



Individual Musculoskeletal Characteristics of Runners and Advanced Footwear Technology

Sebastian Stattin

GYMNASTIK- OCH IDROTTSHÖGSKOLAN

Master's Degree Project 47:2022

Sports Science 2019–2022

Supervisor: Toni Arndt

Co-Supervisor: Johanna Rosén

Examinor: Magnus Lindwall

Abstract

Background: In recent years, sudden improvements in long-distance running performance have been suggested to be due to the latest technological innovations in running footwear. However, inter-individual differences appear to be large in the performance enhancing effect these shoes elicit where some runners experience a decline in performance while others improve substantially. The reason for this is not yet fully understood but may be due to differences in anthropometric and neuromuscular characteristics between runners.

Aim: The aim of this thesis was to investigate the association between individual anthropometrical and neuromuscular characteristics of runners with changes in running mechanics while wearing these new generation shoes.

Method: Eight male endurance runners performed four different testing protocols during one single visit. These consisted of an anthropometrical protocol where measurements of height, weight, leg length and Achilles tendon moment arm length were determined; a jumping protocol where vertical stiffness and eccentric utilization ratio (EUR) were recorded using a force platform; a running protocol where contact time, step length, ankle propulsive power and knee absorption power were measured using a force platform and a 12-camera motion analysis system; and finally a force-velocity protocol where each participant performed calf raises and back squats with incremental loads in a smith machine while barbell velocity was simultaneously recorded. The collected data were then statistically analyzed using Wilcoxon Signed-Rank Test and Spearman's Rank Correlation Coefficient.

Results: Greater peak power in the back squat was associated with a greater reduction in peak knee absorption power ($r = -0,905$, $p = 0,005$) and less vertical stiffness during jumping was associated with longer step lengths with the advanced footwear technology (AFT) shoes ($r = -0,738$, $p = 0,046$). No associations were found between vertical stiffness during jumping and contact time, EUR with step length and contact time, peak power in the calf raise and Achilles tendon moment arm with peak ankle propulsive power.

Conclusion: Runners with less vertical stiffness in the lower limb during jumping exhibited greater step length increase with AFT shoes. This may be due to the spring-like behavior the shoes possess. However, the larger step length increases the demands on lower limb strength and runners with less power in the lower limb may increase their knee absorption power during ground contact, leading to potentially less efficient running mechanics. Those with greater power in the lower limb may, on the other hand, run more efficiently by decreasing their knee absorption power leading to less muscular effort.

Sammanfattning

Bakgrund: De senaste årens förbättringar inom långdistanslöpning har föreslagits bero på de teknologiska framstegen som gjorts inom löparskokonstruktion. Det verkar emellertid finnas en skillnad i den prestationshöjande effekt som dessa skor framkallar, där vissa löpare upplever en försämring medan andra förbättras avsevärt. Orsaken till detta är fortsatt okänt men kan ha att göra med skillnader i antropometriska och neuromuskulära egenskaper mellan löpare.

Syfte: Syftet med denna uppsats var att undersöka sambandet mellan individuella antropometriska och neuromuskulära egenskaper hos löpare med förändringar i löpmekanik som dessa nya generationens skor framkallar.

Metod: Åtta manliga långdistanslöpare utförde fyra olika testprotokoll under ett enda besök. Dessa bestod av ett antropometriskt protokoll där längd, vikt, benlängd och momentarmslängd av Akillessenan mättes; ett hoppprotokoll där vertikal styvhet och EUR registrerades med hjälp av en kraftplatta; ett löpprotokoll där kontakttid, steglängd, fotledskraft och knäledskraft mättes med hjälp av kraftplattor och ett rörelseanalyssystem med 12 kameror; och slutligen ett kraft-hastighetsprotokoll där varje deltagare utförde tåhävningar och knäböj med stigande belastning i en smith-maskin medan skivstångshastighet samtidigt registrerades. Den insamlade data analyserades därefter med Wilcoxon Signed-Rank Test och Spearman's Rank Correlation Coefficient.

