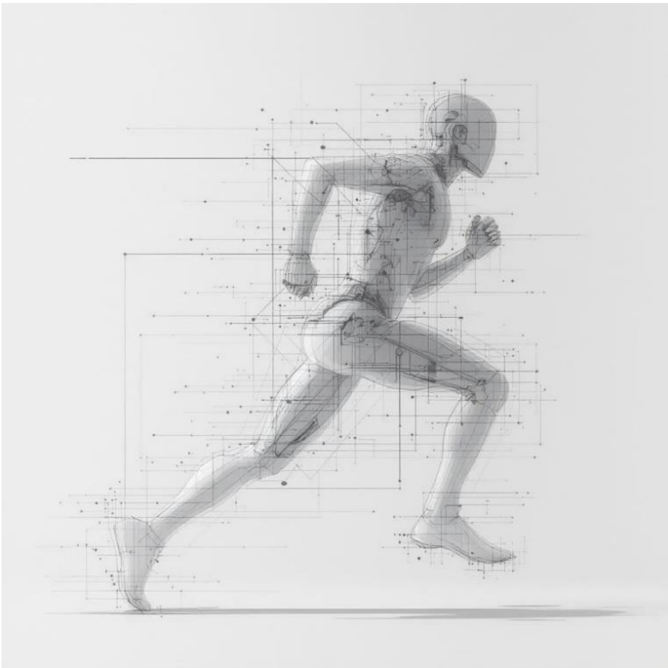
Running Technique Alteration: insights into injury prevention and performance

ABRAN Guillaume

Sports physiotherapist, MSc Public Health



Under the direction of Pr. SCHWARTZ Cédric & Pr. CROISIER Jean-Louis

Thesis submitted to obtain the degree of Doctorate in Physical activity and rehabilitation Sciences

Academic Year 2025-2026

Supervisors

Prof. Schwartz Cédric

Prof. Croisier Jean-Louis

Jury members

Chair:

Prof. Delvaux François (ULiege)

Internal members:

Dr. Hody Stephanie (ULiege)

Pr. Kaux Jean-François (ULiege)

External members:

Prof. Vanwanseele Benedicte (KU Leuven),

Dr. Giandolini Marlène (Salomon)

Acknowledgment

First and foremost, I would like to express my deepest gratitude to my supervisors, Prof. Dr. Cédric Schwartz and Prof. Dr. Jean-Louis Croisier, for their invaluable guidance, expertise, and continuous support throughout the completion of this thesis. Their scientific rigor, constructive feedback, and encouragement have been a constant source of motivation and inspiration.

I am also sincerely thankful to the members of the jury for accepting to evaluate this work and for their insightful comments and suggestions. I would like to warmly acknowledge Prof. Bénédicte Vanwanseele and Dr. Marlène Giandolini as external experts, for the time and effort dedicated to reviewing this dissertation. Their expertise and perspectives have greatly enriched the quality of this work. My gratitude also goes to Dr. François Delvaux, who kindly accepted to chair the jury, as well as to the internal members, Dr. Stéphanie Hody and Prof. Jean-François Kaux, for their constructive remarks that have significantly enhanced this dissertation.

Beyond the academic sphere, I wish to extend my heartfelt thanks to my family and friends for their unwavering support, patience, and encouragement during this journey. Their presence has been essential in overcoming challenges and celebrating achievements along the way.

Finally, I would like to acknowledge my colleagues from the LAM and from the Department of Physical Activity and Rehabilitation Sciences. Their collaboration, stimulating discussions, and friendly environment have made this research endeavor a truly enriching and enjoyable experience.

List of publications and communications arising from this work

This thesis is based on the seven following original papers submitted or published in indexed scientific journals:

1. **Abran, G.,** Berraz, A., Dardenne, N., Gramage Medina, K., Bornheim, S., Delvaux, F., Croisier, J.-L., & Schwartz, C. (2024). A comparison of foot and ankle biomechanics during running drills and distance running. *Sports Biomechanics*, 1-16. doi:10.1080/14763141.2024.2382804
2. **Abran, G.,** Schwartz, C., Delvaux, F., Aguilaniu, A., Bornheim, S., & Croisier, J.-L. (October 2023). Foot and Ankle Muscle Isometric Strength in Nonrearfoot Compared With Rearfoot Endurance Runners. *Foot and Ankle Orthopaedics*, 8(4), 24730114231205305. doi:10.1177/24730114231205305
3. **Abran, G.,** Delvaux, F., Schwartz, C., Martens, G., Hody, S., Dardenne, N., Bruyère, O., Bornheim, S., & Croisier, J.-L. (2022). Current perception and practice of athletics coaches about the modification of footstrike pattern in endurance runners: A survey. *International Journal of Sports Science and Coaching,* 174795412211080. doi:10.1177/17479541221108089
4. **Abran, G.,** Dardenne, N., Bornheim, S., Delvaux, F., Croisier, J.-L., & Schwartz, C. (2024). Minimalist footwear and softer running technique alter injury location but not incidence rate in recreational endurance runners. *Accepted in American Journal of Sports Medicine.*
5. **Abran, G.,** Dardenne, N., Bornheim, S., Delvaux, F., Croisier, J.-L., & Schwartz, C. (2024). Who Struggles with Minimalist Footwear and Running Retraining? A Risk Factor Analysis. (Submitted)
6. **Abran, G.,** Dardenne, N., Bornheim, S., Delvaux, F., Croisier, J.-L., & Schwartz, C. (2024). Improvements in running economy following minimalist footwear and running retraining emerge after 6 months and are sustained at 12 months. . (Submitted)
7. **Abran, G.,** Schwartz, C., Delvaux, F., & Croisier, J.-L. (2025). Acute effect of running retraining interventions on low & high-frequency components of the impact signals. (Submitted)

Not included in the thesis:

1. **Abran, G.,** Aguilaniu, A., Dardenne, N., Bornheim, S., Delvaux, F., Croisier, J.-L., & Schwartz, C. (2024). Running biomechanics and foot-ankle characteristics of endurance runners with and without a history of running-related injuries: a retrospective study including 225 runners. (Submitted)

During the five last years, several presentations have been carried out:

1. **Abran, G.,** Schwartz, C., Delvaux, F., & Croisier, J.-L. (06 June 2025). Acute effect of running retraining interventions on high-frequency signals of impact variables. [Oral presentation]. MathSport.
2. **Abran, G.** (16 November 2024). Effect of two distinct running retraining interventions on running-related injuries in recreational endurance runners. [Paper presentation]. 2nd National Congress of Sports Physiotherapy.
3. **Abran, G.,** Schwartz, C., Delvaux, F., & Croisier, J.-L. (10 February 2024). Lien entre impact au sol et blessures en course à pied : Mythe ou réalité ? [Paper presentation]. Congrès SFMSS 2024 – La course à pied.
4. **Abran, G.,** Schwartz, C., Delvaux, F., & Croisier, J.-L. (22 September 2023). Superior foot & ankle muscle strength in non-rearfoot endurance runners compared with rearfoot runners: implications for the management of running-related knee injuries [Poster presentation]. BFSP-IFSPT International Symposium on Sports Physiotherapy.
5. **Abran, G.,** Delvaux, F., Croisier, J.-L., & Schwartz, C. (09 July 2023). Comparison of foot-ankle mechanics and muscle activation between running drills and running at different speeds [Paper

presentation]. 28th Congress of the European Society of Biomechanics, July 9-12, 2023, Maastricht, the Netherlands.

6. **Abran, G.,** Schwartz, C., Delvaux, F., & Croisier, J.-L. (13 October 2023). Caractéristiques du complexe pied-cheville chez des coureurs récréationnels sains et ayant subi une blessure [Poster presentation]. 3ème Symposium sur la Prévention des Blessures dans le Sport.
7. **Abran, G.,** Delvaux, F., Schwartz, C., & Croisier, J.-L. (09 October 2022). Course à pied, de l'endurance à l’ultra-endurance.: Données biomécaniques et technique de course [Paper presentation]. 10ème colloque sport^2.
8. **Abran, G.,** Delvaux, F., Schwartz, C., & Croisier, J.-L. (06 July 2022). Footstrike pattern influence on foot-ankle muscle strength in endurance runners [Poster presentation]. European College of Sport Science.

Table of contents

Résumé pratique pour entraîneurs et athlètes

La course à pied est l'un des sports les plus pratiqués dans le monde, notamment grâce à son accessibilité et à son faible coût. Au cours des dernières décennies, le niveau de performance en course à pied a considérablement augmenté, comme en témoignent les chronos spectaculaires des vainqueurs de marathon. En revanche, cette amélioration des performances n'a pas été accompagnée d'une réduction des blessures. L'incidence des blessures reste très élevée chez les coureurs d'endurance, malgré les progrès des connaissances et le développement de nouvelles technologies. La technique de course est considérée comme un élément clé pour améliorer les performances, mais aussi pour prévenir les blessures. Cependant, la littérature scientifique ne fournit pas de recommandations claires permettant aux entraîneurs et aux coureurs de savoir quelle technique adopter pour concilier performance et sécurité. Dans cette thèse, nous nous sommes donc intéressés aux effets de la modification de la technique de course sur la performance et la prévention des blessures. Deux méthodes sont fréquemment utilisées pour modifier la technique d'un coureur d'endurance : la modification de la foulée (transition vers une attaque médio- ou avant-pied et augmentation de la cadence d'environ 10 %) et la modification de la chaussure (passage à des chaussures minimalistes). Nous avons constaté que, utilisées séparément, ces deux méthodes pouvaient améliorer l'économie de course, et donc indirectement la performance. Les deux approches réduisaient la consommation d'oxygène d'environ 5 % après six mois et 10 % après un an, ce qui pourrait se traduire par un gain de temps significatif sur une course d'endurance. Par exemple, une réduction de 10 % de la consommation d'oxygène à une vitesse de 13 km/h sur marathon représenterait théoriquement un gain d'environ 20 minutes à l'arrivée. Bien que ces gains soient intéressants, nous avons vérifié qu'ils ne se faisaient pas au détriment d'une augmentation du risque de blessures. Nous avons suivi l'apparition des blessures lors de la transition de foulée et lors du passage aux chaussures minimalistes. Le changement de foulée ne modifiait pas le risque global de blessures, mais influençait leur localisation. Les coureurs passant à une attaque médio/avant-pied avaient tendance à souffrir davantage au niveau du pied et de la cheville, tandis que les coureurs talon souffraient plus souvent de blessures à la hanche. À noter que les coureurs les plus exposés aux blessures lors de la transition de foulée étaient ceux présentant une force du pied plus faible (inférieure à 2,85 N/kg). Pour le passage aux chaussures minimalistes, les coureurs plus lourds (poids supérieur à 71 kg) étaient plus susceptibles de se blesser. Ces observations suggèrent qu'il est important de mesurer la force du pied à l'aide d'un dynamomètre chez un coureur avant de modifier sa technique, et de mettre en place un

programme de renforcement spécifique si nécessaire. Sur le terrain, les entraîneurs utilisent souvent des éducatifs (ou « gammes athlétiques ») pour travailler le pied. Nos analyses en laboratoire ont montré que ces exercices permettent non seulement de renforcer la propulsion du pied, mais aussi d'activer ses muscles de manière plus importante que la course elle-même. Cette approche semble donc intéressante pour préparer le complexe pied-cheville à une transition de foulée ou au passage à des chaussures minimalistes. Nous avons également constaté que tous les éducatifs ne sollicitent pas de la même façon le pied et la cheville. Par exemple, le griffé au sol (B-skip) travaille la propulsion de l'avant-pied sans augmenter la charge sur le médio-pied, tandis que la foulée bondissante (Bounding) renforce le médio-pied tout en réduisant le travail de propulsion de l'avant-pied.

Résumé scientifique

La course à pied est l'un des sports les plus pratiqués au monde notamment grâce à son accessibilité. Au cours du siècle dernier, comme en témoigne la progression marquée des temps réalisés sur marathon, les performances en course à pied se sont nettement améliorées. En revanche, cette amélioration du niveau de performance n'a pas été accompagnée d'une réduction du nombre de blessures. La technique de course joue un rôle crucial dans la régulation des forces d'impact, la répartition des contraintes sur le corps et de la transmission d'énergie au sol. La première étude de cette thèse a consisté en une évaluation sur le terrain, via un questionnaire, des connaissances actuelles des entraîneurs d'athlétisme Belge sur l'influence de la technique de course en lien avec les blessures et la performance. Cette enquête a mis en évidence que, malgré l'absence de preuves scientifiques, les entraîneurs modifient la technique de course des coureurs d'endurance afin d'améliorer la performance ou de réduire le risque de blessures. Selon eux, l'attaque médio-pied est considérée comme la foulée la plus efficace pour performer en endurance (47 %) et réduire le risque de blessures (36 %), tandis que l'attaque talon est perçue comme la moins favorable (50 % et 52 % respectivement). Ces résultats peuvent s'expliquer par deux facteurs principaux : le manque d'études prospectives sur ce sujet et la communication limitée entre les entraineurs et les chercheurs. L'objectif général de cette thèse était donc d'améliorer les connaissances autour de l'effet de la modification de la technique de course chez les coureurs d'endurance récréatifs, sur l'amélioration de la performance et la prévention des blessures.

Comme l'amélioration de la performance est l'un des principaux centres d'intérêt des athlètes et de leurs entraîneurs, la première partie de cette thèse a examiné la relation entre les modifications de technique de course et la performance en course à pied. La deuxième étude de cette thèse consistait en un essai contrôlé randomisé prospectif d'un an impliquant trois groupes de coureurs d'endurance récréatifs et examinant le lien entre la modification de la technique de course et l'amélioration de l'économie de course. Les trois groupes étaient composés de : 1) un groupe ayant effectué une transition vers des chaussures minimalistes, 2) un groupe ayant modifié sa technique de course (adoptant une attaque non-talon et augmentant leur cadence), et 3) un groupe contrôle ayant suivi un programme dit « placebo » constitué d'étirements statiques. Les coureurs ont été évalués à quatre moments au cours de l'année, avec des mesures systématiques de l'économie de course, de la biomécanique et des caractéristiques du complexe pied-cheville. Les résultats ont révélé des améliorations significatives de l'économie de course dans les groupes chaussures minimalistes et modification de la technique de course après six et

douze mois, d'environ 5 % et 10 %. L'économie de course s'est également améliorée dans le groupe contrôle mais de moins de 5 % et uniquement après douze mois. Ces résultats remettent en question les recommandations scientifiques actuelles qui conseillent aux coureurs de ne pas modifier leur technique de course pour améliorer leurs performances.

Cependant, l'effet positif sur la performance des programmes de modification de technique de course ne doit pas être contrebalancé par une augmentation du taux de blessures. La deuxième partie de cette thèse a donc exploré l'impact des modifications de la technique de course sur l'incidence des blessures. Un essai contrôlé randomisé récent a suggéré que les composantes hautes fréquences des variables liées à l'impact pouvaient constituer des facteurs de risque de blessures chez les coureurs d'endurance récréatifs. Néanmoins, l'effet de la modification de la technique de course sur les composantes hautes fréquences des variables liées à l'impact reste inconnu à ce jour. Dans la troisième étude de cette thèse, nous avons montré que l'adoption d'une attaque avant-pied réduisait trois fois plus les composantes hautes fréquences liées à l'impact par rapport à une augmentation de la cadence de 10 %. De plus, la combinaison d'une attaque avant-pied et d'une augmentation de 10 % de la cadence était la stratégie la plus efficace pour réduire les composantes hautes fréquences des variables liées à l'impact. Cette stratégie pourrait donc être prometteuse pour diminuer l'incidence des blessures, mais devait être confirmée par des études prospectives, ce que nous avons entrepris dans une quatrième étude. Cet essai prospectif contrôlé randomisé d'un an, conçu sur le même modèle que la deuxième étude, n'a pas montré de réduction de l'incidence globale des blessures dans les groupes d'intervention. Toutefois, il a révélé une incidence plus élevée de blessures à la hanche dans le groupe contrôle comparé au groupe de modification de la technique de course. D'autre part, nous avons également constaté une augmentation des blessures du pied et de la cheville dans le groupe de modification de la technique de course comparé au groupe contrôle. Notre étude a confirmé les résultats précédents suggérant que la modification de la technique de course peut accroître le risque de blessures du pied et de la cheville. En effet, l'adoption d'une attaque non-talon, l'augmentation de la fréquence des pas ou la transition vers des chaussures minimalistes permettent de réduire les charges au niveau du genou, mais accroissent les contraintes mécaniques sur le pied et la cheville. Ce transfert de charge pourrait expliquer l'augmentation du risque de développer des blessures au sein du complexe pied-cheville durant ou après un programme de modification de la technique de course. Dès lors, il parait essentiel de mieux comprendre les facteurs qui peuvent prédisposer des coureurs à subir une blessure au sein du complexe pied-cheville lors d'un programme de modification de la technique de course et de déterminer des moyens de préparer les coureurs le mieux possible à ces programmes.

La troisième partie de cette thèse se concentre sur l'importance des caractéristiques du complexe pied-cheville lors d'un programme de modification de technique de course. Dans la cinquième étude, nous avons mené une analyse rétrospective comparant les caractéristiques du pied et de la cheville entre des coureurs avec une attaque talon et des coureurs avec une attaque non-talon. Les coureurs non-talon présentaient une plus grande force au niveau du complexe pied-cheville que les coureurs talon. Toutefois, une étude prospective était nécessaire pour déterminer si ces caractéristiques pouvaient constituer des facteurs de risque lors d'un programme de modification de la technique de course. La sixième étude de cette thèse consistait en une analyse secondaire de l'essai longitudinal contrôlé randomisé précédemment décrit. Elle visait à déterminer si les caractéristiques du pied et de la cheville pouvaient être considérées comme des facteurs de risque lors d'une transition vers des chaussures minimalistes ou d'un programme de modification de la technique de course. Les résultats ont montré que les coureurs présentant une force insuffisante des fléchisseurs de l'hallux avaient un risque accru de développer des blessures du pied et de la cheville. Ces résultats soulignent la nécessité d'intégrer des exercices ciblés de renforcement du pied et de la cheville lors de programmes de modification de la technique de course. Enfin, la septième étude s'est concentrée sur l'analyse et la description des caractéristiques biomécaniques des gammes athlétiques couramment utilisées pour renforcer les structures du pied et de la cheville. Cette étude a mis en évidence l'intérêt des gammes athlétiques pour améliorer la propulsion du pied au sol et fournir des recommandations pratiques aux entraîneurs sur l'utilisation des gammes athlétiques.

Scientific summary

Recreational running is one of the most accessible forms of physical activity and has one of the highest participation rates of any sport worldwide. Over the past century, running performance has markedly improved, with substantial reductions in marathon finishing times. In contrast, these improvements in performance have not been accompanied by a corresponding decrease in running-related injuries. The running technique plays a crucial role in modulating impact forces, tissue loading, and energy transmission throughout the body. The first study of this thesis consisted of a field-based assessment of current knowledge using a questionnaire distributed to athletics coaches in Belgium. This survey highlighted that, despite the absence of scientific evidence, athletics coaches modify the running technique of endurance runners to enhance performance or reduce injury risk. According to coaches, midfoot strike is considered the most effective landing pattern for endurance performance (47%) and injury prevention (36%), while rearfoot strike is perceived as the least favourable (50% and 52%, respectively). These findings may be explained by two main factors: a lack of prospective studies on the topic and limited communication between field practitioners and researchers. Therefore, the overall objective of this thesis was to improve our understanding of the role of running technique alterations in recreational endurance runners, with a particular focus on performance enhancement and injury prevention.

As one of the main focus of interest of the athletes and their coaches is the improvement of performance, the first part of this thesis examined the relationship between running technique modifications and running performance. The second study of this thesis was a one-year prospective randomised controlled trial involving three groups of recreational endurance runners that examined the relationship between running technique alteration and running economy enhancement. The three groups were composed of: 1) a group who transitioned to minimalist footwear, 2) a group who altered their running technique (adopting a non-rearfoot strike and increasing running cadence), and 3) a control group who performed a placebo static stretching programme. Runners were evaluated at four time points throughout the year, with systematic assessments of running economy, running biomechanics, and foot–ankle characteristics. The results revealed significant improvements in running economy in the minimalist and running retraining groups after six and twelve months, by approximately 5% and 10% respectively. Running economy also improved in the control group but only at 12 months, by less than 5%. These results challenged current scientific recommendations that advise runners not to alter their running technique to improve running performance.

However, as the positive effect of altering running technique should not be counterbalanced by an increase in running-related injuries, the second part of this thesis explored the effect of running technique alteration on the incidence rate of running-related injuries. A recent randomised controlled trial has indicated that high-frequency components of impact-related variables may constitute risk factors for running-related injuries in recreational endurance runners. Nevertheless, it remained unclear how running technique alterations influence the high-frequency components of impact-related variables. In the third study of this thesis, we showed that adopting a forefoot strike pattern reduced the high-frequency components of impact-related parameters nearly three times more than increasing running cadence by 10% alone. Additionally, combining a forefoot strike pattern with a 10% increase in running cadence appeared to be the most effective strategy for reducing the high-frequency components of impact-related parameters. This strategy may therefore promising to reduce the incidence of running-related injuries, but should be confirmed through prospective studies as we did in a fourth study. This study was a one-year prospective randomised controlled trial based on the same design as the second study of this thesis. Our results did not show a reduction in overall injury incidence in either intervention group. However, it revealed a higher incidence of hip injuries in the control group (N = 9/46) compared to the running retraining group (N = 0/47) and a greater incidence of foot and ankle injuries in the retraining group (N = 12/47) compared to the control group (N = 5/46). Our study confirmed previous findings that running technique alteration may increase the risk of foot–ankle injuries when a runner follows a running technique alteration programme. However, if adopting a non-rearfoot strike pattern, increasing step rate, or transitioning to minimalist footwear can reduce knee joint loading, it simultaneously increases mechanical demands on the foot and ankle. These load transfers could explain the risk of developing secondary injuries during or following a running technique alteration. Given these considerations, it is essential to better understand the factors that may predispose runners to injury when undergoing such interventions and prepare them for this transition.

The third part of this thesis focuses on the importance of foot–ankle conditioning for safer running technique alteration. In the fifth study, we conducted a retrospective analysis comparing foot–ankle characteristics between rearfoot strikers and non-rearfoot strikers. Interestingly, non-rearfoot strikers demonstrated greater strength in the foot–ankle complex than rearfoot strikers. However, a prospective study was needed to understand whether foot and ankle characteristics constituted risk factors for alterations in running technique. The sixth study included in this thesis consisted of a secondary analysis of the previously described longitudinal randomised controlled trial. This study aimed to determine whether foot–ankle characteristics could be considered risk factors during a transition to minimalist footwear or the implementation of a running retraining programme. The results showed that runners with insufficient hallux flexor strength had an increased risk of sustaining foot and ankle injuries (odds ratio [CI95%]: 0.11 [0.02 –0.53]). This finding highlights the importance of incorporating targeted foot and ankle strengthening exercises during interventions involving changes in running technique. Finally, the seventh study focused on analysing and describing the biomechanical characteristics of commonly used running drills intended to strengthen foot and ankle structures. This study demonstrated the potential of these drills to enhance the foot's propulsive function and provided athletics coaches with practical recommendations for their application in field settings.

Abbreviations list

AVLR = Average vertical loading rate

BW = Body weight

FFS = Forefoot strike

GRF = Ground reaction force

IP = Impact peak

IVLR = Instantaneous vertical loading rate

MET = Metabolic equivalent

MVIC = Maximal voluntary isometric contraction

MVIS = Maximal voluntary isometric strength

NRF = Non-rearfoot strike

RE = Running economy

RF = Rearfoot strike

RRIs = Running-related-injuries

SMD = Standardised mean difference

Figures list

Tables list

A. General introduction

1. Running performance: evolution, key physiological and biomechanical determinants

Evolution

Running is one of the most popular physical activities worldwide. In Northern European countries, between 12.5% and 25% of the population regularly engages in running (Videbæk et al., 2015). The increasing appeal of this activity is reflected in the growing number of running events, such as half-marathons and marathons. Within competitive contexts, long-distance races typically range from 5,000 meters to the marathon distance (Casado et al., 2021). In 2016 alone, more than 5,000 marathons were organized globally, attracting over 1.8 million participants (Doherty et al., 2020). The most prestigious of these are the “marathon majors”—Berlin, Boston, Chicago, London, New York, and Tokyo which together drew 229,795 runners in 2016 (Doherty et al., 2020).

A century ago, marathon winning times exceeded 2 hours and 30 minutes, whereas today elite marathoners complete the distance in approximately 2 hours. Marathon performance is influenced by multiple factors, including physiological characteristics, anthropometric profile, nutrition, age, sex, and training practices (Doherty et al., 2020). The progression of marathon records has been attributed to three main factors: the evolution of training methodologies, social developments (e.g., professionalism, the rise of African runners, and increased female participation), and technological innovations such as advanced footwear and pacing systems (Emig & Adam, 2024). Over recent decades, various training strategies have been developed, all sharing the common objective of improving the runner’s physiological profile.

Physiological determinants

Three key physiological factors have been identified as major determinants of performance in long-distance running events: maximal oxygen uptake (VO_2max), running economy (RE), and the fractional utilization of VO_2max ($\%VO_2max$) during submaximal exercise (Joyner & Coyle, 2008). VO_2max is one of the most commonly measured variables in exercise physiology, as it represents the upper limit of ATP production via oxidative phosphorylation. Because it depends largely on maximal cardiac output, VO_2max is also considered a robust indicator of cardiorespiratory fitness (Bassett & Howley, 2000). In the general population, VO_2max can vary substantially, ranging from as low as 20 $mL \cdot kg^{-1} \cdot min^{-1}$ in cardiac patients to over 80 $mL \cdot kg^{-1} \cdot min^{-1}$ in elite endurance athletes such as runners, cyclists, and cross-country skiers. However, most long-distance races are not performed at maximal intensity. When comparing runners with similar VO_2max values, the one capable of sustaining a higher percentage of their VO_2max during competition will typically achieve better performance. Thus, the oxygen consumption during a race is determined not only by VO_2max but also by the fraction of VO_2max that can be maintained (%VO_2max), which is closely related to the lactate threshold (Costill et al., 1973). Running economy (RE) is defined as the steady-state oxygen consumption at a given submaximal running velocity, serving as an index of the energy cost of running (Barnes & Kilding, 2015). A runner with superior economy will consume less oxygen than one with poorer economy at the same speed. Notably, RE can vary by up to 30% among trained runners with comparable VO_2max values (Barnes & Kilding, 2015). A linear regression analysis by McLaughlin et al. (2010) demonstrated that the combination of VO_2max, %VO_2max at LT, and RE accounted for 97.8% of the variance in 16-km run performance, highlighting the predictive power of these physiological parameters in endurance running.

Biomechanical determinants

The running technique is considered a key component of running performance and may explain 4 to 12% of the variance in running economy between runners (Van Hooren, Jukic, et al., 2024). In a narrative review, Moore (2016) explored whether there is an economical running technique based on observational studies. She identified several modifiable intrinsic kinematic, kinetic, spatio-temporal, and neuromuscular variables that are associated with running economy (Table A.1). Similarly, a recent systematic review with meta-analysis of observational studies quantified the relationship between biomechanical parameters and running economy (Van Hooren, Jukic, et al., 2024). They reported that a higher cadence was significantly but weakly associated with a lower oxygen/energy cost ($r = -0.20$ [-0.35 to -0.05]). In addition, smaller vertical displacement as well as higher vertical and leg stiffness showed significant moderate associations with lower oxygen/energy cost ($r = 0.35, -0.31, -0.28$, respectively) (Van Hooren, Jukic, et al., 2024).

Table A.1: Modifiable intrinsic and extrinsic running biomechanics and their effect on running economy (adapted from Moore et al., 2017)

Evidenced effect on RE	Intrinsic				Extrinsic
	Spatiotemporal	Kinetics	Kinematics	Neuromuscular	
Beneficial	Self-selected stride length (minus 3 %)	Greater leg stiffness	Less leg extension at toe-off	Low muscle activation during propulsion	Firm,compliant shoe-surface interaction
	Low vertical oscillation	Alignment of GRF and leg axis during propulsion	Large stride angle	Low agonist–antagonist coactivation	Barefoot or lightweight shoes (\440 g)
		Low lower limb moment of inertia	Maintain arm swing		
Conflicting	Ground contact time	Impact force	Trunk lean	Biarticular coactivation	Orthotics
	Swing time	Anterior-posterior forces			
Limited or unknown	Horizontal distance between the foot and CoM at initial contact	Impulses	Foot-strike	Vastus medialis preactivation	
	Braking/deceleration time		Breast kinematics		
	Speed lost during ground contact				

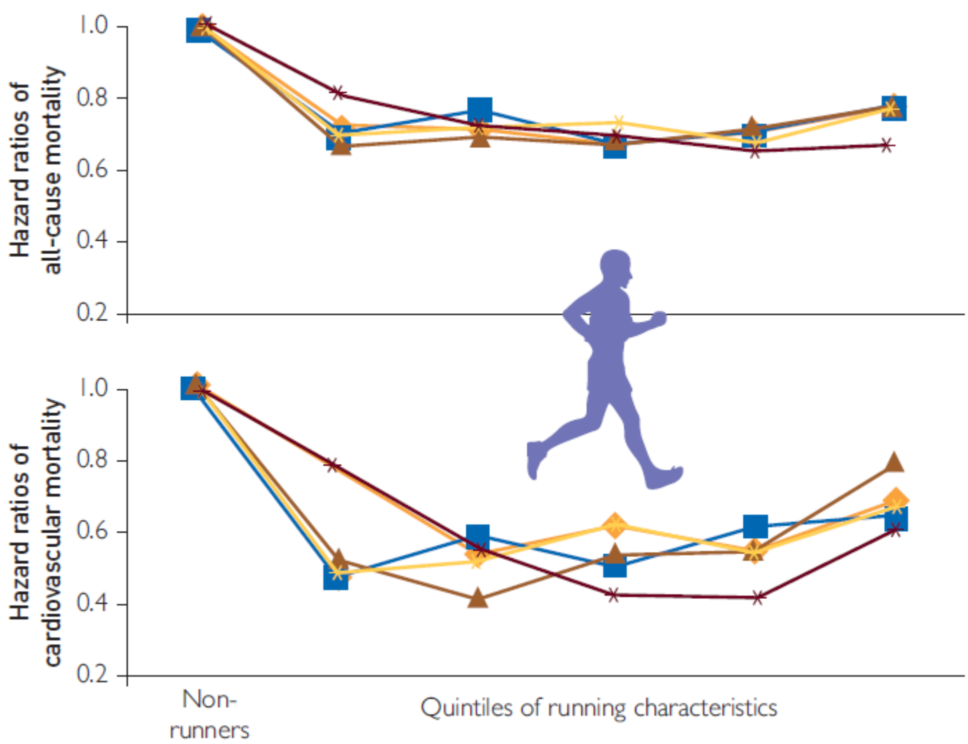
RE = Running economy, CoM = Centre of Mass, GRF = ground reaction force

While performance levels in distance running have markedly improved over the past century, this positive evolution contrasts with the persistent prevalence of running-related injuries. Despite advances in training methodologies, technology, and knowledge of physiological determinants of performance, the incidence of injuries among runners has remained relatively stable and continues to represent a major concern within the running community. Understanding the factors contributing to these injuries is therefore essential to both prevention strategies and the long-term sustainability of the sport. In the following section, we will address the epidemiology and aetiology of running-related injuries, as well as the biomechanical risk factors that may predispose runners to injury.

2. Running-Related Injuries: epidemiology, aetiology, and biomechanical risk factors

Running-related injuries epidemiology

Running success is due to its accessibility, cost-effectiveness, and benefits for mental and physical health. Furthermore, running has been linked to a reduction in several chronic diseases (Lavie et al., 2015). Type 2 diabetes, obesity, and arterial hypertension are chronic diseases and risk factors for the development of cardiovascular diseases. Cardiovascular disease is the leading cause of death in developed countries over the past 15 years (Ralapanawa & Sivakanesan, 2021). Some evidence suggests that physical inactivity, also referred to as a sedentary lifestyle, could be one of the most important modifiable factors in preventing cardiovascular disease (Swift et al., 2013). The current guidelines for aerobic physical activity and exercise training suggest that all individuals should perform at least 150 min/week of moderate physical activity, 75 min/week of vigorous physical activity, or an equivalent combination of both. Running is a particularly attractive form of aerobic physical activity. The practice of running even at low doses is associated with a substantial reduction in cardiovascular mortality (Figure A.1). Compared with non-runners, runners had a 45% reduction in cardiovascular disease, with an average increase in survival of 4.1 years (Lee et al., 2014). Likewise, osteoarthritis is one of the most common chronic diseases in developed countries, with a prevalence of more than 7% of the world's population (528 million people). Osteoarthritis has a high impact on an individual's quality of life and healthcare costs (Rosemann et al., 2007). Osteoarthritis is the 15th leading cause of years lived with disability (YLDs) worldwide, accounting for 2.2% of the total global YLDs in 2019 (Leifer et al., 2022). The direct costs of osteoarthritis are estimated at 1–2.5% of the Gross National Product in countries with established market economies, such as the US, UK, Canada, and Australia (Leifer et al., 2022). Until recently, running was considered dangerous for joint health because of the high number of impact with the ground. Given the emergence of evidence pointing in the opposite direction, this concept has tended to disappear. Current literature suggests that running could have a protective effect on the development of osteoarthritis. A recent systematic review with meta-analysis has shown that competitive runners (international level) have a higher risk of developing osteoarthritis (13.3%; 95% confidence interval (95%CI): 11.6% to 15.2%) of the knee and hip than non-runners (10.2%; 95% CI: 9.9% to 10.6%)(Alentorn-Geli et al., 2017). However, recreational runners have a significantly lower risk of developing knee and hip osteoarthritis (3.5%; 95% CI: 3.4% to 3.6%) than non-runners (Alentorn-Geli et al., 2017).



Time (min/wk)	0	<51	51-80	81-119	120-175	≥176
Distance (miles/wk)	0	<6	6-8	9-12	13-19	≥20
Frequency (times/wk)	0	1-2	3	4	5	≥6
Total amount (MET-min/wk)	0	<506	506-812	813-1199	1200-1839	≥1840
Speed (mph)	0	<6.0	6.0-6.6	6.7-7.0	7.1-7.5	≥7.6

Figure A-1: Effect of running practice on all-cause mortality (Adapted from Lee et al., 2014)

Hazard ratios (HRs) of all-cause and cardiovascular mortality stratified by running characteristics (weekly running time, distance, frequency, total amount, and speed). Participants were classified into six groups: non-runners (reference group) and five quintiles for each running characteristic. All HRs were adjusted for baseline age (years), sex, examination year, smoking status (never, former, or current), alcohol consumption (heavy drinker or not), other physical activities except running (0, 1-499, or >500 MET-min/week), and parental history of cardiovascular disease (yes or no). All P values for HRs across running characteristics were less than .05 for all-cause and cardiovascular mortality, except for running frequency of ≥ 6 times/week (P = .11) and speed of less than 6.0 mph (P = .10) for cardiovascular mortality. MET = metabolic equivalent.

Unfortunately, these benefits are counterbalanced by the high incidence of running-related injuries (RRIs). Studies examining the proportion of injuries among runners have found large variations in incidence rates, ranging from 3.2% to 84.9% (Kluitenberg et al., 2015). From another perspective, RRIs per 1000 hours of running ranged from a minimum of 2.5 to a maximum of 33.0 (Videbæk et al., 2015). These differences could be explained by the heterogeneity between studies in terms of designs, injury definitions, subject characteristics, and follow-up periods (Kakouris et al., 2021). In 2015, a consensus was reached to uniform the definition of a RRIs: “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 seven days or three consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional.” (Yamato et al., 2015). A few studies have reported the economic burden of RRIs, which varies between €83 and €174 per RRI, and €13 and €105 per participant training for an event (Sleeswijk Visser et al., 2021). Although the estimated costs of RRIs are not high when expressed per participant, the absolute costs may be substantial because of the popularity of running and the prevalence of RRIs. The estimated annual total cost of running-related injuries is approximately $4 billion (Chan et al., 2018). Considering these results, prevention programmes are needed to allow the population to benefit from all the advantages of running activities without being exposed to a high risk of RRIs. The four-stage injury prevention model developed by Van Mechelen et al. (1992) is often used to guide research on injury prevention. The first step in this model is to establish the extent of the problem (i.e. injury incidence). Thereafter, the type and aetiology of injuries should be studied, and preventive measures should be introduced.

Running-related injuries location

As introduced previously, RRIs are dependent on runner experience and/or the type of event. The literature distinguishes different categories of runners (Table A.2). The relationship between the incidence of RRIs and running distance appeared to follow a U-shaped curve. Hence, sprinters, middle-distance runners, and marathon runners have a higher injury proportion (> 60%) (Kluitenberg et al., 2015). Interestingly, a systematic review with meta-analysis published by Kluitenberg et al. (2015) did not find any difference in the proportion of injuries between novice and recreational runners. Conversely, a more recent systematic review found moderate-quality evidence that having no previous running experience is a risk factor for RRIs (Van Poppel et al., 2021).

Table A.2: Definitions of different runner populations (adapted from Kluitenberg et al., 2015) .

Population	Definition
Track: sprinters	Track athletes competing in distances of up to 400 m
Track: middle-distance runners	Track athletes competing in distances of 800–3000 m
Track: long-distance runners	Track athletes competing in 5000 or 10,000 m races
Novice runners	Runners with no regular running experience within the previous year
Recreational runners	Non-competitive runners or runners participating in road races shorter than 10 km
Cross-country runners	Runners competing in cross-country races
Road: long-distance runners	Runners competing in races of between 10 km and less than a marathon
Marathon runners	Runners competing in a marathon
Ultra-marathon runners	Runners competing in races longer than a marathon

Sprinting athletes do not sustain the same type of injuries as runners in other disciplines of running. Sprinters sustain a large number of injuries in the upper leg (32.9%) and hip/pelvis (10.9%) (Kluitenberg et al., 2015). In contrast, sprinters have the smallest number of knee injuries (1.3 %) and do not report ankle injuries (Kluitenberg et al., 2015). Runners from other disciplines reported the most injuries to the knee (31.2%), lower leg (20.1%), and foot/toes (14.4%) (Kakouris et al., 2021). Ankle injuries account for approximately 14 % of endurance runners (Kakouris et al. 2021). These divergences between sprinters and endurance runners can be explained by differences in biomechanics. During normal running, propulsion is achieved mainly by the structures of the lower leg; however, during running at high speeds (i.e. sprinting), propulsion is more dependent on the power generated at the hip. This is achieved by increasing the demand on the upper leg muscles, resulting in a greater biomechanical load on these structures (Schache et al., 2014).

The most frequent diagnosis among endurance runners is patellofemoral pain (16.7%) (Kakouris et al., 2021). Patellofemoral pain is characterised by pain around or behind the patella, which is aggravated by at least one activity that loads the patellofemoral joint during weight bearing on a flexed knee (e.g. squatting, stair ambulation, jogging/running, and hopping/jumping). The second most frequent diagnosis among endurance runners is medial tibial stress syndrome (9.1%) (Kakouris et al., 2021). This injury is defined as exercise-induced pain along the distal posteromedial border of the tibia and the presence of recognisable pain on palpation over a length of ≥ 5 cm (Moen et al., 2009). The third most frequent diagnosis is plantar fasciitis (7.9%) (Kakouris et al., 2021). This pathology is characterised by pain in the medial heel that is exacerbated by weight-bearing activity as well as after periods of rest or non-weight bearing (Rhim et al., 2021).

Running-related injuries aetiology

Van Mechelen et al. (1992) described a general model of sports injuries aetiology. In this model, risk factors were divided into two groups: internal and external risk factors. The classification of internal and external factors can be approached based on a stress/capacity model. Stress is determined by external factors, and capacity is determined by the state of the internal factors. Thus, the stress and capacity must be balanced. Therefore, the objectives of preventative measures to reduce the risk of injury must be to achieve or maintain this balance, either by raising capacity, reducing stress, or both.

Since the creation of this general model, Bertelsen et al. (2017) have proposed a specific framework for the aetiology of RRIs (Figure A.2). The conceptual framework of RRI development is presented in four parts: (Part A) structure-specific capacity when entering a running session; (Part B) Structure-specific cumulative load per running session; (Part C) Reduction in the structure-specific capacity during a running session; and (Part D) Exceeding the structure-specific capacity.

A. Structure-specific capacity when entering a running session

The structure-specific load capacity can be defined as the ability of the musculoskeletal system to withstand loads without sustaining injury. Each runner starts a running session with a specific load capacity on each structure of its body. The load applied during the running session induces a positive or negative adaptation of the runner's structures. The adaptation following a running session is influenced by many factors such as time of recovery between sessions, running experience, previous injury, diet, sleep, etc.

B. Structure-specific cumulative load per running session

The development of injuries in runners depends on participation in running. Thus, Bertelsen et al. (2017) claimed that the quantification of running participation is needed to move from risk factor identification alone towards a better understanding of the nature of running-related injury development. Repetition count is frequently considered important when monitoring sports participation in relation to injury risk (Soligard et al., 2016). In a running context, the repetition count is expressed as the number of strides. However, the number of strides does not provide information on the amount of load applied to a specific structure of the body.

In a distance running context, structure-specific cumulative load can be viewed as the sum of stride-specific loads that a certain musculoskeletal structure is exposed to during a single running session. Estimation of the structure-specific cumulative load per running session involves quantification of the load distribution per stride and the load magnitude per stride.

- Load distribution per stride: The term 'load distribution' refers to how the load per stride is distributed across individual anatomical structures (e.g. joint surfaces, muscles, and ligaments). The kinematics and kinetics of the lower limb and trunk during running can be influenced by running shoes, running techniques, surface, etc.
- Load magnitude per stride: The term 'load magnitude' refers to the size of the load per stride applied to the body while engaged in running. During the stance phase, the load magnitude is predominantly determined by the ground reaction force and muscle forces contributing to the joint compression forces and strain on the tendons and muscles. Alternatively, during the swing phase, the load magnitude is predominantly determined by kinematic properties such as hip flexor range of motion. Thus the magnitude of the stride-specific load during stance and swing phases is influenced by factors, including but not limited to, body weight (BW) and surface, running speed, etc.

C. <u>Reduction in the structure-specific load capacity during a running session</u>

The proposed framework indicated that the structure-specific load capacity gradually decreased in response to repetitive loading associated with multiple strides and no restitution period. The extent to which this capacity decreases after each stride depends on the magnitude of the load applied in each stride and the structural sensitivity to that load. Maladaptation may be induced within a certain time frame for recovery depending on the reduction in load capacity, especially when combined with psychological non-sport stressors and inter- and intra-individual heterogeneity.

D. <u>Exceeding the structure-specific capacity.</u>

As discussed previously in the model of Van Mechellen et al. (1992), an inciting event for running-related injury occurs when the structure-specific cumulative load exceeds the capacity of the structure. Injury may occur within one session or over multiple running sessions, given the insufficient recovery between running sessions. In the specific injurious running session, injury is the result of multiple load repetitions (strides) that have gradually decreased the structure-specific load capacity to a level where it has eventually surpassed. The severity of a given injury depends on the degree to which the structure-specific load capacity is exceeded. Soligaard et al (2016) described the relationship between load and health as a well-being continuum progressing from homeostasis, acute fatigue, functional and non-functional over-reaching, overtraining syndrome, subclinical tissue damage, clinical symptoms, time-loss injury or illness, and ultimately death.

The authors of this conceptual framework underline that running-related injury is not sustained because of risk factors such as footwear type, high or low body mass index, or poor running technique. Rather, running injuries are sustained when runners increase their participation to the point where interaction with an existing risk factor becomes significant enough to cause injury. Causal relationships are, thus, better examined by including the level of participation as an exposure to injury.

According to this framework, researchers and healthcare professionals should consider whether changes prior to RRI development have occurred within one or more of the following four categories.

- Change in the amount of participation: This consists of evaluating whether the runner ran more than usual. Gabbett (2016) has proposed to calculate the acute:chronic workload ratio corresponding to identify an increase of the global load induce by running in the last week in comparison to the three weeks before.
- Change in load distribution: For instance, running too much in a new shoe or transitioning to a new running technique may increase the cumulative load in a specific structure to a level which is not usually stressed.
- Change in the magnitude of the load: For instance, increasing running speed will increase the magnitude of the load per stride, and if the increase in speed is excessive and unfamiliar to the runner, an injury might occur (same reasoning for surface, BW, etc.)
- Change in load capacity: Naturally, other sports activities and activities of daily living change the structure's ability to withstand load during running (activity level, sleep, diet, and illness).

As described previously in the conceptual framework established by Bertelsen et al. (2017), the structure-specific cumulative load per running session is an important determinant of RRIs. The structure-specific cumulative load is highly dependent on running biomechanics (kinematics, kinetics, spatio-temporal parameters, and electromyography activity). The next section describes the links between biomechanical parameters and the risk of RRIs in the current literature.

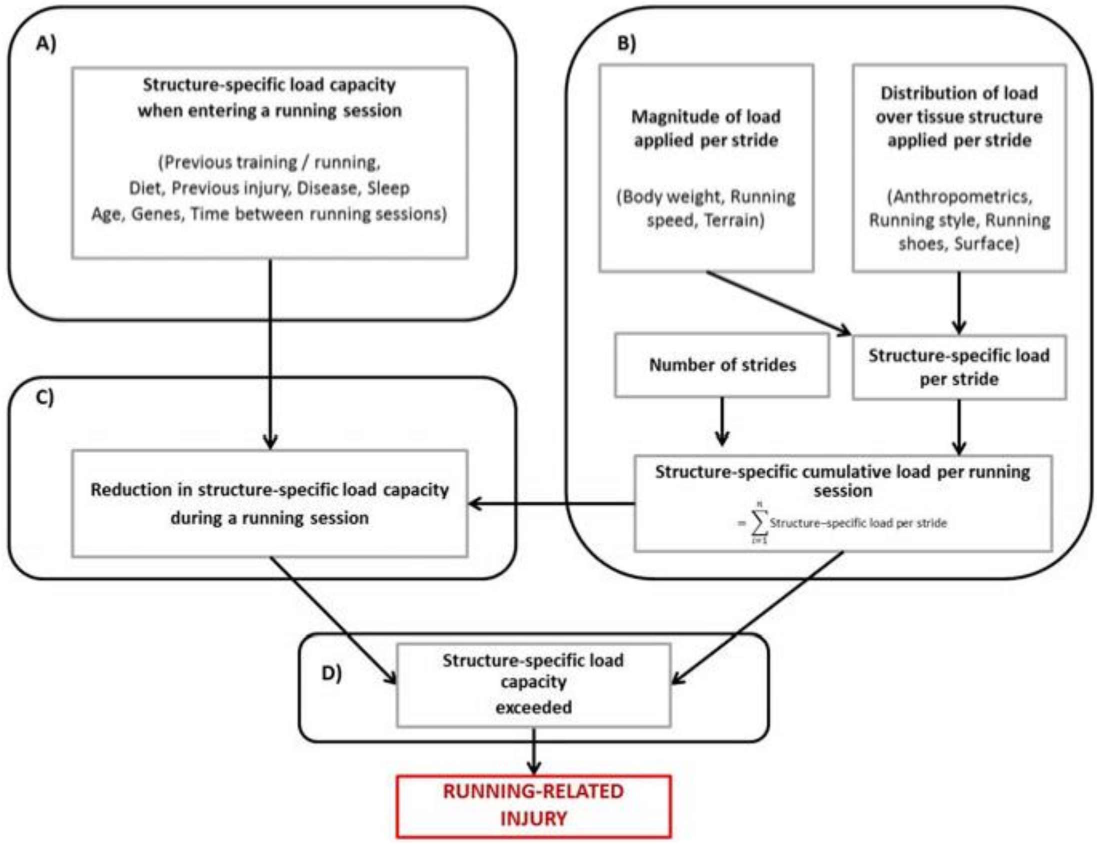


Figure A-2: A conceptual framework for the causal mechanism underpinning running-related injury within one single running session (Adapted from Bertelsen et al., 2017).
Box A represents the structure-specific capacity just before the first stride of a running session. The equation presented in box B, to calculate structure specific cumulative load per session, is adapted of Petersen et al (2015) by using the more generic "load" instead of the biomechanically more specific "stress" (force/area) originally used. Box C represents the reduction in structure-specific capacity caused by the structure-specific cumulative load in box A. Some examples of possible influencing factors are provided within the curved brackets.

Biomechanical risk factors for running-related injuries

In 2019, Ceyssens et al. (2019) summarised biomechanical risk factors prospectively associated with RRIs in a systematic review (Figure A.3). Sixteen studies were included in this systematic review. This study has several limitations.

- Large heterogeneity in the study population: runners with different age, sex, performance level, level of experience, foot strike pattern, and running exposure were included in the same statistical analyses. In addition, almost half of the studies had fewer than 100 runners in their samples which reduced the statistical power of the results.
- Grouping of all injuries: Some studies focused on RRIs in general, while others focused on specific injuries. Pooling all injuries together might therefore under- or overestimate the relevance of specific biomechanical risk factors for specific RRIs
- Inconsistency in the definition of RRIs across studies: The lack of a uniform definition of RRIs across prospective studies may limit the generalisation of results and therefore under- or overestimation of the true burden of RRIs, and/or the relevance of a biomechanical risk factor.
- The length of follow-up: It has been suggested that studies should be followed up for at least six months, yet only seven of the studies in this systematic review met this requirement. Additionally, biomechanical risk factors may not be consistent during the follow-up period, as assumed by all included studies. Continuous monitoring at regular intervals would be a better indicator of overuse injuries, given the chronic appearance of many RRIs.

In the following paragraphs, we detail the findings of this systematic review by grouping them into three categories: kinematics, kinetics, and spatio-temporal parameters.

<u>Kinematic risk factors associated with RRIs</u>

Peak hip adduction: Limited evidence with a large effect size for greater peak hip adduction in female recreational runners developing patellofemoral pain (Noehren et al., 2013) and iliotibial band syndrome (Noehren et al., 2007).

Peak knee internal rotation: Limited evidence with large effect size for greater peak knee internal rotation in female recreational runners developing iliotibial band syndrome (Noehren et al., 2007). However, the magnitude of difference between the groups was relatively small (3.7°), and the ability to detect transversal plane knee kinematics clinically as well as in laboratory settings can be questioned.

Peak knee flexion: Smaller peak knee flexion with medium effect size in runners who developed Achilles tendinopathy (Hein et al., 2014). However, this finding should be interpreted with caution because of the small sample size, high number of dropouts, and lack of statistical tests. Interestingly, the findings from Hein et al. (2014) are inconsistent with those of Messier et al. (2018), who reported no significant differences with a very small effect size in peak knee flexion in recreational runners developing any RRI. This might imply that peak knee flexion can be a risk factor for Achilles tendinopathy but not for all RRIs.

Peak ankle dorsiflexion: Very limited evidence with a very large effect size for smaller peak ankle dorsiflexion in runners developing Achilles tendinopathy (Hein et al., 2014). This prospective evidence should be interpreted with caution given the lack of statistical analysis applied in this study.

<u>Kinetic risk factors associated with RRIs</u>

Vertical average and/or instantaneous loading rate: Retrospective studies have reported greater vertical loading rates in runners with a history of tibial stress fracture (Milner et al., 2006; Pohl et al., 2008) and plantar fasciopathy (Pohl et al., 2009). However, only limited evidence with a large effect size indicates a greater vertical loading rate in male novice runners (Bredeweg et al., 2013), whereas moderate evidence for no significant difference with a very small to small effect size was found in female recreational runners (Davis et al., 2016; Napier et al., 2018) and mixed-sex populations of cross-country runners (Dudley et al., 2017; Kuhman, Paquette, et al., 2016). Limited evidence with large to very large effect sizes indicated greater average and instantaneous loading rates in female recreational runners developing any RRI when comparing runners who required medical attention with runners who had never sustained an injury before, whereas this effect was not observed when comparing injured and non-injured runners (Davis et al., 2016).

The discrepancy between the results of retrospective and prospective studies could be attributed to the fact that prospective studies focused on all RRIs, while retrospective studies focused on specific RRIs.

Vertical impact peak (IP): The strong evidence for no significant difference with a very small to small effect size for vertical IP in relation to RRIs is in line with retrospective findings (Kluitenberg et al., 2016).

Internal knee abduction moment: Limited evidence with a very large effect size for greater internal knee abduction moment impulses was found in a mixed-sex population of experienced runners who developed patellofemoral pain (Stefanyshyn et al., 2006).

Knee joint stiffness: Limited evidence for greater knee joint stiffness in the sagittal plane (Messier et al., 2018) is in line with retrospective findings in runners with a history of tibial stress fracture (Milner et al., 2007). However, the small difference in knee joint stiffness between the groups (2%) with very small effect sizes calls into question the clinical significance of this result.

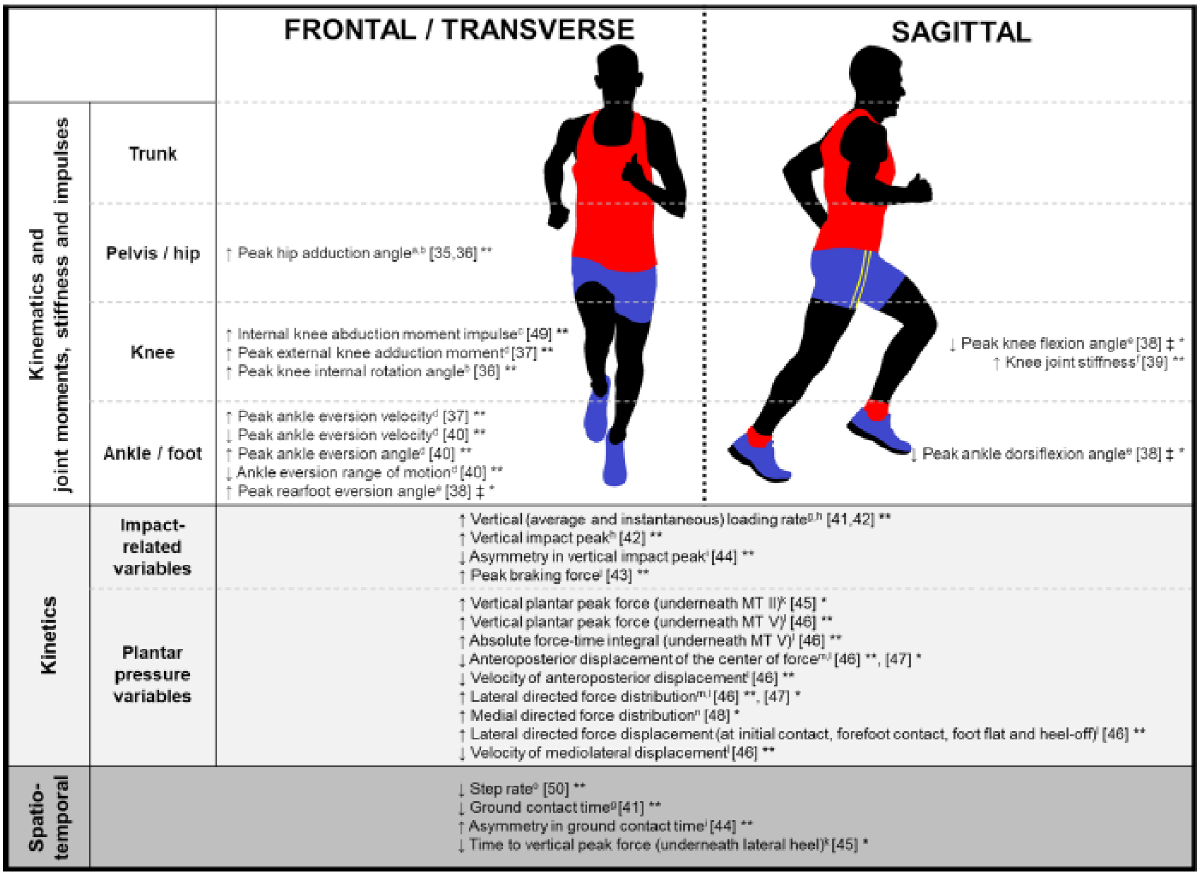


Figure A-3: Summary of biomechanical risk factors prospectively associated with RRIs (Adapted from Ceyssens et al., 2020).
Levels of evidence are shown with the following symbols: (double asterisks) limited evidence, (asterisk) very limited evidence, (double tagger) no statistical analysis. A detailed description of all significant outcome measures is provided using following superscripts: [a] in female runners developing patellofemoral pain, [b] in female runners developing iliotibial band syndrome, [c] in a mixed-sex population of experienced runners developing patellofemoral pain, [d] in a mixed-sex population of cross country runners developing an RRI, [e] in a mixed-sex population of recreational runners developing Achilles tendinopathy, [f] in a mixed-sex population of recreational runners developing an RRI, [g] in male novice runners developing an RRI, [h] in female recreational runners who required medical attention compared with female recreational runners who never sustained an RRI before, [i] in male and female novice runners developing an RRI, [j] in female recreational runners developing an RRI, [k] in a mixed-sex population of novice runners developing patellofemoral pain, [l] in a mixed-sex population of novice runners sustaining an RRI, [m] in a mixed-sex population of novice runners developing Achilles tendinopathy, [n] in male runners developing Achilles tendinopathy, plantar fasciopathy and medial tibial stress syndrome, [o] in a mixed-sex population of cross-country runners developing shin injury. MT metatarsal, RRI running-related injury, ↗ greater, ↘ smaller.

<u>Spatio-temporal parameters associated with RRIs</u>

Ground contact time: Ground contact time was only supported by limited evidence with a large effect size in male runners, but not in female runners (Bredeweg et al., 2013). Typically, shorter ground contact times are related to a higher step rate (Adams et al., 2018). Therefore, the findings associated with shorter ground contact time in male runners with an RRI may partially contradict the potentially beneficial effects of an increased step rate identified in this review (Luedke et al., 2016).

Step rate: Step rate has emerged as a parameter of increasing scientific interest in recent years. To date, step rate was inconsistently associated with RRIs (Bredeweg et al., 2013; Luedke et al., 2016). To the best of our knowledge, no retrospective or cross-sectional study has compared runners with and without RRIs. Regardless, the absence of evidence linking step rate to injury prospectively or retrospectively is interesting, considering the large body of work that has now evaluated the influence of altering step rate on biomechanics and pain (Anderson et al., 2022). Anderson et al., (2022) highlighted that increasing step rate by 10% was associated with limited evidence of no difference in peak vertical ground reaction force (MD (95%CI): 0.24, (-0.11 to 0.59)), no difference in average vertical loading rate (MD (95%CI): 0.24 (-0.23 to 0.70)) and vertical instantaneous loading rate (MD (95%CI): -0.04 (-0.50 to 0.42)). From a kinematics point of view, increasing cadence by 10% was associated with moderate evidence of reduced foot strike angle (MD (95%CI): 0.62 (0.34 to 0.09)), strong evidence of reduced peak knee flexion angle (MD (95%CI): 0.66 (0.40 to 0.92)), moderate evidence of reduced peak hip adduction during stance phase (MD (95%CI): 0.40 (0.11 to 0.69)) and limited evidence of reduced peak hip flexion during stance phase (MD (95%CI): 0.42 (0.10 to 0.75)). From a kinetics point of view, increasing step rate by 10% was associated with limited evidence of no difference in negative ankle work (MD (95%CI): -0.01 (-0.36 to 0.33)), moderate evidence of reduced peak knee extensor moment (MD (95%CI): 0.50 (0.18 to 0.81)), limited evidence of reduced peak patellofemoral joint stress (MD (95%CI): 0.56 (0.07 to 1.05)), reduced negative knee work (MD (95%CI): 0.84 (1.20 to 0.48)) and limited evidence of reduced negative hip work (MD (95%CI): 0.55 (0.91 to 0.20)). A 10% increase in step rate, through its associated biomechanical adaptations, may help lower the risk of knee pathologies.

<u>Association between footstrike patterns and RRIs</u>

A key aspect of analysing running technique is the determination of footstrike patterns in endurance runners. The footstrike pattern is generally defined as the biomechanical manner in which the foot contacts the ground. A commonly used classification distinguishes three main types of footstrike patterns as originally described by (Kerr, 1983):

- Rearfoot strike: the heel contacts the ground first, followed by the forefoot.
- Midfoot strike: the heel and forefoot contact the ground simultaneously.

- Forefoot strike: the forefoot contacts the ground first, typically followed by the heel.

