



Mechanics, energetics and implementation of grounded running technique: a narrative review

Sheeba Davis ¹, Aaron Fox ², Jason Bonacci ², Fiddy Davis ³

To cite: Davis S, Fox A, Bonacci J, *et al.* Mechanics, energetics and implementation of grounded running technique: a narrative review. *BMJ Open Sport & Exercise Medicine* 2020;**0**:e000963. doi:10.1136/bmjsem-2020-000963

Received 17 September 2020
Revised 28 October 2020
Accepted 2 November 2020

ABSTRACT

Grounded running predominantly differs from traditional aerial running by having alternating single and double stance with no flight phase. Approximately, 16% of runners in an open marathon and 33% of recreational runners in a 5 km running event adopted a grounded running technique. Grounded running typically occurs at a speed range of 2–3 m·s⁻¹, is characterised by a larger duty factor, reduced vertical leg stiffness, lower vertical oscillation of the centre of mass (COM) and greater impact attenuation than aerial running. Grounded running typically induces an acute increase in metabolic cost, likely due to the larger duty factor. The increased duty factor may translate to a more stable locomotion. The reduced vertical oscillation of COM, attenuated impact shock, and potential for improved postural stability may make grounded running a preferred form of physical exercise in people new to running or with low loading capacities (eg, novice overweight/obese, elderly runners, rehabilitating athletes). Grounded running as a less impactful, but metabolically more challenging form, could benefit these runners to optimise their cardio-metabolic health, while at the same time minimise running-related injury risk. This review discusses the mechanical demands and energetics of grounded running along with recommendations and suggestions to implement this technique in practice.

What is already known

- ▶ Grounded running is a slow form of running with the presence of a double support phase (ie, absence of a flight phase).
- ▶ Grounded running is not a typically spontaneous running pattern in humans when compared to other bipedals (eg, birds and macaques).
- ▶ Grounded running subjects the human body to lesser impact and loading, but potentially increases the metabolic cost, compared to traditional aerial running.

What are the new findings

- ▶ Grounded running may be beneficial for a select group of people—such as novice, obese and elderly individuals, who are new to running or have low loading capacities.
- ▶ Internal muscle loading of the lower extremities in grounded running is yet to be determined.
- ▶ We provide a series of recommendations on how grounded running can be implemented by practitioners, however, further research is warranted to investigate the feasibility of adopting a grounded running technique.



© Author(s) (or their employer(s)) 2020. Re-use permitted under CC BY-NC. No commercial re-use. See rights and permissions. Published by BMJ.

¹Biomedical Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, India

²Centre for Sport Research, School of Exercise and Nutrition Sciences, Deakin University, Waurn Ponds, Australia

³Centre for Sports Science, Medicine and Research, Manipal College of Health Professions, Manipal Academy of Higher Education, Manipal, India

Correspondence to

Sheeba Davis;
sheeba.davis@manipal.edu

INTRODUCTION

The WHO has identified physical inactivity as a leading risk factor for global mortality.¹ Running is one of the most popular,^{2–5} effective and affordable forms of physical activity which has the potential to offer protection against all-cause mortality and other comorbidities. A recent meta-analysis of 14 prospective cohort trials, with a pooled sample of over 230 000 participants, showed that regular participation in running is associated with 27, 30 and 23% reduction in all-cause, cardiovascular and cancer mortality, respectively.⁵ Although running has a positive influence on one's physical health and fitness, it can also negatively impact the musculoskeletal system via running-related injuries.^{6–9}

Running is distinguished from walking (or other locomotive activities) by a number of characteristics.¹⁰ Of note, we typically consider running to involve a flight phase where

neither foot is in contact with the ground (see [figure 1](#)). Grounded running is an alternative running technique, which maintains characteristics similar to traditional aerial running (eg, low centre of mass (COM) and maximum vertical ground reaction force (vGRF) at mid-stance),^{11–13} while having alternating single and double stance with no flight phase (see [figure 2](#)).¹¹ Though grounded running might look similar to that of walking, the key characteristics that differentiate grounded running from walking are a unimodal vGRF shape, low COM at mid-stance and shorter double support period.^{11–14} Groucho running¹⁵ and terrestrial running¹⁶ share similar characteristics to grounded running (ie, large duty factor, reduced leg stiffness, lower vertical oscillation of COM and smaller vGRF). However, groucho running incurs a larger knee flexion at initial contact, while terrestrial running incurs a small flight phase.

