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Introduction to running analysis in the clinical setting: A masterclass

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A B S T R A C T

Running is a widely-adopted exercise modality, with relatively low financial barriers to access, and is associated with a host of health benefits. However, with this high participation rate, comes a high risk of running related injury (RRI)—with rates of up to 85 % being reported. There are many drivers of RRI such as training load, genetic and anthropometric factors, with biomechanical factors being an important consideration also. Traditionally, biomechanical gait analysis was only able to be performed in expensive specialised 3D gait laboratories. However, since the introduction of smart devices and apps, 2D gait analysis is now an accessible tool to any musculoskeletal clinician. Despite the high availability of these technologies in practice, there is currently a lack of resources for proper application and training in clinical gait analysis. Therefore, the aim of this masterclass is to provide an easy to understand, and apply guide to 2D biomechanical running analysis and running retraining in routine clinical practice.

Implications for practice:

- Structured biomechanical analysis and running retraining can be used in the management of some RRIs.
- Running retraining advice should often be given in conjunction with training load and exercise rehabilitation advice.
- There is no evidence that prospectively changing an un-injured runner's biomechanics can have an influence on RRI development.
- More research needs to be performed on the links between running kinematics and RRI.

1. Introduction

Running is a popular form of exercise globally, with approximately 176 million people reporting regular participation [1]. Individuals who engage in running come from a broad demographic, spanning age group, location, and level of competitive involvement [2]. Running has a range of health benefits, with large population-based studies suggesting that regular runners display a 30–45 % reduction in all-cause mortality [3]. Additional investigations have noted that running reduces rates of cardiovascular disease (CVD) [4], cancer-related mortality [5], and may offer protective effects against certain neurodegenerative diseases including Alzheimer's and Parkinson's disease [6]. Due to the range of health benefits running offers and its low barrier to entry [3], worldwide participation rates have reportedly grown significantly in the 21st century resulting in a $1.4 billion dollar industry [1].

While offering significant health benefits, studies have indicated a running-related injury (RRI) risk of 7.7–17.8 runners per 1000 h of running [7], with overuse being the major risk factor [8]. Contemporary reviews of RRIs suggest that patellofemoral pain syndrome, medial tibial stress syndrome, plantar fasciitis, iliotibial band syndrome and achilles tendinopathy are the five most common conditions, closely followed by stress fractures, ankle sprains, and quadriceps, patellar and hamstring tendinopathies [9]. Given the prevalence of RRIs in runners, and the potential reduction in RRIs that may come with altering running biomechanics [10], running analysis offers a powerful clinical tool to aid runners and health professionals in managing, and potentially reducing, injury risk.

Common methods of gait assessment include motion analysis systems, force platforms, pressure sensors, electromyography, accelerometers, electrogoniometers and gyroscopes [11]. Of these methods, 3D motion capture is considered the gold standard measurement method [12]. Rapid development in digital video technologies have meant that any person with access to a tablet, mobile phone or digital camera has the capacity to record 2D dynamic footage, removing the necessity of dedicated research labs to measure biomechanical parameters. This technological advancement provides the opportunity for practitioners to

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assess relevant running biomechanics and technique with merely a phone or tablet, a tripod, and a treadmill or open space [13]. While research comparing 2D video capture to the 3D video capture in running gait analysis is scarce, a recent systematic review noted that in 84 % of investigations, 2D video capture reported less than a 5° mean difference when compared to the 3D gold standard [14]. They further reported moderate to excellent intra-rater reliability across the studies explored [14]. With low barriers to entry, uptake on the usage of this technology has been substantial, with approximately 50 % of physical therapists reporting using video-based motion analysis in their practice [15].

Despite this uptake by physical therapists, there is a need for further training and upskilling in gait analysis in clinical practice [16,17]. Given the widespread use of newer, more accessible technologies, and the cost and accessibility challenges associated with 3D gait analysis, this masterclass will focus on the methodology and interpretation of 2D gait analysis that is more readily accessible to the clinician in routine clinical practice. This masterclass provides a guide, underpinned by current evidence, that health professionals can use to upskill and implement clinical running analysis (RA) into everyday practice. We start with an overview of the typical RA consultation and a description of the equipment required. The guide then describes the sagittal and frontal plane analyses pertinent to RA and concludes with description of common RRIs and relevant considerations in RA.