Resultat: Högre peak power i benböj var associerat med en större minskning av maximal knäabsorptions power ($r = -0,905$, $p = 0,005$) och mindre vertikal styvhet under vertikalthopp var associerad med längre steglängd med AFT-skorna ($r = -0,738$, $p = 0,046$). Inget samband hittades mellan vertikal styvhet under vertikalthopp och kontakttid, EUR med steglängd och kontakttid, maximal power i tåhävningar och hälsens momentarm med maximal propulsionspower i fotleden.

Konklusion: Löpare med mindre vertikal styvhet i de nedre extremiteten under vertikalthopp uppvisade större steglängdsökning med AFT-skor. Detta kan bero på det fjäderliknande beteende skorna har. Den längre steglängden ökar dock kraven på styrkan i den nedre extremiteten och löpare med mindre kraft, har potentiell ökad knäabsorptions power under markkontakt vilket kan resultera i en mindre effektiv löpmekanik. De med bättre kraftutveckling i de nedre extremiteten kan däremot potentiellt springa mer effektivt med dessa nya generationens skor genom en minskning i knäabsorptions power vilket i sin tur leder till mindre muskulär ansträngning.

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Appendix 1: Literature Review

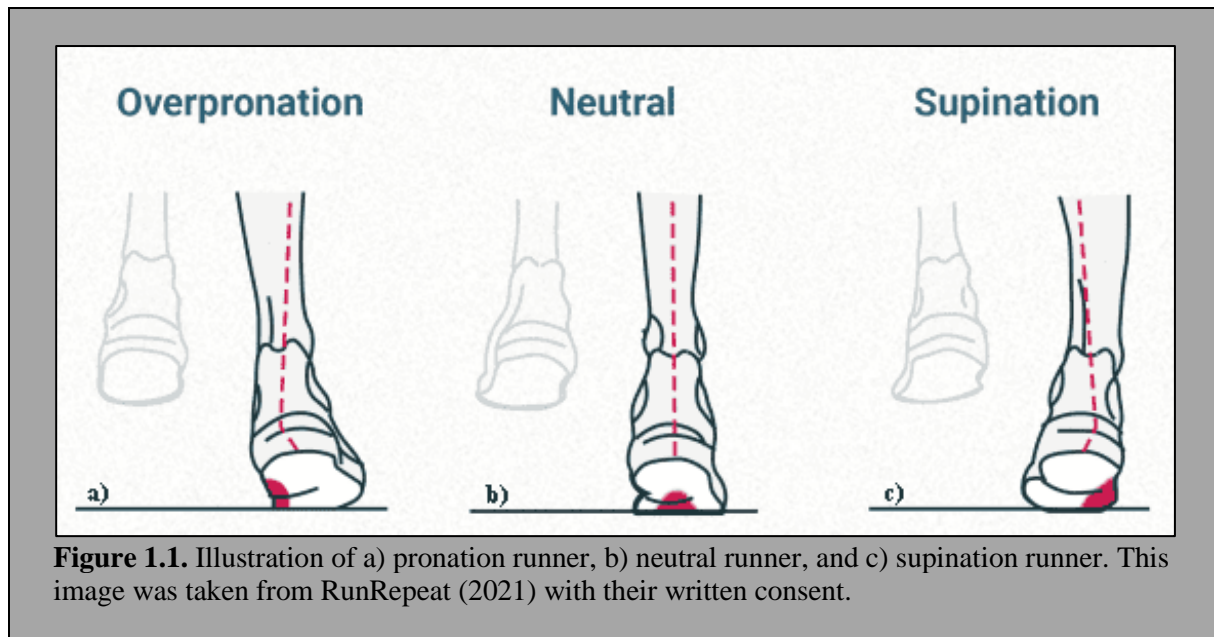
1 Background

Running remains one of the most performed recreational activities worldwide and has grown in popularity the last couple of years. In the United States alone almost 18 million individuals participated in US sanctioned running events in 2019 (Running USA, 2019), while recent data from the UK suggest that 10% of the adult population engage in running-related activities (Active Lives Survey, 2021). Coinciding with this, elite running performances and seasonal best times have seen substantial improvements during the last five years in long-distance running events such as 5 km, 10 km, half marathons, and marathons (Bermon et al., 2021; Senefeld et al., 2021). A large proportion of these improvements have occurred after 2018 and with many national and world records set since then. In 2019, during a special unofficial event in Vienna, the Kenyan athlete Eliud Kipchoge was the first human to run the marathon distance under 2 hours, completing it in 1:59:40 (hours:minutes:seconds) (INEOS, 2019). A strong contributing factor to this ground-breaking achievement, and many other performances and records, is believed to stem from the new advanced footwear technology (AFT) (Muniz-Pardos et al., 2021).

1.1 The History of Running Shoes: A Brief Introduction

For most of our existence, humans have either been walking or running barefoot. During the Upper Paleolithic era there seems to have been a paradigm shift with archeological records suggesting that protective footwear was started being used, at least in parts of Europe (Trinkaus & Shang, 2008). The first direct evidence of footwear, however, was in the form of sandals recovered in Fort Rock, Oregon, USA, dating back 10 000 years (Connolly & Cannon, 1999). With a flat sole made from sagebrush bark and a strap between the toes, the sandals were easy to make and protected the plantar surfaces of the feet from various elements. From the Chalcolithic era, more sophisticated types of footwear were being crafted. One of the oldest