Several methodologies have been developed to assess a runner's footstrike pattern, including visual classification, footstrike angle, and the footstrike index (Hoenig et al., 2020). The visual classification method involves the use of a high-speed camera, preferably exceeding 120 frames per second, combined with slow-motion or frame-by-frame analysis. This approach generally allows the identification of two categories (rearfoot strike and non-rearfoot strike) since distinguishing visually between midfoot and forefoot strikes is challenging. The footstrike angle represents the angle between the foot and the ground at initial contact. Although conceptually similar to visual classification, it requires a three-dimensional motion capture system. Two markers are typically placed on the runner's shoe or foot: one on the calcaneus and one on the fifth metatarsal head. The vector connecting these markers is formed, and the angle between this vector and the ground is measured at initial contact and throughout stance. To classify footstrike angle under the traditional footstrike definitions, Altman & Davis (2012) used the following conversion: Forefoot strike: footstrike angle $< -1.6°$, midfoot strike: $-1.6° <$ footstrike angle $< 8.0°$, rearfoot strike: footstrike angle $> 8.0°$. The footstrike index does not rely primarily on visual observation but instead quantifies the location of the centre of pressure along the foot at ground contact. This requires either an instrumented treadmill or pressure-sensitive insoles to collect force or pressure data. A rearfoot strike is defined when the centre of pressure is located within the posterior third of the total foot length, a midfoot strike when it is within the central third, and a forefoot strike when it is within the anterior third.

From a biomechanical standpoint, systematic reviews have primarily compared differences between rearfoot and non-rearfoot strike patterns, as midfoot and forefoot strikes share similar characteristics (Almeida et al., 2015; Xu et al., 2021). Almeida et al. (2015) reported a significantly greater foot angle at ground contact in rearfoot strikers (indicating a dorsiflexed position) compared with non-rearfoot strikers (plantarflexed position) (MD (95% CI): 16.06 (9.49 to 22.64)). Knee angle at initial contact also differed significantly, with greater knee flexion observed among non-rearfoot runners (MD (95% CI) –3.08 (–4.42 to –1.73)). Xu et al. (2021) found that non-rearfoot runners exhibited lower loading rates (MD (95% CI): –2.10 (–3.18 to –1.01)), peak impact forces (MD (95% CI): –1.77 (–2.21 to –1.33)), ankle stiffness (MD (95% CI): –1.69 (–2.46 to –0.92)), knee extension moment (MD (95% CI): –0.64 (–0.98 to –0.30)), knee eccentric power (MD (95% CI): –2.03 (–2.51 to –1.54)), knee negative work (MD (95% CI): –1.56 (–2.11 to –1.00)), and patellofemoral joint stress peak (MD (95% CI): –0.71 (–1.28 to –0.14)) and integral (MD (95% CI): –0.63 (–1.11 to –0.15)) compared with rearfoot runners. Conversely, non-rearfoot runners demonstrated higher ankle plantarflexion moments

(MD (95% CI): 1.31 (0.66 to 1.96)), eccentric power (MD (95% CI): 1.63 (1.18 to 2.08)), and negative work (MD (95% CI): 2.60 (1.02 to 4.18)).

Daoud et al., (2012) published the first cohort study suggesting that injury occurrence was lower among habitual midfoot and forefoot strikers compared with rearfoot strikers. Their results showed a significantly higher incidence of running injuries per ten thousand miles among rearfoot runners when data were pooled across sex and injury severity. However, a subsequent large-scale epidemiological study including 341 male United States Army soldiers found no significant differences in injury rates between habitual rearfoot and mid- or forefoot strikers (Goss & Gross, 2012). More recently, Anderson et al., (2020) summarised the available literature, concluding that current evidence on the relationship between footstrike pattern and injury risk remains limited to retrospective studies and does not allow for causal inference.

Considering the biomechanical differences between strike patterns, it has been suggested that rearfoot runners may be more prone to knee injuries, whereas non-rearfoot runners may face a higher risk of foot and ankle injuries (Hamill & Gruber, 2017).

Although there is an absence of strong evidence between impact force and RRIs, several modalities targeting a reduction of impact-related parameters have been largely explored in recent years. These methods can be divided into two categories: conscious and unconscious alteration. In the next sections, we will detail the principles of each method and their effects on running biomechanics, performance, injury prevention and injury management.

3. <u>Conscious running technique alteration: running retraining</u>

The concept of gait retraining was first described in patients who had experienced a stroke (Winstein et al., 1989). Winstein et al. (1989) based the concepts of gait retraining on motor learning principles. Winstein defined motor learning as a set of internal processes associated with practice or experience that lead to a relatively permanent change in the capability to respond. These processes are thought to be complex central nervous system phenomena, whereby sensory and motor information are organised and integrated (Winstein, 1991). This author suggests that learning a new motor programme is enhanced by the feedback provided in the two phases. During the first, "acquisition phase", extrinsic feedback is provided on a prescribed schedule. This acquisition phase allows the development of a connection between extrinsic feedback (e.g. metronome) and internal sensory cues (i.e. proprioception) associated with the desired motor pattern. During the second, "transfer phase", the feedback is systematically removed. The feedback fades, which helps with internalisation, and consequently, learning of the new motor pattern and avoids dependence on it. Using this methodology, Winstein et al. (1989) succeeded in improving the standing posture and the gait of adults with hemiparesis.

Based on a theoretical link between running biomechanics and injury, researchers and clinicians have implemented interventions aimed at retraining running gait for injury treatment or prevention. The most common objectives of running retraining intervention are to modify the footstrike pattern, increase the step rate, increase the step width, or adopt a more forward trunk lean (Barton et al., 2016). These objectives are accomplished using feedback strategies such as real-time visual feedback of impact loading, verbal feedback on joint kinematics from a therapist, or audible feedback from an external device (e.g. metronome).

Messier & Cirillo (1989a) conducted one of the earliest gait retraining studies on runners. In this study, the runners were observed three times per week for 5 weeks. Each runner was shown an individual running analysis before each training session. Then, each runner in the experimental group received instructions on specific technique modifications (reduce excessive vertical oscillation, over-striding, excessive trunk lean, and excessive arm motion). Runners in the control group did not receive feedback before their training sessions. Runners in the experimental group succeeded in significantly altering the desired kinematic gait variables compared to those in the control group. This study demonstrates that runners can modify their running techniques by running retraining. Bowser et al. (2018) showed that a running retraining intervention targeting a reduction in impact loading can persist for at least one year.

Effects of running retraining on running kinematic and kinetic

The common objective of running retraining methods is to reduce the impact loading during the stance phase. The three most influential biomechanical parameters on the impact loading are cadence, footstrike, and trunk posture. Therefore, all running retraining methods have an effect on one of these parameters. A previous study showed that a forefoot strike (FFS) pattern induced a greater reduction of loading parameters (-49.7% AVLR and -41.7% IVLR) compared to a 10 % increase in initial cadence (-16% AVLR) or a forward trunk lean (+ 20.6% AVLR and +23.5% IVLR) (Futrell et al., 2020; Y. Huang et al., 2019).

In 2022, Doyle et al. synthesised the scientific literature on the effectiveness of running retraining based on visual and auditory feedback on kinematics and kinetics in distance runners. Doyle et al. included 16 independent randomised controlled trials in their systematic review. The type of retraining intervention varied considerably between trials. Four trials used a step rate intervention (using a smartwatch or a metronome) that targeted a step rate increase between 7.5% and 10% from baseline (Esculier, Bouyer, et al., 2018; J. Wang et al., 2020; Willy, Buchenic, et al., 2016; Willy, Meardon, et al., 2016). Three trials used an intervention that aimed to help runners transition from a rearfoot strike (RF) to either a midfoot or FFS (Ekizos et al., 2018; Roper et al., 2016, 2017). Two trials used impact interventions in which participants were provided with real-time visual feedback of their landing impacts (Chan et al., 2018; Clansey et al., 2014). One trial used an intervention that targeted a reduction in ground contact time (Gilgen-Ammann et al., 2017). The remaining six trials used multiparameter interventions (Dallam et al., 2005; Dunn, 2018; Fletcher et al., 2008; Kumar et al., 2015; Letafatkar et al., 2020; Messier & Cirillo, 1989). These interventions used a combination of feedback strategies such as instructing an increase in step rate, cueing a softer landing, or encouraging a midfoot or FFS. The authors first highlighted that there was moderate-certainty evidence that step rate interventions caused a moderate significant increase in step rate (pooled mean difference 10.0 steps/min [95% CI, 4.8 to 15.3]) (Baumgartner et al., 2019; Esculier, Bouyer, et al., 2018; J. Wang et al., 2020; Willy, Buchenic, et al., 2016), a small significant reduction in AVLR (Mean difference (MD) (95%CI): -11.0 (-21.1 to -0.8) bodyweight/second (BW/s)) (Esculier, Bouyer, et al., 2018; J. Wang et al., 2020; Willy, Buchenic, et al., 2016) and a moderate non-significant decrease in IVLR (MD (95%CI): -17.3 (-45.0 to 10.5) BW/s) (J. Wang et al., 2020; Willy, Buchenic, et al., 2016). A step rate intervention also induced a small significant decrease in the vertical IP (MD (95%CI): -0.23 (-0.43 to -0.03) BW (Willy, Buchenic, et al., 2016). More specifically, a step rate intervention induced a moderate significant reduction in peak patellofemoral joint reaction force (MD (95%CI): -0.40 (-0.78 to -0.02) BW) (Esculier, Bouyer, et al., 2018).

Second, the authors highlighted low-certainty evidence that non-rearfoot footstrike interventions have non-significant effects on step rate (MD (95%CI): 1.7 (-2.3 to 5.8) steps/min) (Craighead et al., 2014; Ekizos et al., 2018; Roper et al., 2016). Conversely, non-rearfoot footstrike intervention induces a large significant reduction in peak patellofemoral joint reaction force (MD (95%CI): -1.31 (-2.25 to -0.37) BW) (Roper et al., 2016).

Thirdly, the authors highlighted that there was low-certainty evidence that impact reduction interventions cause a moderate non-significant reduction in AVLR (MD (95%CI): -14.4 (-95.4 to 66.6) BW/s) and in IVLR (MD (95%CI): -21.7 (-22.0 to -21.4) BW/s)(Chan et al., 2018; Clansey et al., 2014). Only small changes were found in trials using impact intervention to reduce the IP (MD (95%CI): 0.05 (-0.09 to 0.19) BW) (Clansey et al., 2014).

Finally, the authors highlighted that there was low-certainty evidence that multiparameter interventions cause a small non-significant decrease in the AVLR (MD (95%CI): -5.9 (-19.8 to 8.0) BW/s) (Kumar et al., 2015; Letafatkar et al., 2020). Small changes were found in trials using multiparameter intervention to reduce the IP (MD (95%CI): 0.03 (-0.56 to 0.62] BW) (Kumar et al., 2015).

Interestingly, a recent study aimed to implement a running retraining intervention within an ecological environment by employing a real-time, music-based feedback system (Van Den Berghe et al., 2022). Runners in the intervention group wore headphones connected to a sensor affixed to the tibia, which continuously measured peak axial tibial acceleration. When the tibial acceleration reached or exceeded 70% of the runner's baseline, pink noise was superimposed onto tempo-synchronised music. The intensity of this noise was directly linked to the level of tibial acceleration, based on a pre-established experimental relationship between imposed noise levels and their perceived loudness. This feedback mechanism provided runners with continuous auditory cues: higher tibial acceleration resulted in louder, more unpleasant noise, while lower acceleration levels resulted in clearer, more enjoyable music. Specifically, when the peak tibial acceleration dropped below 30% of the baseline, the pink noise was eliminated, and the music played without distortion. Following the intervention, the experimental group demonstrated a significant reduction in peak tibial acceleration by 25.5%, without any change in running cadence (mean: 10.9 ± 2.8 g vs. 8.1 ± 3.9 g, $p = 0.008$, $d = 1.08$, MD (95%CI): = 2.77 (0.94 to 4.61)).

Effects of running retraining on performance

Anderson et al. (2020) have summarised in a systematic review with meta-analysis the effect of footstrike pattern modification at short term in runners. Their results have showed that when habitual RF runners transitioned to a NRF pattern, moderate evidence indicated decreased RE at a medium speed (12.6 km/h: MD(95%CI)): -0.55 (-1.05 to -0.05) and limited evidence indicated decreased RE at a slow speed (10.8 km/h: MD (95%CI): -0.90 (-1.57 to -0.23)(Gruber et al., 2013; Melcher et al., 2017). No change was found in RE at a fast speed (14.0 km/h)(Gruber et al., 2013). Conversely, when habitual NRF runners transitioned to RF pattern, limited evidence indicated no change in RE at slow (10.8 km/h), medium (12.6 km/h), and fast speeds (14.0 km/h) (Gruber et al., 2013; Perl et al., 2012).

Again, Anderson et al. (2022) have summarised in a systematic review with meta-analysis the effect of step rate manipulation at short term in runners. In recreational runners, compared to running with a preferred step rate, very limited evidence indicated an increase in O2 consumption when running at 3.13 m/s and 3.58 m/s with a 15% decrease in step rate (Mercer et al., 2008). Very limited evidence indicated no difference in O2 consumption when running at 4.02 m/s with a 15% decrease in step rate or running at 3.13 m/s, 3.58 m/s and 4.02 m/s with a 15% increase in step rate (Mercer et al., 2008); and, running at maximum speed for a 1-h run with a 4% and 8% increase or decrease in step rate (Hunter & Smith, 2007). Very limited evidence indicated an increase in metabolic energy consumption with an 8% decrease, 15% decrease and 15% increase in step rate, while no difference was observed with an 8% increase in step rate (Swinnen et al., 2021).

Doyle et al. (2022) have summarised in a systematic review with meta-analysis the effect of running retraining intervention on running performance. At mid-term (less than six months), there was low-certainty evidence from three trials that non-rearfoot footstrike retraining has only trivial non significant effects on RE (Craighead et al., 2014; Ekizos et al., 2018; Roper et al., 2017). Similarly, low-certainty evidence from three trials demonstrated that multiparameter interventions (Pose method® or combination of midfoot strike adoption and increased step rate) produce a small non significant increase in oxygen consumption at mid-term (less than six months) (Dallam et al., 2005; Fletcher et al., 2008; Messier & Cirillo, 1989).

To date, there is no randomised controlled trial evaluating the effectiveness of increasing step rate on running performance at mid-term. In the same way, there is still no study that has sought the effect of running retraining intervention (increasing step rate, footstrike pattern modification or impact) in long term (follow-up above six months).

Effects of running retraining on running-related injury prevention

Chan et al. (2018) were the first to conduct a randomised controlled trial on running retraining interventions and injury prevention. This study was laboratory-based, and 320 novice runners (around one year of running experience) were included. Runners were allocated to either a control group (no intervention) or an interventional group (running retraining intervention). Participants in the running retraining group participated in eight sessions of running modification over two weeks (four sessions per week). During the training, participants were asked to run at a self-selected speed on an instrumented treadmill. Visual biofeedback, in the form of a vertical ground-reaction force signal from the treadmill, was displayed on a monitor in front of them. Participants were asked to ‘‘run softer'' to try to reduce the amplitude of the vertical IP. The training time was gradually increased from 15 to 30 minutes over all eight sessions, and visual feedback was progressively removed in the last four sessions. Participants were advised to maintain their new running pattern during their regular running practice. At the end of the training, the interventional group had significantly reduced their AVLR and IVLR whereas the values of the control group remained unchanged. After a one-year follow-up, the interventional group had reduced their injury occurrence by 62% in comparison to the control group.

After this first study, with encouraging results, other studies were conducted to confirm this trend. Letafatkar et al. (2020) have compared the effect of a combination of a strengthening programme with and without a running retraining intervention with a control group (no intervention) on injury occurrence. This study included 49 healthy male runners. The running retraining intervention group performed a run on a treadmill at a self-pace after each session of strengthening training. During the run, participants received verbal instructions ("run softer", "avoid a RF pattern", "run with your knees apart and your kneecaps pointing straight ahead") combined with visual feedback via a full-length mirror located directly in front of the treadmill. The treadmill runtime was gradually increased from 15 to 30 minutes and the feedback was gradually removed during the final two weeks of training (last six sessions) to shift dependence from external to internal cues, and reinforce learning. The results of this study showed that a combination of a strengthening programme with a running retraining intervention can reduce RRI by 64% in comparison with the number of injuries during the previous year. The control group and the strengthening programme without running retraining intervention group had only reduced RRI by 15% and 32% respectively in comparison with the number of injuries during the previous year. On the other hand, Morris et al. (2020) conducted a study comparing the effect of the footstrike pattern modification (RF to a non-rearfoot strike (NRF) pattern) with and without an additional real-time biofeedback (wearable sensor). This study included 191 runners. All of them received a running retraining intervention including a single session of two hours of verbal cues provided by the investigators, such as adopting a soft NRF pattern and reaching a cadence of 180. In addition, the group that benefited from additional real-time biofeedback received an inertial measurement unit (IMU) and mobile application on an iPod. The IMU was attached to the distal medial tibia, just above the medial malleolus. The mobile application alerted the runner when their tibial shock exceeded 6 g (studies in the laboratory established that transition to a NRF pattern occurred when tibial shock values were <6 g while running at a 10-min/mile pace). The system provided audio feedback every five minutes in the form of three audible beeps if the RF pattern occurred > 20% of the time. The app also provided visual feedback of the percentage of RFS patterns (impacts with tibial shock > 6 g) they were producing. The results showed that both groups had a significant number of participants transitioning to a NRF pattern immediately after training and maintained a NRF pattern at the one year follow-up. There was no statistically significant difference in injury rates between RF and NRF runners at the one year follow-up. However, RF runners had a nearly six times greater risk of developing a knee injury than NRF runners. Finally, another recent study conducted by Van Hooren et al. (2024) sought to determine whether alterations in the running technique can lead to a reduction in RRI. However, this study did not include a traditional running retraining intervention but a real-time biofeedback using pressure-sensitive insoles. Participants in the intervention group received real-time feedback on spatiotemporal parameters and relative speed during their runs. The wearable device used data from the pressure sensors (150 Hz), inertial measurement unit (30-50 Hz), and GPS to compute various spatiotemporal metrics, such as cadence and footstrike index. These metrics were used as inputs to an algorithm that used correlations reported in the literature to infer the relative loading of the following two body segments: foot/ankle/lower leg and knee/upper leg. For example, a relatively low step frequency combined with a pronounced heel strike was assumed to result in a relatively higher load at the knee than at the Achilles tendon or foot. This load was inferred from spatiotemporal metrics as measured during a baseline run and subsequent runs and was used with information about previous injuries as input to an algorithm to generate individual target zones for real-time feedback. This algorithm attempted to gradually reduce the loading of the body part with the highest estimated load by providing real-time feedback on modifiable spatiotemporal metrics via a smartphone to minimise injury risk. Modifications in the relative load and speed were achieved by determining the target zones for running speed, cadence, and footstrike index, and providing feedback on these metrics. These three metrics were chosen as variables for real-time feedback because they were considered easily modifiable by runners and because changes in these metrics would likely affect tissue/joint loading. For example, if the load at the knee was estimated to be high relative to the other body parts based on a low cadence and pronounced RF, the feedback instructed the runner to increase cadence, which in turn was expected to reduce knee loading. Their results showed a significantly lower injury rate (24.4 % vs. 37%) and severity in the group that received real-time feedback than the group that did not receive real-time feedback (in an as treated analysis).

In conclusion, alteration of running techniques based on impact reduction, footstrike pattern modification, cadence increase or reduction of individual tissue loading may reduce injury rates in distance runners.

Effects of running retraining on running-related injury management

Three randomised controlled trials have been conducted with runners with patellofemoral pain to assess the effect of running retraining interventions on pain or function.

The first study on this topic was conducted by Roper et al. (2016) with the objective of determining whether gait retraining by modifying footstrike patterns from RF to FFS reduces patellofemoral pain and improves associated biomechanical measures. In this study, 16 subjects were randomly assigned to the control (n=8) or experimental (n=8) groups. Subsequently, the experimental group performed eight gait retraining running sessions over two weeks, where the footstrike pattern was switched from RF to FFS, while the control group performed eight running sessions with no intervention. The results showed that knee pain was significantly reduced after retraining ($p < 0.05$; effect size (ES) = 0.294) and at one-month follow-up ($p < 0.05$; ES = 0.294), whereas knee pain in the control group remained unchanged. However, due to the relatively small sample size, the result of this study should be interpreted with caution.

The second study was a single-blind randomised controlled trial conducted by Esculier et al. (2018) with the objective of comparing the effects of three 8-week rehabilitation programmes on symptoms and functional limitations of runners with patellofemoral pain (PFP). Sixty-nine runners with PFP were randomly assigned to one of three intervention groups: (1) education on symptom management and training modifications (education), (2) an exercise programme in addition to education (exercises), and (3) gait retraining in addition to education (gait retraining). Symptoms and functional limitations were assessed at baseline (T0) and after 4, 8, and 20 weeks (T4, T8, and T20) using the Knee Outcome Survey of the Activities of Daily

Living Scale (KOS-ADLS) and visual analogue scales (VASs) for usual pain, worst pain, and pain during running. No significant group × time interaction effects were found for KOS-ADLS ($p \geq 0.71$). All three groups experienced significant improvements (time effect; $p < 0.05$) in mean scores at T4, T8 and T20 compared with T0. Similarly, no significant group × time interaction effects were found for VASs ($p \geq 0.43$). All three groups exhibited significant changes in baseline values at T4, T8, and T20, and improvements in pain scores were maintained between T8 and T20 (time effect; $p < 0.05$). As for running distance, no group × time interaction effect was observed ($p = 0.649$). A significant time effect ($p < 0.001$) revealed that participants ran significantly more at T8 than at T0. Finally, this study concluded that adding exercises or gait retraining did not provide additional benefits compared to education alone, and the gait retraining group did not exhibit faster improvements than the other groups.
The last and most recent study was conducted by De Souza Júnior et al. (2024) with the objective of investigating the effects of two different two-week partially supervised gait retraining programmes on pain, function, and lower limb kinematics of runners with patellofemoral pain. Thirty runners were allocated to gait retraining groups, focusing on impact (n = 10) or cadence (n = 10), or to a control group (n = 10). The impact group received guidance to reduce tibial acceleration by 50%, whereas the cadence group was asked to increase cadence by 7.5–10%. The control group did not receive any interventions. Both intervention groups had greater improvements in running pain, with a large effect size, compared to the control group at T24 (Impact x Control – MD (95%CI): -3.2 (-5.1 to -1.3), $p = 0.001$, $g = -2.34$; Cadence x Control – MD (95%CI): 2.9 (-4.8 to -1.0), $p = 0.002$, $g = -1.66$). Patients allocated to the impact group had greater improvements in knee function, with a large effect size, than those in the control group at T2 (Impact x Control – MD (95%CI): 10.8 (1.0 to 20.6), $p = 0.027$, $g = 1.22$). However, no significant group x time interaction and a small effect size were found for usual pain ($p = 0.127$, $g = 0.05$). In conclusion of this study, compared to no intervention, two-week partially supervised gait retraining programmes focusing on impact and cadence were more effective in improving running pain six months after the protocol in a sample of Brazilian runners with PFP. Additionally, the two-week partially supervised gait retraining programme focused on impact was more effective in improving knee function immediately post-training.

4. Unconscious running technique alteration: the running footwear

Effects of running footwear features on running kinematics and kinetics

The running footwear features such as the stack height (midsole thickness), heel-toe drop, and footwear mass can influence running biomechanics and impact loading:

a) The stack height: the influence of stack height on the footstrike pattern and cadence does not appear to be linear (Esculier et al., 2022; Z. Zhang & Lake, 2022). However, a higher stack height induced a decrease in the average impact loading rate (AVLR) and instantaneous impact loading rate (IVLR). A stack height of 54 mm reduced the AVLR by 21.2 % and IVLR by 38.2 % compared with a stack height of 30 mm in rearfoot runners.
b) The heel-to-toe drop: a smaller heel-to-toe drop induces less ankle dorsiflexion at initial contact, and thus, a tendency to adopt a FFS pattern (Richert et al., 2019). Conversely, the heel-to-toe drop does not influence the runner's cadence (Richert et al., 2019). The shift towards a more non-rearfoot strike pattern associated with a smaller heel-to-toe drop may explain the 35.2% increase in average vertical loading rate observed with a 12 mm heel-to-toe drop compared with 4 mm.
c) The footwear mass: heavier footwear induces a higher peak in the vertical GRF. compared with footwear weighing 175 g, footwear weighing 415 g induced 2.91% more newtons per BW (I.-L. Wang et al., 2020). The footwear mass did not influence the footstrike pattern or cadence (I.-L. Wang et al., 2020).

Since the beginning of the 2000s, a type of footwear called "minimalist footwear" has been developed. The minimalist footwear combines a smaller stack height, heel-to-toe drop, and mass, as well as lesser anti-pronation technologies and higher longitudinal and torsional flexibility than traditional footwear. For each type of footwear, a minimalist index can be measured using a scale that includes the five items previously described (stack height, heel-to-toe drop, mass, technologies, and longitudinal/torsional flexibility)(Esculier et al., 2015). Minimalist footwear has been developed to induce running biomechanics closer to barefoot biomechanics (e.g. adopting a FFS pattern and a high cadence) than traditional footwear (Davis et al., 2017; Lieberman, 2012). However, short-term studies have shown that minimalist footwear does not induce a higher cadence and tends to increase the impact loading parameters than to reduce them (+ 52.5% AVLR; + 47.3 % IVLR) (Esculier et al., 2022; Hollander et al., 2015; Willy & Davis, 2014). The effect of minimalist footwear on the footstrike pattern in the short term is inconsistent and may depend on the type of minimalist footwear worn. Studies have shown that minimalist footwear seems to reduce the footstrike angle (without inducing a transition to a NRF pattern) (Agresta et al., 2018; Esculier et al., 2022; Hollander et al., 2015), while others have shown no effect on the footstrike angle (Becker & Borgia, 2020; Willy & Davis, 2014). Long-term studies (six to 20 weeks) have shown that runners tend to adopt a more anterior footstrike pattern but do not increase their cadence (Fuller, Thewlis, Tsiros, et al., 2017; Fuller et al., 2019; Miller et al., 2014; Moore et al., 2015). Runners also increase their impact loading parameters with minimalist footwear in comparison to traditional running footwear (+ 218 % AVLR; 177 % IVLR) (Moore et al., 2015).

Finally, Kayll et al. (2023) found eight studies (n = 136 participants) comparing the effect of minimalist footwear versus conventional footwear on the patellofemoral joint reaction force. Pooled analysis indicated that there is low-certainty evidence to suggest that minimalist footwear leads to a small reduction (MD (95% CI) = -0.29 (-0.53 to -0.05), p = 0.02) in peak patellofemoral joint loads during walking and running combined when compared with conventional footwear. This equated to a 7.4% difference on average. After subgrouping by task, the pooled effect estimate for studies that used a running task increased (MD (95% CI) = -0.40 (-0.68 to -0.11)) equating to a 9.5% difference on average.

Interestingly, Giandolini et al. (2013) compared the effects on impact reduction of an intervention based on either adopting a midfoot strike pattern or transitioning to low-drop footwear in 30 RF runners. No change in loading rate variation was observed over three months in both the midfoot strike pattern and low-drop footwear groups. Similarly, the footstrike retraining programme induced no variation in the peak accelerations at the heel, tibia, and metatarsal levels. In contrast, the low-drop footwear intervention induced a decrease in peak heel acceleration (−33.5 ± 12.8 % at 2 months and −25.3 ± 18.8 % at 3 months, p < 0.001) and shock wave propagation speed (−12.1 ± 9.33 % at 2 months and −11.3 ± 14.6 % at 3 months, p < 0.03).

<u>Effects of minimalist footwear on performance</u>

The running footwear is an influential parameter of running economy. While individual responses to shoe characteristics vary considerably, the footwear features most consistently reported to influence running economy include shoe mass, longitudinal bending stiffness, foam properties and midsole geometry (Hébert-Losier et al., 2020). Two studies have found that for every 100 g of mass added to a shoe, the oxygen consumption increases by approximately 1% across a range of submaximal running speeds (Franz et al., 2012; Frederick, 1984). However, such a difference in mass between two shoe models is now rarely observed. Number of studies have explored the effect of longitudinal bending stiffness on running performance and running economy. Different methodologies exist to increase the longitudinal bending stiffness such as full or partial and flat or curved carbon fiber plate. Studies have showed that running with increase longitudinal bending stiffness improve running economy by 2.22 % compared to control footwear (MD (95%CI): -0.43 (-0.58 to -0.28)) (Rodrigo-Carranza et al., 2022). However, the effects of increased longitudinal bending stiffness on running economy were influenced by several variables including the type of plate, length of the plate, shoe mass, longitudinal bending stiffness and running speed. For example, the studies with curve plate showed a 3.45% improvement (MD (95%CI): -0.63 (-0.80 to -0.47)) compared to control condition whereas studies with flat plate did not improve running economy (MD (95%CI): 0.04 (0.26 to 0.18)). Interestingly, a recent study has shown that cutting the carbon-fiber plate and reducing the longitudinal bending stiffness did not have a significant effect on the energy savings. This result suggests that the reported energy savings are likely from a combination and interaction of the foam, geometry, and plate (Healey & Hoogkamer, 2022). The most used midsole foams in running shoes are ethylene-vinyl acetate, thermoplastic polyurethane, and polyether block amide (Rodrigo-Carranza et al., 2024). The polyether block amide midsole foam appears to be more effective for improving the running economy compared to ethylene-vinyl acetate midsole foam when the midsole foam are news (Rodrigo-Carranza et al., 2024). However, after 450 km of use, the polyether block amide midsole foam and ethylene-vinyl acetate midsole foam had similar effect on running economy (Rodrigo-Carranza et al., 2024). Moreover, a study recently highlighted that other midsole properties such as midsole foam compliance and resilience should be also considered given their positive effect on running economy (Ferris et al., 2025). Finally, midsole geometry, such as the rocker, which refers to a curved sole design influences running biomechanics. Rocker midsoles modify the ankle gear ratio and promote a redistribution of positive work among the lower limb joints, shifting it from the hip and knee toward the ankle. Although these biomechanical changes could theoretically benefit running economy, studies investigating rocker designs have not reported any improvement in running economy (Sobhani et al., 2014; J. Zhang et al., 2017).

Minimalist footwear is generally softer than traditional running shoes and lacks the cushioning and technological components found in recent models with advanced footwear technology. Several studies have been conducted on the effect of minimalist footwear on running performance at short term as well as mid-term. A first study conducting by Perl et al. (2012) tested if running economy differs in minimal shoes versus standard running shoes when runners adopt a forefoot versus rearfoot strike pattern. Cost of transport was assessed among 15 runners habituated to minimal or barefoot running on a treadmill at 10.8 km/h during forefoot and rearfoot striking while wearing minimal and standard shoes, controlling for shoe mass and stride frequency. After controlling for shoe mass and stride frequency, runners were 2.41% more economical in the minimal-shoe condition when forefoot striking and 3.32% more economical in the minimal-shoe condition when rearfoot striking. Two main arguments were described by the authors to explain the benefits of minimal footwear on running cost: 1) minimal shoes may permit more elastic energy storage and recoil in the longitudinal arch; 2) runners undergo significantly less knee excursion in minimal shoes (≈ 8.83% less than runners in standard shoes). Without considering the effects of shoe mass and stride frequency, the net decrease in running cost in minimal shoes ranges from 4.4% to 6.8%. Another study based on female recreational runners without any experience in minimalist running found smaller energy consumption reduction in minimalist footwear (≈ -1.1%) compared to traditional footwear without considering shoes mass and stride frequency effect (Sobhani et al., 2014); This discrepancy between results highlights that runners experience in minimalist running could also influence the decrease of energy consumption when comparing minimalist footwear and traditional footwear. Other explanations advanced by the authors are the type of minimalist footwear used and the running speed selected for assessing oxygen consumption.

For the mid and long term, the effect of minimalist footwear on oxygen consumption appears to be heterogeneous across studies. Three studies have assessed the effect of minimalist footwear on oxygen consumption in the mid-term (four to ten weeks of follow-up), and one study has assessed its effect in the long term (five months of follow-up) (Fuller, Thewlis, Tsiros, et al., 2017; Fuller et al., 2019; Ridge et al., 2015; Warne & Warrington, 2014). The first study aimed to investigate the effects of a four-weeks familiarisation of running with minimalist footwear on RE (Warne & Warrington, 2014). Running economy was compared before and after the four-weeks of familiarisation with minimalist footwear and traditional footwear among 15 highly trained runners ($VO_2max = 70.2 \pm 5.2$ mL/kg/min). The minimalist footwear used in this study was the Vibram FiveFingers (Minimalist index = 100%). The results showed that after the familiarisation period, running economy improved by 8.09% ($p = 0.002$) in minimalist footwear and by 2.32% ($p = 0.087$) in traditional footwear, both compared to baseline measurements in traditional footwear. Additionally, compared to baseline measurements in minimalist footwear, running economy improved by 6.9% ($p = 0.011$) in minimalist footwear after the familiarisation period. The second study adopted a design similar to the one used by Warne & Warrington (2014) (Ridge et al., 2015). However, the familiarisation period lasted 10 weeks instead of four, and a control group was included. This study also used Vibram FiveFingers as minimalist footwear. Running economy was measured in both minimalist and traditional footwear at baseline and after 10 weeks in both the experimental and control groups. Surprisingly, post-training measurements showed improved running economy in both groups and in both shoe conditions ($p = 0.015$). However, improvements were around 3% for both minimalist and traditional footwear in the control group, whereas they reached approximately 9% in the experimental group. Finally, the third study, which explores the mid-term effects of minimalist footwear on running economy, consists of the same sample as the only study investigating its long-term effects (Fuller, Thewlis, Tsiros, et al., 2017; Fuller et al., 2019). In this study, runners were allocated either to a control group or minimalist group. Runners of minimalist group received an ASICS Piranha SP4 shoes (Minimalist index = 72%) and had to follow a six-week standardised training programme (from 5% to 35% of weekly running distance). Then, runners continued increasing their allocated shoe use by 5% each week for a further 20 weeks, from 35% to 100% of weekly running distance. Five kilometers time trial performance and running economy were measured at baseline and at six weeks and 26 weeks. At six weeks, time-trial performance improved in the minimalist shoe group ($p < 0.001$) by around 40 seconds and in the conventional shoe group ($p = 0.002$) by around 20 seconds. Training in minimalist shoes improved running economy by 3% whereas no improvement was found in control group. At 26 weeks, no improvement was found in time-trial performance and in running economy in either groups compared to measurement at six weeks.

In summary, the impact of minimalist footwear on running economy varies depending on the adaptation period. In the short term, results are mixed: some studies report a 2–3% improvement when controlling for shoe mass and stride frequency, while others show a smaller effect (~1%), influenced by the runner's experience with minimalist shoes. In the mid-term (4 to 10 weeks), a familiarisation phase leads to greater benefits, with running economy improving by 6.9% to 9% after training in minimalist shoes, compared to 2–3% in traditional shoes. In the long term (26 weeks), although early gains were observed (a 40-second improvement in a 5 km time trial after six weeks), no further improvements in performance or running economy were found after 26 weeks.

Effects of minimalist footwear on running-related injury prevention

To date, three studies have sought to determine the effect of minimalist footwear transitions on RRI prevention. Two studies sought the effect in the short term and one study in the long term. The first of them is the study of Ryan et al. (2014) that examined the effect of progressive increases in footwear minimalism on injury incidence and pain perception in recreational runners preparing for a 10 km race. This randomised controlled trial included 103 runners randomly assigned to one of three groups: neutral footwear (Nike Pegasus 28), partial minimalist (Nike Free 3.0 V2), or full minimalist shoe (Vibram 5-Finger Bikila). All runners followed a 12-week run training programme. The programme followed a gradual increase in total running minutes from 160 minutes in the first week to 215 minutes in week 10 before a 2-week taper. Participants did not always run in their assigned footwear; rather, they had a gradual increase in exposure expressed as a percentage of their total weekly running time, starting at 10 min (19% of volume) in week 1 to 115 min (58%) in week 12. Overall, 23 injury events were recorded over the 12-week period, resulting in an injury rate of 23.2%. There were more injuries in both minimalist groups than in the neutral group, contributing to a 160% and 310% RR of injury in the full minimalist and partial minimalist groups, respectively. Based on injury event data, there is a higher likelihood of experiencing an injury with minimalist footwear, particularly in the partial minimalist conditions. In addition, runners in the full minimalist condition reported greater pain in the shin and calf. The second study investigating the short-term effect of minimalist footwear on RRI prevention was conducted by Salzler et al. (2016). This case series aimed to identify the rate and severity of injuries in runners transitioning from traditional to minimalist footwear. Fourteen runners completed an average of 30 weeks of transition from traditional to minimalist footwear (5-toed minimalist footwear). Twelve of the 14 runners (86%) reported an injury at an average of five weeks (range, 1–19 weeks) after the transition. Average weekly mileage declined from 23.9 miles/week prior to the initiation of the transition in traditional shoes to 18.3 miles/week afterwards (13.8 miles/week in traditional footwear and 4.5 miles/week in minimalist footwear). Injuries reported included: three cases of pain in the metatarsal region, seven complaints of pain in the gastrocnemius/soleus/ Achilles tendon complex, and two complaints of knee pain. Finally, the only long-term randomised controlled trial investigating the effect of minimalist footwear on RRI prevention was conducted by Fuller, Thewlis, Buckley, et al. (2017). This prospective study included 61 rearfoot runners, separated into two groups: minimalist (Asics Piranha) and conventional footwear (Asics Gel Cumulus). All participants completed a standardised training programme during weeks one to six of the intervention, which consisted of two interval running sessions at 85% to 90% maximum heart rate and two continuous running sessions at 65% to 80% maximum heart rate each week. After the initial 6-week run-in period, during which training was controlled, participants were instructed to continue their usual weekly running training for the remainder of the study. Running-related injuries were followed up for one year. Eleven (37%) runners sustained a running-related injury in the conventional shoe group compared with 16 (52%) runners in the minimalist shoe group. Ten lower leg and foot injuries occurred in the minimalist shoe group compared to six in the conventional shoe group. The median number of training days lost to injury was 14 days (interquartile range, 10–27 days) in the minimalist shoe group and 13 days (interquartile range, 7–25 days) in the conventional shoe group. Fuller et al. also found that the weekly training distance influenced the amount of pain experienced by runners transitioning to minimalist shoes. Runners training more than ~35 km per week experienced clinically meaningful increases in weekly running-related pain at the calf and, to a lesser extent, at the ankle and shin. Finally, they found that minimalist shoes increased the risk of RRI in runners with a body mass greater than 71.4 kg. The hazard ratio was more than double for heavy (85.7 kg) runners using minimalist shoes.

Effects of minimalist footwear on running-related injury management

Although there is only one study on this topic; minimalist footwear seems to decrease the patellofemoral joint reaction force during running compared with conventional running footwear in individuals with patellofemoral pain (MD (95%CI): -0.74 (-1.48 to 0.00)) (Bonacci et al., 2018). However, there is still no randomised controlled trial investigating the effect of a minimalist footwear-based intervention on knee pain and function.

By contrast, minimalist footwear appears to be an interesting therapeutic modality for runners with foot pathologies such as plantar fasciitis. People with plantar fasciitis have lower foot muscle strength (R. H. Allen & Gross, 2003; Sullivan et al., 2015). It has been hypothesised that one of the roles of the foot muscle is to protect the plantar fascia by reducing strain forces (Kelly et al., 2015). Therefore, the objective of plantar fasciitis rehabilitation is to improve foot muscle strength in individuals with a deficit (Rathleff et al., 2015). Minimalist footwear has been identified as an efficient tool for improving foot muscle volume and strength (T. L.-W. Chen et al., 2016; Johnson et al., 2015; Miller et al., 2014; Ridge et al., 2019). To date, only one study has investigated the effect of minimalist footwear on pain and function in people with plantar fasciitis (Ribeiro & João, 2022). This study enrolled 26 women with plantar fasciitis and ten women without plantar fasciitis (considered the control group). The 26 women with plantar fasciitis were divided into two groups: minimalist footwear and custom insole. Participants did not specifically engage in running activity. The results showed that minimalist footwear and custom insoles were effective in improving foot function and pain after three months.

In the next section, we present the first study of this thesis, which investigates athletics coaches' current perceptions and practices regarding footstrike pattern modification in endurance runners, particularly in relation to injury prevention and performance enhancement. This study aims to provide an overview of field-based knowledge and compare it with the current scientific evidence.

5. Current perception and practice of athletics coaches about the modification of footstrike pattern in endurance runners: a survey (Study 1).

Published in International Journal of Sport Science & Coaching.

DOI: 10.1177/17479541221108089

ABRAN Guillaume[1], DELVAUX François[2], SCHWARTZ Cédric[1], MARTENS Géraldine[2], HODY Stéphanie[2], DARDENNE Nadia[3], BRUYERE Oliver[2,4], BORNHEIM Stephen[2], CROISIER Jean-Louis[1,2].

[1]Laboratory of Human Motion Analysis, Liège, Belgium. Electronic address: guillaume.abran@uliege.be.

[2]Department of Motricity Sciences, University of Liège, Liege, Belgium.

[3]University and Hospital Biostatistics Center (B-STAT), University of Liège, Belgium.

[4]WHO Collaborating Centre for Public Health Aspects of Musculoskeletal Health and Aging, Division of Public Health, Epidemiology and Health Economics, University of Liège, Liège, Belgium.

Abstract

Purpose: To date, the relationship between footstrike pattern and performance, as well as with injury incidence in endurance running remains unclear. For these reasons, it is currently not recommended to modify footstrike pattern in an uninjured long-distance runner. The purpose of this study was to analyse whether athletic coaches apply these current scientific recommendations with their endurance runners on the field.

Methods: A Delphi method study was used to develop an online survey that was administered to French-speaking athletic coaches in Belgium. The survey comprised three sections: 1) coaches' profile, 2) coaches' perception of footstrike patterns, 3) practices pertaining to footstrike patterns.

Results: One hundred and fourteen respondents completed the entire questionnaire. Ninety-six (84%) athletic coaches reported modifying the footstrike pattern of their endurance runners. They reported that they modify their runners' rearfoot and forefoot strike more often than a midfoot strike ($P < 0.0001$) to prevent injury (83%) and to improve performance (66%). According to them, midfoot strike is considered as the best landing pattern for endurance performance (47%) and injury prevention (36%) whereas rearfoot strike is considered as the worst (respectively, 50% and 52%).

Summary and conclusion: This study highlights the disparities between scientific recommendations and athletic coaches' field practices for modifying footstrike patterns in endurance runners. Contrary to current scientific literature recommendations, a large proportion of coaches modify the natural footstrike pattern of their endurance runners towards a midfoot strike pattern to improve performance and prevent injury.

Introduction

Running is one of the most popular physical activities in the world, mostly done to achieve or maintain good physical and psychological health (Hulme et al., 2017; Van Poppel et al., 2021). The amount of runners has doubled during the last ten years and is ever-increasing (Van Poppel et al., 2021). The participation in long-distance running events is also growing increasingly popular (Ogueta-Alday et al., 2018). In terms of competition, long-distance running races can range from 5.000 m to a marathon in length (Casado et al., 2021). Unfortunately, along with the positive effects of running comes a high risk of sustaining an injury (Fokkema et al., 2020; Hulme et al., 2017; Van Poppel et al., 2021). The incidence of running-related injuries per 1000 hours is around 6.3 compared to 3.4 in all other sports combined (Stam & Valkenberg, 2019).

Footstrike pattern is often cited as a biomechanical component impacting the risk of injury (Burke et al., 2021). Lieberman (2012b) distinguished three different types of landing during running, based on initial contact: rearfoot strike (RFS), midfoot strike (MFS) and forefoot strike (FFS). A large proportion of long-distance runners land with a RFS (65% to 94%) and a minority land with a MFS (5% to 25%) or a FFS (1%) (Hanley et al., 2021; Hasegawa et al., 2007; Hébert-Losier et al., 2021; Kasmer et al., 2014; Larson et al., 2011). In a cohort study, Daoud et al., (2012) were the first authors to conclude that running with a MFS or a FFS could decrease the risk of injury by a factor of two. The absence of an impact peak in ground reaction forces in FFS runners is the main hypothesis to justify this result. However, Gruber et al. (2013) later observed that this impact peak was present in FFS runners, but was delayed. This delay is explained by the deceleration of the lower limb which occurs later compared to RFS runners. Loading rate is another argument in the literature in favour of the protective nature of landing with a more anterior part of the foot. Indeed, loading rate is lower with a FFS than a RFS. However, the association between loading rate and injury remains inconsistent between studies (Van Der Worp et al., 2016). Following the retrospective study by Daoud et al. (2012), there is an equal number of studies (both prospective and retrospective) which have weighed in whether MFS/FFS is protective or not (Davis et al., 2016; Goss & Gross, 2012; Messier et al., 2018; Warr et al., 2015). Because of these findings, Anderson et al., (2020) do not recommend in their systematic review with meta-analysis to modify their endurance runners' footstrike pattern to prevent running-related-injuries. Indeed, they emphasise that the current level of evidence to modify footstrike pattern to prevent injury occurrence is insufficient.

The footstrike pattern is also cited in running as a relevant factor of performance. The main reason which is suggested is that FFS increases elastic energy storage and release compared with RFS (Perl et al., 2012). However, several studies analysing performance in middle and long-distance races report inconsistent results. Several studies concluded that better results are achieved by midfoot and forefoot runners while other studies did not reach the same conclusion (Hanley et al., 2021; Hasegawa et al., 2007; Hébert-Losier et al., 2021; Kasmer et al., 2014; Larson et al., 2011). Therefore, the association between footstrike pattern and performance remains unclear. In the same way, there seems to be no difference in running economy between footstrike patterns. Indeed, several studies report similar oxygen uptake (for a normalised mass) and net metabolic rate between RFS and FFS runners at different sub-maximal speeds(Gruber et al., 2013; Nichols et al., 2016; Patoz et al., 2022). Again, Anderson et al. (2020) do not recommend, following their systematic review with meta-analysis, to modify the footstrike pattern of their endurance runners to improve their running economy.

Considering their recommendations, it appears to be crucial to determine if athletic coaches are aware that footstrike pattern modification does not appear to prevent injury and increase running economy (Anderson et al., 2020). Indeed, athletic coaches are at the forefront of runners' performance preparation and running injury prevention. In addition to the current lack of evidence demonstrating the effectiveness of footstrike pattern modification on performance and injury prevention, modifying the footstrike pattern of an uninjured endurance runner may be detrimental. In fact, modifying footstrike patterns shifts anatomical strain areas and could expose runners to an increased risk of injury (Anderson et al., 2020; Barton et al., 2016). The occurrence of an injury has a direct impact on the level of performance, so it is crucial for coaches to minimise risk exposure (Vella et al., 2021). Finally, the time consumed to modify the footstrike pattern could be used to correct other technical parameters which could have a higher impact on performance according to the current scientific evidence (Moore, 2016).

The purpose of this study was to analyse whether athletic coaches' apply the current scientific recommendations about footstrike pattern modification with their endurance runners on the field. Considering the difficulties highlighted by Fullagar et al., (2019) in other sports to transfer scientific knowledge to the field, our hypothesis is that a gap exists between current scientific recommendations and field practices for modifying footstrike patterns in endurance running.

Methods

Participants

A total of 500 athletic coaches from 50 clubs in Wallonia (Belgium) were invited to participate in an online survey (sondage Online, https://www.sondageonline.com). Coaches were invited to answer the survey regardless of their qualification level, their experience, or their athletes' competition standard. An e-mail invitation was sent to each coach to explain the purpose and procedure of the survey.

Data was collected between 1st July and 1st September 2021 and coaches were asked to answer without using additional resources and in accordance with their practices and experience. Coaches were free to participate and provided consent through the survey platform. Answers were anonymous and confidential. This study was approved by the Ethics Committee of Liege Hospital Faculty prior to data collection.

Survey

To elaborate the questionnaire, a Delphi method study (including 12 experts (four official medical officers of the Belgian League of French-speaking Athletics (LBFA), two official physiotherapists of the LBFA , two Olympic athletes' coaches, one personal trainer following high-level athletes, one expert in epidemiology and two experts in motricity sciences) was conducted. For each section of the questionnaire, experts were asked to indicate the level of relevance of the questions (in regards to the objectives of the section) on a scale: 1 = strongly agree; 2 = agree; 3 = disagree; 4 = strongly disagree. They could also write a suggestion about the questionnaire in open-ended questions. To establish the level of agreement, the total percentage of "strongly agree" and "agree" responses were calculated. Consensus agreement was defined as ≥75%, partial agreement was defined as 50%–75% agreement, while no agreement was defined as <50%. Qualitative data (*i.e.* open-ended answers to questions as part of the online questionnaire) and answers that reached consensus agreement were used to enhance the questionnaire in the following round of the Delphi process. Each expert was contacted individually to participate in the Delphi study and after their consent, they were invited to the first Delphi round. All experts (100%) participated in round 1. Expert consensus (≥75% agreement) was reached on two of the three sections included in the online questionnaire. One section reached partial agreement (50%–75%) and some modifications were done before the second round of the Delphi process. All experts (100%) participated in round 2 and expert consensus (≥75% agreement) was reached for all sections included in the final version of the online questionnaire. The Checklist for Reporting Results of Internet E-Surveys (CHERRIES checklist) was completed during the survey's design and is presented in the supplementary material (Eysenbach, 2004).

The survey was written in French and consisted of 17 questions (14 closed and 3 open) with three sections : 1) coaches' profile, 2) coaches' perception of footstrike patterns, 3) practices pertaining to footstrike patterns. In the first section, coaches were asked about their age, years of experience, athlete's standard of competition (elite; high level; competitive; recreational), personal level of qualification and field of expertise (related to "running" including sprint, middle distance, long-distance, hurdles, trail, multi-events ; or "other" including throwing, high jump, long jump). In the second section, coaches were invited to indicate how often they modify the landing pattern in a competitive long-distance runner with either a RFS or a MFS or a FFS (0 = never; 10 = every time). If they answered that they never modify footstrike patterns (0 for each of the three questions), they were not asked a supplementary conditional question. If they do modify footstrike patterns, they were asked to indicate one or several reasons to justify why (1 = to decrease the injury risk; 2 = to increase performance (increase of running economy or VO_2max); 3 = to shift the load in an injured runner; 4 = other (give details)). In the same section, coaches were asked to rank each pattern (RFS, MFS, FFS) according to their belief in the incidence of injuries (1 = highest injuries incidence; 3 = lowest injuries incidence) and according to the level of performance that each footstrike pattern can allow athletes to reach (1 = best performance; 3 = weakest performance). They could also answer "all similar" for these two questions. In the last section, coaches were to rank the effectiveness of several methods of modifying footstrike patterns (1 = global mobility; 2 = global strengthening; 3 = running drills; 4 = verbal advice; 5 = step rate modification; 6 = shoes modification). If their athletes also undergo a strengthening programme, coaches were to select the three main muscle groups strengthened (1 = no strengthening; 2 = hip flexors; 3 = hip extensors; 4 = hip abductors; 5 = knee extensor; 6 = knee flexors; 7 = ankle dorsiflexors; 8 = ankle plantar flexors; 9 = intrinsic foot muscles; 10 = "I do, but I don't know which ones"). All possible answers for each question came from the Delphi consensus with the field experts. The entire survey is available in the supplementary material.

Survey analysis

Raw data was exported from "SondageOnline®" to Microsoft "Excel®" software (Version 2110, Microsoft® Excel®, USA) and analysed independently by the research team. Only fully completed questionnaires were taken into consideration in the statistical analysis. Normality conditions were checked for each quantitative variable of the survey. A descriptive analysis based on the coaches' profile was done (means and standard deviation for quantitative variables, number and frequency for qualitative variables). In the "coaches' perception of footstrike patterns" section, a statistical model with a comparison of the frequency of footstrike pattern modifications according to the initial footstrike pattern was performed with a Repeated Measures Analysis of Variance (ANOVA). If significant p-values were found, Bonferroni's post-hoc test was applied. Then, effect of coaches' profile (experience, qualification, competition's standard) was also tested with the same statistical model. In the same section, a Pearson Chi-square test was used to compare the distributions of both the "best" and the "weakest" footstrike pattern related to performance. Then, a Pearson Chi-square test was used to compare the distributions of footstrike patterns causing both the "most injuries" and the "least injuries". A Pearson Chi-square test was used to compare the distribution of footstrike patterns of each category ("best", "weakest", "most injuries", "least injuries") first for competition standard and then for each level of the coaches' qualification. Then, a One-Way Analysis of Variance (ANOVA-1) was used to compare footstrike patterns of each category ("best", "weakest", "most injuries", "least injuries") according to coaches' experience. If significant p-values were found, Tukey's post-hoc test was applied. Description of answer distribution obtained from "field practices pertaining to footstrike patterns" section was calculated in percentages. A sub-analysis including only athletics coaches who described themselves as specialists in long-distance running was performed with the same statistical models presented previously. Statistical analyses were performed using R (Version 4.1.1, R Core Team, 2017)(Fox, 2005). An alpha level of 0.05 was used for all inferential statistics.

Results

After closing the survey, 172 coaches of the 500 invited participated (34.4%) and among them 114 completed the whole survey (66.2%) and 58 partially completed the survey (33.7%). Table A.3 describes coaches' profile (age, experience, personal level of qualification, competition's standard and field speciality). Coaches who completed the survey are essentially specialised in running (90%) and support athletes in competition (76%). One third of coaches train athletes with a national or international level of competition.

Table A.3: Baseline characteristics of the participants.

Variables		Number	(%)	Mean ± SD
Age (years)		114		41.7 ± 16.3
Experience (years)		114		12.3 ± 11.9
Qualification level	None	28	(24.5)	
	1st level (15h)	16	(14.0)	
	2nd level (50h)	20	(17.5)	
	3rd level (120h)	30	(26.3)	
	4th level (320h)	20	(17.5)	
Competition's standard	Recreational	27	(23.6)	
	Competitive	51	(44.7)	
	High level	27	(23.6)	
	Elite	9	(7.8)	
Field's speciality	Running	103	(90.3)	
	Others	11	(9.6)	

Qualification corresponds to level of the Belgian League of French-speaking Athletics (LBFA) qualification according to the total number of hours spent in training in their lifetime (1st level = 15 hours; 2nd level = 50 hours; 3rd level = 120 hours; 4th level = 320 hours). Competition's standard corresponds to the highest level of competition of their athletes (Recreational = no competition; competitive = regional competition standard; high level = national competition standard; Elite = international competition standard). Field's speciality corresponding to "running" include sprint, middle distance, long-distance, hurdles, trail, multi-events and field's speciality corresponding to "other" include throwing, high jump, long jump.

Ninety-six (84%) athletics coaches claimed to modify the footstrike pattern of their endurance runners. Repeated Measures ANOVA showed that coaches do not modify the three footstrike patterns with the same frequency ($p < 0.0001$). Bonferroni's test showed that coaches change RFS and FFS more frequently than MFS ($p < 0.0001$). However, they modify RFS and FFS similarly (Figure A.4). Repeated Measures ANOVA showed that the frequency of modification does not depend on coaches' experience, qualification level or competition standard ($p = 0.74$; $p = 0.94$; $p = 0.53$ respectively). Reasons indicated by coaches to modify footstrike patterns are first to prevent injury (83%), then to increase performance (66%) and finally to shift the load in an injured runner (37%).

According to 47% of participants, MFS represents the footstrike pattern associated with the best performance during long distance running, while RFS is mostly associated with the weakest performance level (Table A.4). Finally, it appears that MFS and FFS are similar in reducing injury prevalence (both have 35%). Coaches' qualification and competition standard do not influence these answers. Experience only influences the choice of the footstrike pattern causing the weakest performance ($p < 0.01$). Tukey's test highlights a difference between MFS - RFS ($p < 0.01$). Coaches with more experience indicated that MFS is weaker than RFS relative to performance. Thirty-two (28%) athletics coaches claim to be specialist in long-distance running. The results of the statistical sub-analysis of the coaches specialised in long distance running were identical to those of the entire sample.

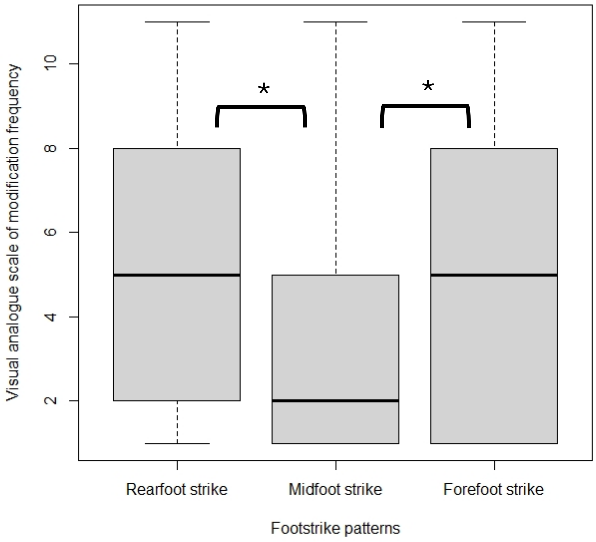


Figure.A-4: Visual analogue scale of modification frequency according to each footstrike pattern. Boxplots illustrating average and standard deviation of modification frequency in a visual analogue scale (0 = Never; 10 = Every time) obtained for each pattern. "*" highlights significant differences of the average of modification frequency between midfoot strike - rearfoot strike and midfoot strike – forefoot strike according to Bonferroni's test. There is no difference of modification frequency between rearfoot strike and forefoot strike.

Forty percent of the coaches panel reported the use of "running drills" to modify footstrike patterns. In contrast, 51% and 23% consider footwear and cadence respectively as the least popular methods in practice (Figure.A.5). In parallel, almost all respondents consider it important to strengthen muscles for modifying footstrike patterns. Coaches firstly strengthen ankle plantar flexors (35,1 %), foot intrinsic muscles (29,8 %) and ankle dorsiflexors (27,2 %).

Table.A.4: Distribution and p-value of Pearson Chi-square test of the best, weakest, most dangerous, safest footstrike patterns in long-distance running according to the coaches panel.

VARIABLES		**Rearfoot N (%)**	**Midfoot N (%)**	**Forefoot N (%)**	**All equivalent N (%)**	**p-value**
CONSIDERATION FOR PERFORMANCE	Best Performance	12 (10.5%)	54 (47.3%)	25 (21.9%)	23 (20.1%)	p < 0.001
	Weakest Performance	57 (50.0%)	7 (6.1%)	27 (23.6%)	23 (20.1%)	p < 0.001
CONSIDERATION FOR INJURY	Most Injuries	60 (52.6%)	9 (7.8%)	31 (27.1%)	14 (12.2%)	p < 0.001
	Least Injuries	19 (16.6%)	41 (35.9%)	40 (35.0%)	14 (12.2%)	p < 0.001

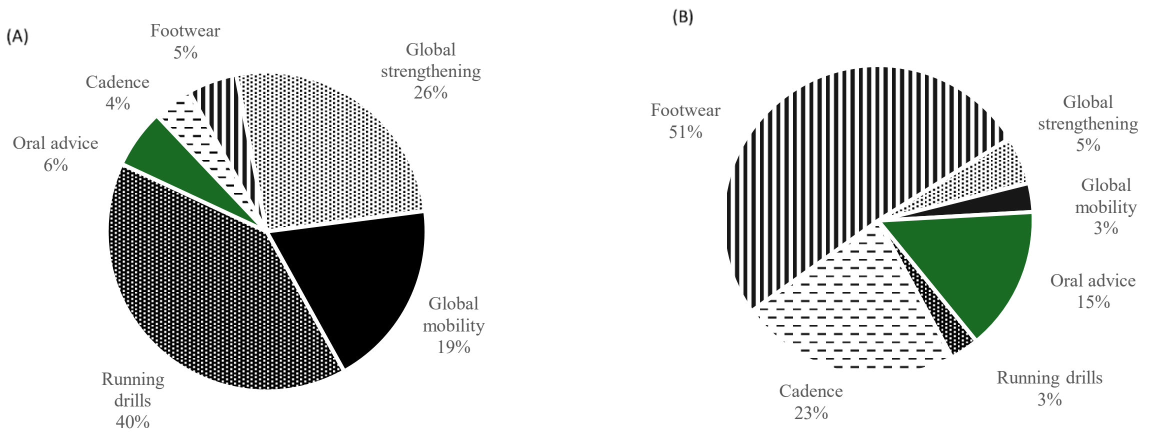


Figure A-5: Pie charts of the most (A) and the least (B) popular methods used by coaches to modify footstrike patterns in a runner according to the panel.
Running drills are the most popular methods (40%) followed by overall strengthening and mobility (26% and 19% respectively). Footwear is the least popular method (51%) followed by cadence (23%).

