotation</td>
<td>(&lt; 25) 30 - 40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&gt;) 45</td>
</tr>
<tr>
<td></td>
<td>External rotation</td>
<td>(&lt; 35) 40 - 50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&gt;) 55</td>
</tr>
<tr>
<td>Knee</td>
<td>Flexion</td>
<td>(&lt; 115) 120 - 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&gt;) 155</td>
</tr>
<tr>
<td></td>
<td>Extension</td>
<td>(&lt; 0) 0 - 10</td>
</tr>
<tr>
<td>Ankle</td>
<td>Dorsiflexion</td>
<td>(&lt; 5) 10 - 20</td>
</tr>
<tr>
<td></td>
<td>Plantarflexion</td>
<td>(&lt; 35) 40 - 50</td>
</tr>
<tr>
<td></td>
<td>Foot eversion</td>
<td>(&lt; 20) 25 - 35</td>
</tr>
<tr>
<td></td>
<td>Foot inversion</td>
<td>(&lt; 40) 45 - 55</td>
</tr>
</tbody>
</table>

In addition to joint ROM, muscle flexibility and trigger points were assessed. Flexibility in the hamstring muscles was assessed using the straight-leg raise test, with the participant lying on their back. The leg being tested was lifted by the test leader, making sure that the knee was fully extended and the contralateral leg maintained contact with the examination bench. The test continued until an obvious resistance was felt, where the leg could not be stretched further, or the patient expressed their limit of stretch. Restricted flexibility in the hamstrings was documented if the participants did not reach at least 90 degrees of hip flexion in the test leg.

The rectus femoris muscle was assessed using Ely’s test where the participant lay on their stomach with both legs extended. The test leader then tested one leg at a time, flexing the leg so that the heel moved towards the gluteus muscles. Even here, an obvious resistance felt by the test leader, or the participant expressing their limit, was regarded as the end of the test. Restricted flexibility in the rectus femoris was documented if the participants did not reach at least 90 degrees of knee flexion.

Finally, the iliopsoas muscle was assessed using the Thomas test, where the participants lay on their back at the edge of an examination bench. The test leader then fully flexed the contralateral hip and knee to flatten out any lumbar lordosis. The test leader observed any movement in the leg which was extended and, if the leg moved into a flexion above neutral position (0 degrees) at the hip, this was regarded as restricted flexibility. Depictions of the tests can be seen in Figure 3. All flexibility assessments were performed passively and unilaterally. The neutral-zero method was used as a reference to determine restricted, normal and excessive values for ROM and flexibility.89
Additionally, trigger points were assessed, defined as localised, hyper-irritable points in skeletal muscle tissue that reproduce pain upon palpation. The test leader palpated points along the tractus iliotibialis, piriformis, gluteus medius, gastrocnemius, soleus, tibialis posterior and tibialis anterior muscles. The participants were instructed to inform the test leader if they experienced any pain in the palpated areas, and these were then documented as positive (painful) trigger points.

**Straight-Leg Raise Test**
Normal flexibility > 90°
Restricted flexibility < 90°

**Ely’s Test**
Normal flexibility > 90°
Restricted flexibility < 90°

**Thomas Test**
Normal flexibility < 0°
Restricted flexibility > 0°

*Values refer to the contralateral leg.*

**Figure 3.** Flexibility test for the hamstring muscles (Straight Leg Raise Test), rectus femoris muscle (Ely’s Test) and iliopsoas muscle (Thomas Test).
**Participants and Methods**

**Biomechanical running analysis**

An approximately 13m long diagonal runway across the biomechanical laboratory was created using 12 pieces of ethylene vinyl acetate (EVA) mats. Sixteen infrared cameras (Qualisys AB, Gothenburg, Sweden) aimed at the centre of the runway were used for 3D motion capture at a sampling frequency of 400 Hz. Two light-beam photocells (Alge-timing, Lustenau, Austria) were placed midway through the runway and were used to control the running speed. Thirty-two retroreflective spherical markers were placed on specific anatomic locations on each runner, according to recommendations by the International Society of Biomechanics (IBS).92 Four markers were placed on the pelvis (anterior and posterior iliac spines), six on the femur (greater trochanter and medial and lateral femur epicondyles), two on the tibia (medial and lateral tibial plateaus, tuberositas tibiae, mid-point of the tibia and the medial malleolus), two on the fibula (lateral malleolus) and ten on the foot (calcaneus: medial, lateral and posterior sides, and the first and fifth metatarsal heads).

Once they had been equipped with the markers, participants ran on the runway to familiarise themselves with the set-up and speed at which they should run and to warm up before testing commenced. A static trial was first recorded with the participants standing still in a neutral anatomic position, relative to which joint angle curves were calculated. The static measurement also allowed the test leader to ensure that all the markers were visible and identified by the Qualisys Track Manager (QTM) software prior to the running analysis. Runners began the testing barefoot, where they ran along the runway at a speed of approximately 12 km·h⁻¹ or within the accepted range of 11.4 to 12.6 km·h⁻¹. They then repeated the test using their own shoes, running on the floor instead of the mats which were removed. For each testing condition, 25 trials were performed, during which one to two complete strides were collected per trial. Subsequently, ten trials per leg were used to calculate average joint angle curves.

**Isometric strength assessment**

Finally, maximum voluntary contractions were measured to obtain information on each runner’s isometric strength. The tests were performed in six different machines (David Health Solutions Ltd., Helsinki, Finland) to assess isometric strength in the trunk; extension flexion and right and left rotation, hip; bilateral abduction and adduction and knee; unilateral flexion and extension. All the tests were performed in a seated position and the participants were fixed in the seat using a seatbelt to avoid any movement. Angles at which each test was measured are presented in Table 3.
Prior to testing, the machines were adjusted to accommodate the height of each participant and the participants were then allowed to familiarise themselves with the machines and perform practice tests at a sub-maximum level. They then performed two maximum voluntary contractions with a rest period of 30 seconds between each test. A third trial was conducted if the difference between the first two trials was greater than 10%. The participants received verbal encouragement from the test leader during the test to aid in achieving maximum performance. The highest torque value was subsequently recorded and normalised to body mass (maximal torque ÷ body mass) to enable comparisons between individuals. All the tests were performed in a standardised way and by the same test leader. Although the gold standard for assessing muscle strength is the use of isokinetic dynamometry, isometric strength assessment has shown to have greater reliability and validity, as well as being a more pragmatic and time-saving method, in comparison. Strength ratios were also calculated for the balance between trunk flexion/extension strength, hip abduction/adduction strength and knee flexion/extension strength.