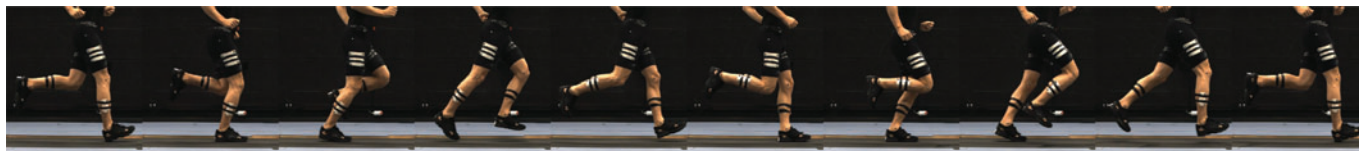


Figure 1 Image sequences depicting various phases of traditional aerial running at $3.2 \text{ m}\cdot\text{s}^{-1}$. (Courtesy: Mr Senne Bonnaerens – Faculty of Medicine and Health Sciences, Ghent University, Belgium)

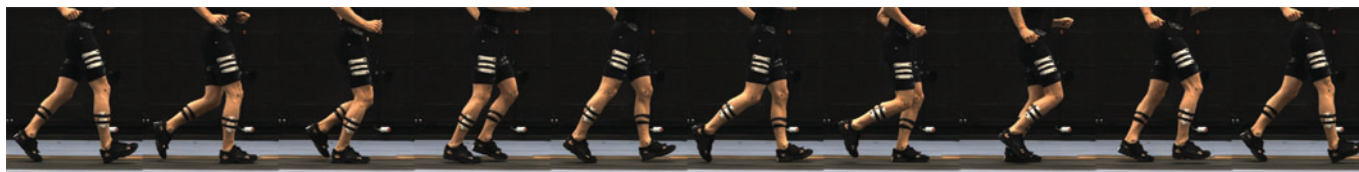


Figure 2 Image sequences depicting various phases of grounded running at $2.1 \text{ m}\cdot\text{s}^{-1}$. (Courtesy: Mr Senne Bonnaerens – Faculty of Medicine and Health Sciences, Ghent University, Belgium)

With no flight phase and increased duty factor, grounded running might appear biomechanically similar to fast walking. However, fast walking differs from grounded running by having an extended knee and a high COM at initial contact, bowing of the knee during mid-stance, lateral pelvic tilt and side flexion of trunk, touchdown in the lateral part of heel and walking at an average velocity of $4.30 \text{ m}\cdot\text{s}^{-1}$ and above.¹⁷ For the purpose of this review, we operationally define grounded running as a locomotive technique characterised by slow running speed, absence of flight phase and lower vertical oscillation of COM.

Grounded running is a habitual gait pattern observed in bipedals, such as birds and certain animals (quails,¹⁸ ostriches,¹⁹ macaques,²⁰ tinamou²¹ etc.). Grounded running is generally not a spontaneous running pattern in humans, likely due to our upright posture in comparison to other animals. However, 16% of participants in a large-scale, open marathon¹¹ and 33% of participants in a 5 km recreational running event²² used a grounded running technique at a relatively slow speed (ie, $1.52\text{--}2.88 \text{ m}\cdot\text{s}^{-1}$). Older adults^{12 22 23} and women with a higher body mass index (BMI)^{11 12 22 24} may more readily adopt a grounded running technique due to their slower running speed and lower vertical displacement. Individuals who use a grounded running technique likely continue to reap the cardiovascular health benefits of running, despite the pattern not conforming to the standard norms of running.

The very fact that grounded running does not have a flight phase, but has a brief double support phase, suggests this form of locomotion could reduce the external loads acting on the body. Knowledge of grounded running biomechanics will aid in a better understanding of the loading patterns and potential injury risk or risk mitigation of this technique. Similarly, an understanding of the energetics may reveal why grounded running is adopted only by a select sub-group of runners and help form the basis for prescribing running intensity and volume. The purpose of this narrative review is to: (i) synthesise the information pertaining to this unique

form of running; (ii) discuss its mechanical and physiological demands; and (iii) suggest recommendations for adoption and implementation.

Biomechanics of grounded running

Grounded running in humans is typically observed when individuals run at a speed of $1.5\text{--}3 \text{ m}\cdot\text{s}^{-1}$ ^{11–14 22} accompanied by a large duty factor (ie, percentage of time each foot spends in contact with the ground).^{12–14 22} By virtue of a lack of flight phase, the duty factor for grounded running is always greater than 50%, higher than that of traditional aerial running.^{12 13} It is important to note, that duty factor progressively reduces with an increase in running speed, irrespective of whether an aerial or grounded technique is used.¹³ There is no evidence of altered cadence between grounded and aerial running, whereas the step length is lesser in grounded when compared to aerial running.¹² Characteristics of grounded running against aerial running is summarised in [table 1](#). Grounded running incurs a lower vertical, but larger antero-posterior oscillation of the COM with each stride.¹² With a reduced vertical oscillation of the COM,

Table 1 Summary of characteristics present in grounded compared to traditional aerial running