2. The running analysis consultation

Depending on the patient presentation and time constraints, clinicians may opt for a standalone gait analysis consultation, or it may form part of a typical consultation. We recommend the former where possible, particularly if they are a new patient, have a complex history, or it is their first gait analysis consult. The consult should begin with a thorough clinical history. However, the clinician should ask extra questions around the patient's running and training history such as: historic and current training load (running and non-running); RRI history; running shoe history; and how the current complaint relates to running. A thorough musculoskeletal assessment is also imperative, as musculoskeletal and orthopedic testing not only assists with diagnosis and management, but it can also guide the running analysis (Box 1).

2.1. Equipment

There are several options for undertaking a RA, however a relatively simple setup is a treadmill (that has a reasonable amount of speed and incline capacity—16-18 km/h and 8–10 % gradient so that a range of runners can be tested), a tablet or smart phone, and a tripod to mount the tablet or smart phone.

To ensure appropriate image depth and quality, enough space is required to the side of the treadmill to set up the tripod and device to allow a full body view of the runner. A perpendicular perspective is the best angle to assess sagittal plane motion [18]. Remember to also look out for rails or handles of the treadmill which may obscure certain anatomical landmarks (most commonly, the hip). Similarly, when recording behind the runner, set up far enough away to record the full body, and be as square on as possible with the runner centered in the image.

Other equipment considerations may include a large screen or monitor to demonstrate the footage to the patient, rather than using the tablet. Your smart device should have an application (app) capable of performing gait analysis. Commonly used apps used in this context are:

- Dartfish (Dartfish, Switzerland)
- On Form (On Form, USA)
- Silicon Coach (The Tarn Group, New Zealand)

2.2. Anatomical markers

Once the cameras are prepared for gait analysis recording, reflective markers/stickers should be placed on the desired landmarks. Expensive reflective markers are not required, one can simply use reflective/fluorescent stickers, which can be obtained from any office supply store. If focusing on the lateral and posterior views of the running subject, the following bony landmarks should be marked: T7 spinous process; posterior superior iliac spines; greater trochanter; lateral femoral epicondyle; fibular head; lateral malleolus; midpoint of gastrocnemius; superior and inferior portions of the shoe heel; and, styloid process of the fifth metatarsal [18,19].

Participants can either wear running shorts, or full-length tights on their lower limbs, while if comfortable, women can wear a sports bra, and men can remove all garments from their torso. It is also important to note that accurate palpation of landmarks and placement of markers can take approximately 10 min or more, so make sure this is factored into the consultation time [19–21].

2.3. Running and footage capture

An important consideration is consent to capture the footage for the purpose of the RA. The patient/client should be made aware of the video that is being captured, and how it will be stored (i.e. with the patients' clinical record) and used. We also suggest that the video avoids capturing the participant's face (where possible). Once the patient/client has consented, a 6-min treadmill acclimatisation run should be performed at the runner's preferred running speed [22]. Once the treadmill acclimatisation has been performed, 30 s of footage should be collected in the sagittal plane and at least 30 s in the frontal plane [19]. As most standard treadmills have the rails to the front, footage can be collected from lateral and posterior views. The footage should be collected at a sample rate of 120 frames per second (FPS) or higher. Depending on the clinic lighting, a strong external light source (i.e. flood light) to ensure that the running footage and joint markers can be adequately viewed as a higher frame rate requires better lighting. The clarity of the image, when the recording is paused, will depend on the right set up and attention to detail here.

2.4. Joint angle measurements

Once the video footage has been collected, the following joint angles

Box 1
Key history questions for running analysis consultations

- Running history and historical and detailed current training load
- RRI history
- Detailed history of current RRI(s)
- Running shoe history/current shoe(s)
- Other interventions/prevention strategies
- Psychosocial history

can be evaluated in one of the apps (or similar) described above. Tables 1, 2 and Figs. 1-9, describe which angles should be measured and at which point in the gait cycle (here we recommend that you play the video frame by frame to allow you to pause the motion at the exact point in time; for example, instant of initial ground contact) [18,19].

2.5. Cadence measurement

As cadence can be a driver in the development of RRI [23], it is also important to evaluate it when performing clinical running analysis. Many smart watches can give you an almost instantaneous cadence rate (in steps per minute). However, if these devices are not available, or if you wish to check the reliability of the device, you can calculate cadence as the number of foot contacts per minute [23].