Discussion

The purpose of this study was to analyse whether athletic coaches apply the current scientific recommendations on footstrike pattern modification with their endurance runners in practice. Athletic coaches appear to support landing on the midfoot in long-distance runners to increase performance and prevent injuries. Likewise, they seem to largely proscribe RFS which they consider to be more harmful both for performance and injuries. However, according to the current literature, there is no study affirming that the footstrike pattern affects the incidence of sustaining a running-related injury or parameters related to performance in endurance running (Anderson et al., 2020). Contrariwise, shifting the landing pattern to a FFS in habitual RFS runners could be detrimental to running economy in the short term and increase the load on different anatomical structures (Almeida et al., 2015; Gruber et al., 2013). The most original finding of this study is the highlighting of a gap between current scientific recommendations and field practices on the modification of footstrike patterns in endurance running.

For injury prevention, coaches indicate that RFS is more dangerous than the other footstrike patterns and, contrariwise, FFS and MFS are more protective. Only twelve percent of the panel responded that all the footstrike patterns are equivalent in regard to injury prevalence, in agreement with the current recommendations. Indeed, to date, there is no good evidence linking prospectively a biomechanical parameter with running-related injury (Ceyssens et al., 2019). The footstrike pattern does not appear to change injury prevalence but may modify injury location in response to their respective joint stresses. Hollander et al., (2021) described that running with a MFS has twice the odds of sustaining an injury to Achilles tendon than injured runners using a FFS or a RFS. They also describe that runners with a FFS sustain 2.6 times more calf injuries than the MFS or RFS ones. In contrast, they did not find any relationship between RFS and a specific injury location. However, previous studies have shown that mechanical constraints on the joint and on the eccentric work at the knee are higher in RFS compared to the FFS pattern (Arendse et al., 2004; Kuhman, Melcher, et al., 2016; Vannatta & Kernozek, 2015). Among coaches who modify the habitual footstrike, only 3% answered simply "to shift the load in an injured runner". In some cases, the scientific literature recommends temporarily modifying the footstrike pattern of an injured runner to reduce overall load and to shift it. In parallel, a specific strengthening intervention has to be added to prevent another injury (Barton, 2018). Reassuringly, 99% of the coaches in this survey add strengthening of the foot-ankle muscles to support a change of the landing pattern. Strengthening sessions of foot-ankle muscles allow improvements of the physical capacity of the tissue undergoing the most stress for MFS and FFS runners to reduce loads (Fredette et al., 2022). This is consistent with the suggested hypothesis of running related injuries which are ultimately due to an excess of loading on anatomical structures compared to their capacity to support it. However, excessive loading is athlete-specific and depends on various factors including lifestyle, recovery, psychological, training load factors (Fredette et al., 2022).

Related to performance, RFS is also considered by coaches to be the weakest technique and MFS as the best to perform in a marathon race. A larger part of the panel (20%) consider that all footstrike patterns are equivalent for this kind of event and the reason could be the difficulty in maintaining a MFS or FFS during a very long distance. Indeed, several studies have shown that recreational runners with a MFS or a FFS evolve towards a RFS during a long-distance race and the main cause seems to be plantarflexor fatigue (Bovalino et al., 2020; Jewell et al., 2017; Larson et al., 2011). The Achilles tendon strength is 18 % greater for FFS than MFS and could be harder to maintain in long-distance running (Hashizume & Yanagiya, 2017). This difference could explain the coaches' preferences for MFS. On the other hand, there is no argument to favour a MFS for a runner compared to a RFS.

MFS appears to be the most desired pattern by athletics coaches to improve performance and decrease injury rates but there is very little evidence of this footstrike pattern in literature. The few studies that included MFS runners have typically grouped them together with FFS to obtain a group with a sufficient number of runners. However, studies which have dissociated MFS and FFS showed differences in tibial shock, peak ground reaction force and loading rate between them (Jamison et al., 2016; Ruder et al., 2019). According to these two studies, MFS kinetics seems to be closer to the RFS than the FFS kinetics.

Another original finding of this study is the difference between methods described in the scientific literature and those used in the field to modify the footstrike pattern in a runner. The most popular methods found in the literature are changing step rate or footwear (D. J. Allen et al., 2016; Hall et al., 2013; Moore et al., 2015; Vella et al., 2021). However, according to the surveyed coaches these two methods are the least popular with 23% and 51% respectively. Interestingly, the most popular method in their view, and used in practice, are "running drills". This is in accordance with Whelan et al. (2016) who highlighted the coaches' interest in using running drills to improve running technique. Running drills are defined as repeated movements produced during the running cycle (Moore et al., 2015). In the literature, there is a lack of evidence on the implication of running drills to change running technique. Only Azevedo et al, (2015) have investigated the effect of adding a running drills programme in recreational runners but they did not highlight any modification of kinetic and spatiotemporal parameters. Future studies should analyse the effect of running drills programme on running kinematics and on lower limbs characteristics.

This study has some limitations that should be taken into account before generalising the results. Firstly, only fully completed questionnaires were integrated into statistical analysis. Considering that one third of questionnaires were only partially completed, a high number of answers were not taken into consideration. This could lead to a selection bias accounting for the answers of the most "motivated" coaches to finish the survey. This choice allows however to analyse each coaches' profile with their own answers. Secondly, the survey did not include questions about the main sources of information and the limits of accessibility for coaches to the scientific literature. It could be relevant in a future study to understand the reasons, in the athletics field, which could explain the differences between the scientific evidence and current coaches' practices. Finally, this survey was only distributed in the French-speaking part of Belgium (i.e., Wallonia), so the conclusions drawn from our findings might have limited external validity and differ in other countries or environments.

Conclusion

This study highlights the disparities between scientific recommendations and field practices of athletics coaches for modifying footstrike patterns in endurance runners. Contrary to current scientific literature recommendations, a large part of the coaches modify the habitual footstrike pattern of their endurance runners towards a midfoot strike pattern to improve performance and prevent injury. On the other hand, there are several shortcomings in the scientific literature, such as the lack of studies concerning running drills which are the most popular methods of gait retraining according to the coaches. This study underlines the gap between research and practice and emphasises the need for sports researchers to get closer to the field practices and to the coaches to keep them up to date on the latest scientific evidence. Simultaneously, researchers should prioritise the collection of scientific data related to current track and field coach practices.

Take Home Messages – General introduction

- ✓ Over the past century, running performance has markedly improved, with substantial reductions in marathon finishing times. In contrast, these improvements in performance have not been accompanied by a corresponding decrease in running-related injuries.

- ✓ Running performance mainly depends on three key physiological determinants: maximal oxygen uptake (VO_2max), the fraction of VO_2max that can be sustained over time, and running economy.

- ✓ The running technique is considered a key component of running performance and may explain 4 to 12% of the variance in running economy between runners

- ✓ Running technique can be altered either consciously through running retraining interventions or unconsciously by adopting minimalist footwear.

- ✓ Many coaches intentionally modify their athletes' habitual footstrike pattern often promoting a midfoot strike in an attempt to enhance performance and prevent injuries.

- ✓ Given the limited number of prospective studies on the topic, current scientific recommendations discouraging running technique modifications to reduce injury risk or improve performance remain largely conjectural.

B. Thesis Objectives and Outline

This thesis begins with a general introduction to the main concepts addressed, including the determinants of running performance, an overview of running-related injuries, and methods for modifying running technique along with their effects on performance and injury risk. The General Introduction concludes with the first study of this thesis, which consisted of a field-based assessment of current knowledge through a questionnaire distributed to athletics coaches in Belgium. This survey highlighted that, despite the absence of scientific evidence, athletics coaches modify the running technique of endurance runners to enhance performance or reduce injury risk. Therefore, prospective studies on this topic are needed in order to provide robust recommendations for running coaches. The overall objective of this thesis was to improve our understanding of the role of running technique alterations in recreational endurance runners, with a particular focus on performance enhancement and injury prevention. The first aim was to evaluate the long-term effects of running technique modifications on running economy, thereby assessing the performance implications of sustained technique changes. The second aim was to investigate whether modifying running technique could influence biomechanical risk factors associated with running-related injuries and whether these modifications might contribute to reducing injury incidence in recreational endurance runners. Given that previous literature has suggested a potential increased risk of injuries to the foot–ankle complex when modifying running technique, the third part of this thesis focused on conditioning the foot–ankle complex to enable a safer transition.

This thesis is structured into three main parts:

Part I – Running technique alteration and performance

Running technique is a key determinant of running economy in endurance runners, accounting for approximately 4% to 12% of the variance observed between individuals. Given this relationship, there has been increasing interest in the literature in exploring the effects of running technique alteration on performance. Adopting a forefoot striking pattern is hypothesised to offer mechanical advantages by allowing greater utilisation of elastic energy stored during foot-ground impact through the stretch and recoil of tendons and ligaments in the ankle and foot. Additionally, an increase in running cadence may reduce braking forces during the landing phase, further enhancing the efficiency of elastic energy recycling. However, unlike running retraining, transitioning to minimalist footwear has been shown to improve running economy. This discrepancy may be attributed to specific biomechanical adjustments, foot and ankle adaptations, or the absence of an external attentional focus typically required during running retraining. This section presents a prospective study evaluating changes in running economy, running biomechanics, and foot–ankle characteristics over a one-year period after the implementation of two distinct methods of running technique alteration. However, it is essential to ensure that such improvements are not achieved at the expense of an increased risk of injury.

Part II – Running technique alteration and injury prevention

Running technique appears to be an important component of running performance. However, the relationship between running technique and injury incidence rate remains unclear. Previous research has indicated that high-frequency components of impact-related variables may constitute risk factors for running-related injuries. Nevertheless, it remains unclear how running technique alterations influence the high-frequency components of impact-related variables. In this section, we conducted a laboratory-based biomechanical investigation comparing the high-frequency component of impact-related parameters across different running techniques. Then, we explored the effect of two distinct methods of running technique alteration on the incidence rate of running-related injuries using a large-scale prospective study.

Part III – Conditioning the foot–ankle complex for a safer running technique transition

Adopting a non-rearfoot strike pattern, increasing step rate, or transitioning to minimalist footwear can reduce knee joint loading but simultaneously increase mechanical demands on the foot and ankle. These load transfers could increase the risk of developing secondary injuries during or following a running technique alteration. Given these considerations, it is essential to better understand the factors that may predispose runners to injury when undergoing such interventions. To date, the relationship between foot–ankle characteristics, running technique and the risk of foot–ankle injuries remains unexplored. In this section, we first compared the foot–ankle characteristics of rearfoot and non-rearfoot runners through a cross-sectional study. We then investigated, via a secondary analysis of our previous prospective study, whether foot–ankle characteristics constitute risk factors for sustaining a secondary injury during running technique transition. Finally, to propose a potential approach for addressing these risk factors, the last study in this section examines the biomechanical characteristics of running drills commonly prescribed to enhance foot function and strengthen the foot musculature.

Each section begins with a brief introduction highlighting the current gaps in the literature, followed by the author's original contributions based on studies submitted to or published in international peer-reviewed journals. The thesis concludes with a general discussion that synthesises the main findings and outlines future research directions.

C. Part I: Running technique alteration and performance

While short- and medium-term studies on running retraining interventions (including footstrike modification and cadence increase) have mostly reported little or no effect(s) on running economy, minimalist footwear has shown slightly more promising outcomes, particularly when adequate familiarisation is allowed. Nevertheless, no study to date has simultaneously investigated both approaches over a long-term exceeding six months, nor compared their respective effects on performance-related variables and underlying mechanisms.

In this context, the next study was designed to compare the effects of minimalist footwear and running retraining on the changes in running economy, running biomechanics, and foot and ankle characteristics over a one-year period. Considering the potential influence of cognitive demand, neuromuscular adaptation, and biomechanical changes, this work aimed to provide novel insights into the time course and mechanisms of performance enhancement in endurance runners following running technique alteration.

1. Effects of running technique alteration on running economy (Study 2).

Study 2: Improvements in running economy following minimalist footwear and running retraining emerge after 6 months and are sustained at 12 months.

Submitted

ABRAN Guillaume[1,2], DARDENNE Nadia[3], DELVAUX François[1,2], CROISIER Jean-Louis[1,2]. SCHWARTZ Cédric[1]

[1]LAM – Motion Lab, Liège, Belgium. Electronic address: guillaume.abran@uliege.be.

[2]Department of Physical Activity and Rehabilitation Sciences, University of Liege, Liege, Belgium.

[3] University and Hospital Biostatistics Center (B-STAT), University of Liège, Belgium.

Abstract

Introduction: Running retraining and minimalist footwear represent two distinct strategies for altering running biomechanics, potentially affecting running economy (RE). Unlike running retraining, transitioning to minimalist footwear has been shown to improve RE. This discrepancy may be attributed to specific biomechanical adjustments, foot and ankle adaptations, or the absence of an external attentional focus typically required during running retraining. The purpose of this study was to compare the effects of these two approaches on RE, foot and ankle adaptations and running biomechanics over a 12-month follow-up period.

Methods: Sixty-one rearfoot runners were randomised into three groups: minimalist (N = 19), running retraining (N = 18), and control (N = 24). Running habits, foot and ankle muscle characteristics and plyometric capacity were measured at baseline, two, six and 12 months. During each evaluation session, the RE and biomechanics were measured at comfort speed on a treadmill.

Results: RE improved compared to baseline in both the minimalist group (+4.9% at six months and +9.3% at 12 months; P = 0.03 and P < 0.001, respectively) and the running retraining group (+5.6% at six months and +10.5% at 12 months; P < 0.001 for both time points). The control group also improved running economy but only by 4.7% at 12 months of follow-up compared to baseline (P = 0.01). No significant changes were observed in foot and ankle posture, muscle strength, or plyometric capacity throughout the follow-up period, either within or between groups.

Conclusion: Whereas no improvement in RE was observed at two months in any group, both the minimalist and the running retraining groups showed an improvements at six months and 12 months by 5% and 10%, respectively. RE also improved in the control group but only at 12 months by less than 5%. These enhancements in running efficiency likely reflect biomechanical adaptations rather than structural or functional changes in foot and ankle characteristics.

Introduction

Running technique is a key determinant of running economy in endurance runners, accounting for approximately 4% to 12% of the variance observed between individuals (Folland et al., 2017; Van Hooren, Jukic, et al., 2024). Given this relationship, there has been increasing interest in the literature in exploring the effects of running technique alteration on performance (Doyle et al., 2022). These modifications can be implemented either consciously, through running retraining intervention, or unconsciously, via the use of minimalist footwear (Davis, 2011).

Among the most frequently modified biomechanical parameters during a running retraining intervention are footstrike pattern and cadence (Barton et al., 2016). Adopting a forefoot striking pattern is hypothesised to offer mechanical advantages by shifting the point of ground reaction force application toward the front of the foot. This results in a smaller effective mechanical advantage (EMA) at the ankle and a greater EMA at the knee, potentially redistributing muscular demands and improving running economy (Ekizos et al., 2018). Additionally, an increase in running cadence may reduce braking forces during the landing phase, further enhancing the efficiency of elastic energy recycling (Folland et al., 2017; Napier et al., 2019). However, transitioning to a non-rearfoot strike pattern has been shown to have no significant effect on oxygen consumption, either immediately or over the subsequent weeks (up to 15 weeks) (Dallam et al., 2005; Deng et al., 2020; Ekizos et al., 2018; Fletcher et al., 2008; Messier & Cirillo, 1989; Roper et al., 2017). Similarly, increasing cadence by 8% above an individual's preferred rate does not result in measurable immediate changes in oxygen consumption in endurance runners (De Ruiter et al., 2014). In the initial months, running retraining intervention requires runners to direct their attention towards an external or internal focus to acquire the new running technique (Ekizos et al., 2018; Whittier et al., 2020). The early stages of motor skill learning are associated with distinct functional reorganisation within the human motor system (Ekizos et al., 2018; Seidel et al., 2017). Consequently, oxygen consumption measured immediately or one month after a running retraining intervention may not accurately reflect its long-term effects (Whittier et al., 2020).

Interestingly, the unconscious alteration of running technique induced by minimalist footwear has been found to improve performance by 2 to 3%, after controlling for shoe mass and stride frequency (Perl et al., 2012). The authors suggest that this improvement could be linked to the newly adopted running technique, which includes a more forefoot strike pattern, without requiring additional attentional focus on external cues (Perl et al., 2012). Moreover, transitioning to minimalist footwear led to more pronounced performance improvements of around 8% a few weeks later compared to the immediate effects (Warne & Warrington, 2014).

This greater improvement may be attributed to enhanced coordination, pre-activation and adaptive changes in the musculoskeletal structure of the foot and ankle muscles in relationship to the new running technique (Peters-Dickie et al., 2025; Warne & Warrington, 2014). Supporting this hypothesis, previous studies have demonstrated that minimalist footwear has been shown to increase foot muscle cross-sectional area and strength (T. L.-W. Chen et al., 2016; Deng et al., 2020; Miller et al., 2014). Currently, it remains unclear whether improvements in running economy following a programme of running technique alteration is dependant of the cognitive load, biomechanical adjustments or foot and ankle adaptations.
Therefore, the aim of this study is to compare the effects of minimalist footwear and running retraining on the evolution of (1) running economy, (2) running biomechanics, and (3) foot and ankle characteristics over one year. These findings may provide valuable insights for athletics coaches seeking effective strategies to improve endurance performance. The results may also contribute to a better understanding of the mechanisms underlying the delayed improvements in running economy following running technique alteration. Firstly, we hypothesise that minimalist footwear will lead to improvements in running economy after two months, whereas running retraining will result in significant improvements only after 12 months of follow-up (Ekizos et al., 2018; Perl et al., 2012; Whittier et al., 2020). Secondly, we expect that both interventions will induce a shift to a non-rearfoot strike pattern and increase the running cadence compared to a control group (Doyle et al., 2022; Warne & Warrington, 2014). Finally, we expect that both interventions will enhance ankle plantar flexor, hallux flexor, and lesser toe flexor strength, while having no significant effect on foot and ankle posture compared to a control group (Peters-Dickie et al., 2025).

Material and methods

A 12-month randomised controlled trial was designed to investigate the effects of minimalist footwear and running retraining in a laboratory on foot and ankle characteristics, running biomechanics, and running economy in recreational long-distance runners. The protocol of this study follows the CONSORT (Consolidated Standards of Reporting Trials) recommendations. This study was prospectively registered at ClinicalTrials.gov (NCT05499871; 11 January 2022).

Participants

The required sample size was estimated using the G*power software (version 3.1.9.2, Germany) for a repeated measures, within–between interaction. A population size of 45 participants (15 per group) was estimated to achieve statistical significance for a Cohen's f = 0.20, and power of 0.80 with an alpha level of 0.05 for the primary outcome (running economy improvement) based on previous study (Ekizos et al., 2018; Fuller et al., 2019). Assuming a 20% total dropout rate and 40% total running-related injury rate, we aimed to recruit at least 115 participants (Chan et al., 2018).

Eligibility criteria included age between 18 and 55 years, running at least 10 kilometres per week for at least one year and no running-related injuries in the three months prior to testing. All participants were habitual rearfoot strikers who wore cushioned shoes and had never tried minimalist shoes or modified their running technique. This study was approved by the local ethics committee (12/05/2022; protocol No. 2022-103).

The participants were randomly allocated to the control group (CG), minimalist group (MG), or running retraining group (RRG). The randomisation was stratified according to the age (under and over 30 years) and weekly mileage (under and over 25 kilometres per week) of the participants in several blocks of six participants.

Treatment Arms

Participants allocated to the RRG received four sessions of real-time feedback supervised by an instructor in a laboratory on a treadmill at comfort speed, and carried out two unsupervised sessions outside the laboratory, distributed over two weeks. Real-time feedback sessions consist of running softer, adopting a non-rearfoot strike and increasing the initial step rate by 7.5% (Willy, Buchenic, et al., 2016). Participants were instructed to run softer, to land on the ball of their foot and match their steps to an audible metronome set to the new rate (Barton et al., 2016). The retraining protocol employed a faded feedback approach (Davis, 2011) (Supplemental Table 1). The first two sessions lasted 15 minutes and were supervised by an instructor in the laboratory. Then, one session of 15 minutes was performed by each participant in their usual running environment using a metronome and focusing on running softer and adopting a non-rearfoot strike pattern. The same approach was used during the second week of the running retraining programme, but each session lasted 20 minutes. The retraining protocol is presented in Supplemental Table 1. The time with oral instructions and the metronome was faded from 12 minutes to 4 minutes during the last session (Davis, 2011). Participants were also encouraged to apply the new technique in a progressive running programme during the first two months and maintain it thereafter (Supplemental Table 2). This progressive running programme was supposed to provide a safe transition toward a forefoot strike pattern and was based on previous recommendations (Warne & Gruber, 2017).

Participants allocated to the MG received either trail minimalist footwear (Merrel trail glove 6; minimalist index = 78%) or road minimalist footwear (Topo athletic ST-4; minimalist index = 76%) according to their preferences. Like the RRG, participants were also encouraged to integrate into their own running training the same progressive running programme, where they had to wear the minimalist footwear. This progressive running programme was intended to provide safe minimalist footwear implementation. After the first two months, participants were encouraged to continue using minimalist footwear during their own running training.
The control group followed a placebo static stretching protocol, performing 5-minute sessions three times per week (C. Baxter et al., 2017).

Experimental protocol

Due to the nature of the interventions, blinding was not feasible. Both participants and outcome assessors were aware of group assignments because the interventions (minimalist footwear and gait retraining) were clearly identifiable. Each participant was assessed at four time points: baseline, two months, six months, and 12 months of follow-up.

Questionnaire

At each session, participants completed a baseline questionnaire assessing training habits. Additionally, at two months, participants in the intervention groups reported their adherence to the proposed running programme (0 = not at all to 3 = entirely). At six and 12 months, participants in the RRG indicated the frequency of using the new running technique (0 = less than one training session in five to 5 = every training session), while participants in the MG reported the weekly distance covered using minimalist footwear.

Indirect calorimetry

Participants were instructed to refrain from engaging in strenuous physical activity and from consuming alcohol or caffeine during the 24 hours preceding the running economy test. On the measurement day, they were also required to avoid any food or drink intake during the three hours prior to testing. Running economy was assessed during 6 minutes of treadmill running at a self-selected comfortable speed. To minimize circadian influences, all tests were only conducted during the afternoon. The test was performed on a motorised treadmill (HP Cosmos Pulsar, Nussdorf-Traunstein, Germany) set at 0% incline. Participant body mass was measured prior to each session. Inspired and expired gases were collected via a mouthpiece connected to a breath-by-breath metabolic system (Ergocard, Medisoft). The gas analyser and flowmeter were calibrated before each test. To allow participants to acclimate to the equipment, the oxygen uptake data from the final minute of the 6-minute bout were averaged and used to quantify running economy. Oxygen uptake was expressed relative to body mass ($mL \cdot kg^{-1} \cdot min^{-1}$). All participants reached steady-state energy expenditure, defined as a respiratory exchange ratio < 1.00 and an absence of variation of the ratio O_2/QR during the final minute. If a plateau in oxygen uptake was not observed by the end of the 6-minute period, the run was extended by one additional minute to ensure a submaximal steady-state effort. Participants were asked to systematically wear the same pair of shoes as used during their baseline assessment. Participants in the minimalist group were evaluated with their own conventional running shoes at baseline, and with the provided minimalist shoes at two, six, and twelve months.

Footstrike determination and cadence

During the final minute of the same 6-minute treadmill run, a high-speed video (240 Hz) was recorded to assess biomechanical parameters. Frame-by-frame analysis with Dartfish® (version Prosuite 10.0, Dartfish, Alpharetta, Georgia) allowed identification of each runner's dominant leg footstrike pattern (forefoot/midfoot or rearfoot). The footstrike pattern analysis showed high reliability (ICC = 0.88) (Murray et al., 2018). Step rate was measured by timing 50 strides (100 steps), with excellent intra- and inter-rater reliability (ICC > 0.98) (Esculier, Silvini, et al., 2018).

Foot-ankle characteristics assessment

Foot-ankle characteristics were assessed on the dominant leg, defined as the preferred leg to kick a ball (van Melick et al., 2017).

Foot posture index (FPI-6) and navicular drop (ND) were used to evaluate foot posture. The FPI-6 presents an excellent test-retest and inter-rater reliability (ICC: 0.81–0.86) as does the ND (ICC: 0.84) (Fraser et al., 2017; Mulligan & Cook, 2013; Redmond et al., 2006) For ND, three trials were performed and averaged.

Then, ankle plantar flexor, hallux flexor, and lesser toe flexor strength were assessed using a digital hand-held dynamometer (MicroFET2, Hoggan Health Industries, West Jordan, UT, USA) in accordance with prior methodology . Participants lay prone for ankle plantar flexor testing (foot off the table, ankle neutral) and supine with knees at 90° and toes extended at 25° for hallux and toe flexor testing. The dynamometer was secured to a height-adjustable bar to minimise examiner interference, and stabilisation was ensured using straps and manual support. The ankle plantar flexor lever arm was measured between the lateral malleolus and the dynamometer contact point. The testing order was randomised. Participants completed two familiarisation trials, followed by three maximal efforts, each lasting 3–5 seconds, with 30 seconds of rest. The highest value was retained. Strength was reported in Newton-meters (N.m) for ankle plantar flexors and in Newtons (N) for hallux and toe flexors. All values were normalised to body mass. These measures demonstrated excellent reliability (test-retest ICC: 0.73–0.88; inter-rater ICC: 0.74–0.89) (Fraser et al., 2017).

The reactive strength index (RSI) is a functional measure of the lower limb's capacity to store and release elastic energy (A. N. Turner & Jeffreys, 2010). The foot and ankle are the major contributor of RSI when participants are advised to keep their hip and their knee straight (Fukashiro et al., 2005), After a familiarisation period, participants performed three single-leg drop jumps from a 30 cm box with their dominant lower limb. In the barefoot condition, participants were instructed to jump as high as possible while keeping their knees and trunk as straight as possible, hands on their hips, and to push off the ground as quickly as possible. Video recording (240 Hz) of the foot from the front of the subject was performed for subsequent analyses using the "MyJump Lab Pro" application (Carlos Balsalobre-Fernández, version 2.1.1). "MyJump Lab Pro" showed a good validity for RSI ($r = 0.97$) and jump height ($r = 0.97$) . "MyJymp Lab Pro" has also a good reliability for RSI (ICC = 0.98) and jump height (ICC = 0.96) (Haynes et al., 2019).

Statistical analysis

A per protocol analysis was performed to investigate the effect of each intervention on running economy and foot-ankle characteristics. Inclusion required participation to the four evaluation sessions and remain injury free during all the follow-up duration. Participants in the MG had to run in minimalist footwear for ≥25% of their weekly mileage at 12 months, and participants in the RRG had to adopt a non-rearfoot strike or increase step rate by ≥ 7.5% from baseline. Participants not meeting these criteria were excluded from the analysis.

Normality conditions were checked for each continuous variables of the database using the Shapiro–Wilk test. Continuous variables at baseline (age, mass, height, BMI, running experience, weekly distance, running volume and comfort speed) were presented either as means and standard deviations or as medians and interquartile ranges Dichotomous variables at baseline (sex: 0 = male, 1 = female) were described in frequency and percentage.

Separate linear mixed-effects models (LMMs) were used to evaluate the impact of interventional groups on running economy. Comparable analyses were conducted for foot-ankle characteristics and running biomechanics. The fixed effects are the intervention group (CG, MG, RRG), time (baseline, two month, six month, twelve month) and comfort running speed, and a random intercept effect is added to account for between-participant variability. Effect sizes (ES) were derived from post-hoc contrasts of the LMMs and reported. ES are presented as standardized mean differences (Cohen's D), with ES between 0.2 and 0.49 representing a small effect, between 0.5 and 0.79 representing a moderate effect, and ≥ 0.8 representing a large effect (Hopkins et al., 2009). ES <0.20 were considered trivial.

Finally, an independent t-test was conducted to examine the impact of running technique alteration (0 = unaltered, 1 = altered) on running economy improvement (percentage difference between running economy at 12 months and running economy at baseline). Participants from both the running retraining and minimalist footwear groups were classified as having altered their technique if, at the 12-month evaluation, they demonstrated either a non-rearfoot strike pattern or a step rate increase of at least 7.5% compared to baseline. Those who did not meet these criteria were considered as having no change. Pearson's correlations were then used to assess the associations between long-term improvements in running economy at comfortable speed and changes in plantar flexor, hallux flexor, and toe flexor strength, as well as in reactive strength index (RSI) and jump height, expressed as percentage changes from baseline to 12 months.

Statistical analyses were performed using the R software (Version 4.1.1, R Core Team, 2017) 15. An alpha level of 0.05 was used for all inferential statistics.

Results

In total, 182 participants were assessed for eligibility. An overview of the inclusion, allocation, and analysis processes is provided in Figure C.1. At baseline, there were no significant differences between the CG (n = 24), MG (n = 19), and RRG (n = 18) in age, sex, mass, height, BMI, running experience, weekly distance, training volume, or comfort speed ($P > 0.05$) (Table C.1).

Adherence to running retraining programme

In the MG, runners self-reported wearing the minimalist footwear 64.2 ± 29.9 % and 57.8 ± 29.2 % of their total weekly distance at six and twelve months, respectively. In the RRG, 90.6 % and 87.4 % of the runners self-reported being attentive to adopting the new running technique during all or almost all their running session at six and 12 months, respectively.

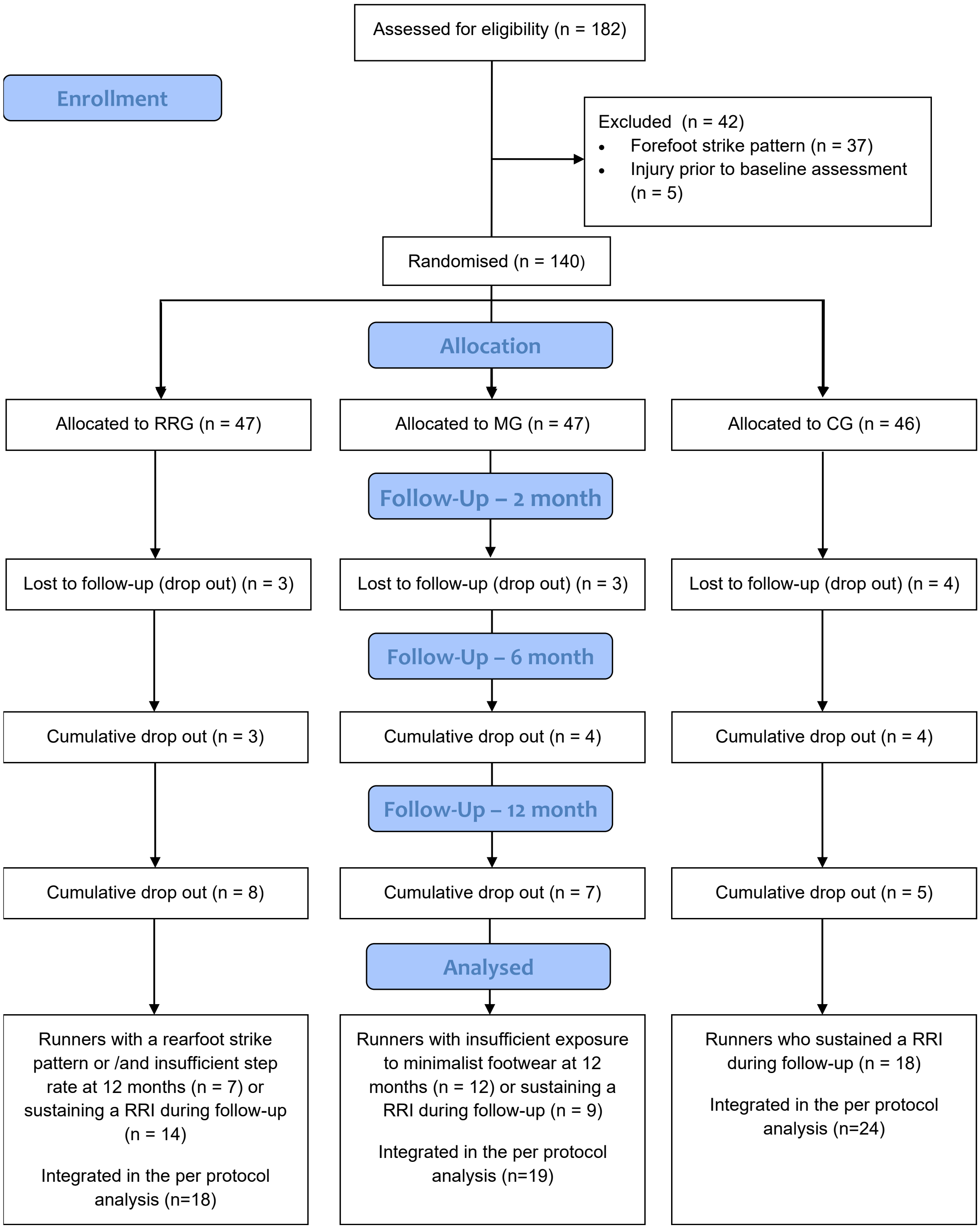


Figure C-1. Participant enrolment, allocation, and analysis flowchart for per-protocol analyses. Sixty-one participants were included in the analysis. In the running retraining group (RRG), 29 participants were excluded from the analysis (eight participants drop out during the follow-up period, seven participants still ran with a rearfoot strike pattern and/or did not increase their running cadence by 7.5 % at 12 months of follow-up and 14 runners sustained a RRI during the follow-up period). In the minimalist group (MG), 28 runners were excluded from the analysis (seven participants dropped out during the follow-up period, 12 runners wore less than 25 % of their total weekly distance at 12 months of follow-up, and nine runners sustained a RRI during the follow-up period). In the control group (CG), 22 runners were excluded from the analysis (five runners drop out and 18 sustained a RRIs during the follow-up period).

Running economy

The results of the linear mixed model showed a significant Group x Time interaction (*P* = 0.004). Post-hoc analysis showed a significant improvement of running economy for the MG and RRG at six (MG: Diff = -4.9%, *d* = -0.2 , *P* = 0.03; RRG: Diff = -5.6%, *d* = -0.24; P < 0.001) and 12 months (MG: Diff = -9.3% *d* = 0.37, *P* < 0.001; RRG: Diff = -10.5%, *d* = 0.40; P < 0.001) of follow-up compared to baseline. Post-hoc analysis also showed a significant improvement of running economy for the CG (Diff = -4.7%, *d* = 0.21, *P* = 0.01) at 12 months of follow-up compared to baseline. Longitudinal changes in running economy across groups is available in Figure C.2.

No significant differences in running economy were found between the CG and intervention groups (MG or RRG) at each evaluation session, with only a small effect size (*P* > 0.05; *d* < 0.2)(Table C.2).

Running biomechanics

The results of the linear mixed model showed a significant Group x Time interaction (*P* = 0.003). Post-hoc analysis showed no significant differences in running cadence across the follow-up period for the CG and MG. Conversely, post-hoc analysis showed that runners in the RRG increased their running cadence at two (Diff = +7.1%, d =0.8, *P* < 0.001), six (Diff = +6.0% d = 0.67, *P* < 0.001), and 12 months (Diff = +4.3%, d = 0.48, *P* < 0.001).

No significant differences in running cadence were found between the CG and MG groups at each evaluation session. Conversely, post-hoc analysis highlighted significant differences in running cadence between the CG and RRG at two (Diff = +9.0%, *d* = 0.57, *P* < 0.001), six (Diff = +8.5%, d = 0.53, *P* < 0.001), and 12 months of follow-up (Diff = +6.66%, d = 0.41, *P* < 0.001).

No change was found in the footstrike pattern among the CG runners. In the MG, seven runners (36.8 %) transited to a non-rearfoot strike pattern at two months, nine runners (47.3 %) transited to a non-rearfoot strike pattern at six months and eight runners (44.4 %) transitioned to a non-rearfoot strike pattern at 12 months of follow-up. In the RRG, 19 runners (100 %) transited to a non-rearfoot strike pattern at two months and 18 runners (94.7 %) transited to a non-rearfoot strike pattern at six and 12 months of follow-up.

Foot and ankle characteristics

The results of the linear mixed model showed no significant Group x Time interaction for FPI-6 (*P* = 0.18), ND (*P* = 0.81), ankle plantar flexor strength (*P* = 0.054), hallux flexor strength (*P*

= 0.82), lesser toe flexor strength (P = 0.75), drop jump height (P = 0.25) and drop jump RSI (P = 0.36). Post-hoc analysis including estimated marginal mean and effect size for each group at each time are available in Table C.3.

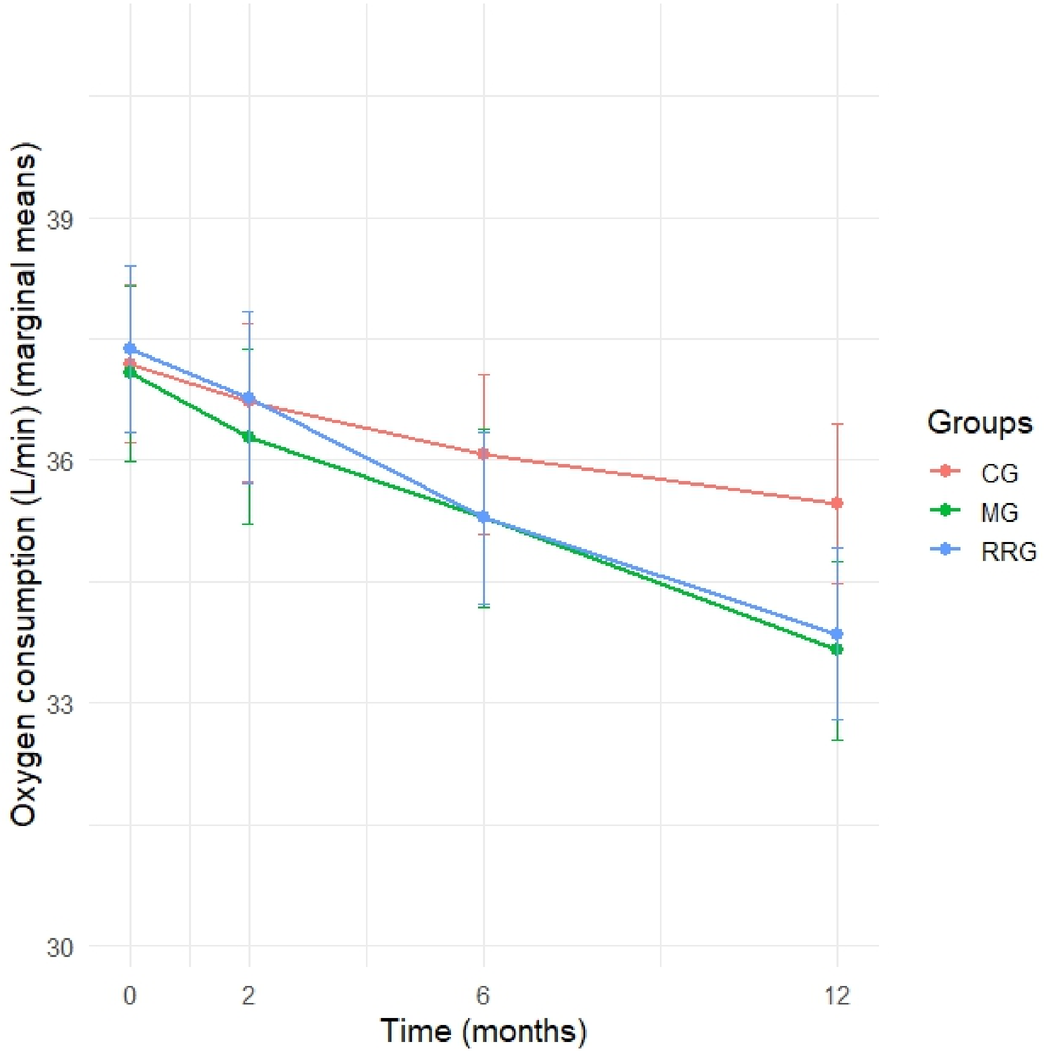


Figure C-2: Longitudinal changes in running economy across the three groups (CG, MG, RRG), based on estimated marginal means from linear mixed models. Within-group significant changes over time ($p < 0.05$) are indicated by color-coded p-values.

Table C.1. Comparisons of individual baseline characteristics between groups.

Variables	Group	Mean (± SD) (1)	p-value	Effect size
Age (years)	CG	29.9 (± 11.3)	0.90♦	0.004┼
	MG	31.4 (± 10.2)		
	RRG	30.5 (± 10.3)		
Sex (M / F)	CG	14 (58.3 %) / 10 (41.7 %)	0.60ǂ	0.128¥
	MG	12 (63.1 %)/ 7 (36.8 %)		
	RRG	9 (47.4 %)/ 10 (52.6 %)		
Mass (kg)	CG	69.0 (± 13.5)	0.87♦	0.005┼
	MG	67.3 (± 8.7)		
	RRG	67.6 (± 11.5)		
Height (m)	CG	1.74 (± 0.10)	0.09♦	0.078┼
	MG	1.72 (± 0.09)		
	RRG	1.67 (± 0.10)		
BMI (kg/m²)	CG	22.5 (± 2.4)	0.13♦	0.065┼
	MG	22.6 (± 2.3)		
	RRG	24.0 (± 3.0)		
Running experience (years)	CG	7.1 (± 7.5)	0.87♦	0.004┼
	MG	7.1 (± 7.9)		
	RRG	8.2 (± 7.3)		
Weekly distance (km)	CG	26.6 (± 17.6)	0.40♦	0.030┼
	MG	25.2 (± 15.2)		
	RRG	20.7 (± 8.0)		
Training volume (hours/week)	CG	2.9 (± 1.5)	0.62♦	0.016┼
	MG	3.0 (± 1.6)		
	RRG	2.6 (± 0.9)		
Comfort speed (km/h)	CG	11.1 (± 1.4)	0.23♦	0.048┼
	MG	10.8 (± 2.1)		
	RRG	10.2 (± 1.9)		

M = Male; F = Female; ♦ = p-value of ANOVA-1 (group effect); ǂ = p-value of chi-squared test; ┼ = eta squared; ¥ = Cramer's V; CG = Control group, MG = Minimalist group, RRG = Running retraining group.

Table C.2: Post-hoc comparisons of the linear mixed model between groups (control group (CG), minimalist group (MG), and running retraining group (RRG)) across the four periods of assessment during one year of follow-up for running performance and running biomechanics.

Category	**Variables**	**Group**	**Baseline**	**Control group differences at baseline**	**T2**	**Baseline vs T2**	**Control group differences at T2**	**T6**	**Baseline vs T6**	**Control group differences at T6**	**T12**	**Baseline vs T12**	**Control group differences at T12**
			EMM (± CI95%)	**ES (± CI95%)**	**EMM (± CI95%)**	**ES (± CI95%)**	**ES (± CI95%)**	**EMM (± CI95%)**	**ES (± CI95%)**	**ES (± CI95%)**	**EMM (± CI95%)**	**ES (± CI95%)**	**ES (± CI95%)**
Running performance	**Running economy (L/min/kg)**	**CG**	37.1 (36.2 – 38.1)		36.7 (35.7 – 37.7)	-0.06 (-0.17 – 0.05)		36.0 (35.0 – 37.0)	-0.14 (-0.25 – -0.03)		35.4 (34.4 – 36.4)	-0.21 (-0.32 – -0.10)**	
		MG	37.1 (36.0 – 38.2)	-0.01 (-0.14 – 0.12)	36.3 (35.2 – 37.4)	-0.09 (-0.20 – 0.02)	-0.04 (-0.17 – 0.15)	35.3 (34.2 – 36.4)	-0.20 (-0.31 – -0.09)*	-0.07 (-0.20 – 0.06)	33.6 (32.5 – 34.8)	-0.37 (-0.48 – -0.26) ***	-0.16 (-0.29 – -0.03)
		RRG	37.4 (36.3 – 38.4)	0.02 (-0.12 – 0.15)	36.8 (35.7 – 37.8)	0.07 (-0.18 – 0.04)	0 (-0.13 – 0.14)	35.3 (34.2 – 36.4)	-0.24 (-0.35 – -0.13)***	-0.07 (-0.20 – 0.06)	33.8 (32.8 – 34.9)	-0.40 (-0.51 – -0.29) ***	-0.15 (-0.28 – -0.01)
Running biomechanics	**Cadence (step/min)**	**CG**	164.2 (161.2 – 167.3)		164.1 (161.0 – 167.1)	-0.1 (-0.12 – 0.10)		163.2 (160.1 – 166.3)	-0.07 (-0.18– 0.03)		163.5 (160.4 – 166.5)	-0.05 (-0.16 – 0.05)	
		MG	165.7 (162.3 – 169.1)	0.06 (-0.11 – 0.23)	166.9 (163.5 – 170.3)	0.07 (-0.04 – 0.18)	0.10 (-0.06 – 0.27)	167.2 (163.8 – 170.3)	0.09 (-0.02 – -0.20)	0.15 (-0.02 – 0.32)	167.1 (163.7 – 170.5)	0.09 (-0.02 – 0.19)	0.13 (-0.03 – 0.30)
		RRG	167.1 (163.8 – 170.3)	0.11 (-0.06 – 0.28)	179.0 (175.8 – 182.3)	0.80 (0.69 – 0.91) ***	0.57 (0.40 – 0.74)***	177.2 (173.9 – 180.4)	0.67 (0.56 – 0.78) ***	0.53 (0.36 – 0.70)***	174.4 (171.1 – 177.7)	0.48 (0.37 – 0.59) ***	0.41 (0.24 – 0.58)***

*EMM = Estimated Marginal Mean; T2 = two months of follow-up; T6 = six months of follow-up; T12 = twelve month of follow-up; ES = effect size, CI95% = confidence interval 95 %, * = p-value < 0.05, ** = p-value < 0.01, *** = p-value < 0.001.*

Table C.3: Post-hoc comparisons of the linear mixed model between groups (control group (CG), minimalist group (MG), and running retraining group (RRG)) across the four periods of assessment during one year of follow-up for foot-ankle posture, foot-ankle muscle strength and drop jump.

Category	Variables	Group	Baseline	Control group differences at baseline	T2	Baseline vs T2	Control group differences at T2	T6	Baseline vs T6	Control group differences at T6	T12	Baseline vs T12	Control group differences at T12
			EMM (± CI95%)	**ES (± CI95%)**	**EMM (± CI95%)**	**ES (± CI95%)**	**ES (± CI95%)**	**EMM (± CI95%)**	**ES (± CI95%)**	**ES (± CI95%)**	**EMM (± CI95%)**	**ES (± CI95%)**	**ES (± CI95%)**
Foot-ankle posture	**Foot posture index (FPI-6)**	**CG**	5.1 (4.1 – 6.1)		5.2 (4.2 – 6.2)	0.03 (-0.08 – 0.14)		5.5 (4.5 – 6.5)	0.09 (-0.02 – 0.20)		5.0 (4.0 – 6.0)	-0.03 (-0.08 – 0.14)	
		MG	4.7 (3.6 – 5.8)	-0.05 (-0.22 – 0.12)	5.1 (4.0 – 6.2)	0.09 (-0.02 – 0.2)	-0.01 (-0.16 – 0.19)	4.9 (3.8 – 6.0)	0.05 (-0.06 – 0.16)	-0.06 (-0.24 – 0.11)	5.0 (3.9 – 6.1)	0.07 (-0.04 – 0.18)	0 (-0.17 – 0.17)
		RRG	5.2 (4.1 – 6.2)	0 (-0.18 – 0.17)	5.2 (4.1 – 6.2)	0 (-0.11 – 0.11)	0.01 (-0.18 – 0.16)	4.8 (3.7 – 5.9)	-0.07 (-0.18 – 0.04)	-0.08 (-0.25 – 0.1)	4.7 (3.6 – 5.8)	-0.09 (-0.20 – 0.02)	-0.03 (-0.20 – 0.14)
	Navicular drop (cm)	**CG**	0.48 (0.43 – 0.53)		0.46 (0.41 – 0.52)	-0.04 (-0.15 – 0.07)		0.47 (0.41 – 0.52)	-0.03 (-0.14 – 0.08)		0.49 (0.44 – 0.55)	0.03 (-0.08 – 0.14)	
		MG	0.42 (0.36 – 0.48)	0.11 (-0.25 – 0.04)	0.40 (0.34 – 0.46)	-0.04 (-0.15 – 0.07)	0.11 (-0.25 – 0.04)	0.42 (0.36 – 0.48)	-0.01 (-0.10 – 0.12)	0.08 (-0.22 – 0.07)	0.45 (0.39 – 0.51)	0.06 (-0.05 – 0.17)	0.08 (-0.22 – 0.06)
		RRG	0.50 (0.44 – 0.55)	0.03 (-0.11 – 0.18)	0.46 (0.40 – 0.52)	-0.08 (-0.19 – 0.03)	0 (-0.14 – 0.15)	0.48 (0.42 – 0.54)	-0.03 (-0.14 – 0.08)	0.03 (-0.11 – 0.17)	0.51 (0.45 – 0.56)	0.02 (-0.09 – 0.13)	0.02 (-0.12 – 0.17)
Foot-ankle muscle strength	**Plantar flexor strength (Nm/kg)**	**CG**	0.90 (0.84 – 0.97)		0.89 (0.83 – 0.96)	-0.03 (-0.14 – 0.08)		0.84 (0.77 – 0.90)	-0.17 (0.28 – 0.06)		0.88 (0.81 – 0.96)	0.06 (-0.17 – 0.05)	
		MG	0.86 (0.79 – 0.93)	-0.07 (-0.23 – 0.09)	0.89 (0.81 – 0.96)	0.06 (-0.05 – 0.17)	-0.01 (-0.17 – 0.15)	0.87 (0.79 – 0.94)	0.01 (-0.10 – 0.12)	0.05 (-0.11 – 0.21)	0.94 (0.87 – 1.02)	0.18 (-0.07 – 0.29)	-0.10 (-0.25 – 0.06)
		RRG	0.85 (0.78 – 0.92)	-0.09 (-0.25 – 0.07)	0.90 (0.83 – 0.98)	0.13 (0.02 – 0.24)	0.02 (-0.14 – 0.18)	0.87 (0.80 – 0.94)	0.05 (-0.06 – 0.16)	0.06 (-0.10 – 0.22)	0.90 (0.82 – 0.97)	0.11 (-0.22 – 0.01)	-0.02 (-0.13 – 0.18)
	Hallux flexor strength (N/kg)	**CG**	2.65 (2.45 – 2.85)		2.77 (2.57 – 2.97)	0.10 (-0.01 – 0.21)		2.63 (2.43 – 2.83)	-0.02 (-0.013 – 0.09)		2.82 (2.62 – 3.02)	0.14 (0.03 – 0.25)	
		MG	2.55 (2.33 – 2.77)	-0.06 (-0.21 – 0.10)	2.76 (2.54 – 2.99)	0.16 (0.05 – 0.27)	0 (-0.16 – 0.16)	2.77 (2.55 – 2.99)	0.17 (0.06 – 0.28)	0.07 (-0.08 – 0.23)	2.78 (2.56 – 3.00)	0.17 (0.06 – 0.28)	-0.02 (-0.18 – 0.14)
		RRG	2.65 (2.43 – 2.86)	0 (-0.16 – 0.15)	2.82 (2.61 – 3.04)	0.14 (0.03 – 0.25)	0.03 (-0.13 – 0.19)	2.89 (2.67 – 3.10)	0.19 (0.08 – 0.30)	0.14 (-0.02 – 0.29)	2.81 (2.60 – 3.03)	0.13 (0.06 – 0.24)	0 (-0.16 – 0.15)
	Lesser toe flexor strength (N/kg)	**CG**	2.38 (2.19 – 2.57)		2.34 (2.15 – 2.53)	-0.04 (-0.15 – 0.07)		2.35 (2.16 – 2.55)	0.03 (-0.14 – 0.08)		2.33 (2.14 – 2.52)	0.05 (-0.16 – 0.06)	
		MG	2.17 (1.96 – 2.39)	-0.12 (-0.28 – 0.04)	2.29 (2.08 – 2.51)	0.09 (-0.01 – 0.20)	-0.03 (-0.318 – 0.13)	2.31 (2.10 – 2.52)	0.11 (0 – 0.22)	-0.03 (-0.18 – 0.13)	2.22 (2.00 – 2.43)	0.03 (-0.08 – 0.14)	-0.06 (-0.22 – 0.10)
		RRG	2.17 (1.97 – 2.38)	-0.12 (-0.28 – 0.04)	2.29 (2.08 – 2.49)	0.09 (-0.02. – 0.20)	-0.03 (-0.19 – 0.13)	2.29 (2.08 – 2.49)	0.09 (-0.02. – 0.20)	-0.04 (-0.19 – 0.12)	2.23 (2.02 – 2.43)	0.04 (-0.07 – 0.15)	-0.06 (-0.22 – 0.10)
Drop jump	**Drop jump height (m)**	**CG**	9.16 (8.07 – 10.25)		8.88 (7.80 – 9.97)	-0.05 (-0.16 – 0.06)		9.38 (8.29 – 10.47)	0.04 (-0.07 – 0.15)		9.20 (8.11 – 10.29)	0.01 (-0.15 – 0.18)	
		MG	9.29 (8.09 – 10.48)	0.01 (-0.15 – 0.18)	9.32 (8.13 – 10.51)	0.01 (-0.11 – 0.12)	0.04 (-0.12 – 0.21)	9.18 (7.98 – 10.38)	-0.02 (-0.13 – 0.09)	-0.02 (-0.18 – 0.14)	9.33 (8.13 – 10.53)	0.01 (-0.10 – 0.12)	0.01 (-0.15 – 0.18)
		RRG	9.29 (8.15 – 10.43)	0.01 (-0.15 – 0.18)	9.56 (8.40 – 10.71)	0.04 (-0.07 – 0.15)	0.07 (-0.09 – 0.23)	8.81 (7.67 – 9.95)	-0.08 (-0.19 – 0.03)	-0.06 (-0.22 – 0.10)	8.95 (7.80 – 10.09)	-0.06 (-0.17 – 0.05)	-0.03 (-0.19 – 0.14)
	Reactive strength index	**CG**	0.90 (0.82 – 0.97)		0.86 (0.79 – 0.94)	-0.09 (-0.20 – 0.02)		0.85 (0.78 – 0.92)	-0.12 (0.23 – 0.01)		0.88 (0.80 – 0.95)	-0.05 (-0.16 – 0.06)	
		MG	0.87 (0.79 – 0.96)	-0.05 (-0.21 – 0.11)	0.87 (0.79 – 0.97)	0.02 (-0.09 – 0.13)	0.02 (-0.15 – 0.18)	0.89 (0.81 – 0.97)	0.05 (-0.06 – 0.16)	0.06 (-0.11 – 0.22)	0.90 (0.82 – 0.98)	0.06 (-0.05 – 0.18)	0.03 (-0.13 – 0.19)
		RRG	0.88 (0.80 – 0.95)	-0.03 (-0.20 – 0.13)	0.89 (0.81 – 0.97)	0.03 (-0.08 – 0.14)	0.04 (-0.12 – 0.20)	0.83 (0.75 – 0.91)	-0.12 (-0.23 – 0.01)	-0.03 (-0.19 – 0.13)	0.82 (0.74 – 0.90)	-0.14 (-0.25 – 0.03)	-0.09 (-0.25 – 0.07)

*EMM = Estimated Marginal Mean; T2 = two months of follow-up; T6 = six months of follow-up; T12 = twelve month of follow-up; ES = effect size, CI95% = confidence interval 95 %, * = p-value < 0.05, ** = p-value < 0.01, *** = p-value < 0.001.*

Relationship between running economy gains, running biomechanics and foot-ankle adaptations

An independent samples t-test showed that runners who successfully altered their running technique (in both interventional groups) exhibited greater improvements in running economy at the 12-month follow-up compared to runners who maintain their running technique (mean ± SD: −9.3% ± 9.8% vs. −5.9% ± 7.4%; $P = 0.041$, $d = 0.38$).

In the MG, no significant correlations were found between running economy gains at comfort speed at 12 months and gains in plantar flexor strength (r = -0.04, $P = 0.87$), toe flexor strength (r = 0.44, $P = 0.06$), RSI (r = -0.04, $P = 0.87$), or jump height (r = 0.05, $P = 0.83$) at 12 months. However, a significant positive correlation was observed between running economy gains and hallux flexor strength gains (r = 0.54, $P = 0.01$) at 12 months. Similarly, in the RRG, no significant correlations were found between running economy gains at comfort speed at 12 months and gains in plantar flexor strength (r = 0.18, $P = 0.47$), hallux flexor strength (r = 0.38, $P = 0.13$), toe flexor strength (r = 0.27, $P = 0.29$), RSI (r = -0.27, $P = 0.30$), or jump height (r = -0.12, $P = 0.63$) at 12 months.

Discussion

The main aim of this study was to compare the effects of minimalist footwear and running retraining on the evolution of running economy over one year in recreational endurance runners. Our first hypothesis was confirmed by the results, highlighting that both interventions had no effect on running economy at two months of follow-up but improved running economy at six and 12 months of follow-up by approximately 5% and 10%, respectively. Interestingly, the control group also showed an improvement in running economy, but only by approximately 4.7% at 12 months of follow-up. Doyle et al. (2022) have summarised in a systematic review with meta-analysis the effect of running technique alteration on running performance (Doyle et al., 2022). During the first four months, there was low certainty evidence from three trials that non-rearfoot footstrike retraining has only trivial non-significant effects on the running economy (Craighead et al., 2014; Ekizos et al., 2018; Roper et al., 2017). Similarly, low-certainty evidence from three trials demonstrated that multiparameter interventions (Pose method® or combination of midfoot strike adoption and increase step rate) produce a small non-significant increase in oxygen consumption during the first four months (Dallam et al., 2005; Fletcher et al., 2008; Messier & Cirillo, 1989). However, our study is the first to explore the effect of altering the running technique over a four-month follow-up period. A longer follow-up period after a running technique alteration protocol could explain the discrepancy in the results compared with previous studies. Altering the running technique requires a high level of attention to an external focus, resulting in an increase in energy demand in the cerebral cortex and an increase in energy consumption (Ekizos et al., 2018; Whittier et al., 2020). An increase in energy consumption due to a higher level of attention in the initial months after a running technique alteration protocol could mask the positive effects of the running technique alteration on energy consumption during running. On the other hand, previous studies have shown that minimalist footwear can reduce oxygen consumption by around 8% after a period of four or ten weeks of familiarisation (Ridge et al., 2015; Warne & Warrington, 2014). This reduction may be attributed to their lighter weight compared to traditional running shoes and the adoption of a more efficient running technique (Ridge et al., 2015; Warne & Warrington, 2014). Our results showed a smaller improvement than previous studies, as we also observed an improvement around 2% at two months and 5% at six months after transitioning to minimalist footwear (Warne & Warrington, 2014). However, the effects of both interventions on energy expenditure reduction varied among runners, highlighting the need for future research to identify the runner profiles most likely to benefit from technique modifications or minimalist footwear. Finally, as previously described, the improvement in running economy observed in the CG may have resulted from their participation in the study (Ridge et al., 2015).

The secondary aim of this study was to compare the effects of minimalist footwear and running retraining on the evolution of running biomechanics over one year. Additionally, the study aimed to determine whether the biomechanical changes induced by each intervention were associated with improvements in running economy. In accordance with previous studies, runners in the RRG modified their running technique to increase their running cadence by 7.1 %, 6.0 %, and 4.3 % at two, six and 12 months of follow-up, respectively (De Souza Júnior et al., 2024; Futrell et al., 2020). In addition, almost all runners (except one) maintained a non-rearfoot strike pattern at 12 months of follow-up in the RRG. Parallelly, the running cadence remained unchanged and approximately 40 % of the runners transitioned to a non-rearfoot strike pattern in the MG. The transition to a non-rearfoot strike pattern could be explained by the absence of a drop in the minimalist footwear selected in this study (Hollander et al., 2015). Furthermore, the study demonstrated that altering running technique, regardless of the intervention group, led to a nearly two-fold greater improvement in running economy at one year compared to those who did not alter their technique. Running with a forefoot strike pattern may shift the point of ground reaction force application forward, resulting in a smaller EMA at the ankle and a greater EMA at the knee. Since the human plantar flexor muscles have shorter fascicles and are metabolically less costly than the long-fibered knee extensor muscles for generating the same force, this redistribution of muscular demands may partly explain the observed enhancement in running economy (Ekizos et al., 2018).