leather shoes, called Areni-1, was found in almost perfect condition in Armenia and dates back to 5 500 BC (Pinhasi et al., 2010). These were made from cowhide and lined with grass, wool or straw and were tied around the foot with a string. Since then, shoes have undergone a lot of changes, but it wasn't until the beginning of the 19th century that the athletic shoe started emerging. In 1832, Wait Webster invented the first rubber sole, which provided greater durability and replaced the older wooden outsole (Knapik et al., 2015). At the end of the 19th century, shoe soles made from vulcanized rubber were

introduced. This allowed for more flexible soles which were later used in the creation of the first pair of sneakers, launched in 1916, called the “Keds” (Vanderbilt & Sjögren, 2001). In the 1890’s, one of the earliest spiked running shoes started being sold commercially by the manufacturing company J.W. Foster and Sons (later Reebok) and in 1926 Adolf Dassler and his brother Rudolf (the founders of Adidas and Puma, respectively) took the spikes a step further when they introduced a variety of spiked running shoes that were tailored for certain running events. These were made famous by Jesse Owens who used a pair of customized shoes in the 1936 Olympic Games in Berlin. The evolution continued in the second half of the 20th century, when the founder of ASICS, Kihachiro Onitsuka, released the first pair of cushioned running shoes called Onitsuka Tiger (Vanderbilt & Sjögren, 2001). Later, in the 1970’s, Nike released the Nike Tailwind which was the first shoe to incorporate air-cushioned soles (Nike Air). These soles were constructed with tiny air bags that were meant to soften the impact upon landing. The shoe was a commercial success and grew in popularity after Nike released an advertisement in the 1979 October issue of the Runner’s World stating that researchers from University of Tennessee had shown that athletes who ran with the Nike Tailwind shoe consumed 2,8 % less energy compared to other conventional running shoes (Runners World, 2018). A year later, however, the article was withdrawn due to claims of bias during the testing of the shoes (Vanderbilt & Sjögren, 2001). In 1975, Brooks released the first pair of running shoes who utilized ethylene vinyl acetate (EVA) in the midsole foam which were lighter than the previous rubber material used and provided better cushioning and shock absorption. Later in 1977 they released the Vantage shoe which had a wedge inside it to reduce overpronation (Brooks, 2021; Knapik et al., 2015). This marked a trend that continued into the ‘80s and well into the 00’s where running shoe design wasn’t merely based upon the type of running, but also what running style the runner had. These were differentiated into three styles: neutral runners, supination runners and pronation runners (Fig 1.1). The idea was that by tailoring the shoe after the runner, the likelihood of injury would be reduced. For instance, runners with a low midfoot arch were presumed to be at higher risk for overpronation and therefore at higher risk of injury. These runners were usually recommended “motion control” shoes as they were advertised as being able to control excessive motion.