Flight Phase ¹¹	×
Double Support ¹¹	✓
Running Speed ^{11–14 22}	$1.5\text{--}3.0 \text{ m}\cdot\text{s}^{-1}$
Vertical Oscillation of COM ¹²	↓
Step Length ¹²	↓
Cadence ¹²	–
Duty Factor ^{12–14 22}	↑
Leg Stiffness ¹⁴	↓
vGRF ^{11 12 14}	↓

×, Absent; ✓, Present; ↓, Lower; ↑, Higher; –, No difference; COM, Centre of mass; vGRF, Vertical ground reaction force.

the work against gravity is likely reduced in grounded running. Although there is no evidence on the adoption of foot strike pattern by the grounded runners, cross sectional studies^{25–26} have shown that slow running speed is related to a rear-foot strike pattern. We speculate that grounded runners will likely exhibit a rear-foot strike. Though unlikely, there is no evidence to suggest that grounded running cannot be performed with other foot strike patterns.

The larger duty factor associated with grounded running reduces vertical leg stiffness when compared to traditional aerial running, leading to a more compliant gait.¹⁴ This increased compliance places a greater demand on these muscles by keeping them active for a longer period, thus increasing their mechanical load.¹³ The typical slower speed of grounded running reduces the biomechanical loading of the lower extremities.¹² The vertical GRF is approximately 30% lower in grounded running than that of aerial running.^{11–12–14} A similar reduction (50% reduction) has also been observed in tibial acceleration and vertical instantaneous loading rate.¹² However, knowledge of the internal muscle loading during grounded running is lacking. Studies that provide an estimate of internal lower limb muscle forces and mechanics can provide further understanding of the actual lower limb musculoskeletal loads experienced during grounded running.

The absence of a flight phase, reduced vGRF and vertical displacement of COM in grounded running also has the potential to minimise extraneous non-sagittal plane motions associated with running-related injuries.^{27–28} For example, increased hip adduction has been linked biomechanically to patellofemoral pain²⁷ and iliotibial band syndrome.²⁹ There is, however, no evidence describing frontal and transverse plane kinematics in grounded vs aerial running. Examination of these variables during ground running is required to test this supposition.

Energetics of grounded running

During walking, the body follows an ‘inverted pendulum’ pattern, resulting in a 180° phase shift of potential energy (PE) and kinetic energy (KE).³⁰ In the case of moderate walking speed (around 1.5 m·s⁻¹, as optimal speed is about 1.11 m·s⁻¹),³¹ PE and KE magnitudes are equal, thereby conserving 70% of mechanical energy.³⁰ As speed increases (around 1.8 m·s⁻¹),³¹ the exchange between PE and KE reduces and more mechanical work is done by the active contraction of muscles, thereby increasing metabolic cost.³⁰ The problem of elevated metabolic cost is avoided by adopting running when walking speed reaches around 2 m·s⁻¹.^{31–32} Congruity of PE and KE^{33–34} is used to differentiate walking (ie, %congruity of 0–50%) from running (ie, %congruity of 50–100%) and is calculated based on the variations in PE and KE of the COM that occur during a gait trial. When the %congruity is slightly greater than 50%, walking transitions to running through an intermediate gait (ie, grounded running). Andrada

and colleagues³⁴ estimated %congruity in quails and showed that at speeds (ie, 0.5 m·s⁻¹) where there is an overlap between walking and grounded running, walking has a %congruity less than 50%, whereas grounded running has greater than 50% congruity. This identifies a similarity between grounded and aerial running, whereby they both have %congruity greater than 50%. In this context, speed is likely a determining factor in whether grounded (below 1.0 m·s⁻¹) or aerial running (above 1.0 m·s⁻¹) is adopted.³⁴ Though the speeds examined in quails do not match the human walk-run transition speed, the concept of %congruity demonstrates that even at slower speeds, grounded running shares certain characteristics of aerial running.

Humans naturally adopt stiffer legs during the stance phase of running to reduce muscle forces and lower metabolic cost.³⁵ Increased duty factor in grounded running reduces leg stiffness and potentially comes with an increase in metabolic cost.¹⁴ Although muscle forces are likely lower in grounded running owing to lower speed, displacement of COM and vGRF, muscle forces must be maintained for a longer duration during each gait cycle. The increase in the duration of knee extensor muscle activation is considered as primarily responsible for the increase in metabolic cost with grounded running.¹³ A reduction in elastic energy use could also contribute to elevated metabolic cost in grounded running. Tendons make better use of elastic strain energy with increased running speed.³⁶ The increased duty factor (ie, increased ground contact time) and lower speed of grounded running likely presents an inefficient use of elastic strain energy, placing a greater demand on muscle tendon units to perform more active positive work. Future studies estimating muscle forces and tendon behaviour via musculoskeletal modelling or ultrasound imaging are warranted to further understand how muscle-tendon unit factors modulate metabolic cost in grounded running.