This study also compared the effects of minimalist footwear and running retraining on the evolution of foot and ankle characteristics over one year. Additionally, the study aimed to determine whether the foot and ankle characteristics changes induced by each intervention were associated with improvements in running economy. The results did not confirm our hypothesis because none of the interventions improved foot and ankle characteristics compared to the control group. Furthermore, no correlation was found between evolution of running economy gains and foot-ankle characteristics at 12 months. These results refute the hypothesis that improvements in running economy following running technique alteration are primarily driven by positive adaptations of the foot–ankle complex. The lack of improvements in foot and ankle muscle strength in both the RRG and MG appears unexpected, given that previous studies have reported increased foot muscle strength following the use of minimalist footwear or the adoption of a non-rearfoot strike pattern (Peters-Dickie et al., 2025; Shen et al., 2022). Previous studies with participants transitioning completely to minimalist footwear in daily or running activities have showed an increase in foot muscle strength of approximately 25 % (Ridge et al., 2019). In our study, runners used minimalist footwear for approximately 60 % of their total weekly running distance. The absence of changes in foot and ankle muscle strength in our sample could be explained by a smaller stimulus induced by a partial transition to minimalist footwear compared with previous studies. Increased foot and ankle muscle strength using minimalist footwear could require a complete transition to minimalist footwear. This study is the first to explore the effect of running retraining intervention on foot muscle strength without any additional modalities. Previous studies have shown that transitioning to a non-rearfoot strike pattern with minimalist footwear induces a 27.5 % increase in isometric plantar flexor muscle strength, 20 % increase in isometric toe flexor strength, and 6.3 % increase in cross-sectional Achilles tendon after 12 weeks (Deng et al., 2020; Shen et al., 2022). Although no significant difference was found in this study, runners in the RRG increased ankle plantar flexor and hallux flexor strength by 6%. Finally, the RSI also remained unchanged in both RRG and MG over the 12 months of follow-up. Nonetheless, RSI measured during a drop jump, even when the knee and hip remain fully extended, may lack specificity to assess the progression of foot and ankle muscle tendon units in storing and releasing elastic energy during running (Tourillon et al., 2024). A recently developed test, specifically designed to evaluate the foot and ankle RSI, could be incorporated in future research to refine our understanding of the mechanisms underpinning improvements in running economy following running retraining interventions (Tourillon et al., 2024).

This study has several limitations that should be considered before generalising the results. First, the duration of the running retraining protocol was shorter than in previous studies consisting of four supervised and two unsupervised sessions instead of the eight supervised sessions typically used (Davis, 2011). However, adherence and retention of the new running technique were comparable to those reported in previous studies. Second, running biomechanics were assessed on a treadmill. Although ecological assessment better reflects the real condition of training for runners, running biomechanical assessment has been considered valid by previous studies (Van Hooren et al., 2020). Third, this study did not monitor changes in cognitive load over the follow-up period in each group. Previous research has shown that cognitive load increases immediately and persists for up to one month after a running retraining intervention (Whittier et al., 2020). Given the hypothesis that elevated cognitive load may increase energy expenditure during running, tracking its evolution could contribute to clarifying the mechanisms underlying the delayed improvements in running economy observed after running technique alteration. Fourth, due to the nature of the running retraining intervention, participants in this group received more direct contact time with the research team compared to those in the minimalist and control groups, which may have influenced their adherence to the intervention. However, given the good adherence observed in the minimalist group, this difference in contact time likely did not affect the study outcomes.

Conclusion

Whereas no improvement in running economy was observed at two months in any group, both the minimalist and the running retraining groups showed an improvements after six and 12 months by 5% and 10%, respectively. Running economy also improved in the control group but only at 12 months by less than 5%. These enhancements in running efficiency likely reflect biomechanical adaptations rather than structural or functional changes in foot and ankle characteristics.

Take Home Messages – Part I

- ✓ Transitioning to minimalist footwear improves running economy, potentially due to the absence of cognitive constraints. The progressive improvement over time may be attributed to enhanced intramuscular coordination.

- ✓ Both interventions lead to approximately a 5% improvement in running economy after six months, increasing to nearly 10% at 12 months. Running economy also improved in the control group but only at 12 months by less than 5%.

- ✓ Neither intervention results in significant gains in foot or ankle morphological or strength characteristics.

Both conscious and unconscious retraining groups demonstrated improvements in running economy. To ensure that such improvements are not achieved at the expense of an increased risk of injury, the relationship between running technique and injury prevention is explored in the next part.

D. Part II: Running technique alteration and injury prevention

In the previous section, we found that both conscious and unconscious alterations of running technique can enhance running economy, which is a major determinant of running performance. However, it is essential to ensure that such improvements are not achieved at the expense of a higher risk of injury. Previous studies have shown that adopting a non-rearfoot strike pattern or increasing running cadence may reduce impact-related parameters. Nevertheless, only the high-frequency component of impact-related parameters has been identified as a risk factor for running-related injuries. To date, the effect of running technique alterations on this high-frequency component remains unknown. Furthermore, the effect of running technique alteration on running-related injuries has only been investigated in novice runners, a specific population in which the risk of injury is substantially higher. Although running technique modification in novice runners has been shown to reduce the incidence of running-related injuries by 62%, its effect on recreational endurance runners has not yet been explored (Chan et al., 2018).

In this part, we therefore conducted a laboratory-based biomechanical investigation comparing the high-frequency component of impact-related parameters across different running techniques. We then examined the effects of two distinct methods of running technique alteration on the incidence of running-related injuries in recreational endurance runners through a large-scale prospective study.

1. Effects of running technique alteration on biomechanical risk factors (Study 3).

Study 3: Acute effect of running retraining interventions on low & high-frequency components of the impact signals.

Submitted

ABRAN Guillaume[1,2], GRAMAGE Kevin[1,2], DELVAUX François[1,2], CROISIER Jean-Louis [1,2], SCHWARTZ Cédric[1].

[1] LAM – Motion Lab, Liège, Belgium. Electronic address: guillaume.abran@uliege.be.

[2] Department of physical activity and rehabilitation sciences, University of Liege, Liege, Belgium.

Abstract

Running-related injuries (RRIs) have been linked to high-frequency components of impact-related variables. While time-domain analyses have shown that running retraining interventions reduce impact-related variables, their influence on low- and high-frequency components of these variables remains unexplored. This study investigated the effects of different retraining strategies on low- and high-frequency components of impact-related variables. Twenty-six habitual rearfoot runners completed four running conditions: no instructions (CON), forefoot strike (FOR), increased cadence by 10% (CAD), and a combination of both (CADFOR). Three-dimensional kinematics were recorded, while ground reaction forces were processed to separate low- and high-frequency signals. Compared to CON, impact peak was reduced in FOR ($P < 0.001$, $d = 2.0$), CAD ($P = 0.006$, $d = 0.6$), and CADFOR ($P < 0.001$, $d = 2.3$). Instantaneous vertical loading rate was significantly reduced only in FOR ($P < 0.001$; $d = 0.6$) and CADFOR ($P < 0.001$; $d = 0.7$). Notably, adopting a forefoot strike pattern reduced high-frequency components of impact-related variables nearly three times more than cadence increase alone. The combination of forefoot strike and increased cadence produced the largest reduction in high-frequency impact components, suggesting it may be the most effective retraining strategy for potentially lowering RRI risk.

Introduction

Running is among the most widely practised physical activities worldwide, due to its accessibility, affordability, and its well-established physical and mental health benefits (Videbæk et al., 2015). However, these advantages are limited by the high incidence of running-related injuries (RRIs) (Videbæk et al., 2015). For decades, impact-related biomechanical parameters have been considered potential risk factors for overuse injuries (Gruber, 2023). This assumption largely stems from animal studies showing that repetitive impacts can cause early cartilage damage in the knees of rats and guinea pigs (Radin et al., 1973; Simon et al., 1972). Despite this, evidence supporting a direct relationship between impact-related parameters and RRIs in humans remains limited (Gruber, 2023).

Traditionally, impact-related parameters have been assessed using time-domain analysis (Gruber, 2023). During running, the vertical ground reaction force (vGRF) typically presents two distinct components: a passive peak, often referred to as the impact peak, and an active peak, associated with the propulsion phase of movement (Nigg et al., 1987). However, time-domain analysis may not always be optimal for capturing impact characteristics (Shorten & Mientjes, 2011). Factors such as footstrike pattern, running speed, and footwear can alter the timing and amplitude of the impact peak, potentially leading to its overlap with the active peak and compromising the accuracy of analysis (Gruber et al., 2015; Shorten & Mientjes, 2011).

As a result, frequency-domain analysis has emerged as a promising alternative for isolating impact forces during running (Shorten & Mientjes, 2011). Notably, a recent randomised controlled trial involving over 800 recreational runners demonstrated that time-domain impact variables were not associated with the risk of RRIs (Malisoux et al., 2022). In contrast, the same variables, when examined using frequency-domain analysis in the same population, were significantly associated with RRI risk (Malisoux et al., 2021). These findings highlight the need for targeted interventions aimed at reducing the high-frequency components of impact-related variables as a potential strategy for injury prevention.

Running retraining, which typically involves transitioning to a forefoot strike pattern or increasing running cadence, has shown promising effects on impact-related variables in time-domain analyses (Doyle et al., 2022). Adopting a forefoot strike pattern has been associated with reductions six months after intervention in both the average vertical loading rate (AVLR) and the instantaneous vertical loading rate (IVLR) by 49.7% and 41.7%, respectively (Futrell et al., 2020). Similarly, increasing running cadence by 7.5% has been reported to reduce AVLR six months after intervention by approximately 16% (Futrell et al., 2020). However, despite their efficacy in time-domain analysis, the effects of these retraining strategies on low- and high-frequency components of impact-related variables remain unknown.

The aim of the present study was to investigate the effects of running retraining interventions on impact-related parameters assessed through frequency-domain analysis. Specifically, the research objective was to examine the influence of adopting a forefoot strike pattern or increasing running cadence by 10% on the high- and low-frequency components of impact forces during running. We hypothesised that both interventions will result in a reduction in AVLR and the magnitude of the impact peak in the frequency-domain (Doyle et al., 2022).

Materials and methods

Participants

The required sample size was calculated using G*Power software (version 3.1.9.2, Germany). A total of 24 participants per group was estimated to be necessary to detect a statistically significant difference in AVLR, assuming an effect size of 0.25, a statistical power of 0.80, and an alpha level of 0.05. Healthy recreational runners were recruited for this retrospective study between September 2024 and November 2024 using social media platforms, flyers, and online advertisements at popular local running competitions and running shoe stores, and via athletics federations.

Eligibility criteria included age between 18 and 55 years, running with a rearfoot strike pattern, running at least 10 km per week for at least one year, no RRIs in the last three months prior to testing, having a European shoe size between 38 and 46 (approximately US men's sizes 6 to 12). This study was approved by the local ethics committee (N°2024/231).

Experimental protocol

Biomechanical variables were collected on an indoor 27.5 m straight running track. Participants performed, with standardised running footwear (®Kalenji, Jogflow 100.1), five continuous running sessions of five minutes each, consisting of repeated back-and-forth runs at a speed of 10 km/h (±5%). The first session consisted of a running speed and running footwear familiarisation. Then, the second session was considered as the “control” condition. Finally, the last three conditions were performed in a random order: “cadence”, “forefoot” and “forefoot and cadence”. According to the literature, a minimum of 25 steps per condition was collected on the force plates to ensure sufficient data (Oliveira & Pirscoveanu, 2021). The running speed was verified in real-time using four time gates positioned every six meters on the running track. The experimental setup is illustrated in Figure D.1.

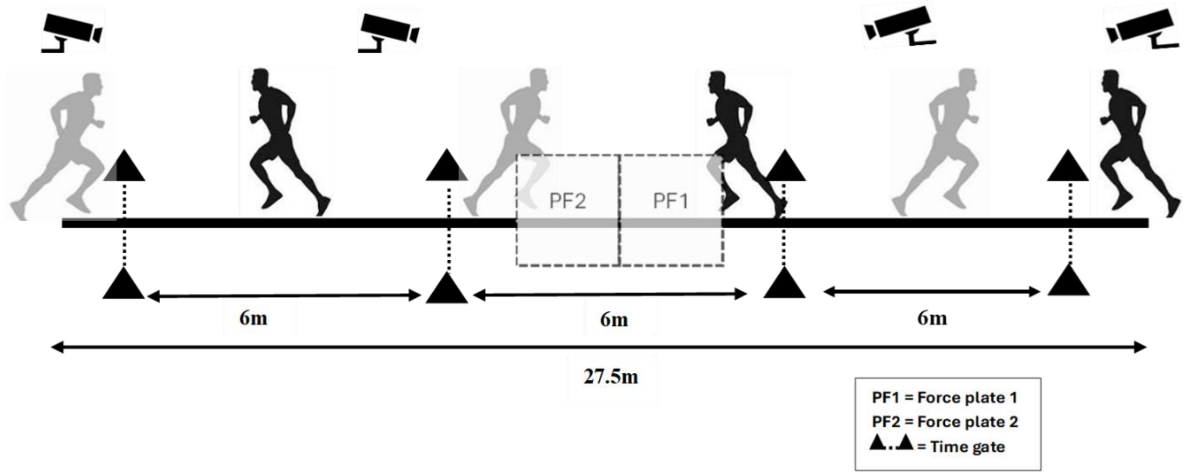


Figure D-1: Illustration of the experimental setup.

Conditions description:

The control condition (CON) involved participants running "as usual". Runners with a non-rearfoot strike pattern were excluded from the analysis at this point. The cadence condition (CAD) consisted of running with a 10% higher running step rate compared to the step rate measured during the control condition using a metronome. The forefoot condition (FOR) consisted of running with a non-rearfoot strike pattern. The experimenter advised the runners to land on the ball of their foot. Finally, the cadence and forefoot condition (CADFOR) consisted of combining a non-rearfoot strike pattern with a 10% higher running step rate compared to the step rate measured during the control condition using a metronome. A period of self-determined recovery was allowed between the trials to minimise fatigue.

Data collection:

Three-dimensional kinematic data were collected using an optical motion capture system (Qualisys AB, Gothenburg, Sweden) equipped with nine cameras operating at 200 Hz. Five markers were placed on the following landmarks: left and right calcaneus, left and right heads of the fifth metatarsals, and pelvis (midpoint between the left and right posterior superior iliac spines).

The ground reaction force (GRF) data were simultaneously captured using two consecutive force plates (Kistler, Kistler Group, Switzerland) at a sampling rate of 1000 Hz.

Data processing

The stance phase was defined between the instant when the vertical GRF increased above 20 N and the instant when it fell below 20 N. The signal present in the vertical GRF was further analysed using the script provided by Blackmore et al. (2016). The vertical GRF signal was decomposed, for each stance phase, into high and low-frequency components (10 Hz as cutoff value) using the Discrete Fourier Transform (Blackmore et al., 2016; Gruber et al., 2015; Shorten & Mientjes, 2011). Both high and low-frequency components were then recomposed into the time-domain using the Inverse Fourier Transform to form the two new signals (the high and low-frequency signals, respectively – Figure D.2). The impact peak, average and instantaneous vertical loading rate and time-to-impact peak of the high-frequency signal were extracted. Likewise, active peak and time to active peak of the low-frequency signal were also extracted. Impact peak was defined as the maximal value of the high-frequency signal, and time-to-impact peak was defined as the time from initial contact to impact peak. Instantaneous vertical loading rate was the maximal slope of the high-frequency signal during the same period. Average vertical loading rate was calculated as the average slope in the high-frequency signal between 20 and 80% of the period between initial contact and impact peak (Blackmore et al., 2016). Active peak was the highest value observed in the low-frequency signal, while time to active peak was defined as the time between initial contact and active peak. Force characteristics were normalised by the participant's body weight.

Each foot was considered as the segment between the heel and the head of the fifth metatarsal. The footstrike angle at initial contact was calculated for both feet using the method described by previous authors (Altman & Davis, 2012). The footstrike angle was defined by subtracting the foot angle in a standing position from the foot angle at footstrike. A positive footstrike angle indicated dorsiflexion. The cadence was calculated from the total number of left and right foot strikes per passage within the 3D camera capture volume (approximately eight meters in the middle of the track). The running speed was estimated from the derivative of the pelvis marker position.

Kinematic variables were calculated for each gait cycle occurring within the 3D camera capture volume during the five-minute recording and then averaged per subject. Spatio-temporal variables were calculated for each passage within the 3D camera capture volume during the same period and also averaged per subject. Kinetic data were calculated for each gait cycle performed on one of the two force plates. Trials were considered valid when the participant's foot landed entirely on one force plate or partially on both, in which case the signals from both plates were combined. Data from both limbs were averaged.

Statistical analysis

Statistical analysis was performed using JASP software. The significance level was set at 5%. Initially, a descriptive analysis of the sample was conducted by calculating the mean, standard deviation, minimum, and maximum of the individual variables (age, height, weight, running experience, and training habits) of the participants.

Before analysing the main outcome variables, a repeated-measures ANOVA was performed to compare the running speed, foot strike angle, and cadence across the four conditions (control, cadence, forefoot, and forefoot + cadence). Mauchly's test of sphericity was systematically conducted, and Greenhouse–Geisser corrections were applied to the p-values when necessary.

Subsequently, a repeated-measures ANOVA was conducted to compare the impact-related parameters in the high-frequency signal (impact peak, time-to-impact peak, instantaneous and average vertical loading rate) and low-frequency signal (active peak, time to active peak) across the four conditions. Partial eta squared (η^2) was used to estimate effect sizes, with values of 0.01, 0.06, and 0.14 interpreted as small, medium, and large effects, respectively (Hopkins et al., 2009). When significant differences were found, a post-hoc analysis was performed with a Bonferroni correction. The mean difference and its 95% confidence interval (95% CI) were calculated for each post-hoc analysis. Cohen's *d* effect size and its 95% CI were also computed, with effect sizes interpreted as small (d = 0.2), medium (d = 0.5), and large (d = 0.8) (Hopkins et al., 2009).

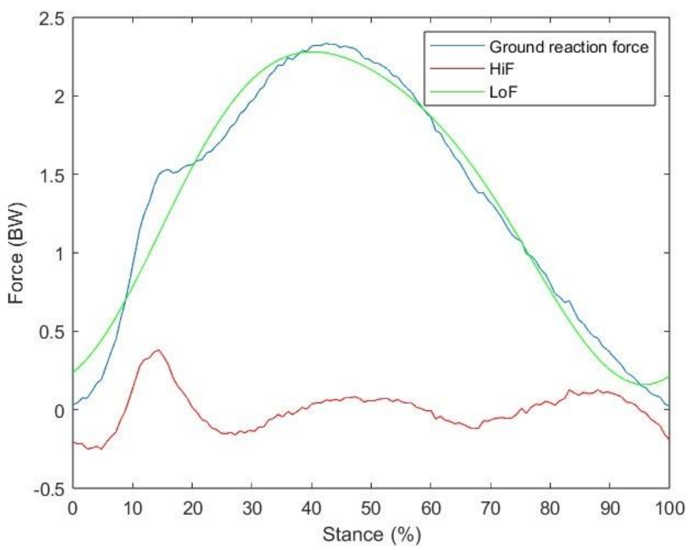


Figure D-2: Example of curves from one participant showing an identified impact peak on the vertical ground reaction force (GRF) signal.
The blue line represents the participant's vertical GRF signal, while the red and green lines correspond to the reconstructed high-frequency (HiF) and low-frequency (LoF) components, respectively.

Results

Sample description

Data were collected for 26 runners (24 males, 2 females, age = 22.7 ± 2.5 years; mass = 70.4 ± 8.7 kg, height = 1.74 ± 0.06 m, personal best in 5.000 metres race = 21.3 ± 3.7 minutes, volume per week = 23.5 ± 20.0 km, running experience = 5.7 ± 4.4 years).

Effect of conditions on running speed, cadence and footstrike angle

Repeated measures ANOVA highlighted a significant difference in footstrike angle between conditions ($P < 0.001$; $\eta^2 = 0.948$). Post-hoc analysis indicated that footstrike angle was significantly smaller in FOR condition compared to CON (diff [95%CI]: 21.7° [19.5 – 23.9]; $P < 0.001$; *d* [95%CI] = 6.2 [4.5 – 7.9]) and CAD (diff [95%CI]: 19.7° [17.5 – 22.0]; $P < 0.001$; *d* [95%CI] = 5.6 [4.1 – 7.1]) conditions. Similarly, footstrike angle was significantly smaller in CADFOR compared to CON (diff [95%CI]: 22.3° [20.0 – 24.5]; $P < 0.001$; *d* [95%CI] = 6.3 [4.7 – 8.0]) and CAD (diff [95%CI]: 20.3° [18.1 – 22.5]; $P < 0.001$; *d* [95%CI] = 5.8 [4.3 – 7.2]).

Repeated measures ANOVA highlighted no significant difference in running speed between conditions ($P = 0.129$; η^2: 0.948).

Repeated measures ANOVA highlighted a significant difference in cadence between conditions ($P < 0.001$; $\eta^2 = 0.879$). Post-hoc analysis indicated that cadence was significantly higher in CAD condition compared to CON (diff [95%CI]: 15.7 step/min [8.4 – 13.3]; $P < 0.001$; *d* [95%CI] = 2.0 [1.1 – 3.0]) and FOR (diff [95%CI]: 10.9 step/min [17.5 – 22.0]; $P < 0.001$; *d* [95%CI] = 1.4 [0.7 – 2.1]) conditions. Similarly, cadence was significantly higher in CADFOR compared to CON (diff [95%CI]: 17.3 step/min [14.8 – 19.7]; $P < 0.001$; *d* [95%CI] = 2.2 [1.3 – 3.2]) and FOR (diff [95%CI]: 12.4 step/min [9.9 – 14.8]; $P < 0.001$; *d* [95%CI] = 1.6 [0.89 – 2.3]). All mean, standard deviations, p-values and effect sizes for the footstrike angle, running speed and running cadence for each condition are available in Table D.1.

Table D.1: Comparison of footstrike angle, running speed and running cadence between running conditions to ensure protocol validity.

Variables	Conditions	Mean ± SD	P-value	ŋ²	Post-hoc test
Footstrike angle (degrees)	Control (1)	17.9 ± 3.5	< 0.001	0.948	
	Cadence (2)	16.0 ± 4.1			
	Forefoot (3)	-3.7 ± 2.9			(3) < (1)***, (2)***
	Cadence + Forefoot (4)	-4.3 ± 3.1			(4) < (1)***, (2)***
Running speed (km/h)	Control (1)	9.85 ± 0.17	=0.129	0.076	
	Cadence (2)	9.92 ± 0.19			
	Forefoot (3)	9.89 ± 0.14			
	Cadence + Forefoot (4)	9.82 ± 0.21			
Cadence (step/min)	Control (1)	158.0 ± 7.6	< 0.001	0.879	
	Cadence (2)	173.8 ± 6.8			(2) > (1)***, (3)***
	Forefoot (3)	162.9 ± 7.9			
	Cadence + Forefoot (4)	175.3 ± 7.6			(4) > (1)***, (3)***

*Repeated measures ANOVA followed by Bonferroni's correction : P > 0.05, not significant; * symbol represents a p-value for post-hoc test inferior to 0.05; ** symbol represents a p-value for post-hoc test inferior to 0.01; *** symbol represents a p-value for post-hoc test inferior to 0.001. Conditions are represented by a number from 1 to 4 in post-hoc test. ANOVA, Analysis of Variance; SD, Standard deviation.*

Effect of running retraining on low- and high-frequency components of impact-related parameters

Effect of running retraining on high-frequency components of impact-related parameters

Repeated measures ANOVA highlighted a significant difference in impact peak between conditions (P < 0.001; ŋ² = 0.773). Post-hoc analysis indicated that impact peak was significantly smaller in FOR condition compared to CON (diff [95%CI]: 0.25 BW [0.19 – 0.31]; P < 0.001; d [95%CI] = 2.0 [1.1 – 3.0]) and CAD (diff [95%CI]: 0.18 BW [0.12 – 0.24]; P < 0.001; d [95%CI] = 1.4 [0.6 – 2.2]) conditions. Similarly, impact peak was significantly smaller in CADFOR compared to CON (diff [95%CI]: 0.29 BW [0.23 – 0.35]; P < 0.001; d [95%CI] = 2.3 [1.2 – 3.4]) and CAD (diff [95%CI]: 0.21 BW [0.15 – 0.27]; P < 0.001; d [95%CI] = 1.7 [0.8 – 2.5]) conditions. Finally, impact peak was significantly smaller in CAD compared to CON (diff [95%CI]: 0.07 BW [0.01 – 0.13]; P = 0.006; d [95%CI] = 0.6 [0.06 – 1.1]) condition. Repeated measures ANOVA highlighted a significant difference in time-to-impact peak between conditions (P = 0.049; ŋ² = 0.132). Post-hoc analysis indicated that time-to-impact peak was significantly higher in CADFOR condition compared to CON (diff [95%CI]: 0.005 s [3.9×10^{-4} – 0.009]; P = 0.024; d [95%CI] = 0.6 [4.2×10^{-5} – 1.2]) condition.

Repeated measures ANOVA highlighted a significant difference in AVLR between conditions (P < 0.001; ŋ² = 0.743). Post-hoc analysis indicated that AVLR was significantly smaller in FOR condition compared to CON (diff [95%CI]: 16.3 $BW.s^{-1}$ [12.1 – 20.4]; P < 0.001; d [95%CI] = 2.0 [1.0 – 2.9]) and CAD (diff [95%CI]: 11.8 $BW.s^{-1}$ [7.7 – 16.0]; P < 0.001; d [95%CI] = 1.4 [0.6 – 2.2]) conditions. Similarly, AVLR was significantly smaller in CADFOR compared to CON (diff [95%CI]: 18.5 $BW.s^{-1}$ [14.3 – 22.6]; P < 0.001; d [95%CI] = 2.2 [1.2 –

3.3]) and CAD (diff [95%CI]: 14.0 BW.s^{-1} [9.9 – 18.2]; $P < 0.001$; *d* [95%CI] = 1.7 [0.8 – 2.5]) conditions. Finally, AVLR was significantly smaller in CAD compared to CON (diff [95%CI]: 4.4 BW.s^{-1} [0.2 – 8.5]; $P = 0.029$; *d* [95%CI] = 0.5 [0.01 – 1.1]) condition.

Repeated measures ANOVA highlighted a significant difference in IVLR between conditions ($P < 0.001$; $\eta^2 = 0.427$). Post-hoc analysis indicated that IVLR was significantly smaller in FOR condition compared to CON (diff [95%CI]: 40.8 BW.s^{-1} [20.2 – 61.3]; $P < 0.001$; *d* [95%CI] = 0.6 [0.2 – 1.03]) and CAD (diff [95%CI]: 28.0 BW.s^{-1} [7.4 – 48.5]; $P = 0.003$; *d* [95%CI] = 0.4 [0.05 – 0.7]) conditions. Similarly, IVLR was significantly smaller in CADFOR compared to CON (diff [95%CI]: 47.6 BW.s^{-1} [27.1– 68.2]; $P < 0.001$; *d* [95%CI] = 0.7 [0.2 – 1.1]) and CAD (diff [95%CI]: 34.8 BW.s^{-1} [14.3 – 55.4]; $P < 0.001$; *d* [95%CI] = 0.5 [0.1 – 0.9]) conditions. All mean, standard deviations, p-values and effect sizes for the impact peak, time-to-impact peak, AVLR and IVLR for each condition are available in Table D.2. Individual responses of the impact peak, time-to-impact peak, AVLR and IVLR across running retraining interventions are show in Figure D.3.

Effect of running retraining on low-frequency components of impact-related parameters

Repeated measures ANOVA highlighted a significant difference in active peak between conditions ($P < 0.001$; $\eta^2 = 0.501$). Post-hoc analysis indicated that active peak was significantly smaller in CAD condition compared to CON (diff [95%CI]: 0.08 BW [0.02 – 0.13]; $P < 0.001$; *d* [95%CI] = 0.3 [0.06 – 0.7]), FOR (diff [95%CI]: 0.17 BW [0.11 – 0.22]; $P < 0.001$; *d* [95%CI] = 0.8 [0.3 – 1.2]) and CADFOR (diff [95%CI]: 0.12 BW [0.06 – 0.18]; $P < 0.001$; *d* [95%CI] = 0.6 [0.2 – 0.9]) conditions. Conversely, active peak was significantly higher in FOR compared to CON (diff [95%CI]: 0.09 BW [0.03 – 0.14]; $P < 0.001$; *d* [95%CI] = 0.4 [0.09 – 0.7]) condition.

Repeated measures ANOVA highlighted a significant difference in time to active peak between conditions ($P < 0.001$; $\eta^2 = 0.435$). Post-hoc analysis indicated that time to active peak was significantly smaller in CAD condition compared to CON (diff [95%CI]: 0.01 s [0.006 – 0.014]; $P < 0.001$; *d* [95%CI] = 0.6 [0.2 – 1.0]) and FOR (diff [95%CI]: 0.006 s [0.001 – 0.010]; $P = 0.004$; *d* [95%CI] = 0.3 [0.04 – 0.7]) conditions. Similarly, time to active peak was significantly smaller in CADFOR condition compared to CON (diff [95%CI]: 0.01 s [0.006 – 0.014]; $P < 0.001$; *d* [95%CI] = 0.6 [0.2 – 1.0]) and FOR (diff [95%CI]: 0.006 s [0.001 – 0.010]; $P = 0.004$; *d* [95%CI] = 0.3 [0.03 – 0.7]) conditions. Finally, time to active peak was significantly smaller in FOR condition compared to CON (diff [95%CI]: 0.004 s [8.2×10^{-6} – 0.008]; $P = 0.049$; *d* [95%CI] = 0.2 [0.03 – 0.6]) condition. All mean, standard deviations, p-values and effect sizes for the active peak and time to active peak for each condition are available in Table D.2. Individual responses of the active peak and time to active peak across running retraining interventions are show in Figure D.3.

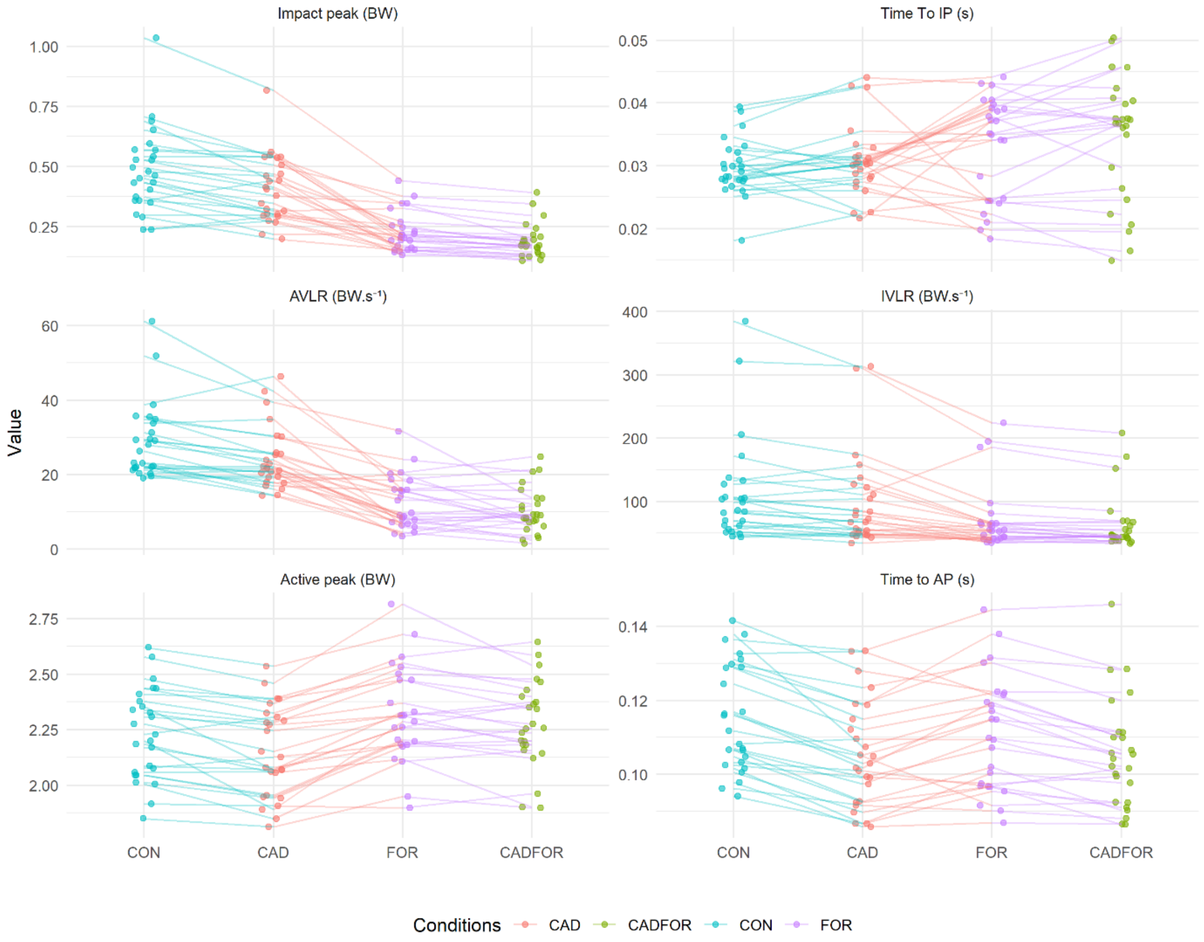


Figure D-3: Individual responses of impact-related parameters across running retraining interventions. Facets display individual data points per condition, grouped by subject. Metrics include impact peak, time to impact peak (time to IP), average vertical loading rate (AVLR) and instantaneous vertical loading rate (IVLR) of the HiF and active peak, time to active peak (Time to AP) of the LoF.

Table D.2: Comparison of impact-related parameters of high and low frequency signals between distinct running retraining intervention.

Variables	Conditions	Mean ± SD	P-value	η²	Post-hoc test
Impact peak (Bw)	**Control (1)**	0.48 ± 0.17	**< 0.001**	0.773	
	Cadence (2)	0.40 ± 0.13			(2) < (1)**
	Forefoot (3)	0.22 ± 0.08			(3) < (1)***, (2)***
	Cadence + Forefoot (4)	0.19 ± 0.07			(4) < (1)***, (2)***
Time to impact peak (s)	**Control (1)**	0.030 ± 0.004	**=0.049**	0.132	
	Cadence (2)	0.031 ± 0.006			
	Forefoot (3)	0.033 ± 0.008			
	Cadence + Forefoot (4)	0.034 ± 0.010			(4) > (1)*
AVLR ($Bw.s^{-1}$)	**Control (1)**	28.8 ± 10.2	**< 0.001**	0.743	
	Cadence (2)	24.4 ± 8.4			(2) < (1)**
	Forefoot (3)	12.5 ± 7.0			(3) < (1)***, (2)***
	Cadence + Forefoot (4)	10.3 ± 6.0			(4) < (1)***, (2)***
IVLR ($Bw.s^{-1}$)	**Control (1)**	112.5 ± 83.3	**< 0.001**	0.427	
	Cadence (2)	99.7 ± 74.1			
	Forefoot (3)	71.7 ±51.4			(3) < (1)***, (2)**
	Cadence + Forefoot (4)	64.8 ± 44.7			(4) < (1)***, (2)***
Active peak (Bw)	**Control (1)**	2.23 ± 0.20	**< 0.001**	0.501	
	Cadence (2)	2.15 ± 0.20			(2) < (1)***, (3)***, (4)***
	Forefoot (3)	2.32 ± 0.21			(4) > (1)***
	Cadence + Forefoot (4)	2.27 ± 0.19			
Time to active peak (s)	**Control (1)**	0.115 ± 0.015	**< 0.001**	0.435	
	Cadence (2)	0.105 ± 0.014			(2) < (1)***, (3)**
	Forefoot (3)	0.111 ± 0.016			(3) < (1)*
	Cadence + Forefoot (4)	0.106 ± 0.015			(4) < (1)***, (3)**

*Repeated measures ANOVA followed by Bonferroni's correction : P > 0.05, not significant; * symbol represents a p-value for post-hoc test inferior to 0.05; ** symbol represents a p-value for post-hoc test inferior to 0.01; *** symbol represents a p-value for post-hoc test inferior to 0.001. Conditions are represented by a number from 1 to 4 in post-hoc test. ANOVA, Analysis of Variance; SD, Standard deviation.*

Discussion

The research objective of this study was to examine the influence of adopting a forefoot strike pattern or increasing running cadence by 10% on the high- and low-frequency components of impact forces during running. Our results confirm the hypothesis that adopting a forefoot strike pattern or increasing the running cadence decreases the impact peak and the AVLR measured in the high-frequency signal compared to the control condition. Increasing the running cadence by 10% reduces the impact peak and AVLR measured in the high-frequency signal by 20% and 15%, respectively. Interestingly, adopting a forefoot strike pattern reduces the impact-related parameters measured in the high-frequency signal by nearly three times more than increasing running cadence by 10% alone (impact peak: -53%, AVLR: -57%). In addition, adopting a forefoot strike pattern also reduces the IVLR measured in the high-frequency signal whereas increasing running cadence alone does not affect the IVLR measured in the high-frequency signal. Finally, combining a 10% increase in running cadence and a forefoot strike pattern is the most efficient running retraining to reduce high-frequency components of impact-related parameters. Indeed, a combination of a 10% higher running cadence and forefoot strike pattern reduces the high-frequency components of the impact peak by 61%, the AVLR by 64%, the IVLR by 43% and increases the time-to-impact peak by 13%. The reduction in impact-related variables associated with forefoot striking may be attributed to changes in the point of initial contact and ankle stiffness (Lieberman et al., 2010). Rearfoot strike typically results in impact beneath the ankle joint, producing a plantarflexion moment. Therefore, the ankle transfers little translational energy into rotational energy, resulting in higher effective mass and increased impact forces (Lieberman et al., 2010). In contrast, forefoot strike initiates contact at the anterior portion of the foot, creating a dorsiflexion moment at the ankle, which is controlled by the triceps surae and the Achilles tendon (Lieberman et al., 2010). This mechanism allows a portion of the translational kinetic energy to be converted into rotational kinetic energy around the ankle, reducing effective mass due to lower ankle stiffness (Lieberman et al., 2010). On the other hand, increasing the running cadence reduces the centre of mass vertical displacement and stride length, thereby attenuating vertical impact forces (Hafer et al., 2015). Previous studies have already highlighted that adopting a forefoot strike pattern may reduce the high-frequency components of the impact-related parameters. Gruber et al. (2017) highlighted that adopting a forefoot strike pattern reduces the maximum power, frequency that peak power occurred, and the weighted mean pseudo-frequency compared to rearfoot strike (Gruber et al., 2015). In addition, Gruber et al. (2014) also highlighted that adopting a forefoot strike pattern reduces the peak tibial acceleration and signal power in the higher frequency range (9-20 Hz) compared to a rearfoot strike pattern (Gruber et al., 2014). Our findings are consistent with previous studies that conducted conventional time-domain analyses without separating the signal into low- and high-frequency components. Such studies report that transitioning to a forefoot strike pattern can acutely reduce AVLR by 31–47% and IVLR by 17–47%, while increasing cadence by 10% yields an approximate 8% reduction in AVLR but no measurable change in IVLR (T. L. Chen et al., 2016; Y. Huang et al., 2019; Laughton et al., 2003; Shih et al., 2013; Yong et al., 2018).

Interestingly, adopting a forefoot strike pattern appears to increase the active peak measured in the low-frequency signal, whereas a 10% increase in running cadence reduces it compared to the control condition. These findings are consistent with previous studies that conducted conventional time-domain analyses. Such studies suggest that a forefoot strike pattern may increase the active peak due to a greater peak ankle plantarflexion moment, which results from increased plantarflexion force during push-off (Williams et al., 2000). In contrast, increasing running cadence reduces step length and consequently lowers the propulsion demands at push-off, which may explain the observed reduction in active peak.

Recent results from a randomised controlled trial involving over 800 runners suggest that higher AVLR and shorter time-to-impact peak measured in the high-frequency signal are associated with increased risk of RRIs (Malisoux et al., 2021). Our findings indicate that a running retraining intervention combining a forefoot strike pattern and a 10% higher cadence may reduce the high-frequency components of the AVLR by 64% and increases the time-to-impact peak by 13%. Therefore, adopting a forefoot strike pattern and increasing running cadence may reduce the risk of RRIs by reducing the magnitude of the high-frequency components of the impact signal. However, a prospective study is needed to explore if an intervention targeting an impact reduction of the high-frequency signal could reduce the risk of RRIs.

Several limitations should be considered before generalising the results of this study. First, the study sample was predominantly male (n = 24), and sex-specific responses to running retraining may differ. Caution is therefore warranted when generalising the findings to female runners (Xie et al., 2022). Second, the protocol was conducted in a laboratory on a 27.5-metre straight runway, requiring participants to turn frequently, which may have introduced biomechanical variability and reduced gait stability compared to treadmill running (Isherwood et al., 2019). Third, a standardised running shoe was used to control for cushioning effects. Since participants were unfamiliar with the model, this may have influenced their natural running biomechanics (M. Huang et al., 2023).

Conclusion

In conclusion, adopting a forefoot strike pattern reduces high-frequency components of impact-related parameters nearly three times more than increasing running cadence by 10% alone. However, combining a forefoot strike pattern with a 10% increase in running cadence appears to be the most effective running retraining strategy for reducing high-frequency components of impact-related parameters. This combined approach may contribute to lowering the incidence of RRIs, although prospective interventional studies are required to confirm this potential benefit.

2. Effects of running technique alteration on the incidence of running-related-injury (Study 4).

Study 4: Minimalist footwear and softer running technique alter injury location but not incidence rate in recreational endurance runners

Accepted in American Journal of Sports Medicine.

ABRAN Guillaume[1,2], GRAMAGE Kevin[1,2], DELVAUX François[1,2], CROISIER Jean-Louis [1,2], SCHWARTZ Cédric[1].

[1] LAM – Motion Lab, Liège, Belgium. Electronic address: guillaume.abran@uliege.be.

[2] Department of physical activity and rehabilitation sciences, University of Liege, Liege, Belgium.

ABSTRACT

Background: Minimalist footwear and running retraining are often recommended by running coaches to reduce the risk of running-related injuries (RRIs) in endurance runners. However, despite their growing popularity, there is limited scientific evidence supporting their effectiveness.

Hypothesis/Purpose: This study investigated the impact of minimalist footwear and running retraining on the incidence rate (primary outcome) and location (secondary outcome) of RRIs in recreational endurance runners.

Study Design: Randomised controlled trial.

Methods: A total of 140 rearfoot runners were randomly assigned to three groups: minimalist footwear (MG, n = 47), running retraining (RRG, n = 47), and control (CG, n = 46). The MG received minimalist footwear, while the RRG completed six retraining sessions aimed at running softer, adopting a non-rearfoot strike and increasing the initial step rate by 7.5%. The CG followed a stretching programme. Running biomechanics were assessed at baseline and at two, six, and 12 months. RRIs were recorded according to recent consensus guidelines. The primary outcome was RRI incidence rate, analysed using adjusted (injury history) and unadjusted Cox regression models across intention-to-treat, as-treated, and per-protocol analyses.

Results: Sixty-four RRIs were reported, including 55 overuse and nine acute injuries. No significant differences in the incidence rate of RRIs, the primary outcome, were observed between groups across all analyses. No significant difference in overall RRI incidence rate was observed between groups in any analysis (intention-to-treat, as-treated, per-protocol).. There were also no differences in injury duration across groups in all analyses. However, the secondary outcome showed that injury distribution varied between groups in both as-treated and per protocol analyses, with more hip injuries in CG (P = 0.015 and P = 0.01, respectively) and more foot injuries in RRG (P = 0.018 and P = 0.04, respectively).

Conclusion: Contrary to popular belief, neither minimalist footwear nor a softer running technique reduced the overall incidence rate of RRIs. However, running retraining altered injury patterns, decreasing hip injuries but increasing foot injuries.

Introduction

Running is one of the most popular physical activities in the world because of its accessibility, cost-effectiveness, and benefits to mental and physical health (Videbæk et al., 2015). Unfortunately, these benefits are counterbalanced by the high incidence of running-related injuries (RRIs). RRIs per 1000 hours of running ranged from a minimum of 2.5 to a maximum of 33.0 (Videbæk et al., 2015). This variation between studies is notably due to population heterogeneity, insufficient follow-up duration, or inconsistent definitions of RRIs (Ceyssens et al., 2019).

Altering running technique has been proposed as a strategy to reduce the risk of running-related injuries by decreasing the overall load on the body (Barton, 2018). The most common methods to alter running technique can be divided into two categories: conscious alteration (running retraining interventions) and unconscious alteration (transition to minimalist footwear) of the running technique (Davis et al., 2017). To date, only one prospective study with adequate follow-up (≥ 6 months) has assessed the impact of running retraining on injury rates (Chan et al., 2018). This study, using real-time visual feedback, reported a 62% reduction in injury occurrence. However, this study was classified as low-certainty evidence in a recent systematic review due to two key issues: first, the participants were novice runners (less than one year of experience); second, compliance with the retraining protocol during follow-up was not reported (Alexander et al., 2022; Gruber, 2023). On the other hand, transition to minimalist shoes, has been considered as a potential strategy to reduce injuries, particularly by promoting a so-called "more natural" running style (Lieberman, 2012). However, running with minimalist footwear may not reduce RRI incidence in comparison to running with traditional footwear in endurance runners (Fuller, Thewlis, Buckley, et al., 2017). Unfortunately, this conclusion is based on a single study with a small sample size (N = 61) that implemented a complete transition to minimalist shoes. A complete transition to minimalist shoes may not represent reality, as endurance runners tend to alternate between shoe models (Malisoux, Ramesh, et al., 2015).

The first objective of this study was to compare the effects of a running retraining intervention for adopting a softer running technique and transition to minimalist footwear on the incidence rate of RRIs in recreational endurance runners. The second objective was to compare the effects of running retraining intervention and minimalist footwear on the location of RRIs in recreational endurance runners. We hypothesise that 1) runners following a running retraining programme will have a lower incidence rate of RRIs than runners in the control group; 2) runners implementing minimalist footwear will have a comparable incidence rate of RRIs to runners in the control group; 3) runners following a running retraining programme would have a lower number of knee RRIs but a higher number of foot RRIs than runners in the control group (Chan et al., 2018; Fuller, Thewlis, Buckley, et al., 2017; Morris et al., 2020).

Materials and methods

A 12-month randomised controlled trial was designed to compare the effect of minimalist footwear and running retraining on RRI incidence rate in recreational long-distance runners. The protocol of this study follows the CONSORT (Consolidated Standards of Reporting Trials) recommendations. It was prospectively registered at ClinicalTrials.gov (NCT05499871). This study was approved by the local ethics committee.

Participants

Sample size was estimated via simulation, based on the primary outcome: time to running-related injury. Assuming cumulative injury incidences of 40%, 16%, and 52% in the control, running retraining, and minimalist footwear groups, respectively, we used a Monte Carlo approach to account for the three-group comparison within a Cox proportional hazards model. For each candidate sample size (20 to 80 participants per group), 1,000 datasets were simulated with group-specific event probabilities and exponential survival times. A global likelihood ratio test was applied to each model to assess the effect of group allocation. Statistical power was defined as the proportion of simulations yielding a p-value < 0.05. Based on this approach, a sample size of 46 participants per group (138 in total) was estimated to achieve 80% power (Chan et al., 2018; Fuller, Thewlis, Buckley, et al., 2017).

Healthy recreational runners were recruited for this prospective study between September 2022 and September 2023 using social media platforms, flyers, and online advertisements at popular local running competitions

Eligibility criteria included: age 18-55 years, running ≥10 km/week for ≥1 year, no injuries in the past three months. All participants were habitual rearfoot strikers who wore cushioned shoes and had never tried minimalist shoes or tried to modify their running technique.

Participants were randomly allocated to the control (CG), minimalist (MG), or running retraining (RRG) groups, with stratified randomisation based on age and weekly mileage in blocks of six.

Footstrike determination and step rate

After five minutes of running, a one-minute video recorded at 240 Hz with a high-speed camera captured participants running at comfort speed on a treadmill. Frame-by-frame analysis with

DartfishTM (version Prosuite 10.0, Dartfish, Alpharetta, Georgia) allowed identification of each runner's dominant leg footstrike pattern (non-rearfoot or rearfoot strike). The footstrike pattern analysis showed high reliability (ICC = 0.88) (Murray et al., 2018). Step rate was measured by timing 50 strides (100 steps), with excellent intra- and inter-rater reliability (ICC > 0.98).

Treatment arms

Participants allocated to the RRG received four sessions of real-time feedback supervised by an instructor in a laboratory on a treadmill at comfort speed, and carried out two unsupervised sessions outside the laboratory, distributed over two weeks. Real-time feedback sessions consist of running softer, adopting a non-rearfoot strike and increasing the initial step rate by 7.5% (Willy, Buchenic, et al., 2016). An increase in step rate of 7.5% above the preferred cadence is sufficient to reduce both the instantaneous vertical loading rate (- 18.9%) and average vertical loading rate (- 17.9%), with large effect sizes (Willy, Buchenic, et al., 2016). Participants were instructed to run softer, to land on the ball of their foot and match their steps to an audible metronome set to the new rate (Barton et al., 2016). The retraining protocol employed a faded feedback approach (Davis, 2011) (Supplemental Table 1). The first two sessions lasted 15 minutes and were supervised by an instructor in the laboratory. Then, one session of 15 minutes was performed by each participant in their usual running environment using a metronome and focusing on running softer and adopting a non-rearfoot strike pattern. The same approach was used during the second week of the running retraining programme, but each session lasted 20 minutes. The time with oral instructions and the metronome was faded from 12 minutes to 4 minutes during the last session (Davis, 2011). Participants were also encouraged to apply the new technique in a progressive running programme during the first two months and maintain it thereafter (Supplemental Table 2). This progressive running programme was supposed to provide a safe transition toward a forefoot strike pattern and was based on previous recommendations (Warne & Gruber, 2017).

Participants allocated to the MG received either trail minimalist footwear (Merrel trail glove 6; minimalist index = 78%) or road minimalist footwear (Topo athletic ST-4; minimalist index = 76%) according to their preferences. Like the RRG, participants were also encouraged to integrate into their own running training the same progressive running programme, where they had to wear the minimalist footwear. This progressive running programme was intended to provide safe minimalist footwear implementation. After the first two months, participants were encouraged to continue using minimalist footwear during their own running training.

The third group received a placebo static stretching protocol without any intensity, based on a previous study (Taddei et al., 2020). In general, endurance runners are at high risk of overuse injuries, and the literature suggests that stretching does not reduce their prevalence (C. Baxter et al., 2017). Therefore, this group could be considered as a control group in comparison with the other groups. Participants in the control group were instructed to perform the protocol in 5-minute sessions, three times per week.

Experimental protocol

Each participant was assessed at four time points: baseline, two months, six months, and 12 months of follow-up.

Questionnaire

Participants completed a baseline questionnaire assessing age, running experience, training volume, injury history, and recent 5000 m personal records. In subsequent sessions, they completed a post-test questionnaire with identical items. Runners also self-reported their average weekly running distance during the first two months (2-month questionnaire), the following four months (6-month questionnaire), and the final six months (12-month questionnaire). Additionally, at two months, participants in the intervention groups reported their adherence to the proposed running programme (0 = not at all to 3 = entirely). At six and 12 months, participants in the RRG indicated the frequency of using the new running technique (0 = less than one training session in five to 5 = every training session), while participants in the MG reported the weekly distance covered using minimalist footwear.

Running-related injuries

RRIs were defined according to a previous expert consensus (Yamato et al., 2015). Back injuries were also included among RRIs, given their reported incidence in running activities (Kakouris et al., 2021). Every two weeks, an e-mail was sent to all participants to ask whether any recent pain had limited or stopped their usual running practice (in terms of mileage, speed, duration, or training frequency). Participants who reported a running-related-injury were asked to fill-out a questionnaire in accordance with recent guidelines for reporting RRIs (Edouard & Tooth, 2024). RRI locations were categorised for each participant as follows: back injury (0 = no; 1 = yes), hip injury (0 = no; 1 = yes), knee injury (0 = no; 1 = yes), tibia injury (0 = no; 1 = yes), overuse foot injury (0 = no; 1 = yes), and traumatic foot injury (0 = no; 1 = yes).

Statistical analysis

Three statistical analyses were conducted to assess the effect of the interventions on injury rates. For both as-treated and per protocol analyses, only participants who attended at least two evaluation sessions were included. In the MG, inclusion required using minimalist footwear for at least 25% of weekly running distance at six months. In the RRG, participants had to demonstrate either a non-rearfoot strike or a step rate increase of at least 7.5% compared to baseline at six months. Participants from both groups who did not meet these criteria were either reclassified into the control group (as-treated analysis) or excluded from the analysis (per protocol analysis).

For each analysis, sample characteristics were compared between groups (CG, MG, RRG) using one-way ANOVA for continuous variables (age, running experience, baseline comfort speed) and chi-square tests for categorical variables (sex). Repeated-measures ANOVA assessed changes in BMI, weekly distance, training volume, and step rate over the 12-month follow-up. Adherence to the intervention was analysed via percentage distributions. In the RRG, frequency of use of the new running technique was reported at six and 12 months. In the MG, adherence was assessed by the ratio of weekly distance run with minimalist footwear to total weekly distance.

Cox proportional hazards models were used to compare distance-to-injury (primary outcome) between groups for the three statistical analyses. In line with previous recommendations, a distance-to-injury analysis was favoured over a time-to-injury analysis (Malisoux, Nielsen, et al., 2015). Distance to injury (in kilometers) was defined from baseline to the first reported injury. Distance to injury was estimated based on self-reported weekly running distances at two, six, and 12 months. Models included history injury (0 = No; 1 = Yes) as a priori covariate. Both unadjusted and adjusted models were tested, and model fit was evaluated using likelihood ratio tests (LRT) and Akaike information criterion (AIC).

One-way ANOVA compared RRI duration across groups for the three statistical analyses. Fisher's exact test examined injury location (secondary outcome) for each statistical analysis (back, hip, knee, tibia, overuse foot, traumatic foot), with post-hoc pairwise tests and Bonferroni correction as needed. When Mauchly's test indicated a violation of sphericity ($p < 0.05$), the Greenhouse-Geisser correction was applied. Effect sizes were reported using partial eta squared (small: $\eta^2 = 0.01$; medium: $\eta^2 = 0.06$; large: $\eta^2 = 0.14$) and Cohen's d (small: $d = 0.2$; medium: $d = 0.5$; large: $d = 0.8$) for post-hoc tests (Hopkins et al., 2009; Maher et al., 2013). All analyses were performed in R (v4.1.1), with $\alpha = 0.05$ (Fox, 2005).

Results:

In total, 182 participants were assessed for eligibility. A flowchart is provided in Supplemental Figure 1.

Sample characteristics

No significant group differences were found at baseline for age, sex, running experience, or comfort speed in the intention-to-treat, as-treated and per protocol analyses. Over the 12-month follow-up, BMI and running volume remained similar across groups. A significant Group × Time interaction showed that weekly distance differed between groups across the four evaluation periods in both as-treated and per protocol analyses. Post-hoc analyses showed that the MG increased their weekly running distance at 12 months compared to both baseline and two-month values. A significant Group × Time interaction indicated that step rate at comfortable speed differed between groups across the four evaluation periods in all analyses ($P < .001$). Post-hoc analyses further revealed that the RRG significantly increased their step rate at comfortable speed at two, six, and 12 months compared to baseline. Moreover, step rate in the RRG was significantly higher than step rate of the CG and MG at two, six, and 12 months. Detailed sample characteristics of intention-to-treat analysis is presented in Table D.3. Detailed sample characteristics of as-treated and per protocol analyses are presented in Supplemental Table 3 and Supplemental Table 4.

Adherence to the running retraining interventions

In the MG, 73.6% of participants reported adhering mostly or completely to the running programme, while 77.2% of participants in the RRG indicated similar compliance. After six months, 83.7% of RRG participants incorporated the newly learned running technique into at least half of their training sessions. This figure increased to 89.8% in the RRG sample at 12 months follow-up. In the MG, participants reported running with minimalist footwear for 46.8% (± 35.5) of their total weekly distance at six months, and 42.1% (± 33.6) at twelve months. All details of adherence to running retraining interventions are available in Supplemental Table 5.

Effects of running retraining interventions on the primary and secondary outcomes

Participants reported a total of 64 RRIs, including 55 overuse RRIs and 9 acute RRIs at one year follow-up. Seven participants sustained two different RRIs. The locations of RRIs were the foot (50.8%), tibia (15.9%), knee (14.3%), hip (14.3%), back (3.1%), and hamstring (1.6%). All the details of the diagnosis of RRIs according to both analyses are presented in Table D.4.

Cox regression model 1 (unadjusted) and model 2 (adjusted) of the intention-to-treat, as-treated and per protocol analyses showed no significant difference between CG and MG or CG and RRG on RRI incidence rate (Table D.5).

The ANOVA-1 showed that duration of injury was not different between CG (24.9 ± 18.1 days), MG (18.1 ± 19.5 days) and RRG (27.3 ± 26.6 days) in the intention-to-treat analysis ($P = .41$, $\eta^2 = 0.03$). ANOVA-1 showed similar results for the as-treated (CG: 24.2 ± 20.9 days, MG: 14.9 ± 9.1 days, and RRG: 29.7 ± 28.0 days; $P = .14$, $\eta^2 = 0.07$) and per protocol analyses (CG: 25.4 ± 19.3 days, MG: 15.0 ± 9.6 days, and RRG: 27.1 ± 25.4 days; $P = .28$, $\eta^2 = 0.06$).

Fisher's exact tests revealed no significant differences between groups in the number of knee, tibia, and overuse foot RRIs in the intention-to-treat analysis. In contrast, hip injuries differed significantly between groups in the intention-to-treat ($P < .001$), as-treated ($P = .003$) and per protocol ($P = 0.002$) analyses with post-hoc comparisons indicating higher injury rates in the CG compared to the RRG ($P = .003$, $P = .015$ and $P = 0.01$, respectively). In both as-treated and per protocol analyses, overuse foot RRIs also differed significantly between groups ($P = .013$ and $P = 0.04$, respectively), with post-hoc analysis again identifying a difference between the CG and RRG ($P = .018$ and $P = 0.04$, respectively). No significant group differences were found for knee and tibia injuries in both as-treated and per protocol analyses. All the details on RRI locations across both analyses are presented in Table D.4.

Table D.3: Characteristics at baseline, two months, six months, and 12 months (except for constant variables such as age, running experience, and comfort speed) for all participants included in the intention-to-treat analysis

Variables	Group	Baseline (1)	Two months (2)	Six months (3)	Twelve months (4)
Age (years)	CG	30.3 (± 11.4)			
	MG	30.9 (± 9.6)			
	RRG	29.2 (± 8.8)			
Sex (M / F)	CG	28 (60.8%) / 18 (39.2%)			
	MG	32 (68%)/ 15 (32%)			
	RRG	25 (53.1%) / 22 (46.9%)			
Running experience (years)	CG	6.9 (± 6.6)			
	MG	6.4 (± 6.1)			
	RRG	6.7 (± 5.6)			
Comfort speed (km/h)	CG	11.1 (± 1.9)			
	MG	11.1 (± 2.0)			
	RRG	10.5 (± 2.0)			
BMI (kg/m²)	CG	22.7 (± 2.0)	22.8 (± 2.0)	23.0 (± 2.0)	22.8 (± 2.2)
	MG	23.1 (± 2.3)	23.1 (± 2.3)	23.2 (± 2.2)	23.2 (± 2.4)
	RRG	23.5 (± 3.1)	23.4 (± 2.9)	23.5 (± 2.9)	23.7 (± 3.0)
Weekly distance (km/week)	CG	30.5 (± 18.3)	31.4 (± 22.3)	29.8 (± 22.5)	30.1 (± 25.3)
	MG	26.0 (± 15.7)	25.6 (± 15.7)	28.2 (± 16.0)	30.5 (± 22.8)
	RRG	24.7 (± 11.9)	24.2 (± 12.8)	26.1 (± 14.0)	25.0 (± 13.7)
Running volume (h/week)	CG	3.1 (± 1.4)	3.3 (± 1.9)	3.3 (± 2.4)	3.0 (± 2.1)
	MG	3.0 (± 1.7)	3.0 (± 1.6)	3.0 (± 1.7)	3.4 (± 2.4)
	RRG	2.8 (± 1.2)	2.8 (± 1.4)	2.8 (± 1.2)	2.8 (± 1.5)
Step rate at comfort speed (step/min)	CG	164.5 (± 9.4)	164.4 (± 10.2)	163.7 (± 9.5)	163.9 (± 10.7)
	MG	165.5 (± 8.2)	167.6 (± 9.4)	168.2 (± 10.0)	167.6 (± 9.4)
	RRG	167.4 (± 10.7)	178.9 (± 12.0)	177.4 (± 11.1)	174.5 (± 11.5)
Footstrike pattern distribution (RF / NRF)	CG	46 (100%) / 0 (0%)	42 (100%) / 0 (0%)	41 (100%) / 0 (0%)	41 (100%) / 0 (0%)
	MG	47 (100%) / 0 (0%)	27 (61.3%) / 17 (38.7%)	26 (59.0%) / 16 (41%)	22 (55%)/ 18 (45%)
	RRG	47 (100%) / 0 (0%)	4 (9.0%) / 40 (91%)	8 (18.1%) / 36 (81.9%)	8 (20.5%)/ 31 (79.5%)

M = Male; F = Female; RF = Rearfoot strike; NRF = Non-rearfoot strike; RRG1 = value of the RRG (running retraining group) at baseline; RRG2 = value of the RRG at two months; RRG3 = value of the RRG at six months; RRG4 = value of the RRG at 12 months; CG1 = value of the CG (control group) at baseline; CG2 = value of the CG at two months; CG3 = value of the CG at six months; CG4 = value of the CG at 12 months; MG1 = value of the MG (minimalist footwear group) at baseline; MG2 = value of the MG at two months; MG3 = value of the MG at six months; MG4 = value of the MG at 12 months.

Table D.4: Diagnosis distribution of running-related injuries (RRIs) for intention-to-treat, as-treated and per protocol analyses

		INTENTION-TO-TREAT ANALYSIS					AS-TREATED ANALYSIS					PER PROTOCOL ANALYSIS				
		CG	**MG**	**RRG**	***P*-value**	**Post-hoc**	**CG**	**MG**	**RRG**	***P*-value**	**Post-hoc**	**CG**	**MG**	**RRG**	***P*-value**	**Post-hoc**
NO. OF PARTICIPANTS		**46**	**47**	**47**			**57**	**34**	**38**			**42**	**34**	**38**		
LOCATION	**DIAGNOSIS**															
Back injury	Acute back pain	1	1	0	n/a		2	0	0	n/a		1	0	0	n/a	
Hip injury	Pelvis stress fracture	0	1	0	> 0.001	CG > RRG**	0	1	0	0.003	CG > RRG*	0	1	0	0.002	CG > RRG**
	Hip impingement	1	1	0			2	0	0			1	0	0		
	Hamstring strain	1	0	0			1	0	0			1	0	0		
	Gluteal tendinopathy	6	0	0			6	0	0			6	0	0		
Knee injury	Patellofemoral pain	2	2	4	0.29		3	1	4	0.30		2	1	4	0.21	
	Iliotibial band syndrome	0	0	2			1	0	1			0	0	1		
Tibia injury	Shin split	4	4	2	0.77		7	3	0	0.11		4	3	0	0.13	
Overuse foot injury	Calf strain	0	2	4	0.09		0	2	4	0.013	RRG > CG*	0	2	4	0.04	RRG > CG*
	Achillean tendinopathy	2	2	3			3	1	2			2	1	2		
	Joint ankle pain	0	2	0			0	2	0			0	2	0		
	Plantar fasciitis	0	3	5			0	3	5			0	3	5		
	Posterior tibialis tendinopathy	2	0	1			2	0	1			2	0	1		
Traumatic foot injury	Ankle sprains	3	1	3	0.54		4	1	2	0.70		3	1	2	0.62	
TOTAL		22	18	24			31	14	19			22	14	19		

Table D.5: Cox regression results for the primary outcome according to the intention-to-treat, as-treated and per protocol analyses.

		Model 1 (unadjusted)			Model 2 (adjusted)		
				INTENTION-TO-TREAT ANALYSIS			
Covariates		HR (95% CI)	*P*	AIC [f]	HR (95% CI)	*P*	AIC
All injuries [b]				355.3			354.3
Interventional group [c]	**MG**	0.64 (0.35-1.33)	0.26		0.59 (0.29-1.19)	0.14	
	RRG	0.72 (0.38-1.37)	0.32		0.67 (0.35-1.28)	0.23	
Injury history [d]	**Yes**	/	-		1.69 (0.94-3.02)	0.07	
Likelihood ratio test			0.5			0.2	
				AS-TREATED ANALYSIS			
All injuries [e]				355.5			354.8
Interventional group	**MG**	0.68 (0.34-1.36)	0.28		0.63 (0.31-1.28)	0.20	
	RRG	0.79 (0.42-1.48)	0.47		0.78 (0.41-1.45)	0.43	
Injury history [d]	**Yes**	/	-		1.61 (0.91-2.84)	0.10	
Likelihood ratio test			0.5			0.3	
				PER PROTOCOL ANALYSIS			
All injuries [g]				291.29			288.34
Interventional group [c]	**MG**	0.60 (0.29-1.27)	0.18		0.49 (0.23-1.07)	0.074	
	RRG	0.73 (0.37-1.43)	0.36		0.66 (0.33-1.30)	0.23	
Injury history [d]	**Yes**	/	-		2.06 (1.09-3.87)	0.02	
Likelihood ratio test			0.4			0.08	

[a] =Model 1 included only the group as a predictor and model 2 included all predictors. HR values < 1 indicated a lower injury (hazard) ratio. 95% confidence intervals (Cis) (lower–upper bound). MG = minimalist group; RRG = running retraining group; HR = hazard ratio; P = P-value.
[b] = No. of injured runners = 57; No. of participants in the analysis = 140.
[c] = Control group is the reference.
[d] = Absence of injury history is the reference.
[e] = No. of injured runners = 57; No. of participants in the analysis = 129.
[f] = Akaike information criterion.
[g] = No. of injured runners = 49; No. of participants in the analysis = 114.

Discussion

Effect of the intervention on the primary outcome

The first objective of this study was to compare the effects of minimalist footwear and running retraining on the incidence rate of RRIs in endurance runners. Our results indicated that neither intervention significantly accounted for the variation in RRI risk ($P > .05$). These findings contrast with a previous study, which reported a 62% reduction in RRI incidence in a running retraining group specifically targeting impact peak reduction (Chan et al., 2018). Several differences in study design could explain the discrepancies in the results. First, the runners in our study were not novices, which may have led to a reduced risk of injuries compared to the participants in the previous study (Van Poppel et al., 2021). Second, unlike the previous study, compliance with the running retraining intervention was assessed four times during the follow-up period, enabling an as-treated and per protocol analyses based on adherence. Failing to account for compliance could lead to an overestimation of the intervention's effect on injury incidence. Finally, the running retraining intervention focused on increasing running cadence and adopting a non-rearfoot strike pattern, rather than reducing vertical impact peaks. Alternative methods such as increasing cadence only or adopting a pronounced rearfoot strike can also reduce impact variables and might be less risky than transitioning to a non-rearfoot strike to reduce RRIs (Doyle et al., 2022; Y. Huang et al., 2019; Van Den Berghe et al., 2022). Unfortunately, no information is provided on impact-reducing strategies adopted by runners in the previous study. Another study on a running-retraining intervention with a smaller follow-up duration (≈ 4.8 months) has recently been conducted (Van Hooren, Plasqui, et al., 2024). This study has investigated whether individualised real-time feedback using commercially available pressure sensitive insoles, is effective at reducing running injuries. The feedback was based on cadence, footstrike pattern, and relative speed. While intention-to-treat and per-protocol analyses showed no significant difference in RRI incidence rate, the as-treated analysis revealed a lower injury rate in the intervention group (24.4%) compared to the control group (37%). This reduction, although smaller than that observed in impact-focused interventions (16% vs. 38%), remains more pronounced than the effect observed in the present study (52% in the intervention group vs. 51% in control group) (Chan et al., 2018).

Similarly, participants who wore minimalist footwear did not have reduced RRI incidence rate. Nevertheless, the injury rate in our study was lower than in a previous study (38% vs. 51%, respectively) (Fuller, Thewlis, Buckley, et al., 2017). The discrepancy in injury rate could be explained by the smaller exposure to minimalist footwear in our study compared to the previous study (≈ 50% versus 100% of the total weekly distance). Variation of running footwear has already been considered as an effective way to reduce RRI incidence (Malisoux, Ramesh, et al., 2015). Furthermore, a partial rather than a complete transition to minimalist footwear could provide runners with the option to alternate between minimalist and traditional footwear in the event of discomfort or pain in the lower limb, potentially reducing the risk of a RRI.

Effect of the interventions on the secondary outcome

Our third hypothesis was that runners who followed running retraining would have a lower number of knee RRIs but a higher number of foot injuries than runners in the control group (Chan et al., 2018; Morris et al., 2020). Interestingly, participants in the RRG did not have a reduced number of knee injuries in comparison with the CG. This finding appears to be counterintuitive according to the reduced load imposed on the knee joint when a runner increases their running cadence and adopts a non-rearfoot strike pattern (Esculier et al., 2023; Willy, Meardon, et al., 2016). However, other factors related to training parameters (i.e., higher running speed or declined slope) that were not measured in this study could, in parallel, increase the load on the knee joint and potentially increase the risk of sustaining a knee injury (Van Hooren et al., 2024). Conversely, participants in the CG sustained a higher number of hip injuries than the RRG participants. The increase in hip injuries could be explained by the twofold increase in energy absorption at the hip during running with a 10% lower step rate and a rearfoot strike pattern (Heiderscheit et al., 2011). Finally, our results confirm that participants in the RRG have a higher risk of sustaining overuse foot injuries than participants in the CG. A higher overuse foot injury rate could be explained by a greater strain on the tendon, extrinsic and intrinsic foot muscles of the foot when the participants switched their footstrike pattern (Almeida et al., 2015; Kelly et al., 2018). Although the reduction of RRI incidence following running retraining interventions is unclear, these interventions remain useful for RRI management, such as anterior knee pain (De Souza Júnior et al., 2024; Roper et al., 2016). Therefore, conducting a prospective study to identify risk factors of sustaining overuse foot injuries during running retraining interventions remains essential.

Clinical implications

Our findings indicate that standardised running retraining interventions do not reduce the overall incidence of RRIs but rather redistribute injury risk, suggesting that clinicians and athletic coaches should consider more tailored approaches. A non-rearfoot strike combined with a higher cadence decreases loading on the hip and knee joints but increases loading on the foot and ankle (Almeida et al., 2015; Heiderscheit et al., 2011). Within the current framework of

RRI aetiology, this load redistribution may explain the observed reduction in hip injuries alongside an increase in foot and ankle injuries (Bertelsen et al., 2017). Moreover, as a history of injury is a major risk factor for recurrence, runners with previous foot injuries may benefit less from such interventions, whereas those with recurrent hip injuries could be particularly suitable candidates. Current recommendations emphasise careful control of training progression during running retraining, with sufficient time allowed for tissue adaptation (Barton et al., 2016). As tissue adaptation is individual-dependent, training progression should also be individualised and guided primarily by each runner's perception and feedback. Finally, recommendations also include foot–ankle strengthening programmes to limit the risk of foot and ankle injuries during the transition to a non-rearfoot strike pattern (Barton et al., 2016).

Similarly, the partial or complete adoption of minimalist footwear has not been shown to reduce the risk of RRIs either in recreational endurance runners. Given the lack of strong evidence linking running footwear to the prevention of RRIs, clinicians and athletic coaches should advise runners to choose footwear primarily based on comfort and personal preference (Malisoux & Theisen, 2020).

Limitations of this study

This study presents several limitations that should be acknowledged before generalising the findings. First, participants did not fully transition either to minimalist footwear or to the newly learned running technique. Adherence to the retraining program was nevertheless substantial, although some participants discontinued or inconsistently applied the instructions. A complete transition in both interventions might have allowed for a more conclusive evaluation of their maximal effects. However, the partial use of minimalist footwear better reflects real-world running behaviours.. First, Second, the protocol was conducted in a laboratory setting. Although treadmill running biomechanics are comparable to overground running biomechanics, no assessment of running technique was performed in an ecological environment [35]. While recent studies suggest that in-field retraining using wearable technologies is feasible, adherence to these devices remains a challenge (Morris et al., 2020; Van Hooren, Plasqui, et al., 2024). Future research should consider combining laboratory-based and in-field approaches to enhance ecological validity and participant adherence. Third, injuries were analysed by anatomical location rather than by specific diagnosis to ensure sufficient statistical power. Although diagnosis-specific analysis might yield different insights, it would require a larger sample size. Finally, training habits were self-reported through questionnaires at four time points, which may limit accuracy compared to a continuous monitoring of training load.

Conclusion

Contrary to popular belief, neither implementation of minimalist footwear nor adoption of a softer running technique seem to decrease RRI incidence rate in recreational endurance runners. Interestingly, a softer running technique led to a shift in injury patterns, decreasing hip injuries but increasing foot injuries. Future studies should identify risk factors in sustaining overuse foot injuries during running retraining interventions.

Supplemental Table 1: Faded feedback scheme of the running retraining protocol. Feedback consisted of oral instructions and an auditive metronome. Feedback was reduced across each session from 12 minutes to 4 minutes.

		SUPERVISION	DURATION (MIN)								TOTAL SESSION DURATION (MIN)
			Feedback	Free	Feedback	Free	Feedback	Free	Feedback		
SESSION 1	1st week	Supervised	4	1	4	1	4	1	/	/	**15**
SESSION 2			3	2	3	2	3	2	/	/	**15**
SESSION 3		Unsupervised	3	2	3	2	3	2	/	/	**15**
SESSION 4	2nd week	Supervised	2	3	2	3	2	3	2	3	**20**
SESSION 5			1	4	1	4	1	4	1	4	**20**
SESSION 6		Unsupervised	1	4	1	4	1	4	1	4	**20**

Supplemental Table 2: Progressive running programme proposed to the participants allocated to the gait retraining and minimalist footwear groups. Each participant was encouraged to follow this programme to ensure a safe implementation of the new running technique or minimalist footwear.

	WEEK 1	**WEEK 2**	**WEEK 3**	**WEEK 4**	**WEEK 5**	**WEEK 6**	**WEEK 7**	**WEEK 8**
SESSION 1	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min
SESSION 2	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min
SESSION 3	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min
DURATION PER WEEK	**15 min**	**30 min**	**45 min**	**60 min**	**75 min**	**90 min**	**105 min**	**120 min**

Supplemental Table 3: Characteristics at baseline, two months, six months, and 12 months (except for constant variables such as age, running experience, and comfort speed) for all participants included in the as-treated analysis.

Variables	Group	Baseline (1)	Two months (2)	Six months (3)	Twelve months (4)
Age (years)	CG	31.0 (± 11.3)			
	MG	30.5 (± 9.6)			
	RRG	29.0 (± 8.9)			
Sex (M / F)	CG	36 (63.1%) / 21 (36.9%)			
	MG	24 (70.5%) / 10 (29.5%)			
	RRG	20 (52.6%) / 18(47.4%)			
Running experience (years)	CG	6.8 (± 6.2)			
	MG	6.7 (± 6.6)			
	RRG	7.2 (± 6.0)			
Comfort speed (km/h)	CG	11.2 (± 1.9)			
	MG	11.2 (± 2.0)			
	RRG	10.6 (± 1.9)			
BMI (kg/m²)	CG	23.2 (± 2.6)	23.2 (± 2.5)	23.4 (± 2.6)	23.3 (± 2.8)
	MG	22.7 (± 2.2)	22.8 (± 2.2)	22.9 (± 2.1)	22.8 (± 2.3)
	RRG	23.4 (± 2.7)	23.3 (± 2.5)	23.3 (± 2.4)	23.5 (± 2.5)
Weekly distance (km/week)	CG	29.6 (± 17.4)	30.0 (± 20.9)	29.0 (± 21.1)	28.9 (± 24.2)
	MG	26.2 (± 16.4)	25.9 (± 16.5)	29.8 (± 15.9)	32.5 (± 22.8)
	RRG	24.8 (± 12.1)	24.4 (± 13.0)	25.6 (± 14.4)	25.3 (± 14.2)
Running volume (h/week)	CG	3.0 (± 1.5)	3.2 (± 1.8)	3.2 (± 2.3)	2.9 (± 2.0)
	MG	3.0 (± 1.7)	3.0 (± 1.7)	3.1 (± 1.7)	3.6 (± 2.5)
	RRG	2.8 (± 1.2)	2.8 (± 1.4)	2.8 (± 1.3)	2.8 (± 1.5)
Step rate at comfort speed (step/min)	CG	164.0 (± 9.2)	165.0 (± 10.6)	164.7 (± 10.3)	164.4 (± 10.7)
	MG	166.4 (± 7.8)	167.5 (± 8.6)	167.8 (± 8.9)	167.7 (± 9.1)
	RRG	168.2 (± 10.7)	180.4 (± 11.3)	178.6 (± 10.7)	175'.7 (± 11.1)
Footstrike pattern distribution (RF / NRF)	CG	57 (100%) / 0 (0%)	51 (89.4%) / 6 (10.6%)	53 (92.9%) / 4 (7.1%)	46 (90.1%) / 5 (9.9%)
	MG	34 (100%) / 0 (0%)	22 (64.7%) / 12 (35.3%)	20 (58.8%) / 14 (41.2%)	19 (59.3%) / 13 (40.7%)
	RRG	38 (100%) / 0 (0%)	0 (0%) / 38 (100%)	2 (5.2%) / 36 (94.8%)	5 (16.1%) / 31 (83.9%)

M = Male; F = Female; RF = Rearfoot strike; FFS = Non-rearfoot strike; RRG1 = value of the RRG (running retraining group) at baseline; RRG2 = value of the RRG at two months; RRG3 = value of the RRG at six months; RRG4 = value of the RRG at twelve months; CG1 = value of the CG (control group) at baseline; CG2 = value of the CG at two months; CG3 = value of the CG at six months; CG4 = value of the CG at twelve months; MG1 = value of the MG (minimalist footwear group) at baseline; MG2 = value of the MG at two months; MG3 = value of the MG at six months; MG4 = value of the MG at twelve months.

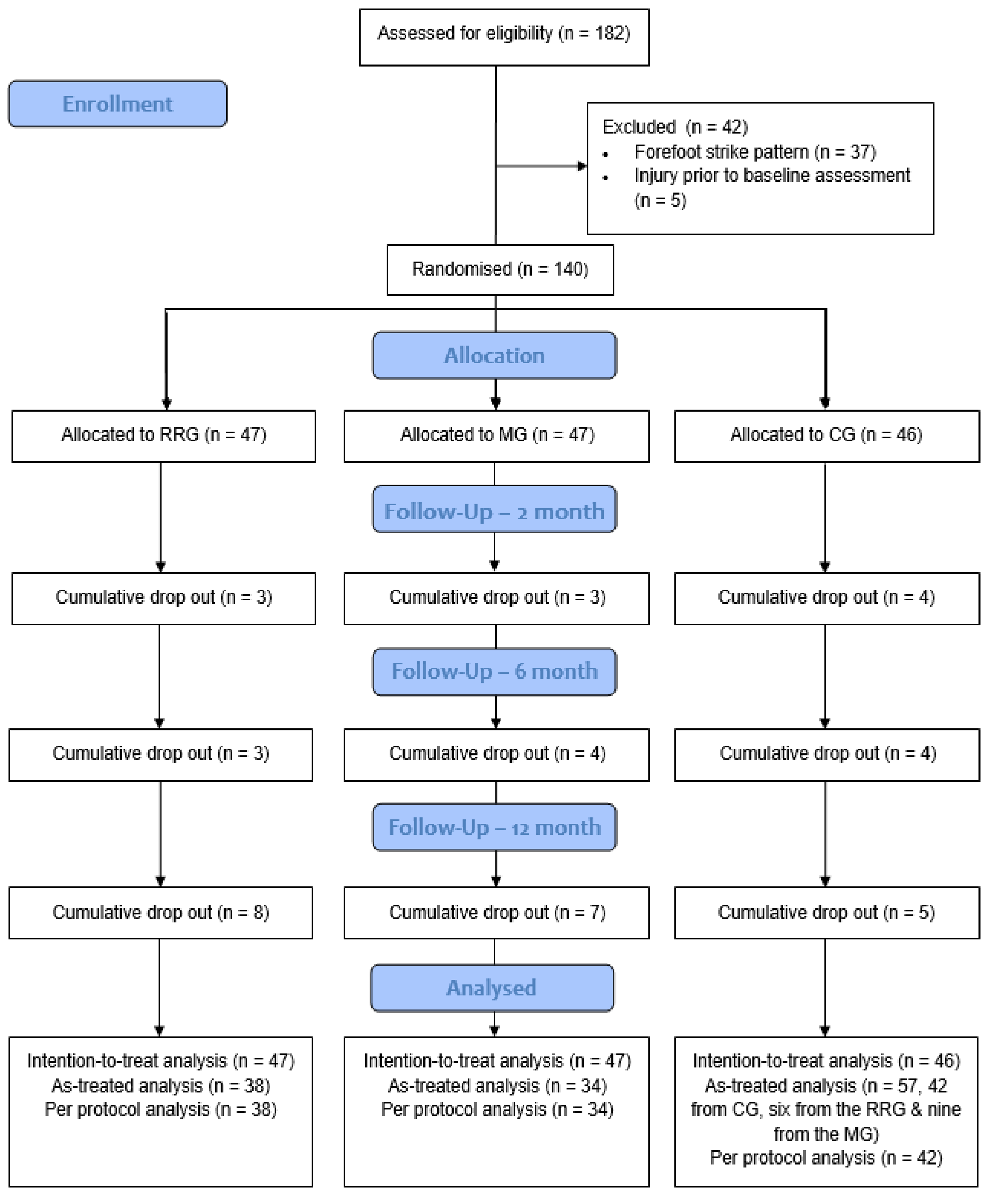
Supplemental Table 4: Characteristics at baseline, two months, six months, and 12 months (except for constant variables such as age, running experience, and comfort speed) for all participants included in the per protocol analysis.

Variables	**Group**	**Baseline (1)**	**Two months (2)**	**Six months (3)**	**Twelve months (4)**	***P*-value**	**Ŋ²**	**Post-hoc**
Age (years)	CG	30.5 (± 11.8)				0.75♦	0.005	
	MG	30.5 (± 9.6)						
	RRG	29.0 (± 8.9)						
Sex (M / F)	CG	25 (59.5%) / 17 (40.5%)				0.29⹋		
	MG	24 (70.5%) / 10 (29.5%)						
	RRG	20 (52.6%) / 18(47.4%)						
Running experience (years)	CG	7.0 (± 6.8)				0.96♦	6.89 × 10^{-4}	
	MG	6.7 (± 6.6)						
	RRG	7.2 (± 6.0)						
Comfort speed (km/h)	CG	11.3 (± 1.8)				0.24♦	0.025	
	MG	11.2 (± 2.0)						
	RRG	10.6 (± 1.9)						
BMI (kg/m²)	CG	22.7 (± 2.0)	22.8 (± 2.0)	23.0 (± 2.0)	22.8 (± 2.2)	0.09†	0.001	
	MG	22.7 (± 2.2)	22.8 (± 2.2)	22.9 (± 2.1)	22.8 (± 2.3)			
	RRG	23.4 (± 2.7)	23.3 (± 2.5)	23.3 (± 2.4)	23.5 (± 2.5)			
Weekly distance (km/week)	CG	30.5 (± 18.3)	31.4 (± 22.3)	29.8 (± 22.5)	30.1 (± 25.3)	**0.02**†	0.005	MG4 > MG1, MG2
	MG	26.2 (± 16.4)	25.9 (± 16.5)	29.8 (± 15.9)	32.5 (± 22.8)			
	RRG	24.8 (± 12.1)	24.4 (± 13.0)	25.6 (± 14.4)	25.3 (± 14.2)			
Running volume (h/week)	CG	3.1 (± 1.4)	3.3 (± 1.9)	3.3 (± 2.4)	3.0 (± 2.1)	0.087†	0.006	
	MG	3.0 (± 1.7)	3.0 (± 1.7)	3.1 (± 1.7)	3.6 (± 2.5)			
	RRG	2.8 (± 1.2)	2.8 (± 1.4)	2.8 (± 1.3)	2.8 (± 1.5)			
Step rate at comfort speed (step/min)	CG	164.5 (± 9.4)	164.4 (± 10.2)	163.7 (± 9.5)	163.9 (± 10.7)	< 0.001†	0.033	RRG2, RRG3, RRG4 > RRG1; RRG2 > CG2, MG2; RGG3 > CG3, MG3; RRG4 > CG4, MG4
	MG	166.4 (± 7.8)	167.5 (± 8.6)	167.8 (± 8.9)	167.7 (± 9.1)			
	RRG	168.2 (± 10.7)	180.4 (± 11.3)	178.6 (± 10.7)	175'.7 (± 11.1)			
Footstrike pattern distribution (RF / NRF)	CG	42 (100%) / 0 (0%)	42 (100%) / 0 (0%)	41 (100%) / 0 (0%)	41 (100%) / 0 (0%)			
	MG	34 (100%) / 0 (0%)	22 (64.7%) / 12 (35.3%)	20 (58.8%) / 14 (41.2%)	19 (59.3%) / 13 (40.7%)			
	RRG	38 (100%) / 0 (0%)	0 (0%) / 38 (100%)	2 (5.2%) / 36 (94.8%)	5 (16.1%) / 31 (83.9%)			

M = Male; F = Female; RF = Rearfoot strike; NRF = Non-rearfoot strike; RRG1 = value of the RRG (running retraining group) at baseline; RRG2 = value of the RRG at two months; RRG3 = value of the RRG at six months; RRG4 = value of the RRG at twelve months; CG1 = value of the CG (control group) at baseline; CG2 = value of the CG at two months; CG3 = value of the CG at six months; CG4 = value of the CG at twelve months; MG1 = value of the MG (minimalist footwear group) at baseline; MG2 = value of the MG at two months; MG3 = value of the MG at six months; MG4 = value of the MG at twelve months.

Supplemental Table 5: Description of variables assessing adherence to the proposed interventions during follow-up for intention-to-treat analysis.

QUALITATIVE VARIABLES	Groups						
		Not at all	Mostly no	Mostly yes	Completely		
Compliance with the running programme after two months	MG	7 (15.9%)	9 (20.4%)	22 (60%)	6 (13.6%)		
	RRG	2 (4.6%)	8 (18.2%)	29 (65.9%)	5 (11.3%)		
		Less than one in five training sessions	One in five training sessions	One in four training sessions	One in three training sessions	One in two training sessions	Every training session
Use of the new running technique during personal running training at 6 months	RRG	1 (2.5%)	2 (4.5%)	3 (6.8%)	1 (2.5%)	12 (27.2%)	25 (56.5%)
Use of the new running technique during personal running training at 12 months	RRG	2 (5.2%)	1 (2.5%)	1 (2.5%)	0 (0%)	10 (25.7%)	25 (64.1%)
QUANTITATIVE VARIABLES		Mean (± SD)					
Ratio weekly distance with minimalist footwear / total weekly distance at 6 months (%)	MG	46.8 (± 35.5)					
Ratio weekly distance with minimalist footwear / total weekly distance at 12 months (%)	MG	42.1 (± 33.6)					



Supplemental Figure 1: Participant enrolment, allocation, and analysis flowchart for the intention-to-treat, as-treated and per protocol analyses. For the intention-to-treat analysis, all participants were analysed according to their original group allocation, resulting in a sample size of 140 runners (47 in the running retraining group (RRG), 47 in the minimalist group (MG), and 46 in the control group (CG)). Furthermore, 38 runners originally allocated to the RRG successfully altered their running technique by adopting a forefoot strike pattern and/or a 7.5% higher step rate than the baseline value. Similarly, 34 runners originally allocated to the MG sufficiently used minimalist footwear in their own running training sessions (≥ 25% of their total weekly distance). On the other hand, six runners originally allocated to the RRG and nine runners originally allocated to the MG were finally allocated to CG for the as-treated analysis and excluded from the analysis for the per protocol analysis.

Take Home Messages – Part II

- ✓ Adopting a forefoot strike pattern reduces impact-related parameters nearly three times more effectively than increasing cadence by 10% alone. Nevertheless, combining both strategies appears to be the most efficient approach for reducing the high-frequency components of impact-related parameters.

- ✓ While neither running retraining nor transitioning to minimalist footwear appears to lower the overall injury risk, both interventions tend to shift the injury location from the proximal to the distal segments of the lower limb.

Adopting a non-rearfoot strike pattern, increasing step rate, or transitioning to minimalist footwear can reduce knee joint loading but simultaneously increase mechanical demands on the foot and ankle. These load transfers could increase the risk of developing secondary injuries during or following a running technique alteration. Given these considerations, it is essential to better understand the factors that may predispose runners to injury when undergoing such interventions. The next part of this thesis focuses on the importance of foot–ankle conditioning for safer running technique alteration.

E. **Part III: Conditioning the foot–ankle complex for a safer running technique transition**

Adopting a non-rearfoot strike pattern, increasing step rate, or transitioning to minimalist footwear can reduce loading at the knee joint. However, these strategies simultaneously increase the mechanical demands placed on the foot and ankle (Almeida et al., 2015). These load transfers, especially towards the distal structures, could increase the risk of developing an injury during or following a running technique alteration (Barton, 2018). Given these considerations, it is essential to better understand the factors that may predispose runners to injury when undergoing such interventions. The aim of this chapter is to compare the foot and ankle characteristics of runners exhibiting different running techniques, to determine whether foot and ankle characteristics constitute risk factors for alterations in running technique, and to propose potential strategies to enhance foot and ankle characteristics. The studies presented in this chapter focus on identifying individual characteristics that may influence the safety and success of transitioning to a modified running technique or footwear. The first study used a retrospective approach to examine how running technique is associated with specific foot-ankle profiles. Building on this foundation, the second study adopts a prospective design to investigate whether certain foot-ankle characteristics act as risk factors for injury during a transition to minimalist footwear or a softer running style. Finally, the third study provides an in-depth biomechanical analysis of common running drills used in retraining programmes, with the objective of determining their potential to strengthen the foot and support safe technique modification. These studies collectively contribute to a more informed and individualised approach for running technique alteration.

1. Difference in foot-ankle characteristics according to running technique (Study 5).

Study 5: Foot & ankle muscle isometric strength in non-rearfoot compared with rearfoot endurance runners.

Published in Journal of foot & ankle Orthopaedics.

DOI: 10.1177/24730114231205305

ABRAN Guillaume[1], SCHWARTZ Cédric[1], DELVAUX François[2], BORNHEIM Stephen[2], CROISIER Jean-Louis[1,2].

[1]Laboratory of Human Motion Analysis, Liège, Belgium. Electronic address: guillaume.abran@uliege.be.

[2]Department of Motricity Sciences, University of Liège, Liege, Belgium.

[3]University and Hospital Biostatistics Center (B-STAT), University of Liège, Belgium.

[4]WHO Collaborating Centre for Public Health Aspects of Musculoskeletal Health and Aging, Division of Public Health, Epidemiology and Health Economics, University of Liège, Liège, Belgium.

Abstract

Background: Transitioning to a forefoot strike pattern can be used to manage running-related knee injuries. However, adopting a non-rearfoot strike induces a higher load on foot and ankle structures than rearfoot strike. Sufficient foot muscle strength is also necessary to prevent excessive longitudinal arch (LA) deformation when running with non-rearfoot strike. The aim of this study was to investigate the potential differences in foot-ankle muscle strength between RF and NRF runners.

Methods: A cross-sectional study including 40 RF and 40 NRF runners was conducted. The foot posture and the maximal voluntary isometric strength (MVIS) of six foot-ankle muscles were measured. The footstrike pattern was determined using a 2-D camera during a self-paced run on a treadmill.

Results: NRF had higher MVIS for ankle plantar flexor (+12.5%, $p = 0.015$), ankle dorsiflexor (+17.7%, $p = 0.01$), hallux flexor (+11%, $p = 0.04$) and lesser toe flexor (+20.8%, $p = 0.0031$). We found a small positive correlation between MVIS of ankle plantar flexor with MVIS of hallux flexor ($r = 0.26$; $p = 0.01$) and lesser toe flexor ($r = 0.28$; $p = 0.01$).

Conclusion: In this cross sectional study we found that NRF runners on average have a higher MVIS of hallux and lesser toe flexor compared with RF runners. NRF runners also have a higher MVIS of ankle plantar flexor and dorsiflexor than RF runners. We found only a small correlation between ankle plantar flexor and foot muscle strength.

Introduction

The footstrike pattern is an important component of the running biomechanics. Footstrike pattern can be made with the heel first (rearfoot strike), the heel and the forefoot simultaneously (midfoot strike) or the forefoot first (forefoot strike) (Lieberman, 2012). As there are few runners with a midfoot and a forefoot strike, it is common to combine these two categories together as "non-rearfoot strike" (Hoenig et al., 2020). It has been suggested that a non-rearfoot strike can reduce the vertical average loading rate (- 49.7 %), the vertical instantaneous loading rate (- 41.7 %) and the patellofemoral joint force (- 12 %)(Esculier et al., 2023; Futrell et al., 2020). Consequently, transitioning to a forefoot strike pattern can be used as a component of a gait retraining intervention to manage running-related knee injuries (Alexander et al., 2022).

However, transitioning to a forefoot strike pattern changes the loading location on the lower limb (Almeida et al., 2015). Non-rearfoot strike appears to increase the load on the ankle and the Achilles tendon, and increases the gastrocnemius activation (Almeida et al., 2015). In response to these biomechanical changes, there is an increase in the plantar flexor strength and the Achilles tendon cross-section area (Deng et al., 2020). Similar to the ankle structures, there is also a greater loading and energy absorbed by the midfoot when running with a non-rearfoot strike comparatively to rearfoot strike (Kelly et al., 2018). This greater loading is associated with a higher foot arch deformation, plantar fascia loading and an increase in the intrinsic foot muscles activation (T. L.-W. Chen et al., 2019; Kelly et al., 2018). It appears that activating the intrinsic muscles of the foot could prevent excessive deformation of the medial longitudinal arch and the associated increase in the plantar aponeurosis strain (Kelly et al., 2015, 2018).

Insufficient intrinsic foot muscle strength could therefore influence loading on the plantar aponeurosis in rearfoot runners undergoing a gait retraining intervention to adopt a non-rearfoot strike (Kelly et al., 2018). Based on the physiopathology of running-related-injuries, abnormal plantar aponeurosis loading could expose runners to a greater risk of sustaining an injury (Napier & Willy, 2021).

The first aim of this study was to investigate whether there is a difference in the intrinsic and extrinsic foot-ankle muscle strength between rearfoot runners (RF) and non-rearfoot runners (NRF). We hypothesise that NRF runners develop higher maximal voluntary isometric strength (MVIS) with their ankle plantar flexor, hallux flexor and lesser toe flexor (T. L.-W. Chen et al., 2016; Fuller et al., 2019). The secondary objectives are to investigate whether foot posture is different between RF and NRF runners, then to investigate the relationship between foot-ankle muscle strength and endurance running performance. Given the existence of a possible relationship between foot posture and foot muscle strength, we hypothesise that NRF runners possess a stiffer passive plantar arch than RF runners (Hashimoto & Sakuraba, 2014). Finally, we also hypothesise that there is no relationship between foot and ankle muscle strength and endurance running performance (Q. Zhang et al., 2022).

Materials And Methods

Participants

The effect size required was estimated using the G*power software (version 3.1.9.2, Germany), with data from a preliminary investigation of ankle plantar flexor strength in RF (N = 10) and NRF (N = 10). A population size of 34 participants for each group was estimated to achieve statistical significance, for an expected effect size of 0.70 and power of 0.80 with an alpha level of 0.05. Data was collected from 40 RF runners (age = 25.5 ± 4.8 years; mass = 71.4 ± 10.1 kg; height = 1.76 ± 0.08 m) and 40 NRF runners (age = 25.2 ± 4.6 years; mass = 69.2 ± 7.6 kg; height = 1.75 ± 0.06) between the year 2021 and 2023. Eligibility criteria included age between 18 and 35 years, distance ran at least 20 kilometres per week for at least six months, no running related injuries in the three months prior to testing. Participants were also asked to report that they had not changed their footstrike pattern in the last six months. This study was approved by the local ethics committee of the Hospital Faculty (27/07/2021; protocol No. 2021/197).

Experimental protocol

Participants filled out a questionnaire on their running level and training habits (age, running experience, training volume, running-related-injuries history, the personal best in a race of 10.000 metres carried out in the last six months). Then, the examinator conducted a footwear assessment, a foot screening, a foot-ankle muscle strength assessment and a footstrike determination during a running protocol on a treadmill. Footstrike determination was done last to allow the examinator to perform the ankle-foot strength assessment and foot screening in single-blind way.

Footwear assessment

Minimalist footwear can improve foot-ankle muscle strength (T. L.-W. Chen et al., 2016; Fuller et al., 2019). Thus, the minimalist index of the running footwear has to be controlled for assessing the relationship between the footstrike pattern and foot-ankle muscle strength. The minimalist index of the two most frequently worn running footwear in the last six months of the participants were assessed. Minimalist index, based on a previous publication, was collected on the running clinic website (https://therunningclinic.com/shoes/) (Esculier et al., 2015). If footwear was not referenced on the website, examinators assessed it according to the "minimalist index scale" including weight, stack height, drop, stability, motion control technologies and longitudinal/torsional flexibility. Minimalist index ranges from 0 to 100 %. Higher values indicated a more minimalist design (e.g. more flexible, lower weight, lower stack height, less stability/motion control technology, and/or smaller heel-toe drop). The highest value of the minimalist index was considered for each participant.

Foot posture

The dominant leg was defined as the leg used to kick a ball (van Melick et al., 2017). The examinator conducted a foot screening of the dominant lower limb, including the "Foot Posture Index-6" (FPI-6) and a "Navicular Drop Test" (ND). Previous studies shown that there is a relationship between these tests and intrinsic foot muscle strength (Headlee et al., 2008; Okamura et al., 2020).

The FPI-6 quantifies the posture of each foot via a total of six items. Thus a total score between -12 and +12 is obtained (a greater positive score indicates a more pronated foot and a greater negative score indicates a more supinated foot) (Redmond et al., 2006).

For the ND, the inferior border of the prominent tuberosity of the navicular bone was marked with a pen, and the distance to the ground was measured using a digital calliper (accuracy of 0.01 mm) with the participant seated and standing. The difference between the two measurements (sitting vs. standing) was considered as the navicular drop. The examinator repeated the measure three times and the average value was recorded (Tourillon et al., 2019).

Foot-ankle muscle strength assessment

A strength assessment of the ankle plantar flexor, ankle dorsiflexor, ankle invertor, ankle evertor, hallux flexor and lesser toe flexor was performed on the dominant lower limb with a digital hand-held dynamometer (MicroFET2, Hoggan Health Industries, West Jordan, UT). These measurements were based on a previous study and done according to the "make test" method (Figure E.1)(Fraser et al., 2017; Stratford & Balsor, 1994). Intraclass correlation coefficients of these strength measures are considered as excellent (.76-.88) (Fraser et al., 2017). To limit the interference caused by the examinator, the hand-held dynamometer was fixed to a bar, adjustable in height. A belt was used to maintain the lower limb or the pelvis (in the hallux and lesser toe flexor assessments) on the table and to minimise compensations during the test. The lever arm was measured for ankle plantar flexor and ankle dorsiflexor between the lateral malleolus and the contact point of the hand-held dynamometer with the foot. The foot-ankle muscle strength assessment was performed in a randomised order.

Participants performed two familiarisation trials for each muscle assessed. For each trial, they were instructed to gradually increase the strength developed on the dynamometer. They were verbally encouraged by the examinator during each muscle contraction and instructed to continue the contraction until the examinator saw a maximum value, which was typically after 3–5 s. Each trial was separated by 30 seconds of recovery to limit the effect of fatigue. The highest value of the three trials was recorded for each muscle assessed and reported in Newton's meter (N.m) for ankle plantar flexor and ankle dorsiflexor. Considering the difficulty to accurately estimate the lever arm of hallux flexor, lesser toe flexor, ankle evertor and ankle invertor, their highest value was expressed in Newton (N). Each final strength value was normalised to body mass.

Figure E-1: Positions used to assess maximal voluntary isometric contraction with a fix digital hand-held dynamometer: A) Ankle plantar flexor, B) Ankle dorsiflexor, C) Hallux flexor, D) Lesser toe flexor, E) Ankle invertor, F) Ankle evertor.

Running protocol and Footstrike determination

Finally, a running warm-up of eight minutes on a motorised treadmill (HP Cosmos Pulsar, Nussdorf-Traunstein, Germany) at participants' own pace was performed. After the warm-up, a video recording of 30 seconds with a high-speed camera sampling at 240 Hz was taken with participants running at a comfortable pace (based on the personal record in a 10.000 m). A comfortable pace was chosen to properly represent the natural footstrike pattern of each runner. Frame by frame analysis with DartfishTM (version Prosuite 10.0, Dartfish, Alpharetta, Georgia) allowed for the visual identification of each runner's dominant leg's foot strike pattern (landing on the ground with forefoot/midfoot or rearfoot) (Figure E.2). The footstrike pattern assessment from a 2D video analysis has shown a very high level of reliability (ICC = 0.88) (Murray et al., 2018).

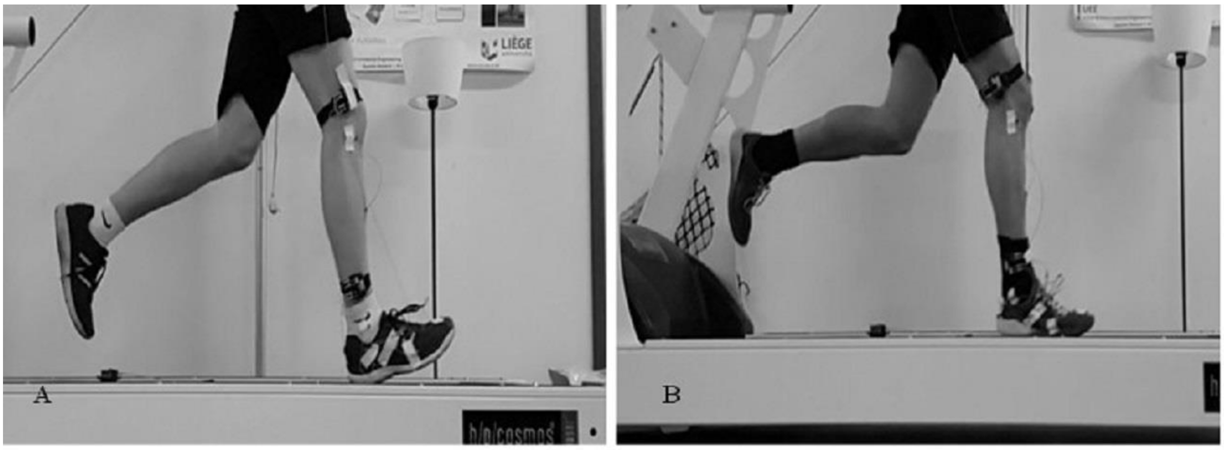


Figure E-2: Footstrike pattern determination in using 2D video analyses. A) an example of a rearfoot strike, B) an example of a non-rearfoot strike.

Statistical analysis

Normality conditions were verified using the Shapiro-Wilk test for quantitative variables such as individual characteristics (age, experience in running (years), training volume (hours), weekly mileage, personal best in 10.000 m (minutes)), a maximal voluntary isometric strength (MVIS) of each muscle group, FPI-6, ND and the footwear's minimalist index. Qualitative variables were categorised (such as the gender (0 = male; 1 = female), footstrike pattern (0 = RF; 1 = NRF)). A descriptive analysis of the sample was done (means and standard deviation or median and percentile for quantitative variables according to the normality condition, number and frequency for qualitative variables).

An outlier detection was performed using the generalized extreme Studentized deviate (ESD) test for the MVIS of each muscle (Rosner, 1983). Outliers detected were excluded from the statistical analysis. Student's *t* test or Mann-Whitney test (according to the normality of each variable) were used to compare respectively the individual characteristics and the footwear's minimalist index between RF and NRF, the maximal isometric strength of the ankle-foot muscles between RF and NRF and the FPI-6 and ND between RF and NRF. The intra-class correlation coefficients (ICC) were calculated for all the maximal isometric strength of the ankle-foot muscles and ND. ICC values less than 0.5 are indicative of poor reliability, values between 0.5 and 0.75 indicate moderate reliability, values between 0.75 and 0.9 indicate good reliability, and values greater than 0.90 indicate excellent reliability (Koo & Li, 2016).

Effect sizes (ES) are presented as standardized mean differences (Cohen's D), with ≤ 0.60 representing a small effect, >0.60 and <1.2 representing a moderate effect, and ≥1.2 representing a large effect (Hopkins et al., 2009). The correlations of the MVIS between each muscles group were analysed using a Pearson's correlation. Likewise, the correlations between MVIS and the values of each foot screening tests (FPI-6 and ND) and between MVIS and personal best were also analysed using a Pearson's correlation. Correlations were classified as follows: small (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), and extremely large (0.9–1.0) (Hopkins et al., 2009). Statistical analyses were performed using R (Version 4.1.1, R Core Team, 2017) (Fox, 2005). An alpha level of 0.05 was used for all inferential statistics. However, a Benjamini and Hochberg corrected significance level was calculated to limit the risk of Type 1 group error in comparison tests (Benjamini & Hochberg, 1995). The corrected significance level for the Student's *t* test or Mann-Whitney test was set to 0,031.

Results

Table E.1 highlights an absence of differences in the individual characteristics relative to running level and training habits between RF and NRF runners. There was no difference in footwear minimalist index between the two groups.

Table E.1: Baseline characteristics of the participants.

Variables	RF (N = 40)	NRF (N = 40)	p-value
Body mass index (kg/m²)	22.65 (21.04- 24.16)	22.46 (21.09-23.28)	p = 0.64[a]
Experience in running (years)	6.5 (3.75-10.0)	6.0 (3.0-10.0)	p = 0.96[a]
Training volume (hours)	3.62 (2.0-6.0)	3.5 (3.0-4.62)	p = 0.63[a]
Weekly distance (km)	24.0 (20.0-55.0)	34.0 (25.0-44.0)	p = 0.28[a]
Personal best in 10.000 m (minutes)	42.29 ± 6.08	41.37 ± 6.49	p = 0.51[b]
Minimalist index (%)	35.75 ± 9.5	39.60 ± 15.0	p = 0.17[b]

RF = rearfoot strikers ; NRF = non rearfoot strikers; SD = Standard deviation; [a] = Mann-Whitney test; [b] = Student's t test.

The generalized extreme Studentized deviate (ESD) test did not detect outliers for the MVIS of each muscle. Table E.2 shows that NRF runners significantly achieved higher MVIS for ankle plantar flexor (+12.5%, $p = 0.015$; d = 0.53), ankle dorsiflexor (+17.7%, $p \leq 0.01$; d = 0.61), hallux flexor (+11%, $p = 0.013$; d = 0.56) and lesser toe flexor (+20.8%, $p \leq 0.001$; d = 0.88). NRF runners had a significantly less pronated feet ($p = 0.02$; d = 0.49) but a similar navicular drop ($p = 0.04$; d = 0.44) than RF runners. ICC indicate that reliability of ankle plantar flexor (0.831), ankle dorsiflexor (0.766), hallux flexor (0.894), lesser toe flexor (0.883) strength and ND (0.899) are good whereas reliability of ankle evertor (0.686) and ankle invertor (0.634) are moderate.

Table E.2: Comparison of foot-ankle muscle strength, navicular drop and foot posture index between rearfoot strikers and non-rearfoot strikers (mean ± sd)

Variables	RF (N = 40)	NRF (N = 40)	Cohen's d	p-value	ICC
Ankle plantar flexor strength (N.m/kg)	0.84 ± 0.20	0.96 ± 0.23	0.53	0.018*	0.831
Ankle dorsiflexor (N.m/kg)	0.31 ± 0.08	0.36 ± 0.08	0.61	0.007*	0.766
Ankle evertor strength (N/kg)	1.60 ± 0.23	1.68 ± 0.28	0.34	0.129	0.686
Ankle invertor (N/kg)	1.71 ± 0.36	1.75 ± 0.31	0.12	0.593	0.634
Hallux flexor strength (N/kg)	2.53 ± 0.49	2.84 ± 0.59	0.56	0.013*	0.894
Lesser toes flexor strength (N/kg)	1.99 ± 0.51	2.48 ± 0.57	0.88	< .001**	0.883
Navicular Drop (cm)	0.65 ± 0.23	0.56 ± 0.21	0.44	0.04	0.899
FPI-6	6.72 ± 2.69	5.35 ± 2.81	0.49	0.029*	N/A

RF = rearfoot strikers ; NRF = non rearfoot strikers ; ICC = Intra-class coefficient correlation ; Student's t test: P > 0.05, not significant; * symbol represents a p-value for post-hoc test inferior to 0.05; ** symbol represents a p-value for post-hoc test inferior to 0.01; *** symbol represents a p-value for post-hoc test inferior to 0.001 ; N/A = not applicable.

There is a moderate positive correlation between MVIS of ankle plantar flexor with MVIS of ankle dorsiflexor (r = 0.42; p < 0.001) and a small positive correlation with MVIS of ankle invertor (r = 0.22; p = 0.04), hallux flexor (r = 0.26; p = 0.01) and lesser toe flexor (r = 0.28; p = 0.01). Likewise, there is a large positive correlation between MVIS of hallux flexor with MVIS of lesser toe flexor (r = 0.66; p < 0.001), a small positive correlation with MVIS of ankle evertor (r = 0.26; p = 0.01) and ankle invertor (r = 0.22; p = 0.04)

Pearson's correlation showed that smaller ND was associated with higher MVIS of ankle evertors (r = -0.27; p = 0.01), ankle invertors (r = -0.29; p = 0.008) and lesser toe flexor (r = -0.35; $p \leq 0.001$). In contrast, no association was found between FPI-6 and MVIS of foot-ankle muscles. Pearson's correlation showed that personal best in 10.000 m (in minutes) was associated with higher MVIS of ankle plantar flexor (r = -0.31; p = 0.004), ankle dorsiflexor (r = -0.26; p = 0.01), ankle invertors (r = -0.24; p = 0.02). No correlation was found between personal best in 10.000 m and hallux flexor (r = -0.13; p > 0.05) or lesser toe flexor (r = -0.21; p > 0.05).

Discussion

The primary aim of this study was to test for group differences in foot and ankle muscle strength between RF and NRF runners. The main finding of this research is somewhat greater MVIS of ankle plantar flexor, ankle dorsiflexor, hallux and lesser toe flexor in non-rearfoot runners compared to rearfoot runners.

Our study highlights that NRF runners have stronger ankle-foot isometric muscle strength (except for evertors and invertors) than RF runners. Previous studies have also found stronger plantar flexor in NRF runners compared to RF runners (Liebl et al., 2014). Our results confirm these findings by assessing a high number of NRF runners (N = 40), while considering the runner's level of performance and the minimalist index of each individual's running footwear. Taking these two confounding variables into account appears relevant. Indeed, the personal best in 10.000 m appears to be correlated (r = -0.31) with maximal isometric ankle plantar flexor strength. Previous studies have also shown than minimalist footwear can increase ankle plantar flexor strength (Fuller et al., 2019).

This is the first study to explore hallux and lesser toe flexor isometric strength in RF and NRF runners. Our study highlights that NRF runners appear to have stronger foot flexor muscles than RF runners. It may be true that the runner's body adapts to the non-rearfoot strike, including an increase of the foot and ankle muscle strength. However, we found in our sample a relative heterogeneity in foot muscle strength in the NRF runners group: 35 % of the runners had hallux flexor strength inferior to 2.5 N/kg and 27.5 % had lesser toe flexor strength inferior to 2.0 N/kg (average values found for RF).

Gait retraining intervention involving a transition to a forefoot strike pattern is often used to reduce patellofemoral pain (Abran et al., 2022; Doyle et al., 2022). In theory, this method allows to shift a part of the load imposed by running from the knee joint to the foot and ankle joint (Doyle et al., 2022; Kelly et al., 2018).Thus, adopting a non-rearfoot strike may require greater foot and ankle muscular capacity to support the higher plantar fascia loading and foot arch deformation (T. L.-W. Chen et al., 2019). According to the small correlation between ankle and foot muscle strength, it seems potentially relevant for clinicians to assess the foot and ankle muscles strength separately before a gait retraining intervention involving a transition to a forefoot strike pattern and consider implementing an individual strengthening programme based on each runner's specific muscle weakness of the foot and/or the ankle. Methods to improve the strength of the foot have been described including specific exercises (short foot, toe spread out,…), running drills, neuromuscular electrical stimulation of the intrinsic foot muscles or walking with minimalist footwear (Abran et al., 2022; Tourillon et al., 2019).

In our cross sectional study, higher isometric ankle plantar flexor, ankle dorsiflexor and ankle invertor strength were associated with better performance in a race of 10.000 meters. This result is not in agreement with a previous study which shown that ankle plantar flexor strength is not associated with running performance (Q. Zhang et al., 2022). However, a previous study highlighted the importance of the interaction between ankle plantar flexor and the function of the medial longitudinal arch to maintain the propulsive capacity during running (Fourchet et al., 2015). Ankle invertors seem to play an important role in supporting the medial longitudinal arch (Semple et al., 2009). Thus, it seems advantageous for a runner to be able to develop a high level of strength with ankle plantar flexor and ankle invertors to maintain propulsion and perform in running. Hallux and lesser toe flexor strength in our current work were found to have no correlation with personal best in the 10.000 m. This is in accordance with previous results showing that strengthening the foot muscles does not increase running economy (RE)(Day & Hahn, 2019). However, these muscles are also important for propulsion and some evidence of their role in running performance exists but only for shorter distances (Farris et al., 2020; Hashimoto & Sakuraba, 2014).

Navicular drop showed a small to moderate correlation with lesser toe flexor, ankle invertor and ankle evertor strength but no correlation with hallux flexor strength. In addition, no correlation was found between the foot-ankle muscle strength and the FPI-6. These findings are in accordance with those of a previous study that showed no relationship between FPI-6 and intrinsic foot muscle size (Taş et al., 2018). Clinicians should be aware that the ND and FPI-6 might not provide a good insight into the runner's foot muscle strength.

Our study has limitations that should be considered before generalizing the results. First, this is a cross sectional study. We did not follow runners longitudinally before and after change in footstrike pattern and cannot specifically comment on what muscle activity and strengthening is required for a successful transition in footstrike pattern. Second, assessing position of maximal voluntary isometric contraction of hallux flexor and lesser toe flexor tries to reduce the participation of the extrinsic foot muscles, the intrinsic foot muscles are not completely isolated (Goldmann & Brüggemann, 2012). Moreover, we used a hand-held dynamometer to assess foot muscle strength but there are other methods such as the toe grip, the "doming" or the paper grip test may yield different results (Bruening et al., 2019; Tourillon et al., 2019). Isometric strength may not translate to activities of interest. Finally, footstrike pattern was not determined by the strike index method which is the gold standard because our treadmill was not equipped with force plates (Hoenig et al., 2020). However, determination of the footstrike pattern with a high-speed camera has already shown a high level of accuracy in comparison with the strike index method (Hoenig et al., 2020).

Conclusion

The main finding of this study is the higher average value of maximal voluntary isometric strength of hallux and lesser toe flexor in NRF runners compared with RF runners. NRF runners also have a higher MVIS of ankle plantar flexor and dorsiflexor than RF runners. There is only a small correlation between ankle plantar flexor and foot muscle strength.

2. Identification of risk factors associated with running technique alteration (Study 6).

Study 6: Who Struggles with Minimalist Footwear and Running Retraining? A Risk Factor Analysis.

Submitted

ABRAN Guillaume[1,2], SCHWARTZ Cédric[1], DARDENNE Nadia[3], DELVAUX François[1,2], CROISIER Jean-Louis[1,2].

[1]LAM – Motion Lab, Liège, Belgium. E-mail: guillaume.abran@uliege.be.

[2]Department of Physical Activity and Rehabilitation Sciences, University of Liege, Liege, Belgium.

[3] University and Hospital Biostatistics Center (B-STAT), University of Liège, Belgium.

Abstract

Background: Minimalist footwear and running retraining are commonly used in clinical practice to manage knee running-related injuries (RRIs) in injured runners. However, the potential benefits of these interventions may be offset by an increased risk of secondary RRIs at the foot or ankle.

Hypothesis/Purpose: To identify risk factors for sustaining running-related injuries in recreational endurance runners following the adoption of either minimalist footwear or a running retraining programme.

Design: Randomised controlled trial with 12-month follow-up.

Methods: One hundred and forty rearfoot-strike recreational runners were randomly assigned to one of three groups: minimalist footwear group (MG, n = 47), running retraining group (RRG, n = 47), and control group (CG, n = 46). Baseline assessments included running habits, biomechanics, foot and ankle muscle strength, foot posture, and plyometric capacity. Follow-up assessments were conducted at 2, 6, and 12 months and RRIs were recorded according to consensus guidelines.

Results: When considering all injury types, no significant differences in baseline characteristics were observed between injured and uninjured runners in the CG and MG. However, within the MG, runners who sustained foot or ankle injuries had a significantly higher body mass (P = .035), with a cut-off identified at 71.4 kg. In the RRG, greater hallux flexor strength was associated with reduced RRI risk (P = .006). A threshold of 2.85 N/kg was established to identify runners at risk when adopting a non-rearfoot strike pattern.

Conclusion: Runners with hallux flexor strength below 2.85 N/kg are at higher risk of foot and ankle injuries when transitioning to a softer running technique. Conversely, foot and ankle muscle strength does not appear to be a risk factor for RRIs when transitioning to minimalist footwear. However, strengthening these muscles may still be beneficial, particularly for runners adopting a non-rearfoot strike.

Introduction

Running technique alteration is often used in clinical practice with injured runners to manage running-related injuries (RRIs), particularly overuse knee injuries (Alexander et al., 2022; Barton, 2018; Barton et al., 2016). The running biomechanical parameters frequently modified are the footstrike pattern and step rate (Barton et al., 2016). The transition to a non-rearfoot strike pattern allows reduction of the patellofemoral joint force (- 12 %) but increases the strain on the plantar fascia and Achilles tendon (T. L.-W. Chen et al., 2019; Lyght et al., 2016). Interestingly, increasing the step rate by 10% also reduces the patellofemoral joint force (- 12 %) but without increasing the load on the ankle (Esculier et al., 2022, 2023). Finally, combining a transition to a non-rearfoot strike pattern with a 10% increase in step rate results in a 43% reduction in peak patellofemoral stress, making this dual approach more effective than either modification alone (Wei et al., 2024). The effectiveness of running retraining in managing overuse knee injuries is supported by studies showing pain reduction and improved running participation in runners with patellofemoral pain following such interventions. (De Souza Júnior et al., 2024; Roper et al., 2016). In parallel, several studies have shown that running with minimalist footwear also decreases patellofemoral joint forces (- 15%) (Bonacci et al., 2018). Although no study has been conducted on the effect of minimalist footwear on patellofemoral pain in runners, long-term use of minimalist footwear can reduce knee pain in elderly women with knee osteoarthritis (Trombini-Souza et al., 2012).

Unfortunately, the benefits of running technique alteration in injured runners are counterbalanced by the risk of a secondary RRI (Barton, 2018). Previous studies that implemented minimalist footwear or a running retraining intervention reported an increase in foot and ankle injuries compared to the control group (Chan et al., 2018). To reduce the risk of secondary RRIs affecting the foot or ankle, experts recommend that clinicians incorporate a foot and ankle strengthening programme alongside a transition to minimalist footwear or a running retraining intervention (Barton, 2018; Davis, 2011; Warne & Gruber, 2017). Strengthened foot and ankle muscles may help mitigate the strain on the plantar fascia and Achilles tendon during running (Kelly et al., 2015; R. Smith et al., 2023). However, no study has investigated whether foot and ankle characteristics influence the risk of injury associated with transitioning to minimalist footwear or implementing a running retraining intervention.

Therefore, the aim of this study was to identify the risk factors of sustaining RRIs that hinder the adoption of these methods by recreational endurance runners. The first research objective was to prospectively compare foot and ankle characteristics between injured and uninjured recreational runners following the transition to 1) minimalist footwear or 2) a softer running technique. A similar comparison will be performed with the control group to assess the specificity of the risk factors. We hypothesised that weakness in ankle plantar flexors, hallux flexors, and lesser toe flexors are risk factors for sustaining RRIs, particularly foot and ankle injuries, when transitioning to minimalist footwear or a softer running technique (Barton, 2018; Davis, 2011).

Materials and Methods

This study is a secondary analysis of a 12-month randomised controlled trial originally designed to compare the effects of minimalist footwear and running retraining on the incidence of RRI in recreational long-distance runners. The protocol of this study follows the CONSORT (Consolidated Standards of Reporting Trials) recommendations. It was prospectively registered at ClinicalTrials.gov (NCT05499871). The study was conducted in accordance with the Declaration of Helsinki and was approved by the local ethics committee.

Participants

Sample size was estimated via simulation, based on the primary outcome of the original study, which was time to running-related injury. Assuming cumulative injury incidences of 40%, 16%, and 52% in the control, running retraining, and minimalist footwear groups, respectively, we used a Monte Carlo approach to account for the three-group comparison within a Cox proportional hazards model. For each candidate sample size (20 to 80 participants per group), 1,000 datasets were simulated with group-specific event probabilities and exponential survival times. A global likelihood ratio test was applied to each model to assess the effect of group allocation. Statistical power was defined as the proportion of simulations yielding a p-value < 0.05. Based on this approach, a sample size of 46 participants per group (138 in total) was estimated to achieve 80% power (Chan et al., 2018; Fuller, Thewlis, Buckley, et al., 2017).