### 4.1.4 Data collection

Weekly training diaries were sent out to all participants via email. The training diary was an extensive Excel document in which the participants submitted information regarding running; distance (km), duration (min) and intensity (Borg rate of perceived exertion), level of training; easy, medium, fast, interval and competition, running surface; soft, medium and/or hard, running terrain in terms of elevation, running-shoe type including the brand and model of the shoe, stretching and any perceived pain. The participants were urged to maintain their regular training habits for the duration of the study and simply report them on a weekly basis. A regular dialogue was maintained between the test leader and the participants during the study, and reminders were sent out to the participants if they did not submit their weekly training diaries.
The main outcome measure was any running-related injury, which was defined as follows:

“A running-related musculoskeletal pain in the lower limbs or back that causes a restriction or stoppage of running (distance, speed, duration, or training) in more than 66% of all training sessions in 2 consecutive weeks or in more than 50% of all training sessions in 4 consecutive weeks, or that requires the runner to consult a physician or other health professional.”

This definition is a slightly modified version of the consensus definition proposed by Yamato et al. where the modification pertains to the scheduling of training sessions as this may not apply to all recreational runners.

4.1.5 Statistical methods

In Studies I and II, participants were censored if they had issues with the training log, illness, non-running-related injuries or injuries to the opposite leg, lack of motivation and/or time, or other personal concerns that hindered their participation in the study.


Study I

The analyses consisted of time-to-event statistics with days as the time scale and primary analysis conducted after 365 days. A generalised linear regression (pseudo-observation method) was used to calculate cumulative risk difference as a measure of association, with 95% confidence intervals and a significance level of p<0.05. In this study, each participant’s individual legs were used as a unit of interest in a shared frailty approach. To analyse movement and strength variables, a 68% prediction limit was used. For each exposure variable, this entailed categorising each individual unit (leg) into one of three groups; 1 standard deviation (SD) below the mean (-1 SD), 1 SD above the mean (+1 SD), or within ±1 SD from the mean (reference group). For joint ROM, each leg was categorised as hypo-mobile, normal, or hypermobile. Dichotomised measures were used to categorise exposure variables pertaining to muscle flexibility and trigger points, namely restricted or non-restricted, or, pain or no pain, for each respective variable.

Study II

A cumulative incidence proportion with censoring taken into account was calculated using Kaplan-Meier estimates as a function of follow-up time. A crude Cox proportional hazards regression was used to evaluate whether previous injury, BMI, age, gender and weekly running distance were associated with running-related injuries. A log-rank test was performed to assess the assumption of proportional hazards.
4.1.6 Ethical approval
Written consent was provided by each of the participants prior to study start. The ethical application was approved on 10 August 2015 by the Regional Ethics Committee in Gothenburg, entry number 712-15.

4.2 Theme 2: Implementation of an injury-prevention programme (Studies II and IV)

4.2.1 Study design
This was an 18-week observational comparative study comprising an intervention group and a control group.

4.2.2 Participants and study groups
Participants were recruited through the Gothenburg Athletics Association. E-mail records of runners who had previously participated in the Gothenburg Half Marathon Event were used to send out information about the study to more than 20,000 runners and information was also uploaded onto the event’s website, where runners could sign up to participate in the study. Runners had to be between 18 and 55 years old, having run at least 15km a week for the preceding year and be injury free for the past six months to be able to participate in the study. Only those who fulfilled the inclusion criteria were able to finalise their online application to participate in the study. A total of 433 recreational runners, male (n= 230, 53%) and female (n=202, 47%), who signed up and were eligible to participate in the study were included and allocated to either an intervention group (n=228) or a control group (n=205). An overview of the recruitment and allocation process can be seen in Figure 4 and the demographics of all participants can be seen in Table 4.

Table 4. Participant demographics of the control and intervention groups

<table>
<thead>
<tr>
<th></th>
<th>Control group (n = 205)</th>
<th>Intervention group (n = 228)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex (female)</td>
<td>91 (44.4)</td>
<td>112 (49.1)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>39.0 (± 8.4)</td>
<td>39.0 (± 8.8)</td>
</tr>
<tr>
<td>Weekly running distance (km)</td>
<td>20.5 (15.7-28.3)</td>
<td>20.6 (15.1-32.9)</td>
</tr>
</tbody>
</table>

Sex is presented as an absolute number and proportion. Age is presented as the mean (± standard deviation) and weekly running distance is presented as the median (interquartile range).
Participants and Methods

Pia Desai – Sahlgrenska Academy, University of Gothenburg

Running-related injuries in recreational athletes

The recruitment process was conducted at two different time points, as the first recruitment did not yield enough participants to have a sufficiently powered study. The first recruitment was conducted in November 2018 with study start in December 2018 and continued for 18 weeks to May 2019, prior to the Gothenburg Half Marathon Event 2019. The second recruitment took place in early September 2020, with study start in late September 2020 and continued over 18 weeks to January 2021. A timeline explaining the recruitment and study periods can be seen in Figure 5.

Figure 4. Schematic overview of the recruitment and allocation process
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**Figure 5.** Recruitment and study phases
4.2.3 Baseline
The participants took part in an introductory meeting at which they were informed of the study details, including the time frame, data submission and ethical aspects. The intervention group were also provided with the equipment needed for the exercise programme including a foam-roller and an elastic training band from BLACK-ROLL® Germany. Practical or digital demonstrations of the exercises were also given to the participants in the intervention group to ensure the correct performance of each exercise and the participants were able to practise the exercises with the test leader present. The introductory meeting took place three weeks prior to study start to allow for a familiarisation period and to resolve any issues relating to the data submission process.

4.2.4 Data collection
All the runners submitted weekly reports of running distance (km), running days (days of the week), any running-related pain (yes/no), how many days were affected by the pain (n) and the location of the pain (foot/ankle, Achilles tendon/calf), lower leg (shin), knee, hip/thigh, lumbar spine, or other), as well as any alternative training performed, including strength training (with/without weights), aerobic exercises (including cycling, swimming etc.), team sports or massage and/or foam-rolling. The weekly training reports were sent out through an online questionnaire created specifically for the study in the Webropol web-based program (Webropol Survey 3.0 2021) (Figure 6). The intervention group logged their performance of the exercise programme using the GoMobilus online platform (2018 Mobilus Digital Rehab AB) where they could, and were encouraged to, also view videos of the exercises and read an instructional text.

The main outcome measure was any running-related injury and the definition used in this study is the same as in Theme 1 (see Section 4.1.4).
Participants and Methods

Pia Desai – Sahlgrenska Academy, University of Gothenburg

Running-related injuries in recreational athletes

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The main outcome measure was any running-related injury and the definition used in this study is the same as in Theme 1 (see Section 4.1.4).