The notion of certain injury preventing running shoes was, however, disrupted in 2004 with the emergence of minimalist shoes. It started with the release of Nike Free, and later in 2005 with the Vibram FiveFingers shoes which aimed to reproduce barefoot running while still providing protection for the plantar surface of the foot (Knapik et al., 2015). These were usually constructed with a flexible upper and heel counter, eliminated arch support and a markedly reduced midsole thickness and heel-to-toe drop. The revolution gained further traction in 2009 after the release of the book “Born to Run” by Chris McDougall. In the book, McDougall argued that the use of minimalist footwear or barefoot running were better options in reducing the likelihood of running injuries compared to other running footwear, which he claims have not shown any empirical evidence of injury reduction despite the technological advancements made over the years (McDougall & Nilsson, 2012). This was based on observations of the Tarahumara Indians who did not appear to suffer from running injuries despite covering long running distances without the aid of modern footwear. During this time, Hoka broke the trend of minimalist shoes with the release of their flagship maximalist shoe, the Hoka One One (Baron, 2020; Megroz, 2013). These shoes were lightweight and, in contrast to the minimalist shoes, had a thick and highly cushioned foam. Since then, the trend has turned to performance, with the latest breakthrough belonging to Nike with the launch of their AFT shoe, the Vaporfly.

1.2 Running Shoes

1.2.1 Technological Evolution or Technological Doping?

The sudden improvements in running performance have been suggested to be related to the latest innovations in running footwear (Joyner et al., 2020). Since 2017, the top 20 and top 100 elite runners' seasonal bests in 10km, half-marathon and marathon have decreased significantly, and a contributing factor seems to be the adoption of AFT (Bermon et al., 2021). Similarly, an improvement of 2,8 and 4,3 minutes were shown for the top 50 elite marathon males and females respectively, while wearing running shoes with AFT (Senefeld et al., 2021). Recreational runners also seem to reap the rewards induced by these shoes. In 2018, the *New York Times* published an analysis in conjunction with Strava in which they concluded that runners across different ranges of running ability, performed better with AFT shoes compared to their habitual running shoes while running half-marathon and marathon (New York Times, 2018). In addition, the probability of breaking a personal record increased by 73-75%. In laboratory settings, several studies have found that the energetic cost of running is reduced by 4 % while wearing AFT shoes among elite and recreational male runners compared to more traditional shoes (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019; Hébert-Losier et al., 2022). The magnitudes of these improvements are akin to the performance enhancing effect of various blood doping substances (Durussel et al., 2013; Haile et al., 2019). However, recent research seems to suggest there is a difference between different AFT shoes with some performing better than others (Joubert & Jones, 2022). Furthermore, inter-individual differences seem to be large while running in AFT shoes, ranging from -9,6 % to a 13,3 % increase in metabolic savings (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019; Hébert-Losier et al., 2022)

Inevitably, these results have sparked a debate whether these new advancements in technology may provide some with an unfair advantage over others, while also raising the question about whether this should be classified as technological doping (Dyer, 2020). Furthermore, the use of AFT shoes seems to contradict World Athletics' (WA) technical rule 5.2 which states the following: "*Athletes may compete barefoot or with footwear on one foot or both feet. The purpose of shoes for competition is to give protection and stability to the feet and a firm grip on the ground. They must not give athletes any unfair assistance or advantage...*" (World Athletic, 2020a). In the late 00's, swimming faced a similar dilemma when polyurethane material was introduced in the swimsuits, which culminated in the 2009 World Championship in Rome with 43 new world records (Morales et al., 2019). This

eventually led to a rule change by FINA (the governing body) from 1 January 2010 which banned the use of this material and only authorized certain models for men and woman. Given similar concerns in running, WA announced in January 2020 a rule change in technical specifications regarding running shoes which limited stack height to 40 mm and the use of a single carbon-fiber plate (World Athletic, 2020b). This was in accordance with a paper released in 2019 (Burns & Tam, 2020), which has been disputed by some for not resolving the issue (Frederick, 2020; Hoogkamer, 2020). The reason for this is that it presupposes that the stack height and the carbon-fiber plate are the main reasons for the increase in performance.