Eligibility criteria included: age 18-55 years, running ≥10 km/week for ≥1 year, and no injuries in the past three months. All participants were habitual rearfoot strikers who wore cushioned shoes and had never tried minimalist shoes or tried to modify their running technique. All participants provided written informed consent prior to participation.

Participants were randomly allocated to the control group (CG), minimalist group (MG) or gait retraining group (GR). The randomisation was stratified according to the age (under and over 30 years old) and weekly mileage (under and over 25 kilometers per week), creating four strata. For each stratum, block randomisation with blocks of six was performed using the online tool Sealed Envelope (https://www.sealedenvelope.com). Sealed opaque envelopes containing group assignments were prepared separately for each stratum. Upon enrolment, participants were classified into their stratum and assigned to a group by opening the next envelope in that stratum's sequence. Allocation concealment was ensured by having an independent researcher manage the randomisation and envelopes.

Treatment arms

Participants in the RRG received four real-time feedback sessions with an instructor in the laboratory and two unsupervised sessions over two weeks. These sessions aimed to modify the footstrike pattern to a non-rearfoot strike and increase step rate by 7.5% (Willy, Buchenic, et al., 2016). Participants were instructed to land on the ball of their foot and match their steps to an audible metronome set to the new rate (Barton et al., 2016). The retraining protocol employed a faded feedback approach (Davis, 2011) (Supplemental Table 1). Participants were also encouraged to apply the new technique in a progressive running programme during the first two months and maintain it thereafter (Supplemental Table 2) (Warne & Gruber, 2017).

Participants allocated to the MG received either trail minimalist footwear (Merrel® trail glove 6; minimalist index = 78%) or road minimalist footwear (Topo athletic® ST-4; minimalist index = 76%) according to their preferences and followed the same progressive running programme of the RRG. After two months, they were encouraged to continue using minimalist footwear in their training.

The control group received a placebo static stretching protocol without any intensity, based on a previous study, which demonstrated no effect on running-related injury prevention (C. Baxter et al., 2017; Taddei et al., 2020). Participants were instructed to perform the protocol during 5-minute sessions, three times per week.

Experimental protocol

Due to the nature of the interventions, blinding was not feasible. Both participants and outcome assessors were aware of group assignments because the interventions (minimalist footwear and gait retraining) were clearly identifiable. Each participant was assessed at four time points: baseline, two months, six months, and 12 months of follow-up.

Questionnaire

At each session, participants completed a baseline questionnaire assessing training habits. Additionally, at two months, participants in the intervention groups reported their adherence to the proposed running programme (0 = not at all to 3 = entirely). At six and 12 months, participants in the RRG indicated the frequency of using the new running technique (0 = less than one training session in five to 5 = every training session), while participants in the MG reported the weekly distance covered using minimalist footwear.

Foot-ankle characteristics assessment

Foot-ankle characteristics were assessed on the dominant leg, defined as the preferred leg to kick a ball (van Melick et al., 2017).

Foot posture index (FPI-6) and navicular drop (ND) were used to evaluate foot posture. The FPI-6 presents an excellent test-retest and inter-rater reliability (ICC: 0.81–0.86) as does the ND (ICC: 0.84) (Fraser et al., 2017; Mulligan & Cook, 2013; Redmond et al., 2006). For ND, three trials were performed and averaged.

Then, ankle plantar flexor, hallux flexor, and lesser toe flexor strength were assessed using a digital hand-held dynamometer (MicroFET2, Hoggan Health Industries, West Jordan, UT, USA) in accordance with prior methodology (Fraser et al., 2017). Participants lay prone for ankle plantar flexor testing (foot off the table, ankle neutral) and supine with knees at 90° and toes extended at 25° for hallux and toe flexor testing. The dynamometer was secured to a height-adjustable bar to minimise examiner interference, and stabilisation was ensured using straps and manual support. The ankle plantar flexor lever arm was measured between the lateral malleolus and the dynamometer contact point. The testing order was randomised. Participants completed two familiarisation trials, followed by three maximal efforts, each lasting 3–5 seconds, with 30 seconds of rest. The highest value was retained. Strength was reported in Newton-meters (N.m) for ankle plantar flexors and in Newtons (N) for hallux and toe flexors. All values were normalised to body mass. These measures demonstrated excellent reliability (test-retest ICC: 0.73–0.88; inter-rater ICC: 0.74–0.89) (Fraser et al., 2017).

Plyometric capacity

After a familiarisation period, participants performed three single-leg drop jumps from a 30 cm box with their dominant lower limb. In the barefoot condition, participants were instructed to jump as high as possible while keeping their knees as straight as possible, hands on their hips, and to push off the ground as quickly as possible. Video recording (240 Hz) of the foot from the front of the patient was performed for subsequent analyses using the "MyJump Lab Pro" application (Carlos Balsalobre-Fernández, version 2.1.1). "MyJump Lab Pro" showed a good validity for RSI (r = 0.97) and jump height (r = 0.97) (Haynes et al., 2019). "MyJymp Lab Pro" has also a good reliability for RSI (ICC = 0.98) and jump height (ICC = 0.96) (Haynes et al., 2019).

Footstrike determination and step rate

After five minutes of running, a one-minute video recorded (240 Hz) captured participants running at comfort speed. Frame-by-frame analysis with Dartfish® (version Prosuite 10.0, Dartfish, Alpharetta, Georgia) allowed identification of each runner's dominant leg footstrike pattern (forefoot/midfoot or rearfoot). The footstrike pattern analysis showed high reliability (ICC = 0.88) (Murray et al., 2018). Step rate was measured by timing 50 strides (100 steps), with excellent intra- and inter-rater reliability (ICC > 0.98) (Esculier, Silvini, et al., 2018).

Running-related injuries

RRIs were defined according to a previous expert consensus (Yamato et al., 2015). Back injuries were also included among RRIs, given their reported incidence in running activities (Kakouris et al., 2021). Every two weeks, an e-mail was sent to all participants to ask whether any recent pain had limited or stopped their usual running practice (in terms of mileage, speed, duration, or training frequency). Participants who reported a RRI were asked to fill out a questionnaire in accordance with recent guidelines (Edouard & Tooth, 2024). RRI locations (back, hip, knee, tibia, overuse foot injury, and traumatic foot injury) were categorised for each participant (0 = no; 1 = yes).

Statistical analysis

An as-treated analysis investigated associations between foot–ankle characteristics and RRIs within each group. Inclusion required participation in at least two evaluation sessions. Participants were reclassified based on their actual exposure to the intervention. Participants in the MG had to run in minimalist footwear for ≥25% of their weekly mileage at six months, and participants in the RRG had to adopt a non-rearfoot strike or increase step rate by ≥ 7.5% from baseline. Participants not meeting these criteria were analysed as part of the CG.

Normality of continuous variables was assessed using the Shapiro–Wilk test. Descriptive data are reported as means (SD) or medians (IQR), depending on distribution. The incidence and location of RRIs were described by group.

A first analysis compared injured and uninjured runners based on individual (age, sex, BMI, experience, training volume), biomechanical (comfort speed, cadence), and foot–ankle (ND, FPI-6, plantar flexors, hallux and lesser toe flexors strength) variables. For injured runners, values from the session prior to injury were used. For uninjured runners, the highest values across sessions were selected, except for ND and FPI-6, where baseline values were retained.

A second analysis focused specifically on runners with foot or ankle injuries, due to previously reported increases in this injury location following running technique alteration (Chan et al., 2018). Depending on distribution, variables were compared using unpaired Student's t-tests or Mann–Whitney U tests for quantitative variables, and chi-squared tests for categorical data.

Effect sizes were calculated as Cohen's d (parametric: small ≤0.70; moderate >0.60–<1.2; large ≥1.2) or rank biserial correlations (non-parametric: small 0.1–0.3; moderate 0.3–0.5; large 0.5–0.7; very large 0.7–0.9; extremely large ≥0.9) (Hopkins et al., 2009).

Multivariate logistic regression was performed using variables associated with injury ($p < 0.20$ in univariate analysis). In case of multicollinearity, the variable with the lowest p-value was retained. Model fit was assessed using McFadden's R^2, and ORs with 95% CIs were reported.

If any variable differed at $p < 0.1$ in multivariate logistic regression, a receiver operating characteristic (ROC) curve was generated to assess predictive accuracy. AUC values were interpreted as null (0.5), low (0.5–0.7), fair to good (0.7–0.9), high (0.9–1), or perfect (1.0). The optimal cut-off was identified using the Youden index (J = sensitivity + specificity – 1). Analyses were conducted using R (v4.1.1, R Core Team, 2017), with significance set at $\alpha = 0.05$ (Fox, 2005).

Results

In total, 182 participants were assessed for eligibility (Figure E.3). In the CG, 26 participants (45.6%) reported a RRI including five foot and ankle injuries. In the MG, 13 participants (38.2%) reported a RRI including eight foot and ankle injuries. In the RRG, 18 participants (47.3%) reported a RRI including 12 foot and ankle injuries. Fisher's exact test also showed that the number of overuse foot RRI was different between groups (*P* = .017). Post-hoc analysis showed that participants of the RRG underwent more overuse foot injuries than CG (*P* = .018).

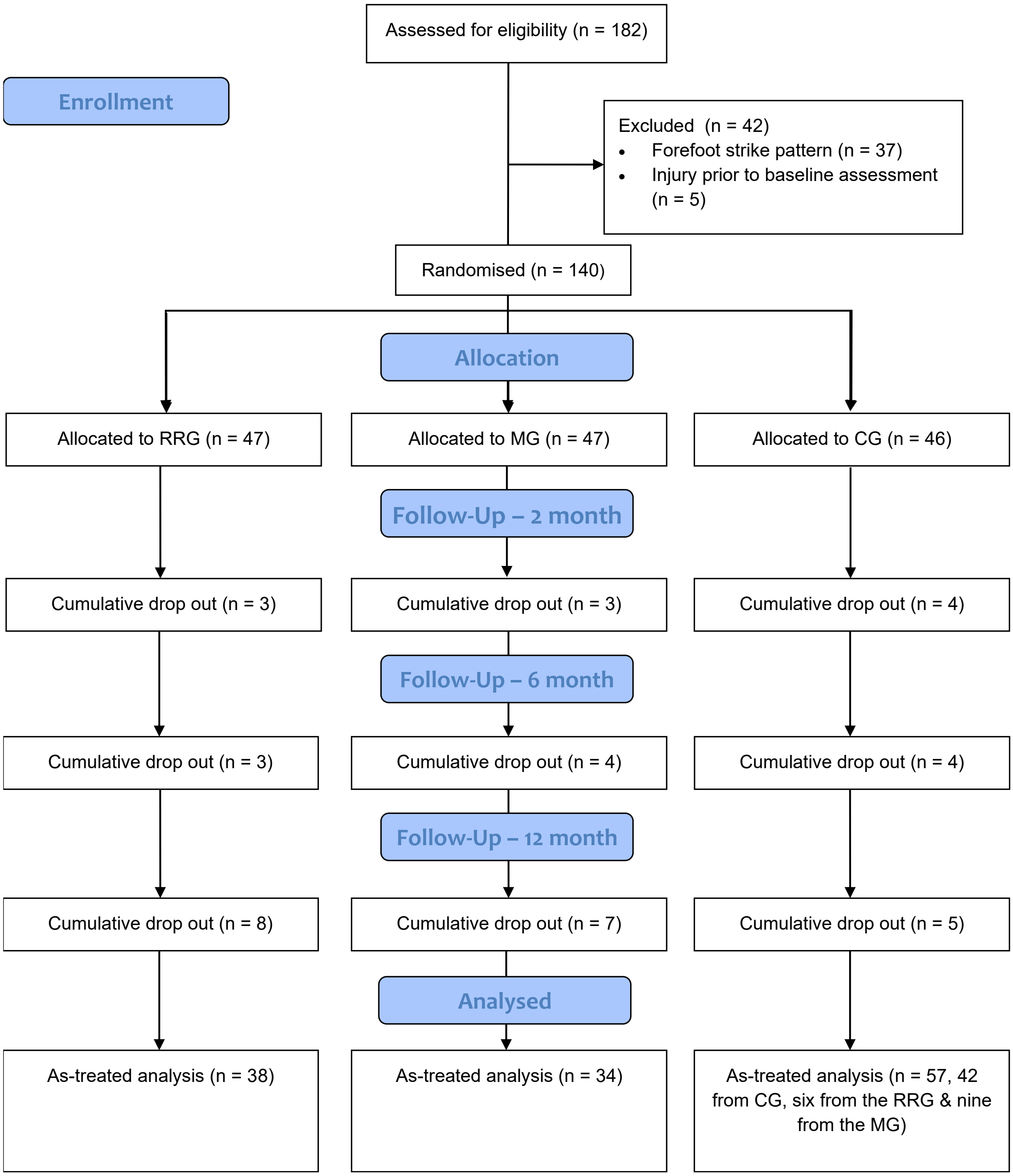


Figure E-3: Participant enrolment, allocation, and analysis flowchart.

In this as-treated analysis, 39 runners originally allocated to the RRG successfully altered their running technique by adopting a forefoot strike pattern and/or 7.5% higher step rate than the baseline value. Similarly, 34 runners originally allocated to the MG have sufficiently used minimalist footwear in their own running training sessions (≥ 25 % of their total weekly distance). On the other hand, six runners originally allocated to the RRG and nine runners originally allocated to the MG were finally allocated to CG for the as-treated analysis.

Adhesion to the running retraining interventions

In the MG, 67.6% of participants reported good or complete adherence to the running programme. In the RRG, 76.3% reported similar adherence. After six months, 84.1% of the RRG participants incorporated the new running technique in at least half of their training sessions, with this proportion rising to 88.8% at 12 months. In the MG, participants ran with minimalist footwear for 58.6% (± 30.6) and 48.9% (± 32.3) of their weekly distance at six months and twelve months, respectively.

Differences between injured and uninjured runners

No significant differences were found in individual characteristics, foot morphology, or foot muscle strength between injured and uninjured runners in the CG or MG. Logistic regression models were conducted for both the CG and MG. A CG logistic regression model included "toe flexor strength" and "weekly distance" was conducted (McFadden's R^2 = 0.037; P = .23). Similarly, a MG logistic regression model included "navicular drop" was conducted (McFadden's R^2 = 0.074; P = .07).

In the RRG, injured runners had significantly lower hallux and toe flexor strength compared to uninjured runners (P = .012 and P = .039, respectively). A RRG logistic regression model including "hallux flexor strength" and "age" was conducted (McFadden's R^2 = 0.259; P = .001). The results of the logistic regression models for variables associated with RRIs in each group (CG, MG, and RRG) are summarised in Table E.3. Medians, rank-biserial correlations, and p-values from the univariate analysis are shown in Table E.5.

Differences between runners with and without foot and ankle injuries:

No differences in individual characteristics, foot morphology, or foot muscle strength were found between injured and uninjured runners in the CG. A CG logistic regression model included "plantar flexor strength", "toe flexor strength", and "weekly distance" was conducted (McFadden's R^2 = 0.29; P = .02).

In the MG, injured runners had significantly higher body mass than uninjured runners (P = .035). A logistic regression model including "body mass" and "running experience" was conducted (McFadden's R^2 = 0.147; P = .066). A ROC curve for body mass was constructed. The AUC was fair to good (0.75), with a cut-off of 71.4 kg, showing 75% sensitivity and 76% specificity for identifying runners at risk of transitioning to minimalist footwear.

In the RRG, hallux and toe flexor strength were significantly lower in injured runners (P = .009 and P = .040, respectively). A RRG logistic regression model including "hallux flexor strength" was conducted (McFadden's R^2 = 0.144; P = .011). A ROC curve for hallux flexor strength was constructed (Figure E.4). The AUC was fair to good (0.79), with a cut-off of 2.85 N/kg, showing 83% sensitivity and 76% specificity for identifying runners at risk of transitioning to a softer running technique (Supplemental Figure 1).

The results of the logistic regression models for variables associated with foot and ankle injuries in each group (CG, MG, and RRG) are summarised in Table E.4. Medians, rank-biserial correlations, and p-values from the univariate analysis are shown in Table E.6.

Discussion

The main hypothesis of this study was that weakness in ankle plantar flexors, hallux flexors, and lesser toe flexors are risk factors for sustaining RRIs, particularly foot and ankle injuries, when transitioning to minimalist footwear or a softer running technique (Barton, 2018; Davis, 2011). Our findings partially confirmed this hypothesis because smaller hallux flexor strength was significantly associated with a higher risk of sustaining a RRI for runner transitioning to a softer running technique. More specifically, runners with a hallux flexor strength inferior to 2.85 N/kg who transit to a softer running technique had a higher risk to sustain a foot-ankle injury. Until now, recommendations advise clinicians to implement a foot-strengthening programme with all runners who undertake a running retraining intervention including a footstrike pattern modification (Barton, 2018). Rather than a "one-size-fits-all" strategy, this study supports a tailored approach that includes assessing hallux flexor strength with a hand-held dynamometer before initiating running retraining. A foot strengthening programme should be considered until a threshold of 2.85 N/kg is reached before adopting a non-rearfoot strike pattern. Interestingly, ankle plantar flexor strength was not significantly different between injured and uninjured runners transitioning to a softer running technique. However, runners injured at the foot and ankle exhibited approximately 16% lower ankle plantar flexor strength compared to their uninjured counterparts, with this difference approaching statistical significance (P = 0.07). A similar trend was observed in jump height during a vertical drop test, where foot and ankle injured runners jumped about 40% lower than uninjured runners (P = 0.07). Therefore, clinicians should be cautious when assessing these factors and consider incorporating ankle plantar flexor strengthening or plyometric programme when necessary.

Table E.3: Results of logistic regression models for variables associated with RRIs in each group (CG, MG, and RRG).

	Risk factors	Direction of association	Odds ratio (95 CI)	Wald statistics	p-value
CG [b]	**Toe flexor strength**	Negative	0.57 (0.25 –1.28)	1.82	0.17
	Weekly distance [a]	Positive	1.01 (0.98 – 1.04)	0.64	0.42
MG	**Navicular drop**	Negative	0.01 (0.001 – 2.5)	2.64	0.10
RRG [c]	**Age**	Negative	0.89 (0.79 –0.99)	4.36	**0.03**
	Hallux flexor strength	Negative	0.11 (0.02 –0.53)	7.49	**0.006**

[a] = Mean of the weekly distance reported by participants at each evaluation session attended. [b] = Due to multicollinearity, hallux flexor strength was excluded from the CG logistic regression model. [c] = Due to multicollinearity, "toe flexor strength", "drop jump height", and "RSI" were excluded from the RRG logistic regression model.

Table E.4: Results of the logistic regression models for variables associated with foot and ankle injuries in each group (CG, MG and RRG).

	Risk factors	Direction of association	Odds ratio (95 CI)	Wald statistics	p-value
CG	**Plantar flexor strength**	Negative	0.009 (0.001 – 5.222214)	2.11	0.14
	Toe flexor strength	Negative	0.22 (0.024 –2.13)	1.68	0.19
	Weekly distance [a]	Positive	1.05 (1.000002 – 1.10)	4.67	**0.03**
MG	**Body mass**	Positive	1.11 (0.99 – 1.24)	2.64	0.06
	Running experience	Positive	1.03 (0.92 – 1.16)	2.64	0.51
RRG[b]	**Hallux flexor strength**	Negative	0.19 (0.04 –0.80)	5.10	**0.02**

[a] = Mean of the weekly distance reported by participants at each evaluation session attended. [b] = due to multicollinearity, the variables "plantar flexor strength" , "toe flexor strength", "drop jump height" and "RSI" were excluded from the RRG logistic regression model.

Table E.5: Differences in individual characteristics between injured and uninjured runners in the CG, MG, and RRG.

Variables	**CG**		**P-value**	**Rank-biserial**	**MG**		**P-value**	**Rank-biserial**	**RRG**		**P-value**	**Rank-biserial**
	Injured (N = 26)	Uninjured (N = 31)			Injured (N = 13)	Uninjured (N = 21)			Injured (N = 18)	Uninjured (N = 20)		
Age (years)	26.50 (22.00–33.00)	28.00 (21.50–41.00)	0.69	-0.03	26.00 (24.00–40.00)	28.00 (22.00–36.00)	0.64	0.049	24.00 (21.00–28.75)	26.00 (24.00–39.25)	0.15	-0.138
Body mass (kg)	70.90 (63.40–75.80)	69.30 (59.30–80.80)	0.89	0.02	71.70 (64.50–73.90)	68.00 (63.50–71.20)	0.42	-0.168	69.20 (64.10–71.37)	66.30 (60.52–74.80)	0.48	-0.136
BMI (kg/m²)	23.05 (22.21–23.99)	23.01 (21.61–25.04)	0.98	0.005	21.65 (21.38–23.12)	22.11 (21.04–24.73)	1.00	0.002	22.63 (21.58–25.37)	23.40 (22.03–25.59)	0.55	-0.058
Running experience (years)	4.50 (2.62–10.00)	6.00 (3.00–8.00)	0.97	0.00	4.00 (3.00–10.00)	4.50 (2.00–9.00)	0.54	0.064	6.00 (2.62–11.75)	5.00 (3.00–10.00)	0.74	0.032
Weekly distance (km) [a]	30.62 (17.56–41.41)	23.75 (11.75–34.75)	0.18	0.10	27.50 (20.62–40.00)	22.50 (15.00–32.50)	0.24	0.123	20.75 (16.94–31.25)	19.81 (14.47–27.81)	0.38	0.083
Training volume (hours) [b]	3.25 (1.84–4.32)	2.62 (2.00–3.75)	0.45	0.06	3.00 (2.12–4.62)	2.62 (1.88–4.12)	0.43	0.082	2.56 (2.05–3.47)	2.56 (1.91–3.28)	0.80	0.025
ND (cm)	0.46 (0.37–0.59)	0.45 (0.36–0.54)	0.71	0.03	0.34 (0.31–0.40)	0.43 (0.33–0.54)	0.12	-0.159	0.38 (0.30–0.56)	0.48 (0.37–0.61)	0.25	-0.109
FPI-6	4.00 (2.25–7.00)	6.00 (3.50–7.00)	0.28	-0.08	4.00 (3.00–7.00)	6.00 (2.00–7.25)	0.85	-0.021	5.00 (3.00–7.00)	6.00 (3.75–9.00)	0.39	-0.082
Comfort speed (km/h)	12.00 (10.25–13.00)	11.00 (10.00–12.00)	0.17	0.10	11.00 (10.00–13.00)	12.00 (9.00–13.00)	0.48	0.073	11.00 (10.00–12.00)	10.50 (8.00–12.00)	0.35	0.089
Plantar flexor strength (Nm/kg)	0.89 (0.76–1.02)	0.94 (0.83–1.08)	0.24	-0.09	0.96 (0.75–1.08)	0.94 (0.89–1.02)	0.72	0.038	0.86 (0.73–1.00)	0.95 (0.81–1.07)	0.51	-0.063
Hallux flexor strength (N/kg)	2.68 (2.46–3.07)	2.77 (2.69–3.04)	0.18	-0.11	2.89 (2.77–3.34)	2.89 (2.41–3.23)	0.32	0.104	2.73 (2.38–2.96)	3.28 (2.89–3.56)	**0.012**	-0.235
Toe flexor strength (N/kg)	2.15 (1.87–2.54)	2.47 (2.07–2.91)	0.12	-0.12	2.43 (2.15–2.67)	2.18 (2.00–2.47)	0.29	0.112	2.18 (1.95–2.54)	2.67 (2.14–3.15)	**0.039**	-0.195
Drop jump height (cm)	8.56 (7.05–11.77)	10.23 (8.02–11.05)	0.21	0.10	12.08 (8.24–13.13)	9.24 (7.21–13.03)	0.52	0.068	7.82 (5.00–11.10)	10.89 (7.48–12.65)	0.15	-0.132
RSI	0.87 (0.72–1.00)	0.89 (0.79–1.08)	0.39	-0.07	0.86 (0.70–1.15)	0.94 (0.78–1.13)	0.69	-0.042	0.78 (0.62–1.02)	0.88 (0.79–1.15)	0.17	-0.126

[a] = Mean of the weekly distance reported by participants at each evaluation session attended; [b] = Mean of the running volume reported by participants at each evaluation session attended.

Table E.6: Differences in individual characteristics between runners with and without foot and ankle injuries in the CG, MG, and RRG.

Variables	CG		P-value	Rank-biserial	MG		P-value	Rank-biserial	RRG		P-value	Rank-biserial
	Injured (N = 5)	Uninjured (N = 52)			Injured (N = 8)	Uninjured (N = 26)			Injured (N = 12)	Uninjured (N = 26)		
Age (years)	26.00 (22.00–46.00)	27.00 (21.00–38.75)	0.49	0.094	33.00 (24.25–42.25)	26.50 (22.25–35.50)	0.41	0.099	24.00 (21.00–33.75)	26.00 (23.25–37.50)	0.49	-0.071
Body mass (kg)	71.80 (57.90–77.30)	70.40 (62.25–77.67)	0.92	0.03	73.45 (70.25–79.1)	67.75 (62.77–71.15)	**0.035**	-0.505	69.20 (64.50–71.07)	67.30 (60.37–74.47)	0.51	-0.138
BMI (kg/m²)	23.98 (22.42–23.99)	23.03 (21.78–24.69)	0.78	0.038	22.36 (21.46–23.62)	21.90 (21.08–23.90)	0.59	0.067	23.70 (22.20–25.53)	23.17 (21.80–25.02)	0.69	0.042
Running experience (years)	5.00 (4.00–5.00)	5.00 (2.50–10.00)	0.98	-0.004	10.00 (5.88–11.25)	3.50 (2.00–8.00)	0.08	0.204	5.50 (2.88–11.25)	5.00 (3.00–10.00)	0.85	0.021
Weekly distance (km)[a]	37.50 (30.00–75.00)	26.00 (12.88–36.72)	0.07	0.244	32.50 (20.34–43.00)	21.88 (15.31–32.50)	0.18	0.161	22.12 (18.12–32.03)	18.50 (14.88–28.44)	0.41	0.085
Training volume (hours)[b]	3.75 (3.00–7.50)	2.88 (1.81–4.00)	0.13	0.206	3.50 (2.09–4.81)	2.50 (1.91–3.92)	0.28	0.130	2.98 (2.09–3.59)	2.50 (2.01–3.16)	0.56	0.061
ND (cm)	0.59 (0.37–0.68)	0.45 (0.36–0.54)	0.35	0.127	0.34 (0.30–0.40)	0.41 (0.32–0.49)	0.32	-0.116	0.41 (0.28–0.52)	0.45 (0.35–0.60)	0.36	-0.095
FPI-6	4.00 (3.00–7.00)	5.00 (3.00–7.00)	0.83	-0.031	4.50 (2.50–7.25)	6.00 (2.00–7.00)	0.98	-0.005	6.00 (4.50–7.00)	5.00 (3.00–8.50)	0.70	0.041
Comfort speed (km/h)	12.00 (11.00–12.00)	11.75 (10.00–12.25)	0.73	0.048	12.50 (10.75–13.00)	11.00 (9.25–13.00)	0.20	0.149	10.50 (10.00–12.00)	11.00 (8.00–12.00)	0.54	0.063
Plantar flexor strength (Nm/kg)	0.68 (0.67–0.90)	0.94 (0.82–1.06)	0.15	-0.196	0.98 (0.74–1.08)	0.94 (0.90–1.04)	0.76	0.038	0.81 (0.70–0.93)	0.96 (0.83–1.08)	0.07	-0.184
Hallux flexor strength (N/kg)	2.75 (1.99–2.82)	2.74 (2.52–3.07)	0.54	-0.085	2.84 (2.78–3.08)	2.92 (2.33–3.27)	0.51	0.082	2.53 (2.25–2.83)	3.21 (2.88–3.53)	**0.009**	-0.266
Toe flexor strength (N/kg)	1.87 (1.77–2.43)	2.32 (1.97–2.87)	0.16	-0.192	2.27 (1.98–2.50)	2.33 (2.02–2.63)	0.73	-0.043	2.18 (1.88–2.51)	2.63 (2.11–3.03)	**0.040**	-0.211
Drop jump height (cm)	9.14 (7.14–11.58)	9.54 (7.36–11.59)	0.93	-0.014	12.08 (8.83–13.20)	9.20 (7.06–13.10)	0.30	0.125	6.55 (4.40–8.70)	10.79 (7.67–12.85)	0.07	-0.189
RSI	0.94 (0.81–1.03)	0.87 (0.76–1.05)	0.77	0.043	0.86 (0.78–1.15)	0.93 (0.76–1.15)	0.76	-0.038	0.70 (0.59–0.89)	0.88 (0.76–1.16)	0.18	-0.142

[a] = Mean of the weekly distance reported by participants at each evaluation session attended; [b] = Mean of the running volume reported by participants at each evaluation session attended.

Conversely, foot and ankle muscle strength were not considered risk factors for transitioning to minimalist footwear in recreational endurance runners. This distinction may stem from the fact that, unlike running retraining, transitioning to minimalist footwear does not consistently result in a systematic running technique alteration. A previous study showed that running alteration with traditional footwear induces more plantar flexor activation and ankle moment than running barefoot without any running alteration (Shih et al., 2013). However, subgroup analysis within the MG was not feasible due to limited sample size. Although foot and ankle muscle strength cannot currently be considered a risk factor, it may still be prudent to consider achieving a hallux flexor cut-off value of 2.85 N/kg for runners transitioning to minimalist footwear and adopting a non-rearfoot strike pattern to reduce the risk of foot and ankle injuries. Additionally, body mass was significantly different between runners with and without foot and ankle injuries. A threshold of 71.4 kg was identified as a risk factor for runners transitioning to minimalist footwear in our sample. This value aligns exactly with the cut-off identified in a previous study (Fuller, Thewlis, Buckley, et al., 2017). As previously described, the impact of minimalist footwear on loading forces is likely to be more pronounced in runners with higher body mass (Fuller, Thewlis, Buckley, et al., 2017). Given the consistent evidence linking an increased risk of secondary injuries to higher body mass in runners transitioning to minimalist footwear, clinicians are advised to favour running retraining interventions using traditional footwear for individuals weighing more than 71.4 kg.

This study has several limitations that should be considered before generalising the results. First, the effect size has been calculated to compare the effect of minimalist footwear and running retraining on RRI incidence in recreational long-distance runners. The sample size in each group limited the number of RRIs, resulting in a low statistical power. However, this is the first study exploring the risk factors of runners altering their running technique and the second study conducted in runners transitioning to minimalist footwear. Second, this study was conducted on healthy runners, whereas altering running technique is often used to manage knee pain in runners. Nevertheless, our findings provide valuable insights into the relationship between foot muscle strength and injury risk during transition. These results remain relevant for all runners, including those modifying their running technique for medical reasons. Finally, the cut-off, specificity, and sensitivity values were derived solely from our sample and did not undergo external validation. Although this study did not aim to develop a predictive model, future research should focus on validating these measures using an independent sample.

Conclusion

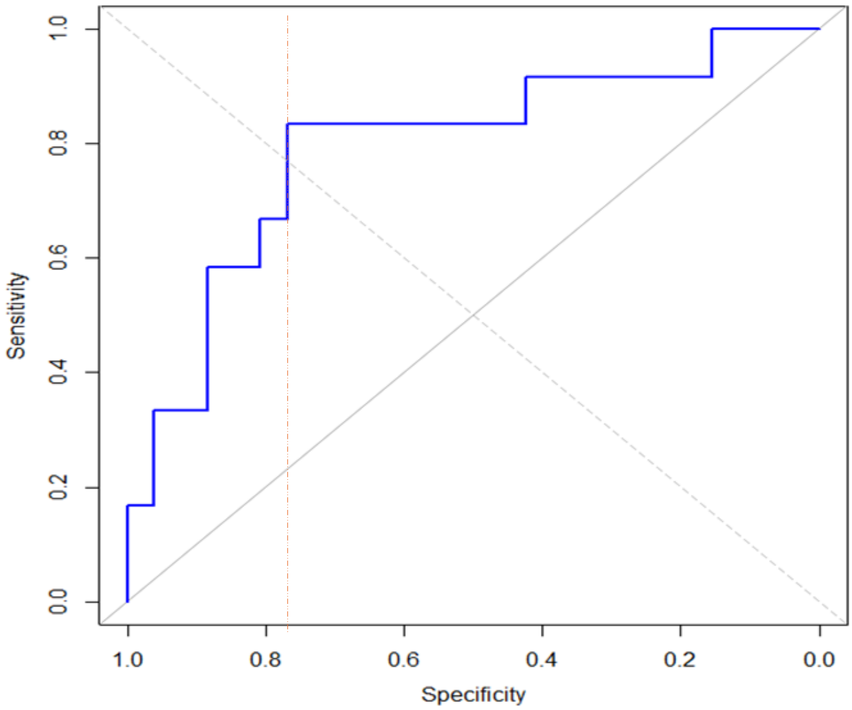
The most important finding of this study is that runners with a hallux flexor strength below 2.85 N/kg who transit to a softer running technique have a higher risk of sustaining a foot and ankle injury. Conversely, foot and ankle muscle strength cannot currently be considered risk factors for RRIs when transitioning to minimalist footwear. However, strengthening these muscles may still be beneficial, particularly for runners adopting a non-rearfoot strike pattern during the transition to minimalist footwear.

Supplemental Table 3: Faded feedback scheme of the running retraining protocol. Feedback consisted of oral instructions and an auditive metronome. Feedback was reduced across each session from 12 minutes to 4 minutes.

		SUPERVISION	**DURATION (MIN)**								**TOTAL SESSION DURATION (MIN)**
			Feedback	Free	Feedback	Free	Feedback	Free	Feedback		
SESSION 1	1^{st} week	Supervised	4	1	4	1	4	1	/	/	**15**
SESSION 2			3	2	3	2	3	2	/	/	**15**
SESSION 3		Unsupervised	3	2	3	2	3	2	/	/	**15**
SESSION 4	2^{nd} week	Supervised	2	3	2	3	2	3	2	3	**20**
SESSION 5			1	4	1	4	1	4	1	4	**20**
SESSION 6		Unsupervised	1	4	1	4	1	4	1	4	**20**

Supplemental Table 4: Progressive running programme proposed to the participants allocated to the gait retraining and minimalist footwear groups. Each participant was encouraged to follow this programme to ensure a safe implementation of the new running technique or minimalist footwear.

	WEEK 1	**WEEK 2**	**WEEK 3**	**WEEK 4**	**WEEK 5**	**WEEK 6**	**WEEK 7**	**WEEK 8**
SESSION 1	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min
SESSION 2	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min
SESSION 3	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min
DURATION PER WEEK	**15 min**	**30 min**	**45 min**	**60 min**	**75 min**	**90 min**	**105 min**	**120 min**



Supplemental Figure 1: Receiver operating characteristic (ROC) curve to assess the predictive validity of the hallux flexor strength to identify runners at risk of transitioning to a softer running technique. Optimal threshold value is highlighted by a vertical red line.

3. Biomechanical analysis of running drills aimed at improving foot function (Study 7).

Study 7: A comparison of foot and ankle biomechanics during running drills and distance running.

Published in Journal of Sport Biomechanics.

DOI: 10.1080/14763141.2024.2382804

ABRAN Guillaume[1,2], BERRAZ Audrey[3], DARDENNE Nadia[4], GRAMAGE Kevin[1,2] , BORNHEIM Stephen[2], DELVAUX François[1,2], CROISIER Jean-Louis [1,2], SCHWARTZ Cédric[1].

[1] LAM – Motion Lab, Liège, Belgium. Electronic address: guillaume.abran@uliege.be.

[2] Department of physical activity and rehabilitation sciences, University of Liege, Liege, Belgium.

[3]Université de Technologie de Compiègne (UTC), Alliance Sorbonne Université, 60200 Compiègne, France

[4] University and Hospital Biostatistics Center (B-STAT), University of Liège, Belgium.

Abstract

The aim of this study was to compare the foot-ankle joint mechanics of running drills and running. Seventeen long-distance runners performed five popular running drills (A-skip, B-skip, Bounding, Heel flicks, Straight leg running) and a run at 3.88 m/s. Kinematics, kinetics and power values were calculated for the ankle, midtarsal (MT) and metatarsophalangeal (MP) joints. Electromyographic activity was recorded for the soleus, gastrocnemius medialis, lateralis and abductor hallucis muscle. The A-skip, the B-skip and the Heel flicks induced a smaller ankle ($P < 0.001$, $\eta^2 = 0.41$), MT ($P < 0.001$, $\eta^2 = 0.43$) and MP ($P < 0.001$, $\eta^2 = 0.47$) dorsiflexion peak than running. No difference was found between the running drills and running for ankle, MT and MP moment. The Bounding induces a higher positive ankle power than running (diff: 5.5±7.5 J/kg, $p = 0.014$, $d = 1.05$). The A-skip (diff: 2.8±2.9 J/kg, $p < 0.001$, $d = 1.5$) and the B-skip (diff: 2.7±2.1 J/kg, $p < 0.001$, $d = 1.4$) induce a smaller MT positive power than running. This study offers an analysis of the mechanical behaviour of the foot-ankle complex to help track and field coaches select their running drills in an evidence-based manner.

Introduction

Plyometric training (PT) is particularly used by athletics coaches and can improve running economy (Oxfeldt et al., 2019; Spurrs et al., 2003; A. M. Turner et al., 2003). These improvements varied from 2% to 6%, according to the runner's level and plyometric protocol. Komi (1984) described the concept of the "stretch-shortening cycle" which is a specific contraction mode used during plyometric tasks and running. The stretch-shortening cycle corresponds to cyclic contraction involving a lengthening movement (eccentric) quickly followed by a shortening movement (concentric) (Komi, 1984). Moreover, PT has several benefits such as improving neuromuscular coordination, higher levels of muscle activation, increased rates of force development and increased ankle plantar flexor and toe flexor strength (Goldmann, Potthast, et al., 2013; Goldmann, Sanno, et al., 2013; Oxfeldt et al., 2019).

In the track and field, the most popular PT implemented by coaches is running drills (Whelan et al., 2016). Running drill training is based on exercises that focus on the phases of the running cycle (Azevedo et al., 2015). According to Whelan et al. (2016), the running drills which are the most commonly used in the field are the "A-skip", "Heel flicks", "Bounding", "B-skip", "Straight leg running". Depending on their form, running drills induce different levels of stress on the muscles that make up the ankle planter flexor group (Trowell et al., 2022). For instance, A-skip induces a lower plantar flexor load than running. In contrast, Bounding induces a higher mechanical load for both plantar flexors (Trowell et al., 2022). However, the study that highlighted these findings used a simplified foot model composed of a single segment. The foot is a complex structure composed of 26 small bones and 33 joints, resulting in high mobility (Leardini et al., 2019). During the last decades, several research groups have used the latter approach to model the foot according to a number of small segments rather that one single rigid segment, generally referred to as multi-segment foot models (Deschamps et al., 2011; Leardini et al., 2019). Multi-segment foot models involve positioning additional markers compared to the simplified model to subdivide the foot into several segments (three to 26 segments) (Cornwall & McPoil, 1999; Oosterwaal et al., 2011). Modelling the foot as a single rigid segment induces an over-estimation of the angular excursion and mechanical power at the ankle joint during hopping (Kessler et al., 2020). Over-estimation of ankle plantar flexor power requirements could lead to inaccurate estimates of the activation and energetics of the plantar flexor muscle group (Kessler et al., 2020). In addition, rigid-foot models do not consider the power generated within the foot. Several studies have shown the importance of the role of the foot in athletic performance, such as horizontal jump performance, the ability to change direction, the personal best in a 50m run (Goldmann, Sanno, et al., 2013; Hashimoto &

Sakuraba, 2014; Yuasa et al., 2018) and in the prevention of running-related injuries (Taddei et al., 2020). Therefore, the function of the foot should be considered as a key component of an athlete's lower limb. Understanding foot mechanics during running drills could help athletic coaches improve their exercise selection to develop foot function.

The aim of this study was to explore the mechanics of the foot-ankle complex during running drills and distance running using a multi-segment foot model. The use of a multi-segment foot model will help to understand the biomechanics within the foot and reduce the risk of inaccurate estimation of the contribution of the plantar flexor muscle group. The research objective is to compare kinematic, kinetic and energetic values at the ankle and the foot from commonly used running drills to distance running at endurance speed. Based on the study of Trowell et al (2022), it is hypothesised that Bounding will induce higher foot and ankle power than running whereas the A-skip and B-skip will induce less than distance running.

Materials and Methods

Participants

An a priori power analysis revealed that a minimum of sixteen participants are required for this study (effect size f = 0.274, α = 0.05, 1-β = 0.8, one group with six tasks (see the tasks description section). Eligibility criteria included age between 18 and 35 years, running in an athletic club for at least five years and practise running drills every week. Participants were recruited by convenience via local running clubs. This study was approved by the local ethics committee (19/04/2022; protocol No. 2022/102). Before the beginning of the study, each participant received a written document that explained the study and its requirements. The document included information about the purpose of the study, procedures involved, risks and benefits, confidentiality, and participant rights. Participants were asked to sign the document as an indication of their willingness to participate.

Experimental protocol

Muscle activation and biomechanical variables were collected on an indoor 30 m straight running track. Participants performed, in barefoot condition, five running drills (Figure E.5) and a run at 3.88 m/s in random order: A-skip, B-skip, Bounding, heel flicks, straight leg running, and running at 3.88 m/s (±5%). The barefoot condition was imposed on the participants because the equipment installed on the foot did not allow them to wear running footwear. A previous study showed that placing material directly on the running footwear does not fully reflect the movement of the foot joint (Perrin et al., 2023).

Tasks description

The A-skip involved participants skipping forward on one leg, while the opposite knee was driven upward by flexing the hip, knee, and ankle. The hip and knee then rapidly extended towards the ground, while the ankle remained in a dorsiflexed position. The skip action required knee lift in the swing leg to occur over two ground contact periods of the stance leg. The B-skip is nearly identical to the A-skip, but requires first extending the leg forward before the foot hits the ground. Bounding involved taking long, leaping strides. The Heel flicks required flexion of the hip as much as during the A-skip and knee flexion in order to hit the buttock with the heel. Finally, the Straight leg running (SLR) involves running forward with the knee locked in extension. The participants were free to use their arms during the running drills. Running was performed by each participant with its self-selected technique. Given their performance level in running, a speed of 3.88 m/s was selected to ensure a sub-maximal running speed and, consequently, a comfortable running technique. Five trials were collected for each single task (running drills and running at 3.88 m/s). For the running task, the running speed was checked after each trial by the experimenter by calculating the speed of the barycentre of the markers placed on the pelvis. Participants received a feedback ("run faster" or "run slower") after each trial to reach a speed of 3.88m/s (±5%) in five trials. A period of self-determined recovery was allowed between the trials to minimise fatigue.

Kinematic

Kinematic data were measured using four optoelectronic units (Codamotion system; Charnwood Dynamics; Rothley, UK) with a sampling rate of 200 Hz. Twenty-five active markers were placed by a single experimented physiotherapist specialized in foot biomechanics on the following anatomical landmarks of the dominant lower limb: distal phalange of the first toe, head of the first, second and fifth metatarsals, base of the first and second metatarsals, posterior calcaneus, navicular tuberosity, and the cuboid bone (Schwartz et al., 2020). Additional markers were placed on the medial and lateral malleoli, medial and lateral femoral condyles, and the anterior and posterior iliac spines. Clusters of four markers were attached to the lateral thigh and shank (Figure E.6). The ground reaction force (GRF) data were simultaneously captured using two consecutive force plates (Kistler, Kistler Group, Switzerland) at a sample rate of 1000 Hz. The four optoelectronic units were placed around the force plates to ensure a good visibility of the markers while the participant is passing.

Electromyography

Surface electromyographic (EMG) signals were simultaneously collected with Trigno Standard sensors (Delsys, Boston, MA, USA) using silver-contact wireless bipolar bar electrodes with fixed 10 mm inter-electrode spacing. Electromyographic signals were recorded on the two heads of the gastrocnemius muscle, the soleus and the abductor hallucis. Electrode placement and skin preparation were performed based on the recommendations of Barbero et al. (2012) and (Branthwaite et al., 2019). Data were acquired at a sample frequency of 1000 Hz.

Kinematic, kinetic and electromyographic devices were connected to a central control unit (CodaHub, Charnwood Dynamics, UK), which ensure the synchronisation of all the inputs.

Data analysis

GRF data were filtered using a 50-Hz, zero-phase low-pass fourth-order Butterworth filter as described in Takabayashi et al. (2021). The stance phase was defined between the instant when the vertical GRF increased above 20 N and the instant when it fell below 20 N. All the biomechanics variables were analysed during the stance phase.

Visual 3D software (C-motion Inc., Germantown MD, USA) was used for biomechanical modelling and analysis. A three-segment kinetic foot model was created, from (Bruening et al., 2012a), containing a hindfoot, midfoot, and phalanges, separated by midtarsal (MT) and metatarsophalangeal (MP) joints. The MT joint centre was positioned midway between the cuboid bone and navicular markers, and the MP joint centre was positioned midway between the first and fifth metatarsal heads. The ankle and MT joint motions were modelled with six degrees-of-freedom (DOF), whereas the MP joint was modelled with two DOF.

Marker trajectories from the running drills and the running trials were low-pass filtered using a zero-phase 4th order Butterworth filter (12 Hz cut-off) as described by previous author (Leardini et al., 2021). The joint angles were derived using a typical Cardan angle rotation sequence (1-sagittal, 2-frontal, 3-transverse) (Leardini et al., 2021). Joint angles were expressed relatively to the individual static position (standing upright, arms by their sides and looking forward). Ankle, MT and MP dorsiflexion and plantarflexion were defined as kinematic output measures. Concerning kinetics, inverse dynamics were used to calculate the net internal moments and powers at each joint of the foot and ankle (Bruening et al., 2012b). The net internal moments and powers were normalised to body weight for each participant.

EMG signals were first band pass filtered (20–500 Hz, zero-phase 4th order Butterworth filter) and then processed using a root mean-square filter (100 ms moving window). The peak of the

EMG signals was extracted for each task repetition. Then, the median of the peaks of the EMG signals was kept as the EMG output measure. The EMG signals were expressed in mV. The trials were not included in the analysis when the participant's foot did not land distinctly on one of the two force plates.

The means of the kinematic and kinetic parameters of the included trials were calculated for the analysis.

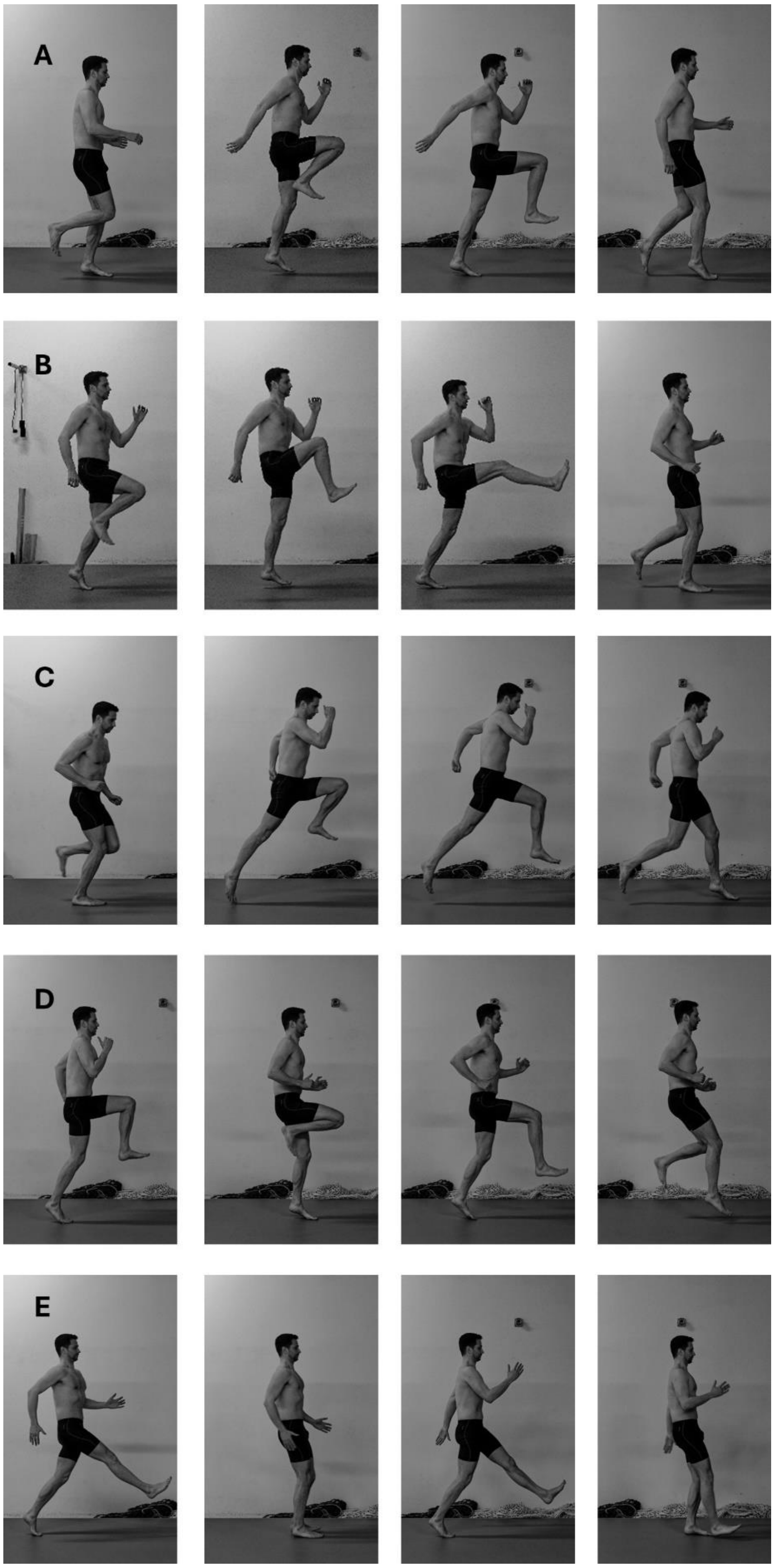


Figure E-4: Diagram of each running drills performed by the participant. A) A-skip; B) B-skip; C) Bounding; D) Heel Flicks; E) Straight leg running (SLR).

Statistical analysis

Statistical analyses were performed using JASP (version 0.17.3, 2023) (Van Doorn et al., 2021). The results were significant at the 5% critical level ($p < 0.05$). Repeated measures analysis of variance (ANOVA) were used to compare the peak of dorsiflexion and plantarflexion, the range of motion, the moments, the positive and negative power of the ankle, the MT and the MP joint across the six tasks (the five running drills and running). If Mauchly's test of sphericity indicated that the assumption of sphericity was violated ($p < 0.05$), a Greenhouse-Geisser test was applied for sphericity correction. The partial eta square was calculated as the measure of effect size defined as small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$) and strong ($\eta^2 = 0.14$)(Maher et al., 2013). A post-hoc analysis was performed with a Bonferroni's correction. Repeated measures analysis of variance tests were also used to compare the values of muscle activity of the medial and lateral heads of the gastrocnemius, soleus and abductor hallucis between running drills and running. The Cohens *d* effect of post-hoc analysis were calculated with effect sizes defined as small ($d = 0.2$), medium ($d = 0.5$) and strong ($d = 0.8$) (Hopkins et al., 2009). As an indication, the percentage of muscle activity of the medial and lateral heads of the gastrocnemius, soleus and abductor hallucis relative to running were calculated for the running drills.

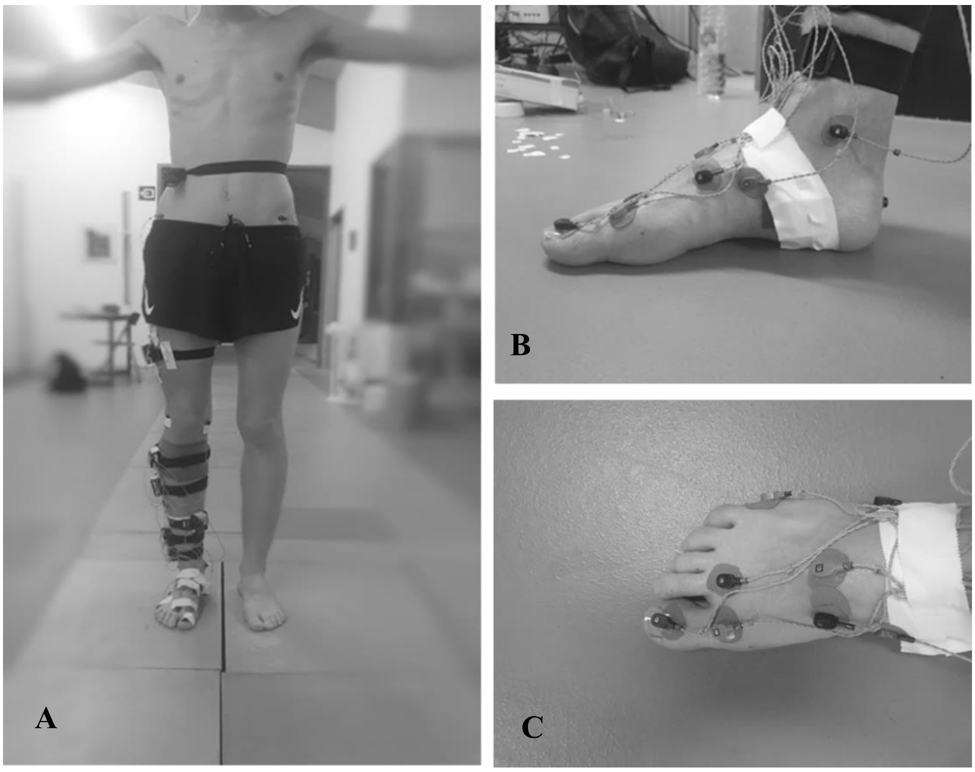


Figure E-5: A) illustration of a volunteer equipped with the active markers and the EMG electrodes on the right lower limb. B) medial view of the foot after material placement. C) Top view of the foot after material placement.

Results

Data were collected for 17 runners (15 males, 2 females, age = 26.6 ± 5.6 years; mass = 67.5 ± 5.5 kg, height = 1.77 ± 0.07 m, personal best in 10.000 metres race = 35.1 ± 4.4 minutes, volume per week = 52.8 ± 22.4 km, experience in running = 9.6 ± 4.1 years).

All mean, standard deviations, p-values and effect sizes for the ankle, MT and MP are shown in Table E.7 (kinematic data), E.8 (kinetic data) and E.9 (energetic data).

Ankle

Ankle plantar flexion peak was similar between the running drills and running ($p = 0.40$, $\eta^2 = 0.58$) whereas the ankle dorsiflexion peak ($p < 0.001$, $\eta^2 = 0.41$) and ankle ROM ($p < 0.001$, $\eta^2 = 0.42$) were different. For ankle dorsiflexion peak, post hoc tests showed that the A-skip (difference (diff): 14.5 ± 18.5°, $p < 0.001$, $d = 1.5$), the B-skip (diff: 13.4 ± 19.3°, $p < 0.001$, $d = 1.4$), the SLR (diff: 10.2 ± 16.3°, $p = 0.01$, $d = 1.0$) and the Heel flicks (diff: 13.4 ± 17.7°, $p < 0.001$, $d = 1.4$) induced smaller values than running. However, only the A-skip (diff: 9.8 ± 7.3°, $p < 0.001$, $d = 1.14$) and the B-skip (diff: 8.7 ± 6.7°, $p = 0.007$, $d = 1.0$) induced a smaller ankle ROM than running.

From a kinetics point of view, differences were only found within the running drills (Bounding vs A-skip & Bounding vs B-skip) but no difference was found between the running drills and running.

For positive ankle power, only the bounding induced a higher value than running (diff: 5.5 ± 7.5 J/kg, $p = 0.014$, $d = 1.05$) whereas the value of the four other running drills was not significantly different to running. No difference was found for negative ankle power between each running drills and running ($p = 0.05$, $\eta^2 = 0.18$)

Midtarsal

MT plantar flexion peak was similar between the running drills and running ($p = 0.35$, $\eta^2 = 0.06$) whereas the MT dorsiflexion peak ($p < 0.001$, $\eta^2 = 0.43$) and MT range of motion ($p < 0.001$, $\eta^2 = 0.29$) were different. For MT dorsiflexion peak, post hoc tests showed that the A-skip (diff: 6.5 ± 5.8°, $p < 0.001$, $d = 1.0$), the B-skip (diff: 6.4 ± 5.3°, $p < 0.001$, $d = 0.9$) and the Heel flicks (diff: 5.2 ± 5.3°, $p = 0.002$, $d = 0.7$) induced smaller values than running. As for the ankle ROM, only the A-skip (diff: 7.7 ± 7.8°, $p = 0.005$, $d = 0.8$) and the B-skip (diff: 6.9 ± 7.9°, $p = 0.007$, $d = 1.0$) induced smaller MT ROM than running.

From a kinetics point of view, a difference was only found between the Bounding and the A-skip ($p = 0.007$, $d = 0.97$) but no difference was found between the running drills and running.

For positive MT power, the A-skip (diff: 2.8 ± 2.9 J/kg, $p < 0.001$, *d* = 1.5) and the B-skip (diff: 2.7 ± 2.1 J/kg, $p < 0.001$, *d* = 1.4) induce a smaller value than running. No difference was found for negative MT power between each running drills and running ($p = 0.052$, $\eta^2 = 0.16$)

Metatarsophalangeal

MP plantar flexion peak was similar between the running drills and running ($p = 0.41$, $\eta^2 = 0.06$) whereas the MP dorsiflexion peak ($p < 0.001$, $\eta^2 = 0.47$) and MT range of motion ($p < 0.001$, $\eta^2 = 0.43$) were different. For MP dorsiflexion peak, post hoc tests showed that the A-skip (diff: 7.2 ± 6.5°, $p < 0.001$, *d* = 1.0), the B-skip (diff: 8.1 ± 4.7°, $p < 0.001$, *d* = 1.1), the Bounding (diff: 4.2 ± 5.3°, $p = 0.015$, *d* = 0.69) and the Heel flicks (diff: 9.2 ± 6.0°, $p < 0.001$, *d* = 1.3) induced smaller values than running. Similarly, the A-skip (diff: 7.3 ± 6.6°, $p < 0.001$, *d* = 0.9), the B-skip (diff: 7.0 ± 3.5°, $p < 0.001$, *d* = 0.9), the bounding (diff: 4.4 ± 6.2°, $p = 0.009$, *d* = 0.64) and the Heel flicks (diff: 9.3 ± 6.4°, $p < 0.001$, *d* = 1.2) induced a smaller MP ROM than running.

No difference was found between the running drills and running for MP moment ($p = 0.49$, $\eta^2 = 0.04$), positive MP power ($p = 0.13$, $\eta^2 = 0.11$) and negative MP power ($p = 0.75$, $\eta^2 = 0.136$).

Muscle activity

All mean, standard deviations, values of muscle activation, p-values and effect sizes for the abductor hallucis, gastrocnemius medialis, lateralis and soleus are shown in Table E.10.

The Bounding (diff: 157.0 ± 96.3 mV, $p < 0.001$, *d* = 1.04) and the SLR (diff: 65.0 ± 127.7 mV, $p = 0.009$, *d* = 0.56) induce a higher abductor hallucis activation than running.

On the other hand, the bounding induce a higher gastrocnemius medialis (diff: 138.0 ± 129.3 mV, $p = 0.006$, *d* = 1.10) and soleus (diff: 131.7 ± 103.2 mV, $p < 0.001$, *d* = 1.06) muscle activation than running.

Table E.7: Comparison of the ankle, the midtarsal and the metatarsophalangeal kinematics between running drills and running (mean ± SD).