---

1. **On which days did you run this week?**
   Specify in numbers the distance (km) for each day.
   - Monday: _____ km
   - Tuesday: _____ km
   - Wednesday: _____ km
   - Thursday: _____ km
   - Friday: _____ km
   - Saturday: _____ km
   - Sunday: _____ km

2. **Did you experience any running-related pain this week?**
   - Yes
   - No
   If yes, on how many of the days this week did you experience pain while running? _____ days

3. **In what part of the body did you experience pain?**
   - Foot/ankle
   - Achilles tendon/calf
   - Lower leg (shin)
   - Knee
   - Hip/thigh
   - Lumbar spine
   - Other (specify) _____

4. **Have you carried out any other training activities this week?**
   Specify number of sessions for each activity.
   - No
   - Strength training core/legs (bodyweight): _____ sessions
   - Strength training core/legs (extra weights): _____ sessions
   - Team sports (e.g. football, floorball, hockey, etc.): _____ sessions
   - Cardio (e.g. aerobic, cross-trainer, rowing, etc.): _____ sessions
   - Cycling/spinning: _____ sessions
   - Swimming: _____ sessions
   - Massage (massage therapist): _____ sessions
   - Massage (foam-roller): _____ sessions
   - Other (specify activity): _____ sessions

**Figure 6.** Weekly training questionnaire sent out to all participants.
**Intervention period**

During a period of 18 weeks, the runners in the intervention group were instructed to follow an exercise programme consisting of neuromuscular control and foam-rolling exercises. They were instructed to perform the exercise programme twice a week, in addition to their regular training. The programme consisted of seven neuromuscular control exercises for the core muscles, abductors, adductors and foot muscles (Figure 7. A-G), as well as six foam-rolling exercises for the gluteal muscles, thigh muscles, lower leg muscles and plantar fascia (Figure 7. H-M). For the duration of the study period, the control group maintained their regular training habits.
Participants and Methods

Pia Desai – Sahlgrenska Academy, University of Gothenburg

Running-related injuries in recreational athletes

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Figure 7. Exercises in the injury-prevention programme. Neuromuscular control exercises: (A) One-leg squat (B) Forward lunge (C) Side-step with resistance band (D) Supine hip abduction with resistance band (E) Diagonal lift (F) Side-plank (G) Foot supination with resistance band. Foam-rolling: (H) Gluteal muscles (I) Hamstring muscles (J) Quadriceps muscles (K) Abductor muscles (L) Calf muscles (M) Plantar fascia.
4.2.5 Statistical methods

In Studies III and IV, the participants were censored if they had issues with the training log, illness, non-running-related injuries, lack of motivation and/or time, sustained an injury prior to study start, or other personal concerns that hindered their participation in the study.


Study III

The weekly changes in running distance were calculated in a bi-weekly manner whereby the total running distance (km) of one week was divided by the total running distance of the preceding week, and multiplied by 100 to obtain a percentage ratio. This was performed for all weeks until a participant sustained an injury or was censored due to the reasons stated above. Week 2 was the starting week, as no ratio could be calculated from week 1. The ratios for each week were then categorised into one of five exposure groups including; regression of < -30%, ≥ -30% to < -10%, reference ≥ -10% to < +10%, or progression of < +10% to < +30% and > +30%. The participants could be placed in several exposure states throughout the study. If a runner did not run for one week, no ratio could be calculated for the following week, and this was then denoted as not applicable (N/A). The week prior to the injury week was used in the analysis i.e. the exposure state into which runners were placed the week before injury.

A generalised linear regression (pseudo-observation method) was used to obtain the cumulative risk difference (RD) for survival between the exposure states. The event was running-related injury, the time scale used was ‘weeks’ and the reference category was ≥ -10% to < +10%. The primary analyses were performed after 18 weeks.

Study IV

Cumulative incidence proportions were calculated using the estimates from the Kaplan-Meier method. Time-to-event statistics were performed to compare the control and intervention groups, using the Kaplan-Meier method, with running-related injury as the ‘event’ and number of days in the study as the time variable. An unadjusted Cox proportional hazards ratio analysis was performed to estimate the risk of running-related injuries for the study groups at 18 weeks. Log-rank tests were performed to assess the assumption of proportional hazards.

4.2.6 Ethical approval

Written consent was provided by each of the participants prior to study start. Ethical application was approved 10 August 2015 by the Regional Ethics Committee in Gothenburg, entry number 713-15.
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5.1 Theme 1: Incidence of and risk factors for running-related injuries

Participants and demographics

A total of 224 runners participated in this part of the study (THEME 1) with a majority of male participants (n= 135, 60.3%). The study population had a mean age of 40.3 (± 8.1) years, with a median of 10.0 years (IQR: 5.1 – 17.0) running experience prior to enrolment while the median weekly running distance for the previous year prior to enrolment was 25.0km (IQR: 20.0-29.5). The baseline demographics for all runners can be seen in Table 1, Chapter 4.2.1.

5.1.1 Study I

The total number of injured legs was 85, of which 65 were unilateral (left leg or right leg) and 20 were bilateral injuries (both legs). The cumulative incidence proportion for legs was 29.0% (95% CI= 24.0%; 34.8%).

The complete results from the analyses investigating the associations between biomechanical and clinical/anthropometric variables and RRI, are presented in Paper I, Tables 1 and 2. The only movement variable that showed a significant association with running-related injury was the timing of maximal eversion (REVTIM). More specifically, runners with a relatively late timing of eversion (+1SD from the mean) sustained significantly more injuries than the reference group (p=0.033) (Table 5). The strength variable that showed a significant association with RRI was the ratio between hip abductor and hip adductor strength (HAB:HAD). Runners with weaker hip abductor strength relative to hip adductor strength sustained a significantly higher number of injuries compared with the reference group (p=0.040).

Finally, although the analysis did not yield significant associations between trigger points and RRI, the results suggest that runners with painful trigger points in the gastrocnemius (G TP), soleus (STP) and tibialis anterior (TATP) muscles sustained more injuries than runners with no painful trigger points (Table 7).
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Participants and demographics
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Table 5. Associations between movement, strength and clinical factors and RRI

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Reference (no pain)</th>
<th>Pain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clinical (trigger points)</td>
<td>Injuries (total)</td>
<td>Risk (%)</td>
</tr>
<tr>
<td>Gastrocnemius</td>
<td>24 (167)</td>
<td>24.8</td>
</tr>
<tr>
<td>Soleus</td>
<td>46 (296)</td>
<td>25.6</td>
</tr>
<tr>
<td>Tibialis anterior</td>
<td>71 (391)</td>
<td>27.7</td>
</tr>
</tbody>
</table>

Injuries = no. of injured legs. Total = total no. of legs. RD = risk difference. 95% CI = 95% confidence interval. HAB: HAD = ratio between hip abductor and adductor strength.

5.1.2 Study II

Injury proportions and anatomical location of injuries

The overall cumulative incidence proportion for RRIs was 45.9% (95% CI= 38.4; 59.5) and was similar between females and males who had a cumulative incidence proportion of 46.0% (95% CI= 34.3; 59.5) and 45.8% (95% CI= 36.4; 56.5) respectively. Forty percent of runners who had a history of previous injury (53 of 133) sustained a new RRI during the study and 24% of runners who had no history of previous injury (22 of 91) sustained a new injury during the study period.