2.6. Advice and running modifications

Once the initial desired joint angles and cadence measurements have been calculated, you can then provide feedback to the patient about their running style, which is best done through a mixture of video and verbal feedback. If you want the runner to implement kinematic or cadence changes, explain why you think the changes need to be made, what benefit they may receive from making that change and then give them the appropriate cues/advice to do so. Be sure to repeat the RA at subsequent visits using the same process, to check if the runner is making the desired changes—this is where a side by side before and after view on the analysis app can be helpful also.

In our experience the most common running variables that can be modified include: over-striding and low cadence; excessive trunk lean; excessive knee extension on impact; and, foot strike pattern extremes (i.e. excessive ankle dorsi flexion on impact). There are a multitude of verbal cues that can be given to the patient that can assist in making the desired kinematic changes - cues such as 'run lighter and quieter,' 'run with shorter, quicker steps,' 'bring your knee higher as you swing through,' and 'try to land on the middle of your foot (or with a flat foot)' are commonly used, however, these are very patient specific. Further examples of running cues can be found in references [24,25].

Once the consultation is finished, we suggest you provide the patient with a report on what you have found, and what (if anything) you want them to change, ideally, with either pictures, or video, so that they can better understand your advice. Whatever app you use should help you download images and create a report, even if this means incorporating the images into a Word document or similar. The report creation should take anywhere from 15 to 60 min, depending on experience and the complexity of the analysis/report.

Follow-up time is again patient and condition specific, but initially we suggest a follow-up gait analysis appointment (within around 1 week) to check how the proposed changes are impacting performance or pain, and to provide any further feedback you deem necessary (and to ensure that the changes are not creating new issues). This should involve the same process as the original analysis but may be truncated/modified depending on the runner. Proposed gait changes should also be combined with any rehabilitation or strength and conditioning exercises, and training load advice.

Table 1
Posterior view angles.

Figure Number and Angle	Gait Phase	How to assess angle/position
1 - Contralateral Pelvic Drop	Mid-Stance	Angle of lines between the two PSIS markers relative to a horizontal line
2 - Hip Adduction	Mid-Stance	Angle of a line intersecting the greater trochanter and lateral femoral condyle relative to a horizontal line
3 - Heel Eversion	Mid-Stance	Angle of the intersection of a line between the two heel markers, and a line running from the top heel maker and calf marker
4 - Stance Width	Mid-Stance	Distance between the vertical midline (using the T7 marker) and the bottom heel marker

Fig. 1. Contralateral Pelvic Drop – Mid-Stance; Angle of lines between the two PSIS markers relative to a horizontal line.

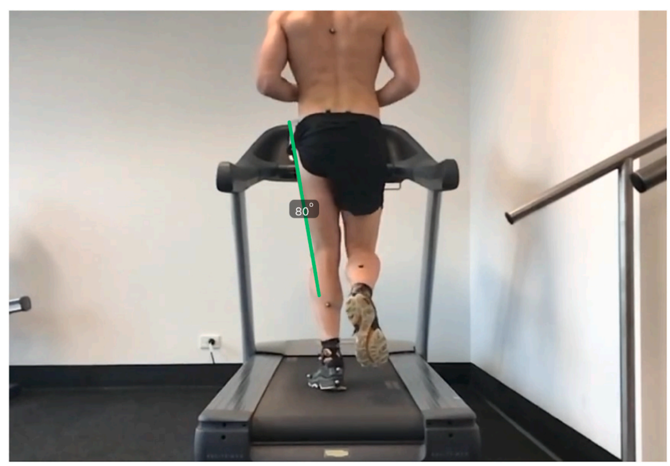

Fig. 2. Hip Adduction Angle – Mid-Stance; Angle of a line intersecting the greater trochanter and lateral femoral condyle relative to a horizontal line.

3. Condition-specific clinical gait analysis interpretation and management

3.1. Patellofemoral pain (PFP)

PFP is characterised by either retro patella pain, or pain around the patella, and is typically provoked by any activities that increase load on the patellofemoral joint (i.e. running, stairs, squatting) [26]. Despite the prevalence of PFP, the underpinning pain-causing mechanisms are unclear [26]. Furthermore, PFP is the most common RRI experienced in recreational athletes [27], with an annual incidence of 22.7 % in the general population [28]. There are many risk factors associated with PFP including: muscle strength and endurance; anthropometric and demographic factors; and psychosocial factors. Running biomechanics can also play a part in the development of PFP [29]. Specifically, there is