1.2.2 Advanced Footwear Technology

The mechanism behind the performance enhancing effect that the AFT shoe elicits is not yet fully understood but is probably due to a combination of various features which makes them stand out from more traditional shoes. The features suggested to be responsible are 1) a stiff plate embedded in the midsole, 2) the midsole foam, 3) shoe mass, 4) stack height and 5) the geometry of the sole. In the following sections, each of these features will be discussed as well as the potential mechanisms of action on running mechanics.

1.2.2.1 Longitudinal Bending Stiffness

The use of a stiff carbon fiber plate or grid in running shoes is not a new phenomenon. Although widely used in sprinting shoes, it is not until recently that it has become popular in long-distance shoes. By increasing the longitudinal bending stiffness (LBS), the embedded stiff plate has shown to potentially reduce the energetic cost of running (Roy & Stefanyshyn, 2006). The reason for this could be because the increased LBS stiffens the metatarsalphalangeal (MTP) joint, limiting dorsiflexion and reducing the energy lost at the joint (Cigoja et al., 2019; Hoogkamer et al., 2019; Willwacher et al., 2013). The MTP joint has been observed to be an important location for energy cost during running (Sun et al., 2020). Another potential source of influence is around the ankle joint. With increased bending stiffness, the point of force application could potentially move more anteriorly, thereby increasing the moment arm to the ankle joint (Oh & Park, 2017; Willwacher et al., 2016; Willwacher et al., 2014). This would increase the ankle joint moment provided that the ground reaction force (GRF) stays the same. During running, the point of force application moves considerably resulting in an external moment arm under constant change. Meanwhile, the internal moment arm to plantar flexor muscles undergoes much less alteration. This refers

to the gear ratio which is the ratio between external and internal moment arms (Carrier et al., 1994). Gear ratio is considered to be a parameter in walking and running that affects efficiency and load regulation. For instance, increasing the gearing ratio by increasing the external moment arm has been found to reduce angular velocity at the joint and the muscle fascicle shortening velocity (Cigoja et al., 2021; Madden et al., 2016; Takahashi et al., 2016). This has also been observed in runners with shorter Achilles tendon moment arms where, given a certain angular velocity, a shorter moment arm permits a slower shortening velocity of the muscle fascicles (Nagano & Komura, 2003). The reduction in shortening velocity of the muscle fascicles is accompanied with an increase in force potential, referring to the optimization the force-velocity potential (Hill, 1938), resulting in less metabolic demand (Fletcher et al., 2013). Due to the substantial contribution of the triceps surae muscle to the energetic cost of running (Fletcher & MacIntosh, 2015), an increase in force potential of the muscle would allow it to work more economically, potentially reducing the metabolic cost overall (Fletcher & MacIntosh, 2018).

Finally, the curvature of the plate may also play a role in the performance enhancing effect seen with increased LBS. Recently, it has been theorized that the curved plate (typically seen in the most prominent AFT shoes) creates a so called “teeter-totter” effect (Nigg et al., 2021). This proposes that during the second half of the stance phase, while the resultant GRF is displaced anteriorly towards the front of the curved plate, it produces a reaction force at the heel in a direction that is perpendicular to the plate. The additional force on the heel may then increase the propulsion during take-off, potentially improving running economy by up to 6 %. However, this has yet to be confirmed as it is based on unpublished simulated data.