The most common injury locations were the knee (n=20, 27%) and the Achilles tendon/calf (n=19, 25%). The frequencies and proportions of the anatomical injury locations for females and males specifically, can be seen in Figure 8.
### Table 5. Associations between movement, strength and clinical factors and RRI

<table>
<thead>
<tr>
<th>Exposure Reference</th>
<th>Movement/strength</th>
<th>Injuries (total)</th>
<th>Risk (%)</th>
<th>Injuries (total)</th>
<th>RD (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1SD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Timing of ankle eversion (REVTIM)</td>
<td>53 (316)</td>
<td>25.7</td>
<td>9 (52)</td>
<td>2.4 (-15.2 ; 20.0)</td>
</tr>
<tr>
<td></td>
<td>HAB : HAD</td>
<td>57 (320)</td>
<td>26.3</td>
<td>17 (62)</td>
<td>17.3 (0.8 ; 33.7)</td>
</tr>
<tr>
<td>Reference (no pain)</td>
<td>Pain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clinical (trigger points)</td>
<td>Gastrocnemius 24 (167)</td>
<td>24.8</td>
<td>61 (281)</td>
<td>7.0 (-4.3 ; 18.4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Soleus 46 (295)</td>
<td>25.6</td>
<td>39 (153)</td>
<td>10.6 (-2.4 ; 23.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tibialis anterior 71 (391)</td>
<td>27.7</td>
<td>14 (57)</td>
<td>11.5 (-4.8 ; 27.9)</td>
</tr>
</tbody>
</table>

Injuries = no. of injured legs. Total = total no. of legs. RD = risk difference. 95% CI = 95% confidence interval. HAB: HAD = ratio between hip abductor and adductor strength.

#### 5.1.2 Study II

**Injury proportions and anatomical location of injuries**

The overall cumulative incidence proportion for RRIs was 45.9% (95% CI = 38.4; 59.5) and was similar between females and males who had a cumulative incidence proportion of 46.0% (95% CI = 34.3; 59.5) and 45.8% (95% CI = 36.4; 56.5) respectively. Forty percent of runners who had a history of previous injury (53 of 133) sustained a new RRI during the study and 24% of runners who had no history of previous injury (22 of 91) sustained a new injury during the study period.

The most common injury locations were the knee (n=20, 27%) and the Achilles tendon/calf (n=19, 25%). The frequencies and proportions of the anatomical injury locations for females and males specifically, can be seen in Figure 8.

**Figure 8.** Frequencies and proportions of injury locations in (A) females (n=29) and (B) males (n=46).

### Risk factors for running-related injuries

The Cox proportional hazards ratio revealed that previous injury was associated with a higher injury rate (hazard ratio: 1.9, 95% CI: 1.2; 3.2). In other words, runners who had previously sustained an injury were almost twice as likely to sustain an injury at any given time point in the study, compared with runners who had no history of injury. The variables of running experience, BMI, weekly running distance, age and sex, were not significantly associated with RRI (see Study II, Table 3).
5.2 Theme 2: Implementation of an injury-prevention programme

Participants and demographics
Four-hundred and thirty-three runners participated in this part of the study (THEME 2), of which 203 (47%) were female and 230 (53%) were male. The mean age of the population was 39.0 (± 8.4) years and the median weekly running distance was 20.5 (IQR: 15.7-32.9) km. In total, 100 running-related injuries were sustained during the 18 weeks by 56 females and 44 males. The number of injured and censored runners for each study group is presented in Table 7.

5.2.1 Study III
A total of 5,317 weeks were categorised into five exposure states of regression or progression of weekly running distance. If a runner reported that they did not run for one week, a ratio could not be calculated using this week as the denominator and the category was then N/A. This group included 821 weeks. In total, 6,138 weeks were categorised, of which 100 were regarded as the week leading up to an injury (i.e. 100 RRRs were sustained during the study). The total number of injuries for each exposure state can be seen in Figure 9.

![Figure 9. Frequency of injuries for each exposure state](image)

Table 6. Risk differences between each exposure state

<table>
<thead>
<tr>
<th>Exposure state</th>
<th>Risk difference (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; -30%</td>
<td>0.4% (-13.6 ; 14.3)</td>
<td>0.959</td>
</tr>
<tr>
<td>≥ -30% to 10%</td>
<td>-11.6% (-24.9 ; 1.8)</td>
<td>0.089</td>
</tr>
<tr>
<td>≥ -10% to &lt; 10% (ref)*</td>
<td>- -</td>
<td>-</td>
</tr>
<tr>
<td>≥ +10% to ≤ + 30%</td>
<td>2.3% (-15.0 ; 19.5)</td>
<td>0.797</td>
</tr>
<tr>
<td>&gt; 30%</td>
<td>10.0% (-5.5 ; 25.6)</td>
<td>0.205</td>
</tr>
</tbody>
</table>

*Reference risk = 25.6% (95% CI= 15.4; 35.7). 95% CI = 95% confidence interval. Statistically significant p<0.05

5.2.2 Study IV
Cumulative incidence proportion of running-related injuries
The cumulative incidence proportion of running-related injuries was 22.9% (95% CI: 17.8; 29.4) for the overall intervention group and 27.2% (95% CI: 21.5; 34.0) for the control group. The intervention subgroups had a cumulative incidence proportion of 43.2% (95% CI: 32.8; 55.4), 16.0% (95% CI: 9.0;27.8) and 4.6% (95% CI: 1.5; 13.6) for the low-, intermediate- and high-compliance groups respectively.

Table 7. Number of injured and censored runners in each study group

<table>
<thead>
<tr>
<th></th>
<th>Control group (n= 205)</th>
<th>Intervention group (n= 228)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low compliance</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>Intermediate</td>
<td>15</td>
<td>37</td>
</tr>
<tr>
<td>High compliance</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 9. Frequency of injuries for each exposure state
The crude analyses revealed no significant difference in injury risk between the exposure groups compared with the reference state (Table 6). Despite lacking statistical significance, progression in weekly running distance of more than 30% showed 10% increased risk of injury compared with the reference state and more injuries (n=33 of 100) were sustained in this exposure state compared with the others.

Table 6. Risk differences between each exposure state

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</tr>
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<tr>
<td></td>
<td>Overall</td>
<td>Low compliance (n = 100)</td>
</tr>
<tr>
<td>Injured (n)</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>Censored (n)</td>
<td>15</td>
<td>37</td>
</tr>
</tbody>
</table>
Compliance with the intervention programme

The median number of training sessions completed by the intervention group was 22.0 sessions (IQR 8.0-32.0). The demographics of the intervention subgroups can be seen in Table 8. The highly compliant runners (n=65) maintained more than 90% compliance for the majority of the 18 weeks, while the intermediate-compliance group (n=63) and the low-compliance group (n=100) varied in their compliance with the intervention program, with the low-compliance group never exceeding 71% during the 18 weeks (Figure 10).