A more recent experimental study showed a marginal increase of about 5% in the energy expenditure during grounded compared to slow aerial running on a treadmill at a speed of 2.1 m·s⁻¹.¹² However, when grounded running was compared to aerial running at a population average speed (3.2 m·s⁻¹), an approximate 25% increase in energy expenditure was observed compared to aerial running.¹² The elevated metabolic cost is likely a primary explanation for why many humans do not naturally use a grounded running technique. This notion is supported by Iwami and Ogihara’s¹⁴ finding that grounded running was difficult to adopt as it was more exhaustive.

It is important to note that the majority of studies on grounded running have enforced this technique on habitual aerial runners,^{12–14} which likely raises metabolic cost due to an unfamiliar gait pattern. Further, these studies^{12–14} have compared the metabolic cost of aerial and grounded running at matched speeds. While employing such strategies controls for potential confounding factors—it may not be an accurate representation of the speed and movement strategies adopted by habitual-grounded runners in

real-world situations. Humans become economical movers through self-optimisation strategies,³⁷ in the pattern and speed of movement they prefer to adopt. There could be a steep increase in the energy cost beyond the likely lower, optimal running speeds used during habitual grounded running. The possible reasons for an elevated cost at higher speeds (ie, those matched to aerial running) could be the greater muscle work required to maintain a beyond-optimal stride length, or the excessive pelvic rotation required to perform grounded running at these speeds. Further, the braking forces during initial stance would be higher with an increased stride length during grounded running, inducing greater hip and thigh muscle eccentric demands. Similar to the transition speed that exists between walking and running, there could be a transition point beyond which aerial running becomes far more economical than grounded running. Investigating the physiological responses across a range of running speeds during grounded and aerial techniques among runners with varying levels of fitness and abilities might reveal this transition point. This may identify the potential speed at which grounded running is energetically efficient, and enable practitioners to better prescribe grounded running.

Can grounded running be recommended for recreational runners?

Individuals seeking a healthier lifestyle and weight control through exercise often choose running, as it is considered low cost and can be easily implemented.³⁸ Despite the health benefits, running-related injuries (particularly overuse injuries) are common.⁸ Naturally, running applies ground reaction forces and loading to the lower extremity—and this biomechanical ‘loading’ in the presence of other intrinsic or extrinsic risk factors may contribute to the development of running injuries.³⁹ Adopting a grounded running technique reduces the magnitude and rate of vertical loading during running¹²—and therefore may offer some protective effect from running-related injuries or pain. This approach has been demonstrated by ultramarathon runners. Ultramarathon runners tend to adopt characteristics of grounded running (ie, slower speed, larger duty factor, reduced vertical oscillation of COM, and lower vGRF) towards the end of their events.^{40 41} It is speculated these alterations are made to lower the overall impact and reduce pain during prolonged running.⁴⁰ In a similar vein, grounded running may also present a particularly useful option for recreational runners with low loading capacities (eg, individuals commencing impact-related exercise; elderly runners).

Grounded running may also be preferable for overweight/obese individuals and novice recreational runners. Running-related injuries are significantly higher in those with a higher BMI,⁴² with this incidence even higher for people with a BMI more than 30 kg·m⁻².⁴³ Novice runners are also at higher risk of running-related injuries.⁴⁴ Musculoskeletal loading during running

depends on multiple factors, such as flexibility, running technique, muscular strength and endurance—but also anthropometry. A recent case-control trial by Vincent and colleagues⁴⁵ observed dampened axial loading and impact in obese runners compared to non-obese runners, for a nearly similar self-selected speed (~2.5 m·s⁻¹). The overweight participants of this study, who were seasoned runners, had a self-optimised movement pattern characterised by reduced vertical excursion of COM and a marginally higher duty factor—that was associated with lower impact forces.⁴⁵ These characteristics notably align with those of grounded running. Overweight and novice runners may not have a high tolerance for the increased load associated with aerial running when they begin training. Thus, grounded running may be a useful recommendation for overweight/obese and novice runners to potentially reduce the incidence of running-related injuries—particularly early on in their transition to exercise. As this form of locomotion appears to offload the bodyweight, it could offer similar benefits to that of lower body positive pressure treadmill (such as Alter G) running. Moreover, the reduced vertical displacement of the COM in grounded running may be more economical for overweight and obese runners, as the amount of work to propel the body against gravity is smaller.

Elderly runners may prefer grounded running over aerial running for improved postural stability during locomotion.⁴⁶ Postural control during locomotion depends on a complex inter-play of sensory inputs from the proprioceptors, cutaneous sensory information from feet, vestibular signals, gravity and vision.⁴⁶ Age-related decline in somatosensory inputs and attenuated cutaneous sensation owing to athletic footwear subjects the elderly to rely on visual inputs more compared to younger counterparts.⁴⁷ Thus, when the limits of stability are challenged (eg, during running) owing to the displacement of the COM and single-limb support, there is a need to have a stable gaze. Reduced oscillation of the COM and the head along with compliant legs during grounded running could enhance an elderly individual’s ability to fix their gaze and improve postural stability. This could be equated to a similar strategy adopted by birds, whereby grounded running is used to stabilise their vertical movement and vision to focus on their prey or for increased vigilance against predators.²¹ This form of running could possibly help overcome running-related kinesiphobia in elders. Grounded running may be an appropriate recommendation to elders who have never run before and are commencing running for health and fitness benefits.

Caution may still be necessary in prescribing grounded running—as the technique conflicts with recommendations often provided to minimise the risk of certain overuse running-related injuries. Rear-foot strike patterns have been related to elevated patellofemoral joint contact forces,^{27 48} vertical loading rate,⁴⁹ peak knee extension moment,⁴⁹ ankle stiffness⁴⁹ and peak impact acceleration at the leg.⁵⁰ Grounded running has never been studied in those with overuse musculoskeletal injuries and there is

no prospective evidence for the development of running-related injuries in those using grounded running. However, the biomechanical factors associated with grounded running such as increased duty factor, reduced leg stiffness, lower oscillation of COM and reduced vGRF appear to offer some protection against biomechanical risk factors for some overuse running-related injuries. Given the dearth of literature on grounded running in people with overuse musculoskeletal injuries, it is not known if this form of running could be beneficial and this is a relevant avenue for future investigations.

The potentially elevated metabolic cost associated with grounded running in the early stages of learning must also be acknowledged when considering it as a recommended technique for recreational runners. It appears that traditional aerial runners shifting to a grounded running technique can expect an increase in their energy cost of running^{12 14}—yet familiarisation may result in only small increases in metabolic cost, or potentially become more economical with regular adoption.¹² The increased metabolic cost in the early stages may be beneficial for overweight and obese runners as their energy expenditure would be higher. It is unknown how a ‘new’ runner (eg, an individual initiating an exercise programme) would respond to grounded running from an energetics perspective—as this is yet to be investigated. To our knowledge, there are also no trials that have investigated the long-term effects on running-economy of adopting grounded running in habitual aerial or untrained runners. Observing whether the acute changes in metabolic cost when shifting to grounded running persist long-term, or whether these are attenuated with longer-term adoption may provide further evidence around the appropriateness of this technique. One might assume that without the habitual background of aerial running, the elevated metabolic cost associated with grounded running may be blunted much earlier, or not present at all. Nonetheless, in any situation it appears that some management of the expected elevated metabolic cost associated with grounded running must be considered (eg, expectations around running volume).

Implementation of grounded running

Grounded running may have the potential for reducing musculoskeletal loading and improving stability during running. Novice runners and obese/overweight individuals, elderly runners, or athletes during the intermediate stages of rehabilitation may see a benefit from employing a grounded running technique. With dampened axial loading and loading impact, grounded running could be equated to lower body positive pressure treadmill (such as Alter G) running. There is a growing body of evidence that lower body positive pressure can be used effectively to offload the bodyweight and give an adequate metabolic stimulus to improve the exercise capacity in clinical and healthy populations.⁵¹ Grounded running could be an effective means of implementing this approach, potentially providing injury prevention

benefits without the need for specialised equipment. The practicability and feasibility of implementing such an intervention is yet to be determined.

Gait retraining is advocated for and practiced by Physiotherapists, Sports Scientists and Biomechanists for both injury prevention and management in runners.^{52–55} A similar approach could be used to shift runners towards a grounded running technique. Generally, two methods of providing augmented feedback are adopted for retraining, those being visual and auditory.⁵⁶ Practitioners could likely focus on two unique characteristics of grounded running to retrain runners to adopt this form: (i) larger duty factor (ie, promoting double support); and (ii) reduced vertical displacement of COM. As there is no difference in cadence between grounded and aerial running, runners need not adjust their cadence to shift to grounded running. Both visual⁵⁷ and auditory cues⁵⁸ attenuated the displacement of COM in recent trials of aerial running, and has been associated with improved economy and a potential protective effect against running-related injuries. A simple phrase ‘keep the body as low to the ground as possible without slouching’ was enough to reduce the vertical loading rate and peak vertical ground reaction force.⁵⁷ Complementing auditory and visual cues through video clips could further enhance the learning process. Similarly, strategies surrounding additive technologies such as pressure insoles or wearable sensors could be developed to provide biofeedback to runners on their adherence to the technique. These cues and solutions could be used to train or retrain a grounded running form. There is, however, a dearth of literature pertaining to prescribing grounded running, particularly in novice runners. Investigating the feasibility of gait-retraining techniques on the adoption of grounded running will provide better understanding of which strategies are effective, and the potential challenges associated with implementing such methods. Until this is addressed, the ideal methods to train new runners or retrain habitual runners to adopt grounded running are unknown. Ascertaining the buy-in of runners in adopting grounded running may also require consideration. This may be easier in new runners who are initiating running for health and fitness benefits, as they may not have developed an internal ‘model’ of running.⁵⁹ Despite this, new runners may still have preconceived notions of what running ‘should’ look like (eg, from viewing other runners) which could reduce buy-in when suggesting a grounded running technique. Similarly, the lack of long-term research on grounded running performance and injury risk may make suggesting this running technique to non-injured, experienced runners challenging due to their existing or current perceptions.