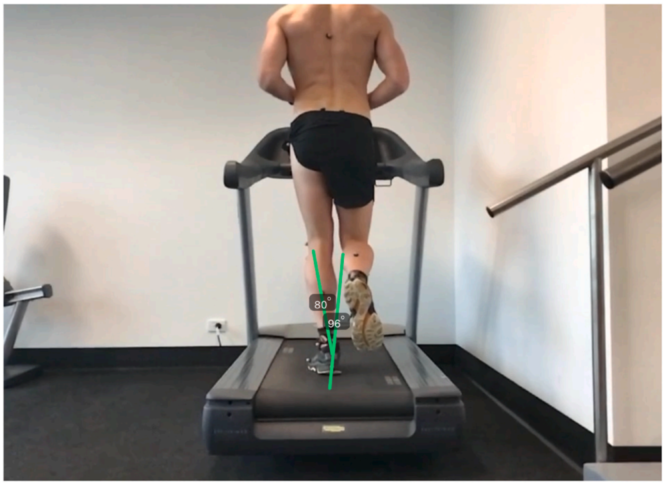

Fig. 3. Heel Eversion – Mid-Stance; Angle of the intersection of a line between the two heel markers, and a line running from the top heel maker and calf marker.

Fig. 4. Stance Width – Mid-Stance; Distance between the vertical midline (using the T7 marker) and the bottom heel marker.

Table 2
Lateral view angles.

Figure number and angle	Gait Phase	How to assess angle/position
5 a-b - Trunk Lean	Initial contact and mid-stance	Angle of line through mid-torso, intersecting the greater trochanter marker
6 - Hip Extension	Toe-off	Line between greater trochanter and lateral femoral condyle relative to a vertical line
7 - Knee flexion	Initial contact, mid-stance and toe off	Angle between femur (greater trochanter and lateral femoral condyle markers) and tibia (fibular head and lateral malleolus markers)
8 - Ankle Dorsi-flexion	Initial contact	Angle between fibula (fibula head and lateral malleolus) and line through styloid process marker
9 - Foot strike type (mid, fore, rear)	Initial contact	Angle between bottom of shoe and treadmill. Identify whether forefoot, midfoot, or rearfoot contacts the treadmill first

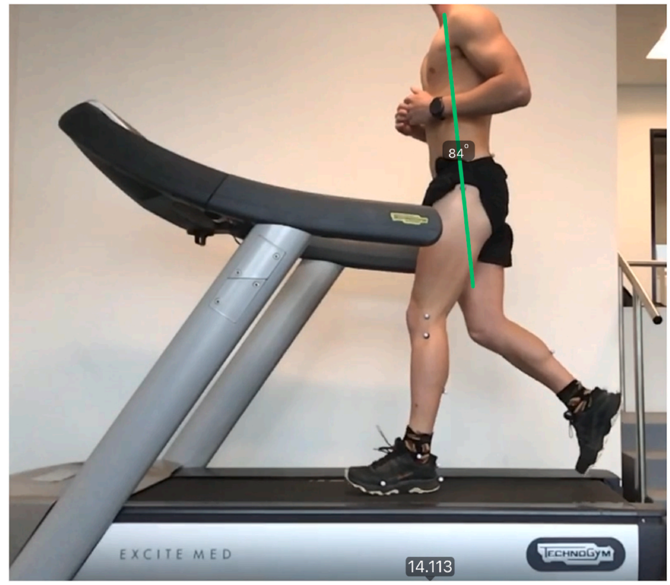

Fig. 5a. Trunk Lean – Initial Contact; Angle of line through mid-torso, intersecting the greater trochanter marker.