Table 8. Demographics of the intervention subgroups

<table>
<thead>
<tr>
<th></th>
<th>Low compliance (n = 100)</th>
<th>Intermediate compliance (n = 63)</th>
<th>High compliance (n = 65)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex (female)</td>
<td>45 (45)</td>
<td>31 (49.2)</td>
<td>36 (55.4)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>39.1 (±8.8)</td>
<td>39.0 (± 8.2)</td>
<td>38.9 (± 9.4)</td>
</tr>
<tr>
<td>Weekly running distance (km)</td>
<td>17.1 (13.0-30.1)</td>
<td>20.3 (14.7-31.4)</td>
<td>24.8 (20.6-35.7)</td>
</tr>
</tbody>
</table>

Sex is presented as an absolute number and proportion. Age is presented as the mean (± standard deviation) and weekly running distance is presented as the median (interquartile range).

Figure 10. Compliance of the intervention subgroups for all 18 study weeks
Differences between the study groups

No significant differences were found when comparing the overall intervention group and the control group (log-rank \( p=0.31 \)), but a significant difference was found when comparing the intervention subgroups with the control group (log-rank \( p=0.00 \)). The high-compliance subgroup was 85% less likely (hazard ratio: 0.15, \( p=0.001 \), 95% CI: 0.05; 0.46) to sustain a running-related injury at any time point during the 18 weeks, compared with the control group. In contrast, the low-compliance group was contrastingly almost twice as likely to sustain an injury at any time point during the 18 weeks, compared with the control group (hazard ratio: 1.89, \( p=0.004 \), 95% CI: 1.22; 2.92). A high censoring rate was present in the low-compliance group, due mainly to a lack of training documentation.

Anatomical location of injuries

Ten runners reported pain in two locations simultaneously at the time of injury and one runner reported pain in three locations simultaneously at the time of injury. Six runners failed to report any locations for their injuries (males = 2 and females = 4). This therefore resulted in 106 injury locations, where 12 were additional locations from the above-mentioned runners, and 6 were missing due to a lack of reporting. The majority of the injury locations were reported at the Achilles tendon/calf/shank (27 of 106, 25.5%), foot/ankle (25 of 106, 23.6%) and knee (23 of 106, 21.7%) (Figure 11). Twenty-two (87%) of the AT/calf injuries and six (66.7%) of the shank injuries were reported by males, while females reported more injuries to the hip/thigh (11 of 18, 61%). Males and females reported similarly with regard to foot/ankle injuries (13 vs. 12 of 25 respectively), knee injuries (11 vs. 12 of 23 respectively) and lumbar spine injuries (2 vs. 2 of 4 respectively).

![Figure 11. Anatomical locations of running-related injuries sustained during 18-weeks. All injuries, injuries in the control group and injuries in the intervention group are presented separately.](image-url)
6.1 Theme 1: Incidence of and risk factors for running-related injuries

6.1.1 Study I
The main finding in this study was that runners with a late timing of maximal eversion and runners with weaker hip abductors compared with hip adductors sustained more running-related injuries than the corresponding reference groups. Rear foot motion, particularly pronation, has been a topic of great interest over the decades. The late timing of rear foot eversion may suggest deficits in neuromuscular activation of the tibialis posterior muscle, but there is conflicting evidence on the association between biomechanical risk factors, such as lower-leg kinematics, and RRIs. Motion control shoes have been shown to be effective in reducing the occurrence of RRIs in persons with over-pronation and more specifically, pronation-related injuries such as Achilles tendinopathy and plantar fasciitis. However, Nielsen et al. (2014) presented contrasting results where the foot posture index was not associated with a higher injury incidence proportion in novice runners. Although the group of runners with a late timing of maximal rear foot eversion appears to be more prone to injuries, more research is needed to determine whether this biomechanical trait in all runners is in fact a predictor of RRIs.

Lower hip abductor strength in relation to hip adductor strength was also a characteristic of runners who sustained more RRIs in the present study. Some evidence in the literature suggests that weaker hip abductor strength is associated with anterior knee pain and with conflicting reports, PFPS and ITBS have also been linked to this, to some extent. It remains apparent that the inconsistencies in the literature call for further investigation of this topic.

Moreover, another topic that causes controversy in the literature is the phenomenon of trigger points. Although trigger points were not significant, they may still play a role in the development of running-related injuries.
Discussion

6.1 Theme 1: Incidence of and risk factors for running-related injuries

6.1.1 Study I

The main finding in this study was that runners with a late timing of maximal eversion and runners with weaker hip abductors compared with hip adductors sustained more running-related injuries than the corresponding reference groups. Rear foot motion, particularly pronation, has been a topic of great interest over the decades.\(^78\)\(^98\) The late timing of rear foot eversion may suggest deficits in neuromuscular activation of the tibialis posterior muscle, but there is conflicting evidence on the association between biomechanical risk factors, such as lower-leg kinematics, and RRIs.\(^99\) Motion control shoes have been shown to be effective in reducing the occurrence of RRIs in persons with over-pronation\(^81\) and more specifically, pronation-related injuries such as Achilles tendinopathy and plantar fasciitis.\(^79\) However, Nielsen et al. (2014) presented contrasting results where the foot posture index was not associated with a higher injury incidence proportion in novice runners.\(^100\) Although the group of runners with a late timing of maximal rear foot eversion appears to be more prone to injuries, more research is needed to determine whether this biomechanical trait in all runners is in fact a predictor of RRIs.

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Moreover, another topic that causes controversy in the literature is the phenomenon of trigger points. Although trigger points were not signifi-
Discussion

The findings in the present study contribute to the existing research, which clearly warrants further insight, but it may be advisable for coaches and clinicians alike to pay extra attention to the group of runners who have late timing of maximal eversion, weaker hip abductor strength and painful trigger points in lower leg muscles, as they appear to be more predisposed to injuries than their counterpart peers.

6.1.2 Study II

The most important finding in this study was that a previous injury is a strong risk factor of RRI. The study revealed that runners with a history of injury are almost twice as likely to sustain a new or recurrent RRI, as runners with no history of injury. This finding is similar to those in other studies and may be the consequence of inadequately recovered injuries (due to insufficient or incomplete rehabilitation, for example) or the adoption of a disadvantageous compensatory running style as a result of pain. Moreover, weakened or altered tissues around the site of the injury may predispose a runner to a new injury, in the same location or in a new location.

Although it is already well known that previous injury is a risk factor for RRI, this finding in the present study is further strengthened by the methodology that was used; the prospective design, the use of censoring in the analyses and a well-established injury definition.
Additional characterises such as sex, BMI and running experience were also investigated in this study, with regard to RRI risk. In this study, we found no associations between sex and overall or specific running-related injuries. In contrast, in 2021, Hollander et al. reported no differences between the sexes in terms of the association of overall running-related injuries, but specific injuries such as bone stress injuries occurred more frequently in females and Achilles tendinopathies were more frequent in males.111

Additionally, BMI was also not found to be associated with the occurrence of RRIs in this study. Although previous reports have considered the difference between normal-weight, overweight and obese runners and RRI risk,43,112 the lack of variation in the BMI of runners in the present study may explain why no association was found. Seventy-eight per cent of the participants in this study fell within a BMI range of 20 to 25kg/m².