CONCLUSIONS

The biomechanical and metabolic responses to running have been extensively explored to understand running-

related performance and injury risk. However, this information is heavily weighted to aerial running, with minimal information pertaining to grounded running. Despite the limited literature, we know that grounded running is adopted by human runners and characterised by compliant legs, increased duty factor, and a reduced vertical COM displacement—and potentially offers a more stable form of running. Thus, grounded running could serve as a better form of locomotive exercise for those who are new to running, older, heavier or have a reduced loading capacity. Grounded running may provide an activity that is less impactful and strenuous than running, but metabolically more challenging than walking.

Future directions

Further investigations into the mechanics, energetics and epidemiologic data about injuries will be beneficial to understand the potential health and fitness implications of grounded running. Specifically, we recommend:

1. Performing large-scale epidemiological studies to assess the prevalence of grounded running across different populations.
2. Using biomechanical analyses to investigate lower limb loading, muscle energetics, muscle force, joint stress and muscle activation patterns of grounded running.
3. Understanding the long-term effects of adopting a grounded running form on musculoskeletal injury risk and metabolic cost.
4. Determining whether there is a running speed(s) at which grounded running is economically efficient.
5. Undertaking prospective interventions to compare the effects of adopting grounded running over walking and/or aerial running on cardio-metabolic health, weight management and the incidence of running-related injuries in relevant populations.

Twitter Sheeba Davis @davis_sheeba, Aaron Fox @aaron_s_fox and Fiddy Davis @DavisFiddy.

Acknowledgements The authors acknowledge the support of Mr Senne Bonnaerens – Faculty of Medicine and Health Sciences, Ghent University, Belgium for providing the video footage of aerial and grounded running.

Contributors All authors have equally contributed to the manuscript.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests None declared.

Ethics approval Not applicable.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Not applicable.

Open access This is an open access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited, appropriate credit is given, any changes made indicated, and the use is non-commercial. See: <http://creativecommons.org/licenses/by-nc/4.0/>.

ORCID iDs

Sheeba Davis <http://orcid.org/0000-0002-4689-4308>

Aaron Fox <http://orcid.org/0000-0002-5639-6388>

Jason Bonacci <http://orcid.org/0000-0002-4333-3214>

Fiddy Davis <http://orcid.org/0000-0003-3088-4911>

REFERENCES

- 1 World Health Organization. Global recommendations on physical activity for health. 2010. Available <https://www.ncbi.nlm.nih.gov/books/NBK305057/> (accessed 1 Mar 2020)
- 2 Lavie CJ, Lee D, Sui X, *et al*. Effects of running on chronic diseases and cardiovascular and all-cause mortality. *Mayo Clin Proc* 2015;90:1541–52.
- 3 Lee DC, Pate RR, Lavie CJ, *et al*. Leisure-time running reduces all-cause and cardiovascular mortality risk. *J Am Coll Cardiol* 2014;64:472–81.
- 4 Mechelen WV. Running injuries: a review of the epidemiological literature. *Sport Med* 1992;14:320–35.
- 5 Pedisic Z, Shrestha N, Kovalchik S, *et al*. Is running associated with a lower risk of all-cause, cardiovascular and cancer mortality, and is the more the better? A systematic review and meta-analysis. *Br J Sports Med* 2020;54:898–905.
- 6 Geiringer SR. The biomechanics of running. *J Back Musculoskeletal Rehabil* 1995;5:273–9.
- 7 Tongen A, Wunderlich RE. Biomechanics of running and walking. Gallian JA, ed. *Mathematics and sports*. USA: Mathematical Association of America, 2010: 315–28.
- 8 Lopes AD, Hespagnol LC, Yeung SS, *et al*. What are the main running-related musculoskeletal injuries? A systematic review. *Sport Med* 2012;42:891–905.
- 9 Nicola TL, Jewison DJ. The anatomy and biomechanics of running. *Clin Sport Med* 2012;31:187–201.
- 10 Novacheck TF. The biomechanics of running. *Gait Posture* 1998;7:77–95.
- 11 Shorten M, Pisciotto E. Running biomechanics: what did we miss? 35th Conference of the International Society of Biomechanics in Sports (ISBS). ISBS: Cologne, Germany, 2017:34–7.
- 12 Bonnaerens S, Fiers P, Galle S, *et al*. Grounded running reduces musculoskeletal loading. *Med Sci Sports Exerc* 2019;51:708–15.
- 13 Gazendam MGJ, Hof AL. Averaged EMG profiles in jogging and running at different speeds. *Gait Posture* 2007;25:604–14.
- 14 Iwami T, Ogihara N. Biomechanical analysis of human grounded running. The 8th international symposium on adaptive motion of animals and machines. Japan: Dai Owaki Sapporo, 2017:98–9.
- 15 McMahon TA, Valiant G, Frederick EC. Groucho running. *J Appl Physiol* 1987;62:2326–37.
- 16 Gindre C, Lussiana T, Hebert-Losier K, *et al*. Aerial and terrestrial patterns: a novel approach to analyzing human running. *Int J Sports Med* 2015;37:25–9.
- 17 Phillips SJ, Jensen JJ. Kinematics of race walking. 2nd International Symposium on Biomechanics in Sports. USA: Colorado Springs, 1984: 71–80.
- 18 Andrada E, Rode C, Blickhan R. Grounded running in quails: Simulations indicate benefits of observed fixed aperture angle between legs before touch-down. *J Theor Biol* 2013;335:97–107.
- 19 Rubenson J, Heliamis DB, Lloyd DG, *et al*. Gait selection in the ostrich: mechanical and metabolic characteristics of walking and running with and without an aerial phase. *Proc R Soc B Biol Sci* 2004;271:1091–9.
- 20 Blickhan R, Andrada E, Hirasaki E, *et al*. Global dynamics of bipedal macaques during grounded and aerial running. *J Exp Biol* 2018;221:1–12.
- 21 Hancock JA, Stevens NJ, Biknevicius AR. Whole-body mechanics and kinematics of terrestrial locomotion in the elegant-crested tinamou *eudromia elegans*. *Ibis* 2007;149:605–14.
- 22 Bonnaerens S, Fiers P, Galle S, *et al*. Running profiles of recreational distance runners: race, training, spatiotemporal and anthropometrical characteristics. *Footwear Sci* 2019;11:S88.
- 23 Cavagna GA, Legramandi MA, Peyré-Tartaruga LA. Old men running: mechanical work and elastic bounce. *Proc R Soc B Biol Sci* 2008;275:411–8.
- 24 Moore IS, Jones AM, Dixon SJ. Reduced oxygen cost of running is related to alignment of the resultant GRF and leg axis vector: a pilot study. *Scand J Med Sci Sports* 2016;26:809–15.
- 25 Cheung RTH, Wong RYL, Chung TKW, *et al*. Relationship between foot strike pattern, running speed, and footwear condition in recreational distance runners. *Sport Biomech* 2017;16:238–47.
- 26 Breine B, Malcolm P, Frederick EC, *et al*. Relationship between running speed and initial foot contact patterns. *Med Sci Sports Exerc* 2014;46:1595–603.
- 27 Noehren B, Hamill J, Davis I. Prospective evidence for a hip etiology in patellofemoral pain. *Med Sci Sports Exerc* 2013;45:1120–4.
- 28 Louw M, Deary C. The biomechanical variables involved in the aetiology of iliotibial band syndrome in distance runners - a systematic review of the literature. *Phys Ther Sport* 2014;15:64–75.