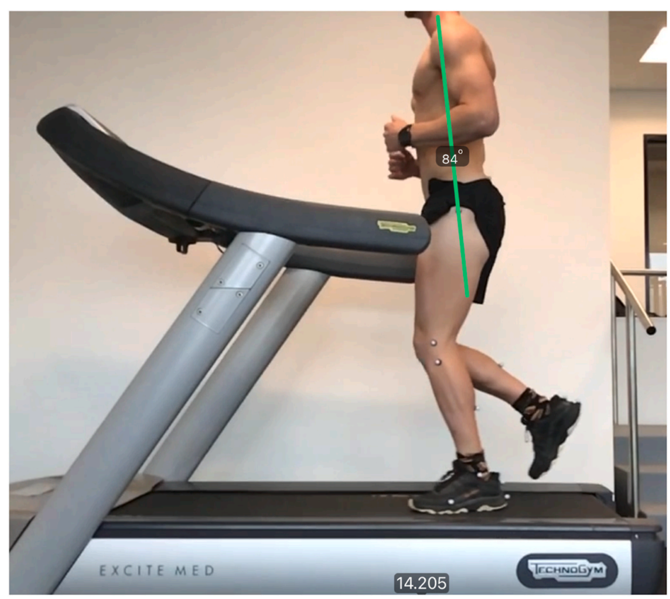

Fig. 5b. Trunk Lean – Mid-stance; Angle of torso relative to a vertical line.

evidence to suggest that increased peak hip adduction, internal rotation and contralateral pelvic drop are associated with PFP [30].

Researchers have evaluated the application of increased running cadence to manage PFP. One study asked their participants to increase their cadence by 10 %. In conjunction with wearing minimalist shoes, the cohort demonstrated a significant improvement in symptoms after a 6-week running program [31]. Similarly, another study used a 10 % increase in cadence (without shoe change), with the participants demonstrating a decrease in PFP pain and favorable change in running kinematics (contralateral pelvic drop and hip adduction), at the 3-month follow up, despite only undergoing one running retraining session and independently tracking their increased cadence rate through the study period [23]. Taken together, these findings suggest that in conjunction with other management strategies (exercise rehabilitation and pain education), increasing cadence by 10 % (and a commensurate decrease in stride length) in runners with PFP may help in the management of the

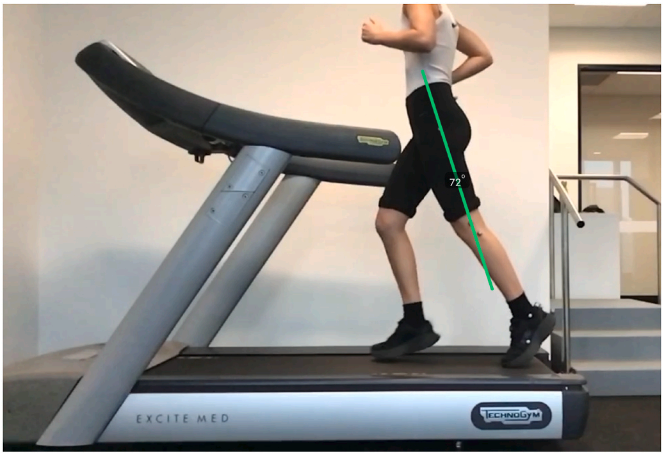

Fig. 6. Hip Extension – Toe-off; Line between greater trochanter and lateral femoral condyle relative to a vertical line.

Fig. 7a. Knee Flexion – Initial Contact; Angle between femur (greater trochanter and lateral femoral condyle markers) and tibia (fibular head and lateral malleolus markers).

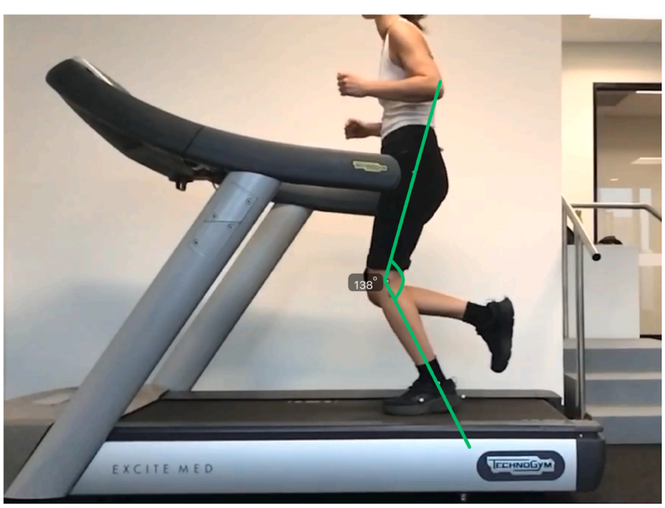

Fig. 7b. Knee Flexion – Mid-stance; Angle between femur (greater trochanter and lateral femoral condyle markers) and tibia (fibular head and lateral malleolus markers).

Fig. 7c. Knee Flexion – Toe-off; Angle between femur (greater trochanter and lateral femoral condyle markers) and tibia (fibular head and lateral malleolus markers).

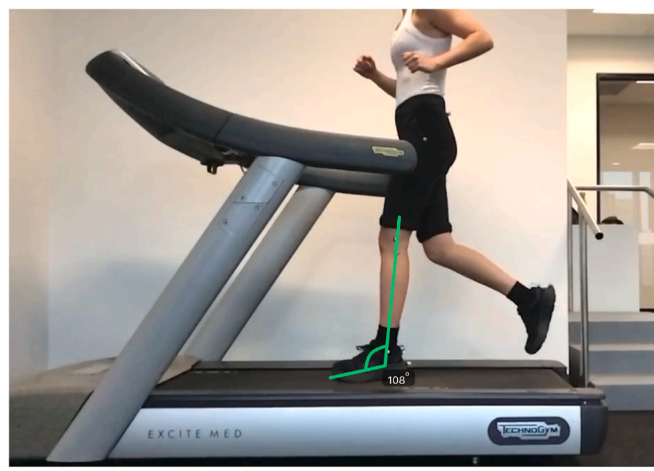

Fig. 8. Ankle Dorsi-Flexion – Initial Stance; Angle between fibula (fibula head and lateral malleolus) and line through styloid process marker.

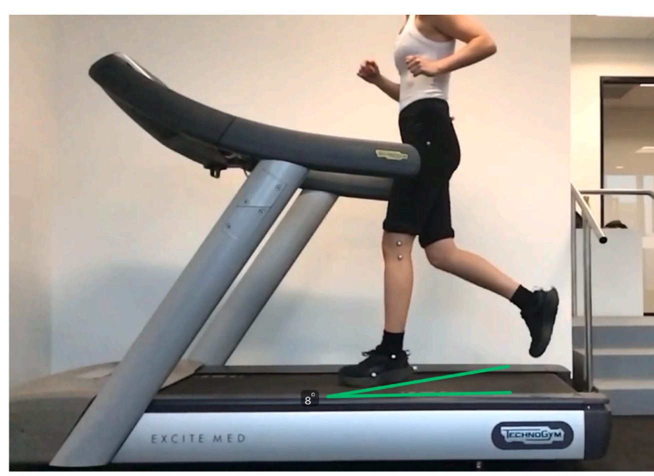

Fig. 9. Foot strike Pattern – Initial contact; Angle between bottom of shoe and treadmill. Identify whether forefoot, midfoot, or rearfoot contacts the treadmill first.

condition.

3.2. Iliotibial band syndrome (ITBS)

Iliotibial band syndrome (ITBS) is characterised by lateral knee pain around the area of the lateral femoral condyle [32], and is the second most common RRI, accounting for approximately 10 % of all RRIs [27]. There are multiple theories about the aetiology of ITBS including friction of the ITB against the lateral femoral condyle, irritation of the ITB bursa and compression of the ITB fat pad, however the true mechanisms are not known [33]. There are multiple risk factors associated with ITBS, including: anatomical variables (leg length and lateral epicondyle prominence); limited flexibility; muscle strength levels; and, training load [32].

Running biomechanics also appears to play a role in the development of ITBS [32–34]. Specifically, peak hip adduction and peak knee internal rotation during stance phase appears to have some relationship with ITBS, however, this has only been found in female runners, and does not appear to correlate in a mixed-sex population of runners [32,34]. Although there is limited evidence concerning running retraining in ITBS, it may be the case that again, by increasing running cadence by approximately 10 %, the associated decrease in peak hip adduction this causes [23,35], may have an impact on the kinematic risk factors associated with ITBS.

3.3. Achilles tendinopathy (AT)

Achilles tendinopathy (AT) affects a wide-spectrum of individuals—from elite athletes to sedentary people with multimorbidity [36]. AT is a clinical diagnosis with its hallmarks being morning stiffness and localized pain at the achilles, as well as difficulties with activities that load the achilles, for example, running and hopping [37]. There are many risk factors associated with AT, including prior injury, diet, plantar muscle strength, and medication use, in addition to multiple biomechanical factors [36,37]. Specifically, the biomechanical alterations that can occur in AT include increased hip adduction and external rotation impulse, greater lateral plantar pressure (when running), and shorter gluteus medius activation time [36,37]. However, it is not clear if making biomechanical alterations will lead to an improvement in AT clinical outcomes [37].

Research has also investigated the impact of foot strike pattern on achilles tendon load. Although there has been no definitive link made between AT and foot strike pattern, evidence suggests runners who adopt a forefoot strike pattern increase the magnitude of load on the achilles tendon [38,39]. Therefore, it may be the case that in forefoot strikers with AT, a short-medium term management strategy may be adopting a more midfoot or rearfoot strike pattern [24]. Instruction to change to a more forefoot or midfoot strike during running should be made with caution, as the increased load on the achilles tendon could possibly predispose a runner to developing AT.

3.4. Exertional leg pain

The diagnosis of chronic exertional compartment syndrome (CECS) dates back to 1956 [40], and is said to mostly affect young active runners, elite athletes, and those involved in the military [41]. The majority of CECS cases (95 %) occur in the anterior and lateral compartments of the leg [41]. The leading mechanistic theory is said to be from poor fascial compliance which can lead to high subfascial and/or intramuscular pressures causing decreased blood flow to the working muscles leading to hypoxia and the subsequent experience of local muscle hypoxia [41,42]. Despite the widespread use of CECS as a diagnosis, there remains a great deal unknown about its onset—namely, the inconsistencies in diagnostic intracompartmental pressure testing and the high number of failed fasciotomies [40,43].

More recently, research has started to evaluate possible kinematic causes of anterior exertional shin pain. This has involved a reconceptualization from CECS to local muscular overload, and hence termed anterior biomechanical overload syndrome (ABOS) [40,42]. The clinical reasoning behind this suggests that with excessive ankle dorsi flexion at foot strike (exemplified clinically by an excessive heel strike and/or excessive stride length), the anterior compartment muscles of the leg become overloaded and fatigued, hence causing the CECS-like symptoms in the anterior compartment [40,42].

Researchers have investigated how changing running kinematics can change the symptoms of anterior compartment biomechanical overload syndrome. Specifically, the intervention cued runners to increase hip flexion, increase cadence by 5–10 %, maintain an upright torso, and achieve a midfoot strike. These strategies have been shown to allow approximately 70 % of runners with ABOS to run pain free [42].

3.5. Limitations and clinical implications

Although there is some evidence describing kinematic risk factors for specific RRIs, caution must be taken when intervening with these clinically. Much of the limited evidence presented, and conditions studied, have not been evaluated using randomized controlled trials, and therefore more research is needed to better explore the links between kinematics and RRIs. A runner's kinematics are only one piece of the 'puzzle,' when it comes to the development of RRIs. There is a myriad of variables such as training load, recovery, anatomical variables and psychosocial general health status, amongst others, that a clinician has to take into account when treating an injured runner [44]. Therefore, kinematic RA should be viewed as part of the clinician's toolkit when managing RRIs, rather than being a stand-alone 'silver bullet'.

Clinicians should appreciate that there is no current evidence for a 'perfect' or 'one-size-fits-all' running style that can be applied to the population at large [24,34]. Rather, each runner should be evaluated individually, and a management plan, including any potential changes in kinematics should be bespoke for them, and be guided by sound clinical reasoning and patient preferences [24]. Additionally, there is no good evidence for supporting kinematic changes in un-injured runners, and it is our recommendation that the running retraining advice synthesized here should largely be applied to injured runners only [34,45]. Additionally, it is important to acknowledge the accuracy limitations of 2D clinical running analysis [14], with results being interpreted through this lens. If fine adjustments, or a more detailed analysis is required (i.e. in an elite performance setting), then 3D lab-based running analysis should be utilised. Despite this, given its low cost and accessibility, along with its acceptable accuracy and repeatability, 2D analysis is suitable for many runners in a routine clinical setting [14,46].

Finally, although there are many RRIs that have not been evaluated kinematically at all, it may be the case that some of the previous running retraining interventions mentioned (i.e. 10 % increase in cadence, without a change in speed but with a change to shorter stride length) may assist in their management but should be guided by strong clinical reasoning.

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Nicholas Tripodi: Conceptualization, Project administration, Methodology, Resources, Writing – original draft, Writing – review & editing. **Jack Feehan:** Resources, Writing – original draft, Writing – review & editing. **Daniel Corcoran:** Resources, Writing – original draft, Writing – review & editing. **Brett Vaughan:** Resources, Writing – original draft, Writing – review & editing. **Patrick McLaughlin:** Resources, Writing – original draft, Writing – review & editing.

Ethical approval

Not applicable.

Declaration of competing interest

The authors declare there are no conflicts of interest.

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