Joint	Tasks	Dorsiflexion peak (Degree)	p-value	η²	Post-hoc test	Plantarflexion peak (degree)	p-value	η²	Post-hoc test	ROM (degree)	p-value	η²	Post-hoc test
Ankle (Degrees)	A-Skip (1)	1.6 ± 6.6	**< 0.001**	0.41		-26.8 ± 9.3	= 0.40	0.05		28.5 ± 7.0	**< 0.001**	0.42	
	B-skip (2)	2.7 ± 3.6				-26.9 ± 5.0				29.6 ± 6.2			
	Bounding (3)	14.4 ± 7.5			(3) > (1)***, (2)***, (4)***, (5)*	-29.2 ± 9.6				43.3 ± 10.1			(3) > (1)***, (2)***, (4)***, (5)*
	Heel flicks (4)	2.7 ± 7.4				-28.5 ± 11.4				31.2 ± 12.7			
	SLR (5)	5.9 ± 5.8				-29.0 ± 7.3				35.0 ± 8.4			
	Running (6)	15.3 ± 16.1			(6) > (1)***, (2)***, (4)***, (5)*	-23.3 ± 18.4				38.6 ± 6.4			(6) > (1)***, (2)**
MT (Degrees)	A-Skip (1)	9.6 ± 5.7	**< 0.001**	0.43		-13.3 ± 7.0	= 0.35	0.06		23.0 ± 3.2	**< 0.001**	0.29	
	B-skip (2)	9.7 ± 5.0				-14.1 ± 6.3				23.9 ± 3.1			
	Bounding (3)	14.0 ± 3.8			(3) > (1)***, (2)***, (4)*	-12.8 ± 7.5				26.8 ± 3.2			
	Heel flicks (4)	11.0 ± 4.6				-13.7 ± 7.1				24.7 ± 3.7			
	SLR (5)	13.7 ± 5.0			(5) > (1)***, (2)***	-15.2 ± 8.1				29.0 ± 4.9			(5) > (1)***, (2)**, (5)*
	Running (6)	14.9 ± 6.2			(6) > (1)***, (2)***, (4)**	-13.2 ± 7.2				28.1 ± 5.9			(6) > (1)**, (2)*
MP (Degrees)	A-Skip (1)	27.1 ± 7.9	**< 0.001**	0.47		1.1 ± 3.9	= 0.41	0.06		25.3 ± 9.4	**< 0.001**	0.43	
	B-skip (2)	26.1 ± 7.6				-0.1 ± 1.9				25.7 ± 8.3			
	Bounding (3)	30.1 ± 7.4			(3) > (4)*	1.0 ± 2.7				28.3 ± 8.4			
	Heel flicks (4)	25.0 ± 7.6				1.1 ± 3.7				23.4 ± 8.5			
	SLR (5)	32.0 ± 8.0			(5) > (1)*, (2)*, (4)***	0.7 ± 3.0				30.5 ± 8.1			(5) > (1)*, (2)*, (4)***
	Running (6)	35.6 ± 9.1			(6) > (1)***, (2)***, (3)*, (4)***	0.9 ± 2.9				33.9 ± 9.1			(6) > (1)***, (2)***, (3)**, (4)***

*MT = midtarsal; MP = Metatarsophalangeal; ROM = Range of Motion; Repeated measures ANOVA followed by Bonferroni's correction : P > 0.05, not significant; * symbol represents a p-value for post-hoc test inferior to 0.05; ** symbol represents a p-value for post-hoc test inferior to 0.01; *** symbol represents a p-value for post-hoc test inferior to 0.001. Tasks are represented by a number from 1 to 8 in post-hoc test. ANOVA, Analysis of Variance; SD, Standard deviation:*

Table E.8: Comparison of ankle, midtarsal and metatarsophalangeal kinetics between running drills and running (mean ± SD).

Joint	Tasks	Moment (N.m/kg)	p-value	ŋ²	Post-hoc test
Ankle (N.m/kg)	A-Skip (1)	3.01 ± 0.53	**= 0.016**	0.02	
	B-skip (2)	3.15 ± 0.45			
	Bounding (3)	3.66 ± 0.72			(3) > (1)**, (2)*
	Heel flicks (4)	3.30 ± 0.61			
	SLR (5)	3.41 ± 0.51			
	Running (6)	3.40 ± 0.66			
MT (N.m/kg)	A-Skip (1)	1.95 ± 0.47	**= 0.039**	0.16	
	B-skip (2)	2.13 ± 0.44			
	Bounding (3)	2.36 ± 0.47			(3) > (1)**
	Heel flicks (4)	2.16 ± 0.47			
	SLR (5)	2.22 ± 0.28			
	Running (6)	2.21 ± 0.35			
MP (N.m/kg)	A-Skip (1)	0.32 ± 0.17	= 0.49	0.04	
	B-skip (2)	0.47 ± 0.26			
	Bounding (3)	0.42 ± 0.44			
	Heel flicks (4)	0.37 ± 0.19			
	SLR (5)	0.40 ± 0.21			
	Running (6)	0.40 ± 0.18			

*MT = midtarsal; MP = Metatarsophalangeal. Repeated measures ANOVA followed by Bonferroni's correction: P > 0.05, not significant; * symbol represents a p-value for post-hoc test inferior to 0.05; ** symbol represents a p-value for post-hoc test inferior to 0.01; *** symbol represents a p-value for post-hoc test inferior to 0.001. Tasks are represented by a number from 1 to 8 in post-hoc test. ANOVA, Analysis of Variance; SD, Standard deviation.*

Table E.9: Comparison of ankle, midtarsal and metatarsophalangeal power data between running drills and running.

		Ankle, midtarsal and metatarsophalangeal Positive/Negative power (J/kg) (Mean ± SD)							
Joint	**Tasks**	**Positive power (J/kg)**	p-value	ŋ²	Post-hoc test	**Negative power (J/kg)**	p-value	ŋ²	Post-hoc test
Ankle	A-Skip (1)	11.16 ± 4.37	**< 0.001**	0.35		-12.98 ± 6.62	= 0.050	0.18	
	B-skip (2)	10.05 ± 2.83				-13.06 ± 5.73			
	Bounding (3)	17.27 ± 5.51			(3) > (1)***, (2)***, (4)***, (5)***, (6)*	-19.45 ± 7.08			
	Heel flicks (4)	11.60 ± 2.68				-18.85 ± 13.47			
	SLR (5)	11.09 ± 2.13				-15.81 ± 5.59			
	Running (6)	13.05 ± 5.17				-13.91 ± 6.09			
MT	A-Skip (1)	4.64 ± 2.09	**< 0.001**	0.39		-4.05 ± 2.53	= 0.052	0.16	
	B-skip (2)	4.79 ± 2.03				-4.59 ± 2.95			
	Bounding (3)	8.24 ± 2.77			(3) > (1)***, (2)***	-6.32 ± 2.46			
	Heel flicks (4)	6.59 ± 3.15				-6.30 ± 3.06			
	SLR (5)	8.03 ± 2.82			(5) > (1)***, (2)**	-5.92 ± 3.29			
	Running (6)	8.86 ± 3.59			(6) > (1)***, (2)***	-5.66 ± 1.52			
MP	A-Skip (1)	0.92 ± 0.73	= 0.13	0.11		-1.36 ± 0.72	= 0.07	0.13	
	B-skip (2)	1.51 ± 1.11				-1.78 ± 1.09			
	Bounding (3)	1.05 ± 0.94				-1.49 ± 1.00			
	Heel flicks (4)	1.55 ± 1.26				-1.98 ± 1.21			
	SLR (5)	1.58 ± 1.56				-2.17 ± 1.51			
	Running (6)	0.90 ± 0.87				-2.13 ± 1.32			

*MT = midtarsal; MP = Metatarsophalangeal. Repeated measures ANOVA followed by Bonferroni's correction: P > 0.05, not significant; * symbol represents a p-value for post-hoc test inferior to 0.05; ** symbol represents a p-value for post-hoc test inferior to 0.01; *** symbol represents a p-value for post-hoc test inferior to 0.001. Tasks are represented by a number from 1 to 8 in post-hoc test. ANOVA, Analysis of Variance; SD, Standard deviation.*

Table E.10: Comparison of muscle activation between running drills and running at different speeds.

Muscles	Tasks	N	Percentage of muscle activation relative to running (%) Mean ± SD	Muscle activation (mV) Mean ± SD	p-value	ŋ²	Post-hoc test
Abd. Hallucis	A-skip (1)	14	107 ± 49.9	256.2 ± 119.0	p < 0.001	0.04	
	B-skip (2)	14	113.8 ± 56.4	271.5 ± 134.6			
	Bounding (3)	14	155.9 ± 60.1	371.8 ± 143.5			(3) > (1)***, (2)***, (4)**, (6)**
	Heel flicks (4)	14	121.1 ± 51.8	288.9 ± 123.7			
	SLR (5)	14	130.3 ± 49.5	310.8 ± 118.1			(5) > (6)**
	Running (6)	14	/	238.4 ± 127.0			
Gastro. Med	A-skip (1)	16	112.5 ± 33.1	288.2 ± 84.9	p = 0.017	0.22	
	B-skip (2)	16	103.2 ± 25.6	264.5 ± 65.7			
	Bounding (3)	16	141.5 ± 56.8	362.5 ± 145.5			(3) > (2)*, (4)*, (5)*, (6)**
	Heel flicks (4)	16	103.8 ± 29.7	266.0 ± 76.2			
	SLR (5)	16	103.5 ± 42.2	265.2 ± 108.1			
	Running (6)	16	/	256.1 ± 76.0			
Gastro. Lat	A-skip (1)	15	96.1 ± 38.0	211.9 ± 83.8	p = 0.04	0.22	
	B-skip (2)	15	93.4 ± 34.9	206.0 ± 77.0			
	Bounding (3)	15	122.8 ± 51.4	270.8 ± 113.3			(3) > (2)* , (5)*
	Heel flicks (4)	15	101.7 ± 31.0	224.2 ± 68.5			
	SLR (5)	15	93.7 ± 46.3	206.6 ± 102.2			
	Running (6)	15	/	220.4 ± 81.7			
Soleus	A-skip (1)	14	101.4 ± 42.6	208.0 ± 87.4	p < 0.001	0.42	
	B-skip (2)	14	97.7 ± 28.2	200.4 ± 57.9			
	Bounding (3)	14	143.8 ± 56.7	294.9 ± 116.4			(3) > (1)***, (2)***, (6)***
	Heel flicks (4)	14	100.9 ± 40.1	207.0 ± 82.3			
	SLR (5)	14	121.4 ± 40.1	249.0 ± 82.3			
	Running (6)	14	/	205.0 ± 68.3			

*Abd.hallucis = Abductor hallucis; Gastro.med = Gastrocnemius medialis; Gastro.Lat = Gastrocnemius lateralis. Repeated measures ANOVA followed by Bonferroni's correction was performed in using the values of muscle activation (mV): P > 0.05, not significant; * symbol represents a p-value for post-hoc test inferior to 0.05; ** symbol represents a p-value for post-hoc test inferior to 0.01; *** symbol represents a p-value for post-hoc test inferior to 0.001. Tasks are represented by a number from 1 to 8 in post-hoc test. ANOVA, Analysis of Variance; SD, Standard deviation. As an indication, percentage of muscle activity of the medial and lateral heads of the gastrocnemius, the soleus and the abductor hallucis relative to running at 5.00 m/s were calculated for the running drills.*

Discussion and Implication

The aim of this study was to compare the foot-ankle mechanics of running drills with distance running using a multi-segment foot model. Based on the study of Trowell et al (2022), it was hypothesised that Bounding will induce higher foot and ankle power than distance running whereas the A-skip and B-skip will induce less than distance running. Our findings confirm that Bounding induce a significant higher ankle positive power than distance running. However, MT and MP positive or negative power were not significantly different between bounding and distance running. Our results have also shown that the A-skip and the B-skip induce less MT positive power than distance running. Contrary to the findings of Trowell et al. (2022), the A-skip and the B-skip do not induce a smaller ankle positive or negative power than distance running. This difference with our results could be explained by the use of multi-segment foot model that more accurately estimates the mechanical power generated at the ankle joint during dynamic activities (Kessler et al., 2020).

The kinematic analysis of our study revealed that all the running drills (except Bounding) induce a smaller ankle, MT and MP dorsiflexion peak than running. Despite this difference in dorsiflexion peak, the Heel flicks and SLR induce similar ankle, MT and MP moment and power than running. Avoiding high amplitudes of ankle dorsiflexion is advised for certain common runner pathologies, such as Achilles tendinopathy, as this may exacerbate pain symptoms (Malliaras, 2022). For this injured population, running can become difficult because of the increased pain during training (Malliaras, 2022). Therefore, the practice of the Heel flicks and SLR could be an interesting alternative to running for maintaining the runner's foot and ankle complex's capacity in limiting the appearance of pain. At the opposite, the practice of Bounding should be avoided before advanced stages of rehabilitation because it requires a high ankle dorsiflexion and power. These statements are consistent with an existing classification of exercise progression for Achilles tendinopathy showing that long forward hopping with one-leg induces a higher loading peak than running (J. R. Baxter et al., 2021).

Although the differences are not statistically significant, the analysis of the biomechanics within the foot showed that all the running drills (except the A-skip) induced a higher positive MP power than running (≈ 50% more). This finding highlights that running drills require a strong propulsion capacity on the forefoot. Parallelly, electromyographic analysis showed that all the running drills induced a higher percentage of abductor hallucis activity than running. In summary, running drills could be useful in improving the capacity of the forefoot to forcefully push into the ground. However, some cautions are necessary for the generalization of these affirmations in shod conditions, given that the running drills in this study were performed barefoot.

A previous interventional study have shown that performing an intensive programme composed by running drills during three weeks (≈5000 to 6000 jumps) can improve toe flexor strength (+ 7% to 16%) (Goldmann, Potthast, et al., 2013). The toe flexor strength improvement was greater whether the programme was performed in minimalist footwear condition compared to traditional footwear (Goldmann, Potthast, et al., 2013). Toe flexor strength enhancement could lead to a performance improvement in athletic tasks requiring strong propulsion, such as long-jump, sprinting or ability to change direction (Goldmann, Sanno, et al., 2013). However, it still remains unknown whether functional training (such as running drills) is more efficient than isolated foot exercises in improving toe flexor strength. Despite the absence of longitudinal follow-up, Willemse et al. (2023) showed that functional exercises induce comparable or even greater activation of the plantar intrinsic foot muscles than muscle-specific isolated foot exercises.

In comparison with previous study, a multi-segment foot model was used in our study to better illustrate ankle biomechanics and provide supplementary information on the biomechanics within the foot. The simultaneous analysis of ankle and foot biomechanics is relevant because previous studies have shown that their mechanical behaviour is interrelated (L. Smith et al., 2015; Welte et al., 2023). Interestingly, in our study, the power generated within the foot were not similar between the running drills. This finding indicates that, as for the ankle, the choice of running drill influences the foot output. Specifically, track and field coaches could use the B-skip to improve the ability of their runners to push into the ground with their forefoot without increasing the load on the midfoot. In contrast, Bounding adds a supplementary load on the midfoot but reduces the amount of propulsive force required with the forefoot in comparison with the other running drills. The power required for the ankle and foot were not similar across the running drills. For example, track and field coaches have to keep in mind that the Bounding exercise induces a low positive power on the MP joint but a high positive power on the ankle compared with the other running drills. From another point of view, this information could also help clinicians implement a progressive loading strategy with runners who have sustained foot injuries (e.g., metatarsal stress fracture or plantar fasciitis).

This study had some limitations that should be considered before generalising the results. First, the participants performed the trials barefoot. This could lead to a potential over-estimation of the kinematic and kinetic values of the foot and ankle joints (Esculier et al., 2022; Hall et al., 2013; Su et al., 2022). In our study, the equipment installed on the foot (markers and EMG electrodes) did not allow for shoes to be worn. The equipment could not be attached directly to the running footwear because this would overestimate the MTP peak plantarflexion angle and moment compared with markers placed on the skin (Perrin et al., 2023). This overestimation can be explained by the movement of the foot inside the shoe, and by the additional deformation of the shoe measured (Perrin et al., 2023). Therefore, caution should be exercised when applying these findings to shod running. Second, only five trials were performed for each task. The literature recommends that studies involving the analysis of traditional running biomechanical variables should use a minimum of 25 steps from each participant to provide appropriate data stability and statistical power (Oliveira & Pirscoveanu, 2021). However, given the number of running drills assessed in this study, it was not possible for the participants to perform 25 repetitions of each task without risking to induce fatigue. Third, the conclusions from the electromyographic data should be interpreted with caution. The interpretation of surface electromyograms in dynamic contractions contains several sources of errors, such as signal properties, electrode shift and tissue conductivity (Farina, 2006). Moreover, given its size and the variety of its position on the foot, it is advisable to use a fine-wire electrode inserted into the muscle rather than a surface electromyogram to measure the activity of the abductor hallucis. Finally, several multi-segment foot models exist and the results of our study could be slightly different when using another model (Deschamps et al., 2017).

Conclusion

The main contribution of this study is to offer a detailed analysis of the mechanical behaviour of the ankle and joints within the foot during running drills. Running drills (except Bounding) induce a smaller ankle, MT and MP dorsiflexion peak than running. Bounding induces a higher ankle positive power than running, but does not induce higher MT and MP positive or negative power. The A-skip and the B-skip induce less MT positive power than running but do not induce less ankle positive or negative power. This analysis could help track and field coaches to select their running drills in an evidence-based manner.

Take Home Messages – Part III

- ✓ Altering running technique may be a valuable therapeutic approach to manage knee injuries in endurance runners.

- ✓ Non-rearfoot runners demonstrate greater foot and ankle muscle strength compared to rearfoot runners.

- ✓ Runners with hallux flexor strength below 2.85 N/kg are at increased risk of foot and ankle injuries when adopting a softer running technique.

- ✓ Runners weighing more than 71.7 kg are at higher risk of foot and ankle injuries during a transition to minimalist footwear.

- ✓ The type of running drills selected influences the biomechanical demands on the lower limb. For instance, Heel flicks and Straight leg running induce smaller ankle dorsiflexion, whereas Bounding requires greater ankle dorsiflexion and generates higher power.

- ✓ Running drills generated approximately 50% greater positive metatarsophalangeal power than running and elicited around 30% higher abductor hallucis activation. These findings suggest that running drills could play a key role in enhancing foot muscle function.

F. Discussion

1. Summary of key findings

In this thesis, we conducted a series of studies exploring the interest of running technique alteration on performance and injury prevention in recreational endurance runners. These studies have revealed that running technique alteration is frequently used in the field by athletics coaches and can have several implications for running-related injuries, foot-ankle characteristics and running economy. In this chapter, the major findings of this thesis, their implications for running performance, injury prevention, injury management, and coaching fields, as well as potential directions for future research will be discussed.

The occurrence of running-related injuries (RRIs) is complex and multifactorial (Bertelsen et al., 2017). One of the major factors influencing RRI development is load, which includes both external and internal components (Bertelsen et al., 2017). Running technique plays a crucial role in modulating external load on the lower limb joints: a rearfoot strike pattern increases load on the hip and knee, whereas a non-rearfoot strike pattern places greater stress on the foot and ankle (Almeida et al., 2015). Similarly, endurance running performance is influenced by multiple factors, with running technique accounting for approximately 4% to 12% of the variance in running economy among individuals (Van Hooren, Jukic, et al., 2024). Prior to this thesis, scientific evidence supporting running technique modifications for injury prevention or performance enhancement remained limited (Hamill & Gruber, 2017). Moreover, little information was available on the methods and risk factors associated with implementing such alterations. In the general introduction section, we presented a survey revealing that, despite the absence of scientific evidence, athletics coaches modify the running technique of endurance runners to enhance performance or reduce injury risk. These modifications predominantly involve transitioning from a rearfoot strike to a midfoot strike. According to coaches, the midfoot strike is considered the most effective landing pattern for endurance performance (47%) and injury prevention (36%), while rearfoot strike is perceived as the least favourable (50% and 52%, respectively). Interestingly, our findings support the theory that altering running technique is beneficial for enhancing running performance. The results from the randomised controlled trial presented in this thesis revealed significant improvements in running economy in the minimalist and running retraining groups after six and twelve months, by approximately 5% and 10%, respectively. Running economy also improved in the control group but only at 12 months, by less than 5%. These results challenged current scientific recommendations that advise runners not to alter their running technique to improve running performance. In addition, adopting a forefoot strike pattern combined with a higher running cadence may mitigate injury risk by decreasing the high-frequency components of impact-related variables, which have been proposed as potential risk factors for running-related injuries (Malisoux et al., 2021). Thus, combining both strategies was found to reduce the impact peak by 61%, the AVLR by 64%, the IVLR by 43% and increases the time to impact peak by 13% of the high-frequency component of the impact signal. However, no significant differences were observed in injury incidence in the prospective study of this thesis between the running retraining group (N = 24), the minimalist footwear group (N = 18), and the control group (N = 20). These results challenge the theory that running technique alteration prevents injuries. Although the running retraining intervention did not reduce overall injury incidence, it led to a shift in injury patterns: hip injuries decreased, whereas foot injuries increased compared to the control group. This result confirmed previous findings that running technique alteration may increase the risk of foot–ankle injuries when a runner follows a running technique alteration programme. Adopting a non-rearfoot strike pattern, increasing step rate, or transitioning to minimalist footwear increases the mechanical demands on the foot and ankle, which may explain the elevated risk of injury at this site during or following running technique modification. Given these considerations, it is essential to better understand the factors that may predispose runners to injury when undergoing such interventions. Interestingly, we found that non-rearfoot runners had different foot-ankle characteristics compared to rearfoot runners such as a greater muscle strength in the ankle plantar flexors (+ 12.5 %), ankle dorsiflexors (+ 17.7 %), hallux flexors (+ 11 %), and lesser toe flexors (+ 20.8 %). Furthermore, we identified that runners with hallux flexor strength below 2.85 N/kg who transition to a non-rearfoot strike pattern have an increased risk of sustaining a foot and ankle injury. Conversely, foot and ankle muscle strength does not appear to be a risk factor when transitioning to minimalist footwear. Nevertheless, given the high proportion of runners who adopt a non-rearfoot strike pattern during a transition to minimalist footwear, strengthening these muscles may still be beneficial. Given the importance of conditioning the foot-ankle complex to facilitate a safer running technique transition, running drills appear to be a promising option for strengthening foot structures. In fact, all running drills, except for the A-skip, generated approximately 50% greater positive metatarsophalangeal power than running and elicited around 30% higher abductor hallucis activation. These findings suggest that running drills could play a key role in enhancing foot muscle function and could be implemented before or during a running technique alteration programme in an attempt to reduce the risk of injury to the foot–ankle complex.

2. Implications

Running performance

Several studies have already explored the relationship between running technique alteration and improvements in running performance (Doyle et al., 2022). The most frequently used indicator is running economy, primarily because it is simple and quick to assess, but also due to its sensitivity to change (Barnes & Kilding, 2015). To date, studies have examined the effects of running retraining programme on running performance over durations of up to 15 weeks, and up to 6 months for transition programme involving minimalist footwear (Doyle et al., 2022; Fuller et al., 2019). As detailed in the general introduction, studies employing running retraining programme have reported immediate detrimental effects on running performance, with an increase of approximately 5.5% in oxygen consumption (Gruber et al., 2013). However, studies using similar methodologies but with longer follow-up periods (ranging from one and a half to fifteen weeks) have shown that oxygen consumption is not adversely affected by the running retraining programme (Doyle et al., 2022). In contrast, the use of minimalist footwear appears to reduce oxygen consumption both immediately (by approximately 6%) and after a habituation period (up to 9%) in endurance runners (Perl et al., 2012; Warne & Warrington, 2014). Our study is the first to compare two different running technique alteration programme in terms of their effects on oxygen consumption, and it is also the first to include a one-year follow-up. Our results show a slight but non-significant reduction in oxygen consumption at two months in the minimalist footwear and running retraining group (-1% and -1.3%, respectively). However, oxygen consumption had decreased significantly in both intervention groups by approximately 5%, after six months and 10% after twelve months whereas the control group only demonstrate a significant reduction at twelve months by less than 5%. To date, the mechanisms underlying the reduction in oxygen consumption following running technique alteration remain to be fully elucidated, as do those explaining the delay before such benefits become apparent. Current hypotheses suggest that the adoption of a non-rearfoot trike pattern offers a mechanical advantages by shifting the point of ground reaction force application toward the front of the foot. This results in a smaller effective mechanical advantage at the ankle and a greater effective mechanical advantage at the knee, potentially redistributing muscular demands and improving running economy (Ekizos et al., 2018). In addition, an increase in cadence may also reduce braking forces at initial contact, further enhancing the efficiency of elastic energy recycling (Folland et al., 2017; Napier et al., 2019). The combination of these factors may lead to a reduction in oxygen consumption during running. Furthermore, the delayed onset of benefits associated with technique alteration could be due to the cognitive load involved in learning a new motor pattern and the gradual improvement in intermuscular coordination of the lower limbs following a period of adaptation (Warne & Warrington, 2014; Whittier et al., 2020). Some studies have shown that conscious alteration of running technique results in increased cerebral activity immediately, which persists for at least a month after the intervention has begun. Elevated cerebral activity during running may, in turn, lead to increased oxygen consumption (Whittier et al., 2020). Finally, other studies have demonstrated that with exposure, intermuscular coordination and co-contraction patterns can be optimised during dynamic movements (Dalen et al., 2013; Janusevicius et al., 2017). Improvements in intermuscular coordination and a reduction in muscular co-contractions could also contribute to the observed reductions in oxygen consumption (Van Hooren, Jukic, et al., 2024).

Injury prevention

RRI prevention remains a major challenge for researchers due to its high incidence and multifactorial nature. Current prevention programmes are generally based on two main strategies derived from the etiological framework of RRIs: either increasing the musculoskeletal capacity of the body or reducing the mechanical load imposed by running (Bertelsen et al., 2017). To date, only a few studies have demonstrated a significant preventive effect in recreational runners. This lack of efficacy can be attributed to several factors, including the multifactorial origins of RRIs, the heterogeneity within the running population, and the methodological challenges associated with conducting sufficiently powered prospective studies (Verhagen, 2012). Previous studies that focused on increasing musculoskeletal capacity such as strength training programmes have not shown significant reductions in injury incidence among recreational runners (Wu et al., 2024). In this thesis, we tested the second approach, aiming to reduce the mechanical load of running through running technique alteration. A recent randomised controlled trial has indicated that high-frequency components of impact-related variables may constitute risk factors for running-related injuries in recreational endurance runners. Interestingly, adopting a forefoot strike pattern reduced the high-frequency components of impact-related parameters nearly three times more than increasing running cadence by 10% alone. Additionally, combining a forefoot strike pattern with a 10% increase in running cadence appeared to be the most effective strategy for reducing the high-frequency components of impact-related parameters. Moreover, a previous study demonstrated a 62% reduction in the incidence of RRIs following a running retraining intervention that decreased impact-related variables in novice runners (Chan et al., 2018). Novice runners are considered a specific population because their risk of injury is substantially higher during the first year of practice (Van Poppel et al., 2021). In contrast, we demonstrated that the running retraining intervention was not as effective in recreational runners with more than one year of running experience. This divergence suggests several possible explanations. First, novice runners may be more sensitive to impact forces than experienced runners. Running generates repetitive impacts of approximately two times body weight (Hamill et al., 1983). Novice runners, depending on their athletic backgrounds, may not be accustomed to such mechanical stress on their skeletal system (Kluitenberg et al., 2016; Van Poppel et al., 2021). Thus, reducing impact peaks could be a particularly effective strategy in this population. Second, although impact-related variables were not measured directly, previous studies have shown that minimalist footwear can increase both the IVLR and AVLR, likely due to reduced cushioning compared to traditional footwear (Esculier et al., 2022). However, runners who transitioned to minimalist footwear did not experience a higher incidence of RRIs than those in the control or running retraining groups. This finding further supports the notion that manipulating impact peaks does not influence RRI incidence in non-novice runners. These results suggest that, after one year of consistent running, the body may have adapted to tolerate the impact peaks associated with running. Consequently, in more experienced runners, RRI risk factors may be more individualised and influenced by other parameters, such as internal load factors including recovery, fatigue, and psychosocial stressors (Gruber, 2023; Truong et al., 2021; van Iperen et al., 2022). Finally, although our study did not demonstrate a reduction in the overall incidence of RRIs following the transition to minimalist footwear or a softer running technique in recreational endurance runners, we observed differences in injury locations. Runners who adopted a softer running technique experienced significantly more injuries in the foot-ankle complex, whereas those in the control group sustained more injuries at the hip. This finding may suggest that impact force is not directly associated with the overall occurrence of RRIs when all injuries are pooled together. However, higher impact peaks may instead be associated with injuries located in the proximal segments of the lower limbs, such as the hip or knee (Gruber, 2023).

In summary, an individualised approach to determine whether a change in running technique is necessary may be more effective than a collective approach. For example, adopting a non-rearfoot strike pattern could be beneficial for individuals with a history of hip or knee injuries, whereas adopting a rearfoot strike pattern may be more appropriate for those with a history of foot–ankle injuries. For runners with no history of injuries, who are not novices and do not aim to improve performance, there is no reason to modify their running technique.

Injury Management

Although it does not appear to reduce injury rates in recreational runners, running retraining remains a relevant therapeutic approach in runners with knee injuries to help maintain running activity (Alexander et al., 2022). Indeed, running technique alteration is included in the "RISK" framework, which is considered an international reference clinical guide for managing injured runners (Barton, 2018). To date, no study has compared, in a population of injured runners, the effects of a transition protocol to minimalist footwear versus a running retraining programme on knee pain and running activity participation. However, conscious running technique alteration appears to be more effective in reducing mechanical loads on the knee during running compared to unconscious running technique alteration (Shih et al., 2013). This reduction in knee loading is, however, counterbalanced by an increase in loads on the foot and ankle (Almeida et al., 2015). Several studies have shown that this additional stress on the foot and ankle, particularly during forefoot strike running, may lead to improvements in plantar flexor strength and intrinsic foot muscle size (Johnson et al., 2015; Miller et al., 2014). These biomechanical differences may partly account for the greater muscle strength observed in the ankle plantar flexors (+12.5%), ankle dorsiflexors (+17.7%), hallux flexors (+11%), and lesser toe flexors (+20.8%) in non-rearfoot runners compared to rearfoot runners. In addition, we highlighted the importance of assessing hallux flexor strength at baseline and during the implementation of a running retraining programme. Although no external validation has yet been conducted, we statistically determined a reference strength threshold (2.85 N/kg) to be achieved to minimise the risk of RRIs during the implementation of a running retraining programme. The establishment of this threshold aimed to guide clinicians in managing their injured runners. In our study, hallux flexor strength emerged as the most discriminative risk factor between injured and uninjured runners. However, plantar flexor strength (approximately 16% difference) and plyometric capacity (approximately 40% difference) also showed clinically significant differences between the injured and uninjured groups. Therefore, it seems pertinent to evaluate the full range of parameters of the foot–ankle complex (mobility, strength, endurance, and reactivity) with the aim of addressing any deficits through individualised rehabilitation programme prior to and during the implementation of running retraining. Interestingly, foot–ankle complex parameters were not identified as risk factors in the transition to minimalist footwear in our study. This may be partly explained by the variability in biomechanical adaptations to minimalist footwear observed among runners in this group. Given these findings, clinicians should nonetheless consider assessing the characteristics of the foot–ankle complex and implementing individualised rehabilitation programme before and during the transition to minimalist footwear, particularly in runners adopting a non-rearfoot strike pattern. A recently proposed eight-week periodised foot strengthening protocol, combining supervised and home sessions, increased metatarsophalangeal isometric flexion torque by approximately 30% and represents a good example of an individualised rehabilitation programme (Tourillon et al., 2025). The programme targeted forefoot and first-ray strength through progressive overload exercises and included forefoot-focused plyometric training. In addition to being attentive to foot–ankle characteristics, clinicians should also take the runner's body mass into account before recommending a transition to minimalist footwear. Our findings, in line with previous studies, indicate that runners with a body mass greater than 71.4 kg have a higher risk of sustaining a RRI during the transition to minimalist shoes (Fuller, Thewlis, Buckley, et al., 2017). Body mass may represent a risk factor in this context because, in accordance with Newton's second law, the impact of minimalist footwear on loading forces is likely to be more pronounced in runners with greater body mass (Fuller, Thewlis, Buckley, et al., 2017).

In summary, the management of runners with knee injuries should primarily include a load management education programme (Esculier, Bouyer, et al., 2018). Depending on individual preferences, response to treatment, and injury history, this programme may be complemented by a strengthening programme and/or a running retraining intervention (Esculier et al., 2020). If necessary, the running retraining programme should be supported by a rehabilitation protocol targeting the foot–ankle complex, tailored to any identified deficits. Regarding the selection of the most appropriate running retraining strategy, current recommendations suggest it should be guided by the runner's body mass, personal preferences, and individual response to the method.

Running coaches

In the first study, we examined athletics coaches' knowledge regarding the relationship between running technique and both performance enhancement and injury prevention. A large proportion of coaches strongly believed that a non-rearfoot strike pattern could improve performance and reduce injury risk, whereas a rearfoot strike pattern was perceived as more detrimental. At the time, the evidence linking footstrike pattern to injury risk was limited and predominantly retrospective (Anderson et al., 2020). Furthermore, the association between footstrike type and performance enhancement had been questioned by several studies, which reported no immediate or no benefits, even up to 15 weeks after running technique alteration (Doyle et al., 2022). The findings from the present thesis confirm the lack of effectiveness of running retraining in preventing RRIs. However, our study highlights a performance improvement six months after a change in running technique or a transition to minimalist footwear. It appears that athletics coaches may have intuitively observed the benefits of transitioning to a non-rearfoot strike pattern in enhancing performance among endurance runners. Although this observation has long existed in the field, it remains important to inform coaches about the actual impact and time course of such interventions. Moreover, the methodology employed to alter running technique should be clearly described to facilitate translation from laboratory to field settings. Interestingly, and consistent with our recommendations for improving the safety of running technique alteration, almost all the coaches in our survey reported incorporating foot–ankle muscle strengthening to support changes in landing pattern. However, it would be relevant to verify whether coaches also assess foot–ankle muscle strength on a regular basis.

Coaches reported using running drills to improve the running technique of endurance athletes. To date, no study has demonstrated changes in running kinematics following a programme based solely on running drills. The most effective method for altering running technique currently appears to be a running retraining programme that includes both an acquisition phase and a transfer phase, grounded in motor learning theory (Winstein, 1991). Nevertheless, running drills may be useful for enhancing neuromuscular aspects (intermuscular coordination and reduced co-contractions) as well as foot propulsion capacity (Dalen et al., 2013; Goldmann, Potthast, et al., 2013). Coaches should also be aware that the choice of running drill influences foot output. Specifically, the B-skip can be used to improve forefoot push-off without increasing midfoot load, whereas Bounding adds supplementary load on the midfoot while reducing the propulsive force required from the forefoot. Additionally, the power demands on the ankle and foot differ between drills. For instance, Bounding induces relatively low positive power at the metatarsophalangeal joint but high positive power at the ankle compared with other running drills.

3. Future directions

The present studies have provided the researchers and the clinicians with some answers regarding running injury prevention, injury management and performance. Nonetheless, this field continues to present numerous avenues for further investigation. Some of the perspectives following the present thesis are summarised here after:

- **Consider implementing protocols in ecological settings:** All studies included in this thesis were conducted in laboratory environments. While previous research has demonstrated the validity of laboratory-based studies, the assessment and monitoring of biomechanical parameters in real-world settings could enhance the external impact and applicability of findings. The advancement and increasing accessibility of wearable sensors may facilitate such research in the future, although recent studies have highlighted new limitations, such as user compliance and the general public's understanding of these technologies (Van Hooren, Plasqui, et al., 2024).
- In summary, if a runner wishes to modify their running technique to improve performance, they should be informed that: 1) this can be achieved either through a running retraining programme or a transition to minimalist footwear; 2) minimalist footwear may induce a direct positive impact, unlike conscious modification of running technique; and 3) the positive effects on running performance will become noticeable after six months and will continue to increase up to one year following the transition.
- **Extend investigations to injured runner populations:** All studies included in this thesis were conducted with healthy runners. Given the lack of conclusive results regarding injury prevention, research on running technique alteration methods should preferably be conducted among injured runners, particularly those with knee-related injuries. In this context, several research questions remain unresolved: the effectiveness of minimalist shoe transition protocols on knee pain and running participation; the identification of the most effective running technique alteration methods for reducing pain and maintaining participation in running among runners with knee injuries (minimalist footwear vs. running retraining vs. a combination of both); and finally, the validation of specific risk factors associated with these interventions in populations of runners with knee injuries.
- **Development of strengthening programmes targeting the foot–ankle complex:** Since the identified risk factors also appear to be relevant in runners with knee injuries,

it would be pertinent to investigate whether implementing individualised strengthening programmes, in combination with running technique alteration methods could help reduce the incidence of secondary injuries.

- **Evaluate the utility of running technique alteration methods for other common RRIs:** To date, running technique alteration methods have been primarily studied in the context of knee injuries (Alexander et al., 2022). Further research should investigate their applicability to other frequently observed pathologies in runners, such as medial tibial stress syndrome and Achilles tendinopathy.

- **Identify runner profiles that show performance improvements following running technique alteration:** In this thesis, we demonstrated that, on average, runners who modified their running technique through either a running retraining programme or a transition to minimalist footwear experienced significant improvements in performance. However, further research aimed at identifying the runner profiles that benefit most from such interventions could help guide coaches in weighing the risk–benefit balance of running technique alteration methods.

G. Conclusion

The objective of this thesis was to enhance our understanding of the role of running technique alterations in recreational endurance runners, with particular emphasis on performance enhancement and injury prevention. The relationship between running technique and performance enhancement was investigated through a prospective study assessing changes in running economy over a one-year period following the implementation of two running retraining programmes. Both conscious and unconscious retraining groups demonstrated improvements in running economy at six and twelve months, by approximately 5% and 10% respectively. To ensure that such improvements are not achieved at the expense of an increased risk of injury, the relationship between running technique and injury prevention was then conducted. The relationship between running technique and injury prevention was investigated through an analysis of the association between impact forces and running technique, as well as through a one-year evaluation of two running retraining programme and their effects on injury risk. These studies revealed that adopting a forefoot strike pattern and increasing running cadence reduce the high-frequency components of the impact signal. However, these modifications did not lead to a reduction in the incidence of running-related injuries over the one-year period. Notably, running retraining appeared to induce a redistribution of injury locations, with a decrease in hip injuries but an increase in foot and ankle injuries. Given these considerations, it is essential to better understand the factors that may predispose runners to injury when undergoing running technique alteration programme. The last part of this thesis focuses on the importance of foot–ankle conditioning for safer running technique alteration. This part was composed by a retrospective analysis of foot and ankle characteristics according to running technique, an assessment of risk factors associated with two running retraining programme, and a biomechanical evaluation of the foot–ankle complex during commonly prescribed running drills. Results indicated that rearfoot runners exhibit lower maximal voluntary isometric strength of the hallux and lesser toe flexors compared to non-rearfoot runners. Moreover, runners with hallux flexor strength below 2.85 N/kg were found to be at greater risk of sustaining foot or ankle injuries when transitioning to a softer running technique. Running drills may represent a valuable preparatory modality for rearfoot runners with insufficient foot muscle strength, as they may help reduce injury risk prior to initiating a transition to a softer running technique. Running drills elicit higher positive metatarsophalangeal joint power and greater relative activation of the abductor hallucis muscle compared to running.

References

1. Abran, G., Delvaux, F., Schwartz, C., Martens, G., Hody, S., Dardenne, N., Bruyere, O., Bornheim, S., & Croisier, J.-L. (2022). Current perception and practice of athletics coaches about the modification of footstrike pattern in endurance runners: A survey. *International Journal of Sports Science & Coaching*, *17*(6), 1345–1353. https://doi.org/10.1177/17479541221108089

2. Adams, D., Pozzi, F., Willy, R. W., Carrol, A., & Zeni, J. (2018). Altering cadence or vertical oscillation during running: Effects on running related injury factors. *International Journal of Sports Physical Therapy*, *13*(4), 633–642. https://doi.org/10.26603/ijspt20180633

3. Agresta, C., Kessler, S., Southern, E., Goulet, G. C., Zernicke, R., & Zendler, J. D. (2018). Immediate and short-term adaptations to maximalist and minimalist running shoes. *Footwear Science*, *10*(2), 95–107. https://doi.org/10.1080/19424280.2018.1460624

4. Alentorn-Geli, E., Samuelsson, K., Musahl, V., Green, C. L., Bhandari, M., & Karlsson, J. (2017). The association of recreational and competitive running with hip and knee osteoarthritis: A systematic review and meta-analysis. *Journal of Orthopaedic & Sports Physical Therapy*, *47*(6), 373–390. https://doi.org/10.2519/jospt.2017.7137

5. Alexander, J. L. N., Culvenor, A. G., Johnston, R. R. T., Ezzat, A. M., & Barton, C. J. (2022). Strategies to prevent and manage running-related knee injuries: A systematic review of randomised controlled trials. *British Journal of Sports Medicine*, *56*(22), 1307–1319. https://doi.org/10.1136/bjsports-2022-105553

6. Allen, D. J., Heisler, H., Mooney, J., & Kring, R. (2016). The effect of step rate manipulation on foot strike pattern of long distance runners. *International Journal of Sports Physical Therapy*, *11*(1), 54–63.

7. Allen, R. H., & Gross, M. T. (2003). Toe flexors strength and passive extension range of motion of the first metatarsophalangeal joint in individuals with plantar fasciitis. *Journal of Orthopaedic & Sports Physical Therapy*, *33*(8), 468–478. https://doi.org/10.2519/jospt.2003.33.8.468

8. Almeida, M. O., Davis, I. S., & Lopes, A. D. (2015). Biomechanical differences of foot-strike patterns during running: A systematic review with meta-analysis. *Journal of Orthopaedic & Sports Physical Therapy*, *45*(10), 738–755. https://doi.org/10.2519/jospt.2015.6019

9. Altman, A. R., & Davis, I. S. (2012). A kinematic method for footstrike pattern detection in barefoot and shod runners. *Gait & Posture*, *35*(2), 298–300. https://doi.org/10.1016/j.gaitpost.2011.09.104

10. Anderson, L. M., Bonanno, D. R., Hart, H. F., & Barton, C. J. (2020). What are the benefits and risks associated with changing foot strike pattern during running? A systematic review and meta-analysis of injury, running economy, and biomechanics. *Sports Medicine*, *50*(5), 885–917. https://doi.org/10.1007/s40279-019-01238-y

11. Anderson, L. M., Martin, J. F., Barton, C. J., & Bonanno, D. R. (2022). What is the effect of changing running step rate on injury, performance and biomechanics? A systematic review and meta-analysis. *Sports Medicine - Open*, *8*(1), 112. https://doi.org/10.1186/s40798-022-00504-0

12. Arendse, R. E., Noakes, T. D., Azevedo, L. B., Romanov, N., Schwellnus, M. P., & Fletcher, G. (2004). Reduced eccentric loading of the knee with the pose running method: *Medicine & Science in Sports & Exercise*, *36*(2), 272–277. https://doi.org/10.1249/01.MSS.0000113684.61351.B0

13. Azevedo, A. P. S., Mezêncio, B., Valvassori, R., Anjos, F. O. M., Barbanti, V. J., Amadio, A. C., & Serrão, J. C. (2015). Usage of running drills in an interval training program: Implications related to biomechanical parameters of running. *Journal of Strength and Conditioning Research*, *29*(7), 1796–1802. https://doi.org/10.1519/JSC.0000000000000831

14. Barbero, M., Merletti, R., & Rainoldi, A. (2012). *Atlas of Muscle Innervation Zones*. https://doi.org/10.1007/978-88-470-2463-2

15. Barnes, K. R., & Kilding, A. E. (2015). Running economy: Measurement, norms, and determining factors. *Sports Medicine - Open*, *1*(1), 8. https://doi.org/10.1186/s40798-015-0007-y

16. Barton, C. J. (2018). Managing risk when treating the injured runner with running retraining, load management and exercise therapy. *Physical Therapy in Sport*, *29*, 79–83. https://doi.org/10.1016/j.ptsp.2017.10.002

17. Barton, C. J., Bonanno, D. R., Carr, J., Neal, B. S., Malliaras, P., Franklyn-Miller, A., & Menz, H. B. (2016). Running retraining to treat lower limb injuries: A mixed-methods study of current evidence synthesised with expert opinion. *British Journal of Sports Medicine*, *50*(9), 513–526. https://doi.org/10.1136/bjsports-2015-095278

18. Bassett, D. R., & Howley, E. T. (2000). Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Medicine and Science in Sports and Exercise*, *32*(1), 70–84. https://doi.org/10.1097/00005768-200001000-00012

19. Baumgartner, J., Gusmer, R., Hollman, J., & Finnoff, J. T. (2019). Increased stride-rate in runners following an independent retraining program: A randomized controlled trial. *Scandinavian Journal of Medicine & Science in Sports*, *29*(11), 1789–1796. https://doi.org/10.1111/sms.13509

20. Baxter, C., Mc Naughton, L. R., Sparks, A., Norton, L., & Bentley, D. (2017). Impact of stretching on the performance and injury risk of long-distance runners. *Research in Sports Medicine*, *25*(1), 78–90. https://doi.org/10.1080/15438627.2016.1258640

21. Baxter, J. R., Corrigan, P., Hullfish, T. J., O'Rourke, P., & Silbernagel, K. G. (2021). Exercise progression to incrementally load the achilles tendon. *Medicine & Science in Sports & Exercise*, *53*(1), 124–130. https://doi.org/10.1249/MSS.0000000000002459

22. Becker, J., & Borgia, B. (2020). Kinematics and muscle activity when running in partial minimalist, traditional, and maximalist shoes. *Journal of Electromyography and Kinesiology*, *50*, 102379. https://doi.org/10.1016/j.jelekin.2019.102379

23. Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57*(1), 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

24. Bertelsen, M., Hulme, A., Petersen, J., Brund, R., Sorensen, H., Finch, C., Parner, E., & Nielsen, R. (2017). A framework for the etiology of running-related injuries. *Scand J Med Sci Sports*, *27*(11), 1170–1180. https://doi.org/10.1111/sms.12883

25. Blackmore, T., Willy, R. W., & Creaby, M. W. (2016). The high frequency component of the vertical ground reaction force is a valid surrogate measure of the impact peak. *Journal of Biomechanics*, *49*(3), 479–483. https://doi.org/10.1016/j.jbiomech.2015.12.019

26. Bonacci, J., Hall, M., Fox, A., Saunders, N., Shipsides, T., & Vicenzino, B. (2018). The influence of cadence and shoes on patellofemoral joint kinetics in runners with patellofemoral pain. *Journal of Science and Medicine in Sport*, *21*(6), 574–578. https://doi.org/10.1016/j.jsams.2017.09.593

27. Bovalino, S. P., Cunningham, N. J., Zordan, R. D., Harkin, S. M., Thies, H. H. G., Graham, C. J., & Kingsley, M. I. C. (2020). Change in foot strike patterns and performance in recreational runners during a road race: A cross-sectional study. *Journal of Science and Medicine in Sport*, *23*(6), 621–624. https://doi.org/10.1016/j.jsams.2019.12.018

28. Bowser, B. J., Fellin, R., Milner, C. E., Pohl, M. B., & Davis, I. S. (2018). Reducing impact loading in runners: A one-year follow-up. *Medicine & Science in Sports & Exercise*, *50*(12), 2500–2506. https://doi.org/10.1249/MSS.0000000000001710

29. Branthwaite, H., Aitkins, C., Lindley, S., & Chockalingam, N. (2019). Surface electromyography of the foot: A protocol for sensor placement. *The Foot*, *41*, 24–29. https://doi.org/10.1016/j.foot.2019.07.001

30. Bredeweg, S. W., Kluitenberg, B., Bessem, B., & Buist, I. (2013). Differences in kinetic variables between injured and noninjured novice runners: A prospective cohort study. *Journal of Science and Medicine in Sport*, *16*(3), 205–210. https://doi.org/10.1016/j.jsams.2012.08.002

31. Bruening, D. A., Cooney, K. M., & Buczek, F. L. (2012a). Analysis of a kinetic multi-segment foot model. part i: Model repeatability and kinematic validity. *Gait & Posture*, *35*(4), 529–534. https://doi.org/10.1016/j.gaitpost.2011.10.363

32. Bruening, D. A., Cooney, K. M., & Buczek, F. L. (2012b). Analysis of a kinetic multi-segment foot model part ii: Kinetics and clinical implications. *Gait & Posture*, *35*(4), 535–540. https://doi.org/10.1016/j.gaitpost.2011.11.012

33. Bruening, D. A., Ridge, S. T., Jacobs, J. L., Olsen, M. T., Griffin, D. W., Ferguson, D. H., Bassett, K. E., & Johnson, A. W. (2019). Functional assessments of foot strength:

A comparative and repeatability study. *BMC Musculoskeletal Disorders*, *20*(1), 608. https://doi.org/10.1186/s12891-019-2981-6

34. Burke, A., Dillon, S., O'Connor, S., Whyte, E. F., Gore, S., & Moran, K. A. (2021). Risk factors for injuries in runners: A systematic review of foot strike technique and its classification at impact. *Orthopaedic Journal of Sports Medicine*, *9*(9), 232596712110202. https://doi.org/10.1177/23259671211020283

35. Casado, A., Hanley, B., Santos-Concejero, J., & Ruiz-Pérez, L. M. (2021). World-class long-distance running performances are best predicted by volume of easy runs and deliberate practice of short-interval and tempo runs. *Journal of Strength and Conditioning Research*, *35*(9), 2525–2531. https://doi.org/10.1519/JSC.0000000000003176

36. Ceyssens, L., Vanelderen, R., Barton, C., Malliaras, P., & Dingenen, B. (2019). Biomechanical risk factors associated with running-related injuries: A systematic review. *Sports Medicine*, *49*(7), 1095–1115. https://doi.org/10.1007/s40279-019-01110-z

37. Chan, Z. Y. S., Zhang, J. H., Au, I. P. H., An, W. W., Shum, G. L. K., Ng, G. Y. F., & Cheung, R. T. H. (2018). Gait retraining for the reduction of injury occurrence in novice distance runners: 1-year follow-up of a randomized controlled trial. *The American Journal of Sports Medicine*, *46*(2), 388–395. https://doi.org/10.1177/0363546517736277

38. Chen, T. L., An, W. W., Chan, Z. Y. S., Au, I. P. H., Zhang, Z. H., & Cheung, R. T. H. (2016). Immediate effects of modified landing pattern on a probabilistic tibial stress fracture model in runners. *Clinical Biomechanics*, *33*, 49–54. https://doi.org/10.1016/j.clinbiomech.2016.02.013

39. Chen, T. L.-W., Sze, L. K. Y., Davis, I. S., & Cheung, R. T. H. (2016). Effects of training in minimalist shoes on the intrinsic and extrinsic foot muscle volume. *Clinical Biomechanics*, *36*, 8–13. https://doi.org/10.1016/j.clinbiomech.2016.05.010

40. Chen, T. L.-W., Wong, D. W.-C., Wang, Y., Lin, J., & Zhang, M. (2019). Foot arch deformation and plantar fascia loading during running with rearfoot strike and forefoot strike: A dynamic finite element analysis. *Journal of Biomechanics*, *83*, 260–272. https://doi.org/10.1016/j.jbiomech.2018.12.007

41. Clansey, A. C., Hanlon, M., Wallace, E. S., Nevill, A., & Lake, M. J. (2014). Influence of tibial shock feedback training on impact loading and running economy. *Applied Sciences*.

42. Cornwall, M., & McPoil, T. (1999). Three-dimensional movement of the foot during the stance phase of walking. *Journal of the American Podiatric Medical Association*, *89*(2), 56–66. https://doi.org/10.7547/87507315-89-2-56

43. Costill, D. L., Thomason, H., & Roberts, E. (1973). Fractional utilization of the aerobic capacity during distance running. *Medicine and Science in Sports*, *5*(4), 248–252.

44. Craighead, D. H., Lehecka, N., & King, D. L. (2014). A novel running mechanic's class changes kinematics but not running economy. *Journal of Strength and Conditioning Research*, *28*(11), 3137–3145. https://doi.org/10.1519/JSC.0000000000000500

45. Dalen, T., Welde, B., Tillaar, R. van den, & Aune, T. K. (2013). Effect of single vs. Multi joint ballistic resistance training upon vertical jump performance. *Acta Kinesiologiae Universitatis Tartuensis*, *19*, 86–97. https://doi.org/10.12697/akut.2013.19.08

46. Dallam, G. M., Wilber, R. L., Jadelis, K., Fletcher, G., & Romanov, N. (2005). Effect of a global alteration of running technique on kinematics and economy. *Journal of Sports Sciences*, *23*(7), 757–764. https://doi.org/10.1080/02640410400022003

47. Daoud, A. I., Geissler, G. J., Wang, F., Saretsky, J., Daoud, Y. A., & Lieberman, D. E. (2012). Foot strike and injury rates in endurance runners: A retrospective study. *Medicine & Science in Sports & Exercise*, *44*(7), 1325–1334. https://doi.org/10.1249/MSS.0b013e3182465115

48. Davis, I. S. (2011). Gait retraining: Altering the fingerprint of gait. *Journal of Foot and Ankle Research*, *4*(S1), A5. https://doi.org/10.1186/1757-1146-4-S1-A5

49. Davis, I. S., Bowser, B. J., & Mullineaux, D. R. (2016). Greater vertical impact loading in female runners with medically diagnosed injuries: A prospective investigation. *British Journal of Sports Medicine*, *50*(14), 887–892. https://doi.org/10.1136/bjsports-2015-094579

50. Davis, I. S., Rice, H. M., & Wearing, S. C. (2017). Why forefoot striking in minimal shoes might positively change the course of running injuries. *Journal of Sport and Health Science*, *6*(2), 154–161. https://doi.org/10.1016/j.jshs.2017.03.013

51. Day, E. M., & Hahn, M. E. (2019). Increased toe-flexor muscle strength does not alter metatarsophalangeal and ankle joint mechanics or running economy. *Journal of Sports Sciences*, *37*(23), 2702–2710. https://doi.org/10.1080/02640414.2019.1661562

52. De Ruiter, C. J., Verdijk, P. W. L., Werker, W., Zuidema, M. J., & De Haan, A. (2014). Stride frequency in relation to oxygen consumption in experienced and novice runners. *European Journal of Sport Science*, *14*(3), 251–258. https://doi.org/10.1080/17461391.2013.783627

53. De Souza Júnior, J. R., Rabelo, P. H. R., Lemos, T. V., Esculier, J.-F., Barbosa, G. M. P., & Matheus, J. P. C. (2024). Effects of two gait retraining programs on pain, function, and lower limb kinematics in runners with patellofemoral pain: A randomized controlled trial. *PLOS ONE*, *19*(1), e0295645. https://doi.org/10.1371/journal.pone.0295645

54. Deng, L., Zhang, X., Xiao, S., Yang, Y., Li, L., & Fu, W. (2020). Changes in the plantar flexion torque of the ankle and in the morphological characteristics and mechanical properties of the achilles tendon after 12-week gait retraining. *Life*, *10*(9), 159. https://doi.org/10.3390/life10090159

55. Deschamps, K., Eerdekens, M., Desmet, D., Matricali, G. A., Wuite, S., & Staes, F. (2017). Estimation of foot joint kinetics in three and four segment foot models using an existing proportionality scheme: Application in paediatric barefoot walking. *Journal of Biomechanics*, *61*, 168–175. https://doi.org/10.1016/j.jbiomech.2017.07.017

56. Deschamps, K., Staes, F., Roosen, P., Nobels, F., Desloovere, K., Bruyninckx, H., & Matricali, G. A. (2011). Body of evidence supporting the clinical use of 3d multisegment foot models: A systematic review. *Gait & Posture*, *33*(3), 338–349. https://doi.org/10.1016/j.gaitpost.2010.12.018

57. Doherty, C., Keogh, A., Davenport, J., Lawlor, A., Smyth, B., & Caulfield, B. (2020). An evaluation of the training determinants of marathon performance: A meta-analysis

with meta-regression. *Journal of Science and Medicine in Sport*, *23*(2), 182–188. https://doi.org/10.1016/j.jsams.2019.09.013

58. Doyle, E., Doyle, T. L. A., Bonacci, J., & Fuller, J. T. (2022). The effectiveness of gait retraining on running kinematics, kinetics, performance, pain, and injury in distance runners: A systematic review with meta-analysis. *Journal of Orthopaedic & Sports Physical Therapy*, *52*(4), 192-A5. https://doi.org/10.2519/jospt.2022.10585

59. Dudley, R. I., Pamukoff, D. N., Lynn, S. K., Kersey, R. D., & Noffal, G. J. (2017). A prospective comparison of lower extremity kinematics and kinetics between injured and non-injured collegiate cross country runners. *Human Movement Science*, *52*, 197–202. https://doi.org/10.1016/j.humov.2017.02.007

60. Dunn, M. D. (2018). Effects of running retraining on biomechanical factors associated with lower limb injury. *Human Movement Science*.

61. Edouard, P., & Tooth, C. (2024). Methods for recording and reporting of epidemiological data on injury and illness in sport: Reform synthesis of the international olympic committee consensus statement. *British Journal of Sports Medicine*, *58*(17), 941–943. https://doi.org/10.1136/bjsports-2024-108516

62. Ekizos, A., Santuz, A., & Arampatzis, A. (2018). Short- and long-term effects of altered point of ground reaction force application on human running energetics. *Journal of Experimental Biology*.

63. Emig, T., & Adam, G. (2024). Evolution of world running record performances for men and women: Physiological characteristics. *Frontiers in Physiology*, *15*, 1372092. https://doi.org/10.3389/fphys.2024.1372092

64. Esculier, J.-F., Bouyer, L. J., Dubois, B., Fremont, P., Moore, L., McFadyen, B., & Roy, J.-S. (2018). Is combining gait retraining or an exercise programme with education better than education alone in treating runners with patellofemoral pain? A randomised clinical trial. *British Journal of Sports Medicine*, *52*(10), 659–666. https://doi.org/10.1136/bjsports-2016-096988

65. Esculier, J.-F., Bouyer, L. J., & Roy, J.-S. (2023). Running gait modifications can lead to immediate reductions in patellofemoral pain. *Frontiers in Sports and Active Living*, *4*, 1048655. https://doi.org/10.3389/fspor.2022.1048655

66. Esculier, J.-F., Charlton, J. M., Krowchuk, N. M., De Pieri, J., & Hunt, M. A. (2022). Immediate effects of manipulating footwear or cadence on the lower limb biomechanics of female masters runners. *Journal of Applied Biomechanics*, *38*(5), 312–319. https://doi.org/10.1123/jab.2021-0387

67. Esculier, J.-F., Dubois, B., Dionne, C. E., Leblond, J., & Roy, J.-S. (2015). A consensus definition and rating scale for minimalist shoes. *Journal of Foot and Ankle Research*, *8*(1), 42. https://doi.org/10.1186/s13047-015-0094-5

68. Esculier, J.-F., Maggs, K., Maggs, E., & Dubois, B. (2020). A contemporary approach to patellofemoral pain in runners. *Journal of Athletic Training*, *55*(12), 1206–1214. https://doi.org/10.4085/1062-6050-0535.19

69. Esculier, J.-F., Silvini, T., Bouyer, L. J., & Roy, J.-S. (2018). Video-based assessment of foot strike pattern and step rate is valid and reliable in runners with patellofemoral pain. *Physical Therapy in Sport*, *29*, 108–112. https://doi.org/10.1016/j.ptsp.2016.11.003

70. Eysenbach, G. (2004). Improving the quality of web surveys: The checklist for reporting results of internet e-surveys (cherries). *Journal of Medical Internet Research*, *6*(3), e34. https://doi.org/10.2196/jmir.6.3.e34

71. Farina, D. (2006). Interpretation of the surface electromyogram in dynamic contractions: *Exercise and Sport Sciences Reviews*, *34*(3), 121–127. https://doi.org/10.1249/00003677-200607000-00006

72. Farris, D. J., Birch, J., & Kelly, L. (2020). Foot stiffening during the push-off phase of human walking is linked to active muscle contraction, and not the windlass mechanism. *Journal of The Royal Society Interface*, *17*(168), 20200208. https://doi.org/10.1098/rsif.2020.0208

73. Ferris, J., Hazelwood, B., Cheuvront, S. N., & Gottschall, J. S. (2025). Compliant midsole foam is a primary contributor to improved running economy, biomechanics, and perception in advanced footwear in male runners. *Footwear Science*, *17*(sup1), S71–S72. https://doi.org/10.1080/19424280.2025.2491025

74. Fletcher, G., Bartlett, R., Romanov, N., & Fotouhi, D. A. (2008). Pose® method technique improves running performance without economy changes. *International Journal of Sports Science*, *3*(3).