- 29 Noehren B, Davis I, Hamill J. ASB clinical biomechanics award winner 2006. Prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech* 2007;22:951–6.
- 30 Cavagna GA, Heglund NC, Taylor CR. Mechanical work in terrestrial locomotion: two basic mechanisms for minimizing energy expenditure. *Am J Physiol Regul Integr Comp Physiol* 1977;233:R243–R261.
- 31 Saibene F, Minetti AE. Biomechanical and physiological aspects of legged locomotion in humans. *Eur J Appl Physiol* 2003;88:297–316.
- 32 Kung SM, Fink PW, Legg SJ, et al. What factors determine the preferred gait transition speed in humans? A review of the triggering mechanisms. *Hum Mov Sci* 2018;57:1–12.
- 33 Ahn AN, Furrow E, Biewener AA. Walking and running in the red-legged running frog, *Kassina maculata*. *J Exp Biol* 2004;207:399–410.
- 34 Andrada E, Nyakatura JA, Bergmann F, et al. Adjustments of global and local hindlimb properties during terrestrial locomotion of the common quail (*Coturnix coturnix*). *J Exp Biol* 2013;216:3906–16.
- 35 Moore IS, Ashford KJ, Cross C, et al. Humans optimize ground contact time and leg stiffness to minimize the metabolic cost of running. *Front Sport Act Living* 2019;1:53.
- 36 Lai A, Schache AG, Lin YC, et al. Tendon elastic strain energy in the human ankle plantar-flexors and its role with increased running speed. *J Exp Biol* 2014;217:3159–68.
- 37 Moore IS. Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. *Sport Med* 2016;46:793–807.
- 38 Taunton JE, Ryan MB, Clement DB, et al. A retrospective case-control analysis of 2002 running injuries. *Br J Sports Med* 2002;36:95–101.
- 39 Davis IS, Bowser BJ, Mullineaux DR. Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. *Br J Sports Med* 2016;50:887–92.
- 40 Morin JB, Tomazin K, Edouard P, et al. Changes in running mechanics and spring-mass behavior induced by a mountain ultra-marathon race. *J Biomech* 2011;44:1104–7.
- 41 Thompson MA. Physiological and biomechanical mechanisms of distance specific human running performance. *Integr Comp Biol* 2017;57:293–300.
- 42 Buist I, Bredeweg SW. Higher risk of injury in overweight novice runners. *Br J Sports Med* 2011;45:338.
- 43 Nielsen RO, Buist I, Parner ET, et al. Predictors of running-related injuries among 930 novice runners: a 1-year prospective follow-up study. *Orthop J Sport Med* 2013;1:1–7.
- 44 Nielsen RO, Buist I, Sørensen H, et al. Training errors and running related injuries: a systematic review. *Int J Sports Phys Ther* 2012;7:58–75.
- 45 Vincent HK, Kilgore JE, Chen C, et al. Impact of body mass index on biomechanics of recreational runners. *PM&R* 2020;12:1106–12.
- 46 Osoba MY, Rao AK, Agrawal SK, et al. Balance and gait in the elderly: a contemporary review. *Laryngoscope Invest Otolaryngol* 2019;4:143–53.
- 47 Franz JR, Francis CA, Allen MS, et al. Advanced age brings a greater reliance on visual feedback to maintain balance during walking. *Hum Mov Sci* 2015;40:381–92.
- 48 Bonacci J, Vicenzino B, Spratford W, et al. Take your shoes off to reduce patellofemoral joint stress during running. *Br J Sports Med* 2014;48:425–8.
- 49 Almeida MO, Davis IS, Lopes AD. Biomechanical differences of foot-strike patterns during running: a systematic review with meta-analysis. *J Orthop Sports Phys Ther* 2015;45:738–55.
- 50 Derrick TR. The effects of knee contact angle on impact forces and accelerations. *Med Sci Sports Exerc* 2004;36:832–7.
- 51 Farina KA, Wright AA, Ford KR, et al. Physiological and biomechanical responses to running on lower body positive pressure treadmills in healthy populations. *Sport Med* 2016;47:261–75.
- 52 Chan ZYS, Zhang JH, Au IPH, et al. Gait retraining for the reduction of injury occurrence in novice distance runners: 1-year follow-up of a randomized controlled trial. *Am J Sports Med* 2018;46:388–95.
- 53 Roper JL, Harding EM, Doerfler D, et al. The effects of gait retraining in runners with patellofemoral pain: a randomized trial. *Clin Biomech* 2016;35:14–22.
- 54 Willy RW, Buchenic L, Rogacki K, et al. In-field gait retraining and mobile monitoring to address running biomechanics associated with tibial stress fracture. *Scand J Med Sci Sport* 2016;26:197–205.
- 55 Willy RW, Meardon SA, Schmidt A, et al. Changes in tibiofemoral contact forces during running in response to in-field gait retraining. *J Sports Sci* 2016;34:1602–11.
- 56 Eriksson M, Halvorsen KA, Gullstrand L. Immediate effect of visual and auditory feedback to control the running mechanics of well-trained athletes. *J Sports Sci* 2011;29:253–62.
- 57 Adams D, Pozzi F, Willy RW, et al. Altering cadence or vertical oscillation during running: effects on running related injury factors. *Int J Sports Phys Ther* 2018;13:633–42.
- 58 Copriviza C. The effect of manipulating vertical motion on running economy [Doctoral dissertation], 2019.
- 59 Chapman AR, Vicenzino B, Blanch P, et al. Is running less skilled in triathletes than runners matched for running training history? *Med Sci Sports Exerc* 2008;40:557–65.