Finally, the lack of association between running experience and RRI in the present study can be attributed to the fact that the study included a majority (75%) of experienced runners (with more than five years of running experience). Studies have previously reported that a lack of running experience increases the risk of RRI,113,114 where more experienced runners may be better adapted to the load accompanied by running and have a better understanding of their thresholds.115 Importantly, using years or months as a unit of measure may not be the most optimal way of quantifying running experience. Runners with the same amount of experience in years or months may well run very different weekly volumes. Instead, training load in terms of weekly kilometres may be more appropriate, given the link between running-related injuries and training load.37

The findings of this study may help coaches or clinicians to identify runners who are possibly more susceptible to injuries, for example those with a previous injury. Additionally, the prospective design, well-established injury definition and robust analytical approach may have contributed to put forward a more accurate and interpretable representation of the cumulative incidence proportions of RRIs.

6.1.3 Strengths and limitations

One major strength of these studies is the prospective design. Retrospective studies are accompanied by recall bias and should therefore be reconsidered when designing injury surveillance studies.83 Moreover, the study is strengthened by the comprehensive baseline screening and the use of a well-established injury definition, according to which all RRIs were diagnosed and documented by a medical professional affiliated to the study. The use of robust statistics with censoring taken into account adds to the strengths of this project, as cumulative injury incidence proportions could be reported more accurately. Many cross-sectional studies simply report the number of injured runners in the total study sample,
Discussion

producing a prevalence proportion and possibly underestimating the proportion of new injuries. Censoring eliminates the assumption that all participants run the same risk of injury and participate in the study for the same amount of time, thereby producing more accurate cumulative incidence proportions.

The low number of injuries sustained in this study is a limitation and did not fulfil the recommended five to 10 events per variable studied and, due to the limited power of the study, specific RRIs could not be fully explored. Moreover, as the weekly reporting of training was heavily dependent on the time and motivation of each participant to do so, a potential bias may be present, as a large number of participants (33.6%) were censored due to a lack of precisely that; time and motivation.

Although all injuries were examined and diagnosed by a medical professional, a standardised protocol ensuring uniform examinations and diagnosing of each injury, as well as diagnostic tools such as medical imaging, may have produced more objective injury information. However, it is still the case that medically diagnosed injuries are more favourable compared with the common method of self-reporting often seen in studies.

The recovery time for previous injuries may have been too short in this study. A six-month period of being injury and symptom free was a criterion to be able to participate in the study and may have been too short a time to allow previous injuries to fully recover. Studies have shown that even injuries sustained within the past 12 months are associated with higher injury occurrence. The reasons for this are not fully understood, but it is speculated that change in running biomechanics may be adopted due to pain, or that the ‘new’ injury is in fact an exacerbation of an ongoing injury which has not recovered, or that scar tissue development following the injury may alter the characterises and weaken the tissues, all of which may increase the risk of recurrent injuries. Moreover, practical aspects such as the study design (retrospective (recall bias) or injury definition) may also lead to the false reporting of ‘new’ injuries during a study. The thresholds for recovery time from previous injuries need further investigation and are yet to be established.

6.2 Theme 2: Implementation of an injury-prevention programme

6.2.1 Study III

This study aimed to investigate whether weekly changes in running distance were associated with RRIs in recreational runners enrolled in an 18-week study. No significant differences were found between the exposure states of increased or decreased running distance, compared with the common 10% rule (10% progression
or regression). Runners who progressed their weekly running distance by more than 30% appeared to sustain a higher number of injuries compared with the other exposure states (n=33 of 100) and analyses revealed a 10% higher risk of RRI in these runners compared with the reference. Although this difference was not statistically significant, it appears that this exposure state could contribute to the risk of RRI in this study and more insight into this result is therefore needed.

One reason for the lack of significant differences between the changes in weekly running distance and RRI could be that only external loading was taken into account in this study. Monitoring running distance, duration and pace are common measures of external loading, easily measured by global positioning systems (GPS), for example. However, the exclusive use of weekly running distance to quantify training load may lead to misinterpretations, as the actual biomechanical demands (specific or individual) of running may be overlooked.\textsuperscript{121} Instead, the combination of internal (e.g. session rating of perceived exertion, sRPE) and external loading is recommended to obtain a better understanding of the training stress, both psychological and physiological.\textsuperscript{121,122} At the same time, in the present study, simply looking at the absolute running distance and overlooking the internal measure of training load, may have led to an incomplete picture of the actual stress caused by running in each runner. Although they may have been exposed to similar amounts of external loading (running distance), other aspects such as intensity, session frequency, duration and internal loading may have affected each runner differently and must therefore also be taken into consideration.\textsuperscript{46}

Additionally, in the present study, we used the exposure state in which runners were categorised the week before an injury occurred, in order to acquire an understanding of the change in running distance prior to injury. This may have led to the exclusion of some running sessions performed in the actual week of injury, which may, in fact, have been the reason why they were classified as injured. Exploring the immediate changes in external loading, on a weekly basis, as opposed to over a longer period of time may be seen as an advantage, as these changes can be more precisely tracked, but the use of cumulative running distance after each running session and six days prior, has previously been used in studies.\textsuperscript{48,123} This method may possibly be better at capturing a true representation of the weekly running distance compared with the present study. Moreover, including chronic load may also help in understanding how longer-term loading may affect the development of RRRs, although the method does also have its limitations.\textsuperscript{122,124} Additionally, exploring the multiple changes in weekly running distance over a longer period of time (multi-state transitions) may add vital information compared with investigating single changes from one week to another, as was done in the present study.
Discussion

More robust statistical analyses, perhaps more events per exposure state and larger cohorts are needed in order to adequately investigate how, and to what extent training load plays a role in the development of RRIs. In the present study, we aimed to include at least 10 events (injuries) per exposure state as is recommended.\textsuperscript{126} This was fulfilled with the exception of one state that only had 9 injuries. The present study contributes to this research topic with strengths such as prospective data collection, a large cohort and a sound analytical approach. However, even larger studies are warranted and perhaps other aspects of exposure, such as steps over a given running distance, may contribute with a more suitable quantification of training load.\textsuperscript{29}

6.2.2 Study IV

The main finding in this study was that high compliance with the injury-prevention programme, significantly reduced the cumulative incidence proportions of RRIs, compared with the control group. More specifically, runners who performed the prescribed exercises, twice a week on average for 18 weeks, were 85% less likely to sustain an RRI than those who did not receive the intervention. Additionally, the cumulative incidence proportion for this group was 4.6%, which is significantly lower than the control group (22.9%) and the low- (43.2%) and intermediate- (16.0%) compliance groups as well.

Compliance as a strong influential factor affecting the outcome of injury prevention interventions has been reported elsewhere, consistent with the results of the present study.\textsuperscript{87,127,128} The definitions of compliance levels vary in the literature, making it difficult to directly compare the effects of specific interventions based on compliance. At the same time, high compliance with an intervention, regardless of what it means to each study, is necessary in order to adequately evaluate its effectiveness.\textsuperscript{24} Nevertheless, despite being high, some degree of compliance deterioration as the study moves forward, as seen in the present study, or a lack of correctly utilised interventions, is still a challenge that commonly occurs and must be faced.\textsuperscript{87,129} Supervision of the intervention and feasible, easy-to-follow protocols, where any equipment needed is readily available and the training programmes are easily accessible (e.g. online), are some ways in which compliance can be improved throughout the study.\textsuperscript{73,85,86}

Moreover, the positive effects on RRIs seen in the high-compliance group may be attributed to the type of exercises that were chosen. Neuromuscular exercises have previously been reported to reduce the risk of injuries in sports,\textsuperscript{130,131} but they are lacking in the context of RRIs.\textsuperscript{67,52} This study contributes to the context of neuromuscular control and running-related injuries and may serve as a base for future interventions implementing exercise programmes of this kind.
Surprisingly, the low-compliance group appeared to have a higher cumulative incidence proportion (43.2%) of RRIs compared with the control group (22.9%). One reason for this may be the large number of censored runners in the low-compliance group, possibly resulting in an overestimated cumulative incidence proportion, making it difficult to evaluate the true effect of the intervention programme on this group of runners. Possible reasons for the high number of censored runners are that these runners lacked motivation, or experienced difficulty with the exercises (or possibly even found them too easy and may therefore have lost interest). It has been speculated that runners with a previous injury may be more willing to take part in an injury-prevention study, given their history. It is also possible to speculate that in this study, the low-compliance runners might not previously have experienced an injury or, for other reasons, did not see the purpose of completing the intervention and therefore discontinued their participation. Nevertheless, this finding must be met with a degree of caution, as the true effects of the injury-prevention programme cannot be fully evaluated for this group.

**6.2.3 Strengths and limitations**

One of the major strengths of the present study is the large sample of runners representing the general population of recreational runners. The simple and feasible training programme can also be seen as a strength as it provides the opportunity to complete the intervention at home, thereby increasing compliance and catering for runners with or without previous experience of neuromuscular control and/or foam-rolling exercises. In a further attempt to increase compliance among participants, we used simple tools to document and report weekly training, by creating a specific questionnaire which was sent out by the test leader every week. The questionnaire that was sent to the participants by email took approximately two minutes to fill in, making data submission quick and easy. Additionally, the intervention group was able to access the training programme through an online platform, where they were able to view the exercises in pictures, instructional videos and text. Documentation of the performed intervention programme was also made using this platform after each session.

Despite these strengths, the self-reporting of training and injury information was a limitation. Although still commonly used in studies, self-reporting is accompanied by a degree of subjectivity and, in an optimal situation, tools such as GPS watches, monitored intervention sessions and clinical examination of injuries would provide more accurate and objective measures of data. However, for logistical reasons, these methods were not feasible in the present study and could therefore not be utilised. For example, we recruited runners from all over Sweden and some from other European countries, all of whom have previously taken part in the Gothenburg Half Marathon event; to provide each runner with a GPS watch and monitor each training session was outside of the scope of our resources, both economically and from a time/personnel perspective.
6.3 Ethical considerations

Ethical vetting was applied for and approved prior to the commencement of all studies included in this thesis. Personal information (such as date of birth, contact information, injury information and health status) was collected during the studies and was the reason as to why ethical vetting was required. No direct risks to the participants were expected during the collection of baseline data, or during the intervention, however, participants were informed that muscle soreness after the isometric strength tests or unforeseen events (such as twisting of the ankle) during the biomechanical running analysis, may arise. To address this, precautions were taken to ensure the safety of the participants at all times; participants familiarized themselves with the equipment, testing protocols and/or exercises before performing them. Additionally, a warm-up was performed to minimise any risk of discomfort or injury.

With regards to sensitive information, all participants were anonymised using unique ID-numbers and data was stored on a secure, encrypted server, accessible only by relevant personnel. Data collection for Theme I was conducted prior to the introduction of the General Data Protection Regulation (GDPR), however, all data handling and storing was conducted in a secure way both prior to and after the introduction of this regulation. Data collection for Theme II was done in accordance with the GDPR and safeguarded accordingly.

If participants sustained any injuries in Theme I, they were offered a medical examination by a sports medicine physician affiliated with the study. In some instances, further medical investigations were required (for example diagnostic imaging), which were then performed at primary healthcare facilities, outside of the scope of the study. All participants were given the best possible support by the study personnel in such instances, despite them no longer participating in the study, to enable their return to injury-free running.
Running-related injuries in recreational athletes

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STUDY I: Runners with late timing of maximal eversion or weak hip abductor strength in relation to hip adductor strength run a higher risk of sustaining an RRI compared with their counterpart peers.

STUDY II: Seventy-five RRIs were sustained during the study period, with a cumulative incidence proportion of 46%. The most common injuries occurred in the knee and Achilles tendon/calf. Runners with a previous injury were twice as likely to sustain a new RRI than runners with no previous injury.

STUDY III: Weekly progressions or regressions exceeding 10% were not associated with an increased risk of running-related injuries, after 18 weeks. Runners progressing their weekly running distance by more than 30% sustained more injuries and ran a 10% higher risk of injury compared with runners keeping within a ± 10% weekly running distance, however, this result was not statistically significant.

STUDY IV: Runners who performed the injury-prevention programme twice a week on average for 18 weeks, were 85% less likely to sustain an RRI compared with the control group. Additionally, the time to injury for these runners was 18 days longer on average compared with the control group. The cumulative incidence proportion for the highly compliant runners was 4.6% after 18 weeks, compared with 22.9% for the control group.

Conclusions: Running-related injuries in recreational athletes...
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The results presented in this thesis are primarily aimed at recreational runners and may therefore not apply to all types of runners or subgroups of runners. Although the road to fully understanding why RRIs occur is long and winding, this thesis will hopefully help us to understand which runners are more susceptible to running-related injuries, and how certain characteristics (both behavioural, such as compliance, and physical, such as previous injuries or biomechanical characteristics) in the individual runner may lead to injury. Prospective studies, implementing the use of censoring, are highly encouraged for future studies, in order more accurately to report the incidence of RRIs.

We aimed to evaluate whether general injury-prevention guidelines could be effective in reducing running-related injuries in the ‘general’ population of recreational runners. However, as we know that these injuries are multifaceted and complex and each individual runner possesses unique traits, it may be of value to explore whether tailored interventions, based on the individual, would be more effective. It goes without saying that this method requires more resources, time and effort, particularly when conducting large-scale studies, which are inevitably required in order to fully assess the true effects. Additionally, we have seen that high compliance is of the utmost importance and that more efforts are needed to maintain high compliance throughout studies, in order to evaluate the effects of an intervention. Future research must focus on these aspects, creating ‘optimal’ conditions in which injury-prevention programmes can be implemented and succeed in a real-world setting.
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This thesis would not have been possible without the support and assistance of many that I have had the privilege to have in my life, to meet and to work with along the way. To you all, I express my greatest gratitude for being an important part of this journey.