75. Fokkema, T., De Vos, R.-J., Visser, E., Krastman, P., IJzerman, J., Koes, B. W., Verhaar, J. A. N., Bierma-Zeinstra, S. M. A., & Van Middelkoop, M. (2020). Enhanced injury prevention programme for recreational runners (the sprint study): Design of a randomised controlled trial. *BMJ Open Sport & Exercise Medicine*, *6*(1), e000780. https://doi.org/10.1136/bmjsem-2020-000780

76. Folland, J. P., Allen, S. J., Black, M. I., Handsaker, J. C., & Forrester, S. E. (2017). Running technique is an important component of running economy and performance. *Medicine & Science in Sports & Exercise*, *49*(7), 1412–1423. https://doi.org/10.1249/MSS.0000000000001245

77. Fourchet, F., Kelly, L., Horobeanu, C., Loepelt, H., Taiar, R., & Millet, G. (2015). High-Intensity Running and Plantar-Flexor Fatigability and Plantar-Pressure Distribution in Adolescent Runners. *Journal of Athletic Training*, *50*(2), 117–125. https://doi.org/10.4085/1062-6050-49.3.90

78. Fox, J. (2005). The *R* commander: a basic-statistics graphical user interface to *R*. *Journal of Statistical Software*, *14*(9). https://doi.org/10.18637/jss.v014.i09

79. Franz, J. R., Wierzbinski, C. M., & Kram, R. (2012). Metabolic cost of running barefoot versus shod: Is lighter better? *Medicine & Science in Sports & Exercise*, *44*(8), 1519–1525. https://doi.org/10.1249/MSS.0b013e3182514a88

80. Fraser, J. J., Koldenhoven, R. M., Saliba, S. A., & Hertel, J. (2017). Reliability of ankle-foot morphology, mobility, strength, and motor perfomance measures. *International Journal of Sports Physical Therapy*, *12*(7), 1134–1149. https://doi.org/10.26603/ijspt20171134

81. Frederick, E. C. (1984). Physiological and ergonomics factors in running shoe design. *Applied Ergonomics*, *15*(4), 281–287. https://doi.org/10.1016/0003-6870(84)90199-6

82. Fredette, A., Roy, J.-S., Perreault, K., Dupuis, F., Napier, C., & Esculier, J.-F. (2022). The association between running injuries and training parameters: A systematic review. *Journal of Athletic Training*, *57*(7), 650–671. https://doi.org/10.4085/1062-6050-0195.21

83. Fukashiro, S., Kurokawa, S., Hay, D. C., & Nagano, A. (2005). Comparison of muscle-tendon interaction of human m. Gastrocnemius between ankle- and drop-

jumping. *International Journal of Sport and Health Science*, *3*(Special_Issue_2), 253–263. https://doi.org/10.5432/ijshs.3.253

84. Fullagar, H. H. K., McCall, A., Impellizzeri, F. M., Favero, T., & Coutts, A. J. (2019). The translation of sport science research to the field: A current opinion and overview on the perceptions of practitioners, researchers and coaches. *Sports Medicine*, *49*(12), 1817–1824. https://doi.org/10.1007/s40279-019-01139-0

85. Fuller, J. T., Thewlis, D., Buckley, J. D., Brown, N. A. T., Hamill, J., & Tsiros, M. D. (2017). Body mass and weekly training distance influence the pain and injuries experienced by runners using minimalist shoes: A randomized controlled trial. *The American Journal of Sports Medicine*, *45*(5), 1162–1170. https://doi.org/10.1177/0363546516682497

86. Fuller, J. T., Thewlis, D., Tsiros, M. D., Brown, N. A. T., & Buckley, J. D. (2017). Six-week transition to minimalist shoes improves running economy and time-trial performance. *Journal of Science and Medicine in Sport*, *20*(12), 1117–1122. https://doi.org/10.1016/j.jsams.2017.04.013

87. Fuller, J. T., Thewlis, D., Tsiros, M. D., Brown, N. A. T., Hamill, J., & Buckley, J. D. (2019). Longer-term effects of minimalist shoes on running performance, strength and bone density: A 20-week follow-up study*. *European Journal of Sport Science*, *19*(3), 402–412. https://doi.org/10.1080/17461391.2018.1505958

88. Futrell, E. E., Gross, K. D., Reisman, D., Mullineaux, D. R., & Davis, I. S. (2020). Transition to forefoot strike reduces load rates more effectively than altered cadence. *Journal of Sport and Health Science*, *9*(3), 248–257. https://doi.org/10.1016/j.jshs.2019.07.006

89. Gabbett, T. J. (2016). The training—injury prevention paradox: Should athletes be training smarter *and* harder? *British Journal of Sports Medicine*, *50*(5), 273–280. https://doi.org/10.1136/bjsports-2015-095788

90. Giandolini, M., Horvais, N., Farges, Y., Samozino, P., & Morin, J.-B. (2013). Impact reduction through long-term intervention in recreational runners: Midfoot strike pattern versus low-drop/low-heel height footwear. *European Journal of Applied Physiology*, *113*(8), 2077–2090. https://doi.org/10.1007/s00421-013-2634-7

91. Gilgen-Ammann, R., Wyss, T., Troesch, S., Heyer, L., & Taube, W. (2017). Positive effects of augmented feedback to reduce time on ground in well-trained runners. *International Journal of Sports Physiology and Performance*.

92. Goldmann, J.-P., & Brüggemann, G.-P. (2012). The potential of human toe flexor muscles to produce force: Toe flexor muscle strength. *Journal of Anatomy*, *221*(2), 187–194. https://doi.org/10.1111/j.1469-7580.2012.01524.x

93. Goldmann, J.-P., Potthast, W., & Brüggemann, G.-P. (2013). Athletic training with minimal footwear strengthens toe flexor muscles. *Footwear Science*, *5*(1), 19–25. https://doi.org/10.1080/19424280.2012.744361

94. Goldmann, J.-P., Sanno, M., Willwacher, S., Heinrich, K., & Brüggemann, G.-P. (2013). The potential of toe flexor muscles to enhance performance. *Journal of Sports Sciences*, *31*(4), 424–433. https://doi.org/10.1080/02640414.2012.736627

95. Goss, D. L., & Gross, M. T. (2012). Relationships among self-reported shoe type, footstrike pattern, and injury incidence. *U.S. Army Medical Department Journal*, 25–30.

96. Gruber, A. H. (2023). The "impacts cause injury" hypothesis: Running in circles or making new strides? *Journal of Biomechanics*, *156*, 111694. https://doi.org/10.1016/j.jbiomech.2023.111694

97. Gruber, A. H., Boyer, K. A., Derrick, T. R., & Hamill, J. (2014). Impact shock frequency components and attenuation in rearfoot and forefoot running. *Journal of Sport and Health Science*, *3*(2), 113–121. https://doi.org/10.1016/j.jshs.2014.03.004

98. Gruber, A. H., Edwards, W. B., Hamill, J., Derrick, T. R., & Boyer, K. A. (2015). Ground reaction forces in rearfoot and forefoot running assessed by a continuous wavelet transform: 2638 board #4 may 29, 1 00 pm - 3 00 pm. *Medicine & Science in Sports & Exercise*, *47*(5S), 710. https://doi.org/10.1249/01.mss.0000478661.95317.63

99. Gruber, A. H., Umberger, B. R., Braun, B., & Hamill, J. (2013). Economy and rate of carbohydrate oxidation during running with rearfoot and forefoot strike patterns. *Journal of Applied Physiology*, *115*(2), 194–201. https://doi.org/10.1152/japplphysiol.01437.2012

100. Hafer, J. F., Brown, A. M., deMille, P., Hillstrom, H. J., & Garber, C. E. (2015). The effect of a cadence retraining protocol on running biomechanics and efficiency: A pilot study. *Journal of Sports Sciences*, *33*(7), 724–731. https://doi.org/10.1080/02640414.2014.962573

101. Hall, J. P. L., Barton, C., Jones, P. R., & Morrissey, D. (2013). The biomechanical differences between barefoot and shod distance running: a systematic review and preliminary meta-analysis. *Sports Medicine*, *43*(12), 1335–1353. https://doi.org/10.1007/s40279-013-0084-3

102. Hamill, J., Bates, B. T., Knutzen, K. M., & Sawhill, J. A. (1983). Variations in ground reaction force parameters at different running speeds. *Human Movement Science*, *2*(1), 47–56. https://doi.org/10.1016/0167-9457(83)90005-2

103. Hamill, J., & Gruber, A. H. (2017). Is changing footstrike pattern beneficial to runners? *Journal of Sport and Health Science*, *6*(2), 146–153. https://doi.org/10.1016/j.jshs.2017.02.004

104. Hanley, B., Tucker, C. B., Bissas, A., Merlino, S., & Gruber, A. H. (2021). Footstrike patterns and race performance in the 2017 iaaf world championship men's 10,000 m final. *Sports Biomechanics*, 1–10. https://doi.org/10.1080/14763141.2020.1856916

105. Hasegawa, H., Yamauchi, T., & Kraemer, W. J. (2007). Foot strike patterns of runners at the 15-km point during an elite-level half marathon. *Journal of Strength and Conditioning Research*, *21*(3), 888–893. https://doi.org/10.1519/R-22096.1

106. Hashimoto, T., & Sakuraba, K. (2014). Strength training for the intrinsic flexor muscles of the foot: effects on muscle strength, the foot arch, and dynamic parameters before and after the training. *Journal of Physical Therapy Science*, *26*(3), 373–376. https://doi.org/10.1589/jpts.26.373

107. Hashizume, S., & Yanagiya, T. (2017). A forefoot strike requires the highest forces applied to the foot among foot strike patterns. *Sports Medicine International Open*, *01*(02), E37–E42. https://doi.org/10.1055/s-0042-122017

108. Haynes, T., Bishop, C., Antrobus, M., & Brazier, J. (2019). The validity and reliability of the my jump 2 app for measuring the reactive strength index and drop

jump performance. *The Journal of Sports Medicine and Physical Fitness*, *59*(2). https://doi.org/10.23736/S0022-4707.18.08195-1

109. Headlee, D. L., Leonard, J. L., Hart, J. M., Ingersoll, C. D., & Hertel, J. (2008). Fatigue of the plantar intrinsic foot muscles increases navicular drop. *Journal of Electromyography and Kinesiology*, *18*(3), 420–425. https://doi.org/10.1016/j.jelekin.2006.11.004

110. Healey, L. A., & Hoogkamer, W. (2022). Longitudinal bending stiffness does not affect running economy in Nike Vaporfly Shoes. *Journal of Sport and Health Science*, *11*(3), 285–292. https://doi.org/10.1016/j.jshs.2021.07.002

111. Hébert-Losier, K., Finlayson, S., Driller, M., Dubois, B., Esculier, J.-F., & Beaven, C. (2020). Metabolic and performance responses of male runners wearing 3 types of footwear: Nike Vaporfly 4%, Saucony Endorphin racing flats, and their own shoes. *Journal of Sport and Health Science*, *11*. https://doi.org/10.1016/j.jshs.2020.11.012

112. Hébert-Losier, K., Patoz, A., Gindre, C., & Lussiana, T. (2021). Footstrike pattern at the 10 km and 39 km points of the singapore marathon in recreational runners. *Footwear Science*, *13*(1), 43–53. https://doi.org/10.1080/19424280.2020.1803993

113. Heiderscheit, B. C., Chumanov, E. S., Michalski, M. P., Wille, C. M., & Ryan, M. B. (2011). Effects of step rate manipulation on joint mechanics during running. *Medicine & Science in Sports & Exercise*, *43*(2), 296–302. https://doi.org/10.1249/MSS.0b013e3181ebedf4

114. Hein, T., Janssen, P., Wagner-Fritz, U., Haupt, G., & Grau, S. (2014). Prospective analysis of intrinsic and extrinsic risk factors on the development of A chilles tendon pain in runners. *Scandinavian Journal of Medicine & Science in Sports*, *24*(3). https://doi.org/10.1111/sms.12137

115. Hespanhol Junior, L. C., Pena Costa, L. O., & Lopes, A. D. (2013). Previous injuries and some training characteristics predict running-related injuries in recreational runners: A prospective cohort study. *Journal of Physiotherapy*, *59*(4), 263–269. https://doi.org/10.1016/S1836-9553(13)70203-0

116. Hoenig, T., Rolvien, T., & Hollander, K. (2020). Footstrike patterns in runners: Concepts, classifications, techniques, and implicationsfor running-related injuries. *Deutsche Zeitschrift Für Sportmedizin*, *71*(3), 55–61. https://doi.org/10.5960/dzsm.2020.424

117. Hollander, K., Argubi-Wollesen, A., Reer, R., & Zech, A. (2015). Comparison of minimalist footwear strategies for simulating barefoot running: A randomized crossover study. *PLOS ONE*, *10*(5), e0125880. https://doi.org/10.1371/journal.pone.0125880

118. Hollander, K., Johnson, C. D., Outerleys, J., & Davis, I. S. (2021). Multifactorial determinants of running injury locations in 550 injured recreational runners. *Medicine & Science in Sports & Exercise*, *53*(1), 102–107. https://doi.org/10.1249/MSS.0000000000002455

119. Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise*, *41*(1), 3–12. https://doi.org/10.1249/MSS.0b013e31818cb278

120. Huang, M., Mo, S., Pak-Kwan Chan, P., Chan, Z. Y. S., Zhang-Lea, J. H., & Cheung, R. T. H. (2023). The influence of running shoes on familiarization time for treadmill running biomechanics evaluation. *Sports Biomechanics*, *22*(3), 459–472. https://doi.org/10.1080/14763141.2022.2046144

121. Huang, Y., Xia, H., Chen, G., Cheng, S., Cheung, R. T. H., & Shull, P. B. (2019). Foot strike pattern, step rate, and trunk posture combined gait modifications to reduce impact loading during running. *Journal of Biomechanics*, *86*, 102–109. https://doi.org/10.1016/j.jbiomech.2019.01.058

122. Hulme, A., Nielsen, R. O., Timpka, T., Verhagen, E., & Finch, C. (2017). Risk and protective factors for middle- and long-distance running-related injury. *Sports Medicine*, *47*(5), 869–886. https://doi.org/10.1007/s40279-016-0636-4

123. Hunter, I., & Smith, G. A. (2007). Preferred and optimal stride frequency, stiffness and economy: Changes with fatigue during a 1-h high-intensity run. *European Journal of Applied Physiology*, *100*(6), 653–661. https://doi.org/10.1007/s00421-007-0456-1

124. Isherwood, J., Hughes, L., Qian, J. Y., & Sterzing, T. (2019). Biomechanics measured during continuous loop and discontinuous runway running differ while running shoe comparisons appear consistent. *Footwear Science*, *11*(sup1), S115–S116. https://doi.org/10.1080/19424280.2019.1606108

125. Jamison, S., Young, B., & Davis, I. S. (2016). *Are midfoot strike patterns similar to forefoot strike patterns when running in minimal footwear?*

126. Janusevicius, D., Snieckus, A., Skurvydas, A., Silinskas, V., Trinkunas, E., Cadefau, J. A., & Kamandulis, S. (2017). Effects of high velocity elastic band versus heavy resistance training on hamstring strength, activation, and sprint running performance. *Journal of Sports Science & Medicine*, *16*(2), 239–246.

127. Jewell, C., Boyer, K. A., & Hamill, J. (2017). Do footfall patterns in forefoot runners change over an exhaustive run? *Journal of Sports Sciences*, *35*(1), 74–80. https://doi.org/10.1080/02640414.2016.1156726

128. Johnson, A., Myrer, J., Mitchell, U., Hunter, I., & Ridge, S. (2015). The effects of a transition to minimalist shoe running on intrinsic foot muscle size. *International Journal of Sports Medicine*, *37*(02), 154–158. https://doi.org/10.1055/s-0035-1559685

129. Joyner, M. J., & Coyle, E. F. (2008). Endurance exercise performance: The physiology of champions. *The Journal of Physiology*, *586*(1), 35–44. https://doi.org/10.1113/jphysiol.2007.143834

130. Kakouris, N., Yener, N., & Fong, D. T. P. (2021). A systematic review of running-related musculoskeletal injuries in runners. *Journal of Sport and Health Science*, *10*(5), 513–522. https://doi.org/10.1016/j.jshs.2021.04.001

131. Kasmer, M. E., Wren, J. J., & Hoffman, M. D. (2014). Foot strike pattern and gait changes during a 161-km ultramarathon. *Journal of Strength and Conditioning Research*, *28*(5), 1343–1350. https://doi.org/10.1519/JSC.0000000000000282

132. Kayll, S. A., Hinman, R. S., Bryant, A. L., Bennell, K. L., Rowe, P. L., & Paterson, K. L. (2023). Do biomechanical foot-based interventions reduce patellofemoral joint loads in adults with and without patellofemoral pain or osteoarthritis? A systematic review and meta-analysis. *British Journal of Sports Medicine*, *57*(13), 872–881. https://doi.org/10.1136/bjsports-2022-106542

133. Kelly, L. A., Farris, D. J., Lichtwark, G. A., & Cresswell, A. G. (2018). The influence of foot-strike technique on the neuromechanical function of the foot. *Medicine & Science in Sports & Exercise*, *50*(1), 98–108. https://doi.org/10.1249/MSS.0000000000001420

134. Kelly, L. A., Lichtwark, G., & Cresswell, A. G. (2015). Active regulation of longitudinal arch compression and recoil during walking and running. *Journal of The Royal Society Interface*, *12*(102), 20141076. https://doi.org/10.1098/rsif.2014.1076

135. Kerr, B. (1983). *Footstrike patterns in distance running.* https://scholar.google.com/scholar_lookup?title=Biomechanical%20aspects%20of%20sports%20shoes%20and%20playing%20surfaces:%20Proceedings%20of%20the%20International%20Symposium%20on%20Biomechanical%20Aspects%20of%20Sport%20Shoes%20and%20Playing%20Surfaces&author=BA%20Kerr&author=L%20Beauchamp&author=V%20Fisher&author=R%20Neil&publication_year=1983&

136. Kessler, S. E., Lichtwark, G. A., Welte, L. K. M., Rainbow, M. J., & Kelly, L. A. (2020). Regulation of foot and ankle quasi-stiffness during human hopping across a range of frequencies. *Journal of Biomechanics*, *108*, 109853. https://doi.org/10.1016/j.jbiomech.2020.109853

137. Kluitenberg, B., Van Der Worp, H., Huisstede, B. M. A., Hartgens, F., Diercks, R., Verhagen, E., & Van Middelkoop, M. (2016). The nlstart2run study: Training-related factors associated with running-related injuries in novice runners. *Journal of Science and Medicine in Sport*, *19*(8), 642–646. https://doi.org/10.1016/j.jsams.2015.09.006

138. Kluitenberg, B., Van Middelkoop, M., Diercks, R., & Van Der Worp, H. (2015). What are the differences in injury proportions between different populations of runners? A systematic review and meta-analysis. *Sports Medicine*, *45*(8), 1143–1161. https://doi.org/10.1007/s40279-015-0331-x

139. Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

140. Kuhman, D. J., Melcher, D., & Paquette, M. R. (2016). Ankle and knee kinetics between strike patterns at common training speeds in competitive male

runners. *European Journal of Sport Science*, *16*(4), 433–440. https://doi.org/10.1080/17461391.2015.1086818

141. Kuhman, D. J., Paquette, M. R., Peel, S. A., & Melcher, D. A. (2016). Comparison of ankle kinematics and ground reaction forces between prospectively injured and uninjured collegiate cross country runners. *Human Movement Science*, *47*, 9–15. https://doi.org/10.1016/j.humov.2016.01.013

142. Kumar, D., McDermott, K., Feng, H., Goldman, V., Luke, A., Souza, R. B., & Hecht, F. M. (2015). Effects of form-focused training on running biomechanics: A pilot randomized trial in untrained individuals.

143. Larson, P., Higgins, E., Kaminski, J., Decker, T., Preble, J., Lyons, D., McIntyre, K., & Normile, A. (2011). Foot strike patterns of recreational and sub-elite runners in a long-distance road race. *Journal of Sports Sciences*, *29*(15), 1665–1673. https://doi.org/10.1080/02640414.2011.610347

144. Laughton, C. A., Davis, I. M., & Hamill, J. (2003). Effect of strike pattern and orthotic intervention on tibial shock during running. https://doi.org/10.1123/jab.19.2.153

145. Lavie, C. J., Lee, D., Sui, X., Arena, R., O'Keefe, J. H., Church, T. S., Milani, R. V., & Blair, S. N. (2015). Effects of running on chronic diseases and cardiovascular and all-cause mortality. *Mayo Clinic Proceedings*, *90*(11), 1541–1552. https://doi.org/10.1016/j.mayocp.2015.08.001

146. Leardini, A., Caravaggi, P., Theologis, T., & Stebbins, J. (2019). Multi-segment foot models and their use in clinical populations. *Gait & Posture*, *69*, 50–59. https://doi.org/10.1016/j.gaitpost.2019.01.022

147. Leardini, A., Stebbins, J., Hillstrom, H., Caravaggi, P., Deschamps, K., & Arndt, A. (2021). Isb recommendations for skin-marker-based multi-segment foot kinematics. *Journal of Biomechanics*, *125*, 110581. https://doi.org/10.1016/j.jbiomech.2021.110581

148. Lee, D., Pate, R. R., Lavie, C. J., Sui, X., Church, T. S., & Blair, S. N. (2014). Leisure-time running reduces all-cause and cardiovascular mortality risk. *Journal of the American College of Cardiology*, *64*(5), 472–481. https://doi.org/10.1016/j.jacc.2014.04.058

149. Leifer, V. P., Katz, J. N., & Losina, E. (2022). The burden of OA-health services and economics. *Osteoarthritis and Cartilage*, *30*(1), 10–16. https://doi.org/10.1016/j.joca.2021.05.007

150. Letafatkar, A., Rabiei, P., Farivar, N., & Alamouti, G. (2020). Long-term efficacy of conditioning training program combined with feedback on kinetics and kinematics in male runners. *Scandinavian Journal of Medicine & Science in Sports*, *30*(3), 429–441. https://doi.org/10.1111/sms.13587

151. Lieberman, D. E. (2012). What we can learn about running from barefoot running: An evolutionary medical perspective. *40*(2), 10.

152. Lieberman, D. E., Venkadesan, M., Werbel, W. A., Daoud, A. I., D'Andrea, S., Davis, I. S., Mang'Eni, R. O., & Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, *463*(7280), 531–535. https://doi.org/10.1038/nature08723

153. Liebl, D., Willwacher, S., Hamill, J., & Brüggemann, G.-P. (2014). Ankle plantarflexion strength in rearfoot and forefoot runners: A novel clusteranalytic approach. *Human Movement Science*, *35*, 104–120. https://doi.org/10.1016/j.humov.2014.03.008

154. Luedke, L. E., Heiderscheit, B. C., Williams, D. S. B., & Rauh, M. J. (2016). Influence of step rate on shin injury and anterior knee pain in high school runners. *Medicine & Science in Sports & Exercise*, *48*(7), 1244–1250. https://doi.org/10.1249/MSS.0000000000000890

155. Lyght, M., Nockerts, M., Kernozek, T. W., & Ragan, R. (2016). Effects of foot strike and step frequency on Achilles tendon stress during running. *Journal of Applied Biomechanics*, *32*(4), 365–372. https://doi.org/10.1123/jab.2015-0183

156. Maher, J. M., Markey, J. C., & Ebert-May, D. (2013). The other half of the story: Effect size analysis in quantitative research. *CBE—Life Sciences Education*, *12*(3), 345–351. https://doi.org/10.1187/cbe.13-04-0082

157. Malisoux, L., Gette, P., Backes, A., Delattre, N., Cabri, J., & Theisen, D. (2021). Relevance of frequency-domain analyses to relate shoe cushioning, ground impact forces and running injury risk: A secondary analysis of a randomized trial with

800+ recreational runners. *Frontiers in Sports and Active Living*, *3*, 744658. https://doi.org/10.3389/fspor.2021.744658

158. Malisoux, L., Gette, P., Delattre, N., Urhausen, A., & Theisen, D. (2022). Spatiotemporal and ground-reaction force characteristics as risk factors for running-related injury: A secondary analysis of a randomized trial including 800+ recreational runners. *The American Journal of Sports Medicine*, *50*(2), 537–544. https://doi.org/10.1177/03635465211063909

159. Malisoux, L., Nielsen, R. O., Urhausen, A., & Theisen, D. (2015). A step towards understanding the mechanisms of running-related injuries. *Journal of Science and Medicine in Sport*, *18*(5), 523–528. https://doi.org/10.1016/j.jsams.2014.07.014

160. Malisoux, L., Ramesh, J., Mann, R., Seil, R., Urhausen, A., & Theisen, D. (2015). Can parallel use of different running shoes decrease running-related injury risk? *Scandinavian Journal of Medicine & Science in Sports*, *25*(1), 110–115. https://doi.org/10.1111/sms.12154

161. Malisoux, L., & Theisen, D. (2020). Can the “appropriate” footwear prevent injury in leisure-time running? Evidence versus beliefs. *Journal of Athletic Training*, *55*(12), 1215–1223. https://doi.org/10.4085/1062-6050-523-19

162. Malliaras, P. (2022). Physiotherapy management of Achilles tendinopathy. *Journal of Physiotherapy*, *68*(4), 221–237. https://doi.org/10.1016/j.jphys.2022.09.010

163. Melcher, D. A., Paquette, M. R., Schilling, B. K., & Bloomer, R. J. (2017). Joint stiffness and running economy during imposed forefoot strike before and after a long run in rearfoot strike runners. *Journal of Sports Sciences*, *35*(23), 2297–2303. https://doi.org/10.1080/02640414.2016.1266016

164. Mercer, J., Dolgan, J., & Griffin, J. (2008). The physiological importance of prefered stride frequency during running at different speeds.

165. Messier, S. P., & Cirillo, K. J. (1989). Effects of a verbal and visual feedback system on running technique, perceived exertion and running economy in female novice runners. *Journal of Sports Sciences*, *7*(2), 113–126. https://doi.org/10.1080/02640418908729830

166. Messier, S. P., Martin, D. F., Mihalko, S. L., Ip, E., DeVita, P., Cannon, D. W., Love, M., Beringer, D., Saldana, S., Fellin, R. E., & Seay, J. F. (2018). A 2-year prospective cohort study of overuse running injuries: The runners and injury longitudinal study (trails). *The American Journal of Sports Medicine*, *46*(9), 2211–2221. https://doi.org/10.1177/0363546518773755

167. Miller, E. E., Whitcome, K. K., Lieberman, D. E., Norton, H. L., & Dyer, R. E. (2014). The effect of minimal shoes on arch structure and intrinsic foot muscle strength. *Journal of Sport and Health Science*, *3*(2), 74–85. https://doi.org/10.1016/j.jshs.2014.03.011

168. Milner, C. E., Ferber, R., Pollard, C. D., Hamill, J., & Davis, I. S. (2006). Biomechanical factors associated with tibial stress fracture in female runners. *Medicine & Science in Sports & Exercise*, *38*(2), 323–328. https://doi.org/10.1249/01.mss.0000183477.75808.92

169. Milner, C. E., Hamill, J., & Davis, I. (2007). Are knee mechanics during early stance related to tibial stress fracture in runners? *Clinical Biomechanics*, *22*(6), 697–703. https://doi.org/10.1016/j.clinbiomech.2007.03.003

170. Moen, M. H., Tol, J. L., Weir, A., Steunebrink, M., & De Winter, T. C. (2009). Medial tibial stress syndrome: A critical review. *Sports Medicine*, *39*(7), 523–546. https://doi.org/10.2165/00007256-200939070-00002

171. Moore, I. S. (2016). Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. *Sports Medicine*, *46*(6), 793–807. https://doi.org/10.1007/s40279-016-0474-4

172. Moore, I. S., Pitt, W., Nunns, M., & Dixon, S. (2015). Effects of a seven-week minimalist footwear transition programme on footstrike modality, pressure variables and loading rates. *Footwear Science*, *7*(1), 17–29. https://doi.org/10.1080/19424280.2014.971352

173. Morris, J. B., Goss, D. L., Miller, E. M., & Davis, I. S. (2020). Using real-time biofeedback to alter running biomechanics: A randomized controlled trial. *Translational Sports Medicine*, *3*(1), 63–71. https://doi.org/10.1002/tsm2.110

174. Mulligan, E. P., & Cook, P. G. (2013). Effect of plantar intrinsic muscle training on medial longitudinal arch morphology and dynamic function. *Manual Therapy*, *18*(5), 425–430. https://doi.org/10.1016/j.math.2013.02.007

175. Murray, L., Beaven, C., & Hébert-Losier, K. (2018). Reliability of overground running measures from 2d video analyses in a field environment. *Sports*, *7*(1), 8. https://doi.org/10.3390/sports7010008

176. Napier, C., MacLean, C. L., Maurer, J., Taunton, J. E., & Hunt, M. A. (2018). Kinetic risk factors of running-related injuries in female recreational runners. *Scandinavian Journal of Medicine & Science in Sports*, *28*(10), 2164–2172. https://doi.org/10.1111/sms.13228

177. Napier, C., MacLean, C. L., Maurer, J., Taunton, J. E., & Hunt, M. A. (2019). Real-time biofeedback of performance to reduce braking forces associated with running-related injury: An exploratory study. *Journal of Orthopaedic & Sports Physical Therapy*, *49*(3), 136–144. https://doi.org/10.2519/jospt.2019.8587

178. Napier, C., & Willy, R. W. (2021). The prevention and treatment of running injuries: A state of the art. *International Journal of Sports Physical Therapy*, *16*(4). https://doi.org/10.26603/001c.25754

179. Nichols, R., Germano, C., Burke, M., Nolan, K., Youngs-Grand, K., & Girard, J. (2016). The effects of foot strike on running economy in distance runners: A narrative review. *Physical Therapy Reviews*, *21*(1), 32–37. https://doi.org/10.1080/10833196.2016.1193970

180. Nigg, B. M., Bahlsen, H. A., Luethi, S. M., & Stokes, S. (1987). The influence of running velocity and midsole hardness on external impact forces in heel-toe running. *Journal of Biomechanics*, *20*(10), 951–959. https://doi.org/10.1016/0021-9290(87)90324-1

181. Noehren, B., Davis, I., & Hamill, J. (2007). ASB clinical biomechanics award winner 2006. *Clinical Biomechanics*, *22*(9), 951–956. https://doi.org/10.1016/j.clinbiomech.2007.07.001

182. Noehren, B., Hamill, J., & Davis, I. (2013). Prospective evidence for a hip etiology in patellofemoral pain. *Medicine & Science in Sports & Exercise*, *45*(6), 1120–1124. https://doi.org/10.1249/MSS.0b013e31828249d2

183. Ogueta-Alday, A., Morante, J. C., Gómez-Molina, J., & García-López, J. (2018). Similarities and differences among half-marathon runners according to their performance level. *PLOS ONE*, *13*(1), e0191688. https://doi.org/10.1371/journal.pone.0191688

184. Okamura, K., Fukuda, K., Oki, S., Ono, T., Tanaka, S., & Kanai, S. (2020). Effects of plantar intrinsic foot muscle strengthening exercise on static and dynamic foot kinematics: A pilot randomized controlled single-blind trial in individuals with pes planus. *Gait & Posture*, *75*, 40–45. https://doi.org/10.1016/j.gaitpost.2019.09.030

185. Oliveira, A. S., & Pirscoveanu, C. I. (2021). Implications of sample size and acquired number of steps to investigate running biomechanics. *Scientific Reports*, *11*(1), 3083. https://doi.org/10.1038/s41598-021-82876-z

186. Oosterwaal, M., Telfer, S., Tørholm, S., Carbes, S., Van Rhijn, L. W., Macduff, R., Meijer, K., & Woodburn, J. (2011). Generation of subject-specific, dynamic, multisegment ankle and foot models to improve orthotic design: A feasibility study. *BMC Musculoskeletal Disorders*, *12*(1), 256. https://doi.org/10.1186/1471-2474-12-256

187. Oxfeldt, M., Overgaard, K., Hvid, L. G., & Dalgas, U. (2019). Effects of plyometric training on jumping, sprint performance, and lower body muscle strength in healthy adults: A systematic review and meta-analyses. *Scandinavian Journal of Medicine & Science in Sports*, *29*(10), 1453–1465. https://doi.org/10.1111/sms.13487

188. Patoz, A., Lussiana, T., Breine, B., Gindre, C., & Hébert-Losier, K. (2022). There is no global running pattern more economic than another at endurance running speeds. *International Journal of Sports Physiology and Performance*, *17*(4), 659–662. https://doi.org/10.1123/ijspp.2021-0345

189. Perl, D. P., Daoud, A. I., & Lieberman, D. E. (2012). Effects of footwear and strike type on running economy. *Medicine & Science in Sports & Exercise*, *44*(7), 1335–1343. https://doi.org/10.1249/MSS.0b013e318247989e

190. Perrin, T. P., Morio, C. Y. M., Besson, T., Kerhervé, H. A., Millet, G. Y., & Rossi, J. (2023). Comparison of skin and shoe marker placement on metatarsophalangeal joint kinematics and kinetics during running. *Journal of Biomechanics*, *146*, 111410. https://doi.org/10.1016/j.jbiomech.2022.111410

191. Peters-Dickie, J.-L., Detrembleur, C., Guallar-Bouloc, M., Rastelli, M., Lobet, S., Hidalgo, B., & Deschamps, K. (2025). The effects of foot core exercises and minimalist footwear on foot muscle sizes, foot strength, and biomechanics: A systematic review and meta-analysis. *Clinical Biomechanics*, *122*, 106417. https://doi.org/10.1016/j.clinbiomech.2024.106417

192. Pohl, M. B., Hamill, J., & Davis, I. S. (2009). Biomechanical and anatomic factors associated with a history of plantar fasciitis in female runners. *Clinical Journal of Sport Medicine*, *19*(5), 372–376. https://doi.org/10.1097/JSM.0b013e3181b8c270

193. Pohl, M. B., Mullineaux, D. R., Milner, C. E., Hamill, J., & Davis, I. S. (2008). Biomechanical predictors of retrospective tibial stress fractures in runners. *Journal of Biomechanics*, *41*(6), 1160–1165. https://doi.org/10.1016/j.jbiomech.2008.02.001

194. Radin, E. L., Parker, H. G., Pugh, J. W., Steinberg, R. S., Paul, I. L., & Rose, R. M. (1973). Response of joints to impact loading—Iii. *Journal of Biomechanics*, *6*(1), 51–57. https://doi.org/10.1016/0021-9290(73)90037-7

195. Ralapanawa, U., & Sivakanesan, R. (2021). Epidemiology and the magnitude of coronary artery disease and acute coronary syndrome: A narrative review: *Journal of Epidemiology and Global Health*, *11*(2), 169. https://doi.org/10.2991/jegh.k.201217.001

196. Rathleff, M. S., Mølgaard, C. M., Fredberg, U., Kaalund, S., Andersen, K. B., Jensen, T. T., Aaskov, S., & Olesen, J. L. (2015). High-load strength training improves outcome in patients with plantar fasciitis: A randomized controlled trial with 12-month follow-up. *Scandinavian Journal of Medicine & Science in Sports*, *25*(3). https://doi.org/10.1111/sms.12313

197. Redmond, A. C., Crosbie, J., & Ouvrier, R. A. (2006). Development and validation of a novel rating system for scoring standing foot posture: The foot posture index. *Clinical Biomechanics*, *21*(1), 89–98. https://doi.org/10.1016/j.clinbiomech.2005.08.002

198. Rhim, H. C., Kwon, J., Park, J., Borg-Stein, J., & Tenforde, A. S. (2021). A systematic review of systematic reviews on the epidemiology, evaluation, and treatment of plantar fasciitis. *Life*, *11*(12), 1287. https://doi.org/10.3390/life11121287

199. Ribeiro, A. P., & João, S. M. A. (2022). The effect of short and long-term therapeutic treatment with insoles and shoes on pain, function, and plantar load parameters of women with plantar fasciitis: A randomized controlled trial. *Medicina*, *58*(11), 1546. https://doi.org/10.3390/medicina58111546

200. Richert, F. C., Stein, T., Ringhof, S., & Stetter, B. J. (2019). The effect of the heel-to-toe drop of standard running shoes on lower limb biomechanics. *Footwear Science*, *11*(3), 161–170. https://doi.org/10.1080/19424280.2019.1630016

201. Ridge, S. T., Olsen, M. T., Bruening, D. A., Jurgensmeier, K., Griffin, D., Davis, I. S., & Johnson, A. W. (2019). Walking in minimalist shoes is effective for strengthening foot muscles. *Medicine & Science in Sports & Exercise*, *51*(1), 104–113. https://doi.org/10.1249/MSS.0000000000001751

202. Ridge, S. T., Standifird, T., Rivera, J., Johnson, A. W., & Mitchell, U. (2015). The effect of training in minimalist running shoes on running economy. *2015*.

203. Rodrigo-Carranza, V., González-Mohíno, F., Santos-Concejero, J., & González-Ravé, J. M. (2022). The effects of footwear midsole longitudinal bending stiffness on running economy and ground contact biomechanics: A systematic review and meta-analysis. *European Journal of Sport Science*, *22*(10), 1508–1521. https://doi.org/10.1080/17461391.2021.1955014

204. Rodrigo-Carranza, V., Hoogkamer, W., González-Ravé, J. M., Horta-Muñoz, S., Serna-Moreno, M. del C., Romero-Gutierrez, A., & González-Mohíno, F. (2024). Influence of different midsole foam in advanced footwear technology use on running economy and biomechanics in trained runners. *Scandinavian Journal of Medicine & Science in Sports*, *34*(1), e14526. https://doi.org/10.1111/sms.14526

205. Roper, J., Doerfler, D., Kravitz, L., Dufek, J., & Mermier, C. (2017). Gait retraining from rearfoot strike to forefoot strike does not change running economy. *International Journal of Sports Medicine*, *38*(14), 1076–1082. https://doi.org/10.1055/s-0043-110225

206. Roper, J., Harding, E. M., Doerfler, D., Dexter, J. G., Kravitz, L., Dufek, J. S., & Mermier, C. M. (2016). The effects of gait retraining in runners with patellofemoral pain: A randomized trial. *Clinical Biomechanics (Bristol, Avon)*, *35*, 14–22. https://doi.org/10.1016/j.clinbiomech.2016.03.010

207. Rosemann, T., Laux, G., & Szecsenyi, J. (2007). Osteoarthritis: Quality of life, comorbidities, medication and health service utilization assessed in a large sample of primary care patients. *Journal of Orthopaedic Surgery and Research*, *2*(1), 12. https://doi.org/10.1186/1749-799X-2-12

208. Rosner, B. (1983). Percentage points for a generalized ESD many-outlier procedure. *Technometrics*, *25*(2), 165–172. https://doi.org/10.1080/00401706.1983.10487848

209. Ruder, M., Jamison, S. T., Tenforde, A., Mulloy, F., & Davis, I. S. (2019). Relationship of foot strike pattern and landing impacts during a marathon. *Medicine & Science in Sports & Exercise*, *51*(10), 2073–2079. https://doi.org/10.1249/MSS.0000000000002032

210. Ryan, M., Elashi, M., Newsham-West, R., & Taunton, J. (2014). Examining injury risk and pain perception in runners using minimalist footwear. *British Journal of Sports Medicine*, *48*(16), 1257–1262. https://doi.org/10.1136/bjsports-2012-092061

211. Salzler, M. J., Kirwan, H. J., Scarborough, D. M., Walker, J. T., Guarino, A. J., & Berkson, E. M. (2016). Injuries observed in a prospective transition from traditional to minimalist footwear: Correlation of high impact transient forces and lower injury severity. *The Physician and Sportsmedicine*, *44*(4), 373–379. https://doi.org/10.1080/00913847.2016.1238282

212. Schache, A. G., Dorn, T. W., Williams, G. P., Brown, N. A. T., & Pandy, M. G. (2014). Lower-limb muscular strategies for increasing running speed. *Journal of Orthopaedic & Sports Physical Therapy*, *44*(10), 813–824. https://doi.org/10.2519/jospt.2014.5433

213. Seidel, O., Carius, D., Kenville, R., & Ragert, P. (2017). Motor learning in a complex balance task and associated neuroplasticity: A comparison between endurance athletes and nonathletes. *Journal of Neurophysiology*, *118*(3), 1849–1860. https://doi.org/10.1152/jn.00419.2017

214. Semple, R., Murley, G. S., Woodburn, J., & Turner, D. E. (2009). Tibialis posterior in health and disease: A review of structure and function with specific reference to electromyographic studies. *Journal of Foot and Ankle Research*, *2*(1), 24. https://doi.org/10.1186/1757-1146-2-24

215. Shen, B., Zhang, S., Cui, K., Zhang, X., & Fu, W. (2022). Effects of a 12-week gait retraining program combined with foot core exercise on morphology, muscle strength, and kinematics of the arch: A randomized controlled trial. *Frontiers in Bioengineering and Biotechnology*, *10*, 1022910. https://doi.org/10.3389/fbioe.2022.1022910

216. Shih, Y., Lin, K.-L., & Shiang, T.-Y. (2013). Is the foot striking pattern more important than barefoot or shod conditions in running? *Gait & Posture*, *38*(3), 490–494. https://doi.org/10.1016/j.gaitpost.2013.01.030

217. Shorten, M., & Mientjes, M. I. V. (2011). The 'heel impact' force peak during running is neither 'heel' nor 'impact' and does not quantify shoe cushioning effects. *Footwear Science*, *3*(1), 41–58. https://doi.org/10.1080/19424280.2010.542186

218. Simon, S. R., Radin, E. L., Paul, I. L., & Rose, R. M. (1972). The response of joints to impact loading—Ii *in vivo* behavior of subchondral bone. *Journal of Biomechanics*, *5*(3), 267–272. https://doi.org/10.1016/0021-9290(72)90042-5

219. Sleeswijk Visser, T. S. O., Van Middelkoop, M., Fokkema, T., & De Vos, R. (2021). The socio-economic impact of running-related injuries: A large prospective cohort study. *Scandinavian Journal of Medicine & Science in Sports*, *31*(10), 2002–2009. https://doi.org/10.1111/sms.14016

220. Smith, L., Preece, S., Mason, D., & Bramah, C. (2015). A comparison of kinematic algorithms to estimate gait events during overground running. *Gait & Posture*, *41*(1), 39–43. https://doi.org/10.1016/j.gaitpost.2014.08.009

221. Smith, R., Lichtwark, G., Farris, D., & Kelly, L. (2023). Examining the intrinsic foot muscles' capacity to modulate plantar flexor gearing and ankle joint contributions to propulsion in vertical jumping. *Journal of Sport and Health Science*, *12*(5), 639–647. https://doi.org/10.1016/j.jshs.2022.07.002

222. Sobhani, S., Bredeweg, S., Dekker, R., Kluitenberg, B., Van Den Heuvel, E., Hijmans, J., & Postema, K. (2014). Rocker shoe, minimalist shoe, and standard running shoe: A comparison of running economy. *Journal of Science and Medicine in Sport*, *17*(3), 312–316. https://doi.org/10.1016/j.jsams.2013.04.015

223. Soligard, T., Schwellnus, M., Alonso, J.-M., Bahr, R., Clarsen, B., Dijkstra, H. P., Gabbett, T., Gleeson, M., Hägglund, M., Hutchinson, M. R., Janse van Rensburg,

C., Khan, K. M., Meeusen, R., Orchard, J. W., Pluim, B. M., Raftery, M., Budgett, R., & Engebretsen, L. (2016). How much is too much? (Part 1) international olympic committee consensus statement on load in sport and risk of injury. *British Journal of Sports Medicine*, *50*(17), 1030–1041. https://doi.org/10.1136/bjsports-2016-096581

224. Spurrs, R. W., Murphy, A. J., & Watsford, M. L. (2003). The effect of plyometric training on distance running performance. *European Journal of Applied Physiology*, *89*(1), 1–7. https://doi.org/10.1007/s00421-002-0741-y

225. Stam, C., & Valkenberg, H. (2019). Sportblessures in nederland. 44.

226. Stefanyshyn, D. J., Stergiou, P., Lun, V. M. Y., Meeuwisse, W. H., & Worobets, J. T. (2006). Knee angular impulse as a predictor of patellofemoral pain in runners. *The American Journal of Sports Medicine*, *34*(11), 1844–1851. https://doi.org/10.1177/0363546506288753

227. Stratford, P. W., & Balsor, B. E. (1994). A comparison of make and break tests using a hand-held dynamometer and the kin-com. *Journal of Orthopaedic & Sports Physical Therapy*, *19*(1), 28–32. https://doi.org/10.2519/jospt.1994.19.1.28

228. Su, W., Zhang, S., Ye, D., Sun, X., Zhang, X., & Fu, W. (2022). Effects of barefoot and shod on the in vivo kinematics of medial longitudinal arch during running based on a high-speed dual fluoroscopic imaging system. *Frontiers in Bioengineering and Biotechnology*, *10*, 917675. https://doi.org/10.3389/fbioe.2022.917675

229. Sullivan, J., Burns, J., Adams, R., Pappas, E., & Crosbie, J. (2015). Musculoskeletal and activity-related factors associated with plantar heel pain. *Foot & Ankle International*, *36*(1), 37–45. https://doi.org/10.1177/1071100714551021

230. Swift, D. L., Lavie, C. J., Johannsen, N. M., Arena, R., Earnest, C. P., O'Keefe, J. H., Milani, R. V., Blair, S. N., & Church, T. S. (2013). Physical activity, cardiorespiratory fitness, and exercise training in primary and secondary coronary prevention. *Circulation Journal*, *77*(2), 281–292. https://doi.org/10.1253/circj.CJ-13-0007

231. Swinnen, W., Mylle, I., Hoogkamer, W., De Groote, F., & Vanwanseele, B. (2021). Changing stride frequency alters average joint power and power distributions

during ground contact and leg swing in running. *Medicine & Science in Sports & Exercise*, *53*(10), 2111–2118. https://doi.org/10.1249/MSS.0000000000002692

232. Taddei, U. T., Matias, A. B., Duarte, M., & Sacco, I. C. N. (2020). Foot core training to prevent running-related injuries: A survival analysis of a single-blind, randomized controlled trial. *The American Journal of Sports Medicine*, *48*(14), 3610–3619. https://doi.org/10.1177/0363546520969205

233. Takabayashi, T., Edama, M., Inai, T., & Kubo, M. (2021). Differences in rearfoot, midfoot, and forefoot kinematics of normal foot and flatfoot during running. *Journal of Orthopaedic Research*, *39*(3), 565–571. https://doi.org/10.1002/jor.24877

234. Taş, S., Ünlüer, N. Ö., & Korkusuz, F. (2018). Morphological and mechanical properties of plantar fascia and intrinsic foot muscles in individuals with and without flat foot. *Journal of Orthopaedic Surgery*, *26*(3), 230949901880248. https://doi.org/10.1177/2309499018802482

235. Tourillon, R., Fourchet, F., Edouard, P., & Morin, J.-B. (2024). Test–retest reliability and usefulness of a foot–ankle rebound-jump test for measuring foot–ankle reactive strength in athletes. *International Journal of Sports Physiology and Performance*, *19*(9), 949–952. https://doi.org/10.1123/ijspp.2024-0062

236. Tourillon, R., Fourchet, F., Edouard, P., & Morin, J.-B. (2025). Effects of a forefoot strengthening protocol on explosive tasks performance and propulsion kinetics in athletes: A single-blind randomized controlled trial. *PloS One*, *20*(6), e0313979. https://doi.org/10.1371/journal.pone.0313979

237. Tourillon, R., Gojanovic, B., & Fourchet, F. (2019). How to evaluate and improve foot strength in athletes: An update. *Frontiers in Sports and Active Living*, *1*, 46. https://doi.org/10.3389/fspor.2019.00046

238. Trombini-Souza, F., Fuller, R., Matias, A., Yokota, M., Butugan, M., Goldenstein-Schainberg, C., & Sacco, I. C. N. (2012). Effectiveness of a long-term use of a minimalist footwear versus habitual shoe on pain, function and mechanical loads in knee osteoarthritis: A randomized controlled trial. *BMC Musculoskeletal Disorders*, *13*(1), 121. https://doi.org/10.1186/1471-2474-13-121

239. Trowell, D., Fox, A., Saunders, N., Vicenzino, B., & Bonacci, J. (2022). A comparison of plantarflexor musculotendon unit output between plyometric exercises

and running. *Journal of Science and Medicine in Sport*, *25*(4), 334–339. https://doi.org/10.1016/j.jsams.2021.11.037

240. Truong, L. K., Bekker, S., & Whittaker, J. L. (2021). Removing the training wheels: Embracing the social, contextual and psychological in sports medicine. *British Journal of Sports Medicine*, *55*(9), 466–467. https://doi.org/10.1136/bjsports-2020-102679

241. Turner, A. M., Owings, M., & Schwane, J. A. (2003). Improvement in running economy after 6 weeks of plyometric training. *Journal of Strength and Conditioning Research*, *17*(1), 60–67. https://doi.org/10.1519/1533-4287(2003)017<0060:iireaw>2.0.co;2

242. Turner, A. N., & Jeffreys, I. (2010). The stretch-shortening cycle: Proposed mechanisms and methods for enhancement. *Strength & Conditioning Journal*, *32*(4), 87–99. https://doi.org/10.1519/SSC.0b013e3181e928f9

243. Van Den Berghe, P., Derie, R., Bauwens, P., Gerlo, J., Segers, V., Leman, M., & De Clercq, D. (2022). Reducing the peak tibial acceleration of running by music-based biofeedback: A quasi-randomized controlled trial. *Scandinavian Journal of Medicine & Science in Sports*, *32*(4), 698–709. https://doi.org/10.1111/sms.14123

244. Van Der Worp, H., Vrielink, J. W., & Bredeweg, S. W. (2016). Do runners who suffer injuries have higher vertical ground reaction forces than those who remain injury-free? A systematic review and meta-analysis. *British Journal of Sports Medicine*, *50*(8), 450–457. https://doi.org/10.1136/bjsports-2015-094924

245. Van Doorn, J., Van Den Bergh, D., Böhm, U., Dablander, F., Derks, K., Draws, T., Etz, A., Evans, N. J., Gronau, Q. F., Haaf, J. M., Hinne, M., Kucharský, Š., Ly, A., Marsman, M., Matzke, D., Gupta, A. R. K. N., Sarafoglou, A., Stefan, A., Voelkel, J. G., & Wagenmakers, E.-J. (2021). The JASP guidelines for conducting and reporting a bayesian analysis. *Psychonomic Bulletin & Review*, *28*(3), 813–826. https://doi.org/10.3758/s13423-020-01798-5

246. Van Hooren, B., Fuller, J. T., Buckley, J. D., Miller, J. R., Sewell, K., Rao, G., Barton, C., Bishop, C., & Willy, R. W. (2020). Is motorized treadmill running biomechanically comparable to overground running? A systematic review and meta-

analysis of cross-over studies. *Sports Medicine*, *50*(4), 785–813. https://doi.org/10.1007/s40279-019-01237-z

247. Van Hooren, B., Jukic, I., Cox, M., Frenken, K. G., Bautista, I., & Moore, I. S. (2024). The relationship between running biomechanics and running economy: A systematic review and meta-analysis of observational studies. *Sports Medicine*, *54*(5), 1269–1316. https://doi.org/10.1007/s40279-024-01997-3

248. Van Hooren, B., Plasqui, G., & Meijer, K. (2024). The effect of wearable-based real-time feedback on running injuries and running performance: A randomized controlled trial. *The American Journal of Sports Medicine*, *52*(3), 750–765. https://doi.org/10.1177/03635465231222464

249. van Iperen, L. P., de Jonge, J., Gevers, J. M. P., & Vos, S. B. (2022). Linking psychological risk profiles to running-related injuries and chronic fatigue in long-distance runners: A latent profile analysis. *Psychology of Sport and Exercise*, *58*, 102082. https://doi.org/10.1016/j.psychsport.2021.102082

250. Van Mechelen, W., Hlobil, H., & Kemper, H. C. G. (1992). Incidence, severity, aetiology and prevention of sports injuries: A review of concepts. *Sports Medicine*, *14*(2), 82–99. https://doi.org/10.2165/00007256-199214020-00002

251. van Melick, N., Meddeler, B. M., Hoogeboom, T. J., Nijhuis-van der Sanden, M. W. G., & van Cingel, R. E. H. (2017). How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. *Plos One*, *12*(12), e0189876. https://doi.org/10.1371/journal.pone.0189876

252. Van Poppel, D., Van Der Worp, M., Slabbekoorn, A., Van Den Heuvel, S. S. P., Van Middelkoop, M., Koes, B. W., Verhagen, A. P., & Scholten-Peeters, G. G. M. (2021). Risk factors for overuse injuries in short- and long-distance running: A systematic review. *Journal of Sport and Health Science*, *10*(1), 14–28. https://doi.org/10.1016/j.jshs.2020.06.006

253. Van Hooren, B., Van Rengs, L., & Meijer, K. (2024). Per-step and cumulative load at three common running injury locations: The effect of speed, surface gradient, and cadence. *Scandinavian Journal of Medicine & Science in Sports*, *34*(2), e14570. https://doi.org/10.1111/sms.14570

254. Vannatta, C. N., & Kernozek, T. W. (2015). Patellofemoral joint stress during running with alterations in foot strike pattern. *Medicine & Science in Sports & Exercise*, *47*(5), 1001–1008. https://doi.org/10.1249/MSS.0000000000000503

255. Vella, S., Bolling, C., Verhagen, E., & Moore, I. S. (2021). Perceiving, reporting and managing an injury – perspectives from national team football players, coaches, and health professionals. *Science and Medicine in Football*, 1–13. https://doi.org/10.1080/24733938.2021.1985164

256. Verhagen, E. (2012). Prevention of running-related injuries in novice runners: Are we running on empty? *British Journal of Sports Medicine*, *46*(12), 836–837. https://doi.org/10.1136/bjsports-2012-091505

257. Videbæk, S., Bueno, A. M., Nielsen, R. O., & Rasmussen, S. (2015). Incidence of running-related injuries per 1000 h of running in different types of runners: A systematic review and meta-analysis. *Sports Medicine*, *45*(7), 1017–1026. https://doi.org/10.1007/s40279-015-0333-8

258. Wang, I.-L., Graham, R. B., Bourdon, E. J. P., Chen, Y.-M., Gu, C.-Y., & Wang, L.-I. (2020). Biomechanical analysis of running foot strike in shoes of different mass. *Journal of sports science & medicine*, *19*(1), 130–137. PMCID: PMC7039018

259. Wang, J., Luo, Z., Dai, B., & Fu, W. (2020). Effects of 12-week cadence retraining on impact peak, load rates and lower extremity biomechanics in running. *PeerJ*, *8*, e9813. https://doi.org/10.7717/peerj.9813

260. Warne, J. P., & Gruber, A. H. (2017). Transitioning to minimal footwear: A systematic review of methods and future clinical recommendations. *Sports Medicine - Open*, *3*(1), 33. https://doi.org/10.1186/s40798-017-0096-x

261. Warne, J. P., & Warrington, G. D. (2014). Four-week habituation to simulated barefoot running improves running economy when compared with shod running. *Scandinavian Journal of Medicine & Science in Sports*, *24*(3), 563–568. https://doi.org/10.1111/sms.12032

262. Warr, B. J., Fellin, R. E., Sauer, S. G., Goss, D. L., Frykman, P. N., & Seay, J. F. (2015). Characterization of foot-strike patterns: Lack of an association with injuries or performance in soldiers. *Military Medicine*, *180*(7), 830–834. https://doi.org/10.7205/MILMED-D-14-00220

263. Wei, Z., Hou, X., Qi, Y., & Wang, L. (2024). Influence of foot strike patterns and cadences on patellofemoral joint stress in male runners with patellofemoral pain. *Physical Therapy in Sport*, *65*, 1–6. https://doi.org/10.1016/j.ptsp.2023.10.006

264. Welte, L., Holowka, N. B., Kelly, L. A., Arndt, A., & Rainbow, M. J. (2023). Mobility of the human foot's medial arch helps enable upright bipedal locomotion. *Frontiers in Bioengineering and Biotechnology*, *11*, 1155439. https://doi.org/10.3389/fbioe.2023.1155439

265. Whelan, N., Kenny, I. C., & Harrison, A. J. (2016). An insight into coaches' knowledge and use of sprinting drills to improve sprinting technique and performance. *International Journal of Sports Science*.

266. Whittier, T., Willy, R. W., Sandri Heidner, G., Niland, S., Melton, C., Mizelle, J. C., & Murray, N. P. (2020). The cognitive demands of gait retraining in runners: An ecg study. *Journal of Motor Behavior*, *52*(3), 360–371. https://doi.org/10.1080/00222895.2019.1635983

267. Willemse, L., Wouters, E. J. M., Pisters, M. F., & Vanwanseele, B. (2023). Plantar intrinsic foot muscle activation during functional exercises compared to isolated foot exercises in younger adults. *Physiotherapy Theory and Practice*, 1–13. https://doi.org/10.1080/09593985.2023.2204947

268. Williams, D. S., McClay, I. S., & Manal, K. T. (2000). Lower extremity mechanics in runners with a converted forefoot strike pattern. *Journal of Applied Biomechanics*, *16*(2), 210–218. https://doi.org/10.1123/jab.16.2.210

269. Willy, R. W., Buchenic, L., Rogacki, K., Ackerman, J., Schmidt, A., & Willson, J. D. (2016). In-field gait retraining and mobile monitoring to address running biomechanics associated with tibial stress fracture. *Scandinavian journal of medicine & science in sports*, *26*(2), 197–205. https://doi.org/10.1111/sms.12413

270. Willy, R. W., & Davis, I. S. (2014). Kinematic and kinetic comparison of running in standard and minimalist shoes. *Medicine & Science in Sports & Exercise*, *46*(2), 318–323. https://doi.org/10.1249/MSS.0b013e3182a595d2

271. Willy, R. W., Meardon, S. A., Schmidt, A., Blaylock, N. R., Hadding, S. A., & Willson, J. D. (2016). Changes in tibiofemoral contact forces during running in

response to in-field gait retraining. *Journal of Sports Sciences*, *34*(17), 1602–1611. https://doi.org/10.1080/02640414.2015.1125517

272. Winstein, C. J. (1991). Knowledge of results and motor learning—Implications for physical therapy. *Physical Therapy*, *71*(2), 140–149. https://doi.org/10.1093/ptj/71.2.140

273. Winstein, C. J., Gardner, E. R., McNeal, D. R., Barto, P. S., & Nicholson, D. E. (1989). Standing balance training: Effect on balance and locomotion in hemiparetic adults. *Archives of Physical Medicine and Rehabilitation*, *70*(10), 755–762.

274. Wu, H., Brooke-Wavell, K., Fong, D. T. P., Paquette, M. R., & Blagrove, R. C. (2024). Do exercise-based prevention programs reduce injury in endurance runners? A systematic review and meta-analysis. *Sports Medicine (Auckland, N.Z.)*, *54*(5), 1249–1267. https://doi.org/10.1007/s40279-024-01993-7

275. Xie, P.-P., István, B., & Liang, M. (2022). Sex-specific differences in biomechanics among runners: A systematic review with meta-analysis. *Frontiers in Physiology*, *13*, 994076. https://doi.org/10.3389/fphys.2022.994076

276. Xu, Y., Yuan, P., Wang, R., Wang, D., Liu, J., & Zhou, H. (2021). Effects of foot strike techniques on running biomechanics: a systematic review and meta-analysis. *Sports Health: A Multidisciplinary Approach*, *13*(1), 71–77. https://doi.org/10.1177/1941738120934715

277. Yamato, T. P., Saragiotto, B. T., & Lopes, A. D. (2015). A consensus definition of running-related injury in recreational runners: A modified delphi approach. *Journal of Orthopaedic & Sports Physical Therapy*, *45*(5), 375–380. https://doi.org/10.2519/jospt.2015.5741

278. Yong, J. R., Silder, A., Montgomery, K. L., Fredericson, M., & Delp, S. L. (2018). Acute changes in foot strike pattern and cadence affect running parameters associated with tibial stress fractures. *Journal of Biomechanics*, *76*, 1–7. https://doi.org/10.1016/j.jbiomech.2018.05.017

279. Yuasa, Y., Kurihara, T., & Isaka, T. (2018). Relationship between toe muscular strength and the ability to change direction in athletes. *Journal of Human Kinetics*, *64*(1), 47–55. https://doi.org/10.1515/hukin-2017-0183

280. Zhang, J., Fiers, P., Witte, K., Jackson, R., Poggensee, K., Atkeson, C., & Collins, S. (2017). Human-in-the-loop optimization of exoskeleton assistance during walking. *Science*, *356*(6344), 1280–1284. https://doi.org/10.1126/science.aal5054

281. Zhang, Q., Nassis, G. P., Chen, S., Shi, Y., & Li, F. (2022). Not lower-limb joint strength and stiffness but vertical stiffness and isometric force-time characteristics correlate with running economy in recreational male runners. *Frontiers in Physiology*, *13*, 940761. https://doi.org/10.3389/fphys.2022.940761

282. Zhang, Z., & Lake, M. (2022). A re-examination of the measurement of foot strike mechanics during running: The immediate effect of footwear midsole thickness. *Frontiers in Sports and Active Living*, *4*, 824183. https://doi.org/10.3389/fspor.2022.824183