1.2.2.2 Midsole Foam

The new generation of shoes also contains a thick, lightweight, compliant and resilient midsole foam. This is usually made of thermoplastic rubber, for instance polyamide block elastomer (PEBA) (Burns & Tam, 2020). The primary role of the foam is to cushion impact and return mechanical energy stored during ground contact (Sun et al., 2020). These factors depend on the compliance and resilience of the foam. Compliance is the amount of deformation that the material goes through while potential energy is stored under load, while resilience is the fraction of mechanical energy returned. Naturally, some of the energy returned will dissipate as heat, as with all materials with viscoelastic properties (Shorten, 1993), but the new types of material used in the foam have been shown to be very effective in

minimizing this loss. In comparison with other foam materials, PEBA has been shown to return 87% of the potential energy stored while also being more compliant (Hoogkamer et al., 2018). These two in combination may greatly improve the performance enhancing effect the shoes possess. As early as the 1980's, research has shown that a more compliant and resilient foam can improve performance, which has also been confirmed in later studies (Black et al., 2022; Worobets et al., 2014). This may be due to the higher mechanical energy returned from the foam.

The ability to efficiently store and return energy has been considered an important trait in runners (Barnes & Kilding, 2015, Novacheck, 1998). To explain this, the spring-mass model is frequently used where the leg is described to behave like a linear spring, loaded by the runner's weight during initial ground contact (Dalleau et al., 1998). During this time, elastic potential energy is transmitted from the body's muscles, joints, tendons, and ligaments and then subsequently returned during propulsion (Yin et al., 2020). This spring-like mechanism is characterised by its stiffness which is based on Hooke's law which states that the force required to compress or extend a linear spring with a constant stiffness, is proportional to the deformation it goes through (A. Freedman & D. Young, 2015). In running, vertical stiffness is a proxy often used to reflect this ability with previous studies showing that greater vertical stiffness in runners leads to more economical running (Barnes et al., 2014, Dalleau et al., 1998). This enhanced storage and return of elastic energy that greater stiffness may facilitate, improves the stretch-shortening cycles (SSC) during running and subsequent performance (Brazier et al., 2019). Vertical stiffness is calculated by dividing peak vertical GRF with maximal vertical displacement of centre of mass (COM) (Morin et al., 2005). Another often used proxy for SSC in various sports are eccentric utilization ratio (EUR). This is described as the ratio between the countermovement jump (CMJ) and squat jump (SJ) performance where an ideal EUR is suggested to be circa 1,1 (McGuigan et al., 2006). With the new soles more energy efficient, the muscles are required to perform less work in order to aid the tendons absorbing and returning energy, leading to a reduction in the rate of oxygen demand (Shorten, 1993). Runners with poorer SSC ability or lower vertical stiffness may therefore benefit more with these AFT shoes due to the spring-like behaviour the midsole foam possess.

Finally, the performance enhancing effect can also be due to the alteration in leg stiffness induced by the compliant material. While running on surfaces of different degrees of stiffness, humans usually adapt by modifying leg stiffness to reduce impact forces. For instance, while running on a more compliant surface such as natural grass, humans tend to

increase leg stiffness compared to harder surfaces where a decrease in leg stiffness usually occurs (Ferris et al., 1998). Runners typically increase leg stiffness by reducing knee flexion which in turn reduces knee extensor moment resulting in an improved mechanical advantage of the muscles around the joint (Biewener, 1989). This reduces the required muscle force of the knee extensor muscles and thus metabolic demand (Kipp et al., 2018). Leg stiffness, compared to vertical stiffness, is calculated by multiplying the GRF vector acting through the leg with maximal leg compression. This has earlier been found to have a strong correlation with vertical stiffness during jumping (Rogers et al., 2017).