Jón Karlsson, Professor, MD, PhD, my main supervisor. I want to thank you for the opportunity to embark on this rollercoaster ride of challenging, insightful and educational research years. Your professionalism and knowledge have and continue to be inspirational and I am grateful for your support and guidance throughout my doctoral studies. As an added bonus, I have been able to sharpen my knowledge of the Icelandic language, although I may need another 4 years to master it! Takk kærlega fyrir, Jón!

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Mats, my first meeting at the Center for Health and Performance (CHP) was with you back in 2016. Since then, I have been a member of the team at CHP, and for that, I would like thank you! You have supported me throughout my doctoral studies, from the starting block to the finish line, and your guidance along the way is greatly appreciated.

To my colleagues at CHP, working with you all has truly been a privilege and made every day that much brighter. I do not take for granted all of the knowledge and help shared, the insights into so many different aspects of research and the discussions around the lunch table. I feel lucky to have worked with such great colleagues and friends. Thank you for these past years!
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I would like to extend a special thanks to some of my colleagues in particular, Rebekka Hils and Klara Boije Af Gennäs, thank you for all of the laughs, lunches and foam-rolling classes! Getting through the challenges of this journey was so much easier with colleagues and friends like you.

Thank you, Mikael Gustafsson, for always having your door open when I needed help with technical issues, had a question, or had excel-data in need of concatenation.

Andreas Lundberg Zachrisson, thanks to you I became an expert in using the Mobee-device and gained valuable insights into the world of research in elite athletics. Thank you for these past years as your colleague.

Jonatan Jungmalm, you have been like my unofficial supervisor during my doctoral studies, and for that I would like to express my deepest gratitude! You have always been willing to help whenever possible and your positive attitude made it easy to knock on your office door with any questions. I really appreciate all your help!

To the exchange student and interns, Frithjof, Theresa, Iris and Raphaela, thank you all for your contributions.

My co-authors, Jón Karlsson, Stefan Grau, Mats Börjesson and Jonatan Jungmalm Writing the articles would not have been possible without your support, contributions and dedication and for that, I thank you!

Cina Holmer. Thank you for all your help with every administrative aspect during my doctoral studies.

Jeanette Kliger. Your detailed and professional work with the language review of this thesis is greatly appreciated.

Pontus Andersson. Many thanks for the fantastic illustrations both on the front cover and in the thesis.

Guðni Ólafsson. Thank you for your excellent work with the lay-out and design of this thesis.

Christer Johansson. Thank you for the statistical help with studies II and IV.

Ola Rolfson. Current head of the Department of Orthopaedics, Sahlgrenska Academy. Thank you for the opportunity to conduct this research.
**Acknowledgements**

**Helena Brisby.** Former head of the Department of Orthopaedics, Sahlgrenska Academy. Thank you for the opportunity to conduct this research.

**Adad Baranto.** Head of Orthopaedic research unit, Sahlgrenska University Hospital. Thank you for the opportunity to conduct this research.

**Funding support**

This thesis was received financial support from the following funding bodies:

- The Swedish state under the agreement between the Swedish government and the country councils, the Alf-agreement (LUA-ALF, 74020).
- The Sten A. Olsson Foundation for Research and Culture.

**Recruitment and equipment**

Thank you to the Gothenburg Half Marathon Association for assistance with the recruitment of runners.

- Thank you to BLACKROLL® Germany for providing the foam-rollers and elastic training bands.
- I would like to thank all of the runners who participated in this project, this thesis would not have been possible without you.

Finally, to all my friends and family who have supported me during the past years, I am truly grateful to you all. My parents, Ashok and Barbro, thank you for all your support and encouragement over the years. My siblings Annika, Misha and Neel-with family Karin, Alicia and Alexi, thank you for the support, occasional intense discussions and the unconditional joy from the ‘mini-supporters’, Alicia and Alexi!

**Rúnar,** you have probably had to put up with the worst side of me during the most stressful times of this journey. Thank you for being patient and calm, not taking it personally and always trying to find the positives in every situation! Thank you for the love and support during these past years.

This thesis would not have been possible without you all.
References


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Appendix
### Appendix A1. Exercises in the intervention program

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<tr>
<th>Exercise</th>
<th>Information</th>
<th>Repetitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-leg squat</td>
<td>One-leg squat from a step. Step down with one leg, heel first and avoid touching the ground. Focus on maintaining a neutral position on the standing leg to avoid inward movements of the knee. Target: Knee control, quadriceps activation</td>
<td>10 per leg</td>
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<tr>
<td>Forward lunges</td>
<td>Forward lunge. Take a step forward while maintaining control in the knee to avoid inward movement. Keep the core activated to maintain good posture. Target: Knee control, quadriceps and core activation</td>
<td>10 per leg</td>
</tr>
<tr>
<td>Side-steps</td>
<td>Side-steps with elastic resistance band. With an activated core, take steps to the side with lightly flexed knees, against the resistance of the band. Target: Abductor and core activation</td>
<td>10 steps in each direction</td>
</tr>
<tr>
<td>Supine hip abduction</td>
<td>Hip abduction with elastic resistance band. Participants lay supine on the ground and pressed knees outwards against the resistance of the band. Focus on maintaining a neutral spine position with feet firmly on the ground to isolate the abduction movement. Target: Abductor activation</td>
<td>10</td>
</tr>
<tr>
<td>Side-plank</td>
<td>With feet, hips and shoulders aligned and elbow directly below the shoulder, hold a side-plank position, activating their core to maintain a neutral spine position. Target: Core and abductor activation</td>
<td>30 seconds on each side</td>
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<td>Target: Core and abductor activation</td>
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<tr>
<td>Diagonal lift</td>
<td>10 per side</td>
</tr>
<tr>
<td>Standing on all fours with knees directly under hips and hands directly under shoulders, lift opposite arm and leg while maintaining a neutral spine position.</td>
<td></td>
</tr>
<tr>
<td>Target: Core activation</td>
<td></td>
</tr>
<tr>
<td>Foot supination</td>
<td>10 per foot</td>
</tr>
<tr>
<td>With an elastic resistance band around one foot and looped around a stable object such as a table leg, lift the heel off the ground using a rolled up towel and press the foot inwards/upwards against the resistance of the band.</td>
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<tr>
<td>Focus: Foot supinator activation</td>
<td></td>
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<tr>
<td>Foam-rolling</td>
<td></td>
</tr>
<tr>
<td>Gluteal muscles</td>
<td></td>
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<tr>
<td>Hamstrings</td>
<td></td>
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<tr>
<td>Quadriceps</td>
<td></td>
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<tr>
<td>Abductors</td>
<td></td>
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<tr>
<td>Calf muscles</td>
<td></td>
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<tr>
<td>Plantar fascia</td>
<td></td>
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<tr>
<td>Participants rolled each muscle group for one minute (30 seconds per leg). Added pressure could be applied by placing the non-rolling leg on top of the rolling-leg. While slight discomfort is normal when foam-rolling, participants were advised to perform this section of the training program according to their pain limits and as a result, they should not experience pain during or after the foam-rolling.</td>
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