1.2.2.3 Shoe Mass and Stack Height

Another advantage that these new generation of foams provides is its low density. By being made from material with lower density, the shoes weight will decrease which has previously been shown to reduce the energetic cost of running by 1% per 100g of mass removed (Franz et al., 2012; Hoogkamer et al., 2016). The likely reason for this is the reduced moment of inertia of the leg during swing phase (Barnes & Kilding, 2015). Furthermore, the low density material also facilitates a thicker foam without adding any significant mass. The thicker midsole would allow for more deformation to occur within the shoe which would increase the energy stored in the foam (Nigg et al., 2020). This would also increase the time spent on the ground as thicker midsoles need more time to deform (Chambon et al., 2014). With increased contact time, less metabolically expensive muscle fibres need to be recruited and shortening velocity will decrease which would benefit performance (Kram & Taylor, 1990; Roberts et al., 1998). Another possible explanation could be the increase in effective leg length of the runner. Previous research has found that longer legs are advantageous for running performance (Mooses et al., 2015; Sleivert & Rowlands, 1996), although the underlying mechanism for this is not yet clear (Lucia et al., 2006). One would think that because longer legs contribute to greater moment of inertia, the cost of moving the legs during swing phase would be greater, but it doesn't appear to be any consensus on whether this increase is of any significance or not when it comes to running performance (Saunders et al., 2004). However, the explanation for the improvement in performance could be due to an increase in step length. By increasing the step length, the number of steps for a given distance is reduced and less energy is spent accelerating the leg compared to an increase in frequency. This has been found to be more efficient (Mooses et al., 2015) and would therefore be more beneficial for running performance. In addition, runners who experience a greater artificial increase in leg length due to thicker midsoles may see larger improvements in running performance (Pontzer,

2007; Steudel-Numbers et al., 2007). With a stack height above 30 mm, the new generation of shoes may be more beneficial for those with shorter legs.

1.2.2.4 Sole Geometry

Finally, the geometry of the sole could also play a role in the performance enhancing effect. Virtually all new running shoes with AFT have an outsole with a concave shape. This could potentially make the transition from foot-strike to toe-off much smoother while also orienting the GRF more anteriorly during toe-off, taken that the anterior part of the sole aids in the sole rebound sufficiently (Nigg et al., 2020). Furthermore, changes in running mechanics induced by the rocker-like bottom could also be of importance. Previously, several studies have shown significant changes in ankle biomechanics with rocker shoes. For instance, both ankle joint moment and work have been seen to be reduced (Boyer & Andriacchi, 2009; Sobhani et al., 2013; Sobhani et al., 2017) and may be related to changes in terminal stance. In more traditional shoes, the point of GRF application is usually located at the MTP joint, while in rocker shoes a proximal shift is seen where the force application is applied at the apex of the rocker bottom (Sobhani et al., 2015). This shift in force application reduces the moment arm and therefore ankle joint moment. While these changes in ankle biomechanics have in some studies been accompanied with changes in knee kinematics such as peak knee extension moment and net work (Sobhani et al., 2017), others have found no significant difference (Boyer & Andriacchi, 2009; Sobhani et al., 2013; Sobhani et al., 2015).

1.2.3 Effect on Running Mechanics

Numerous studies have previously shown the effect of running footwear on running mechanics (Sun et al., 2020). However, many of these have used custom shoes with specific characteristics (e.g., modified stack height, weight or midsole bending stiffness), while few have specifically looked at AFT shoes. Most of the research that has studied AFT shoes has looked at gross biomechanical measures such as stride length and ground contact time (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert & Jones, 2022). These have shown conflicting results with increased (Hoogkamer et al., 2018; Joubert & Jones, 2022), decreased (Barnes & Kilding, 2019) or no difference (Hoogkamer et al., 2019; Hunter et al., 2019) in ground contact time, greater (Hunter et al., 2019) or no difference (Joubert & Jones, 2022) in center of mass vertical oscillation and greater (Hoogkamer et al., 2019) or no difference (Hunter et al., 2019) in vertical impulse. The reason

for this could be because of difference in methodology, but also because of individual difference in running mechanics and/or individual characteristics. Step length and aerial time seems to be the only consistent gross biomechanical variables in the literature which have been found to increase with AFT shoes (Barnes & Kilding, 2019; Hoogkamer et al., 2019; Hunter et al., 2019; Joubert & Jones, 2022), suggesting a “bouncier” step.

While there appear to be some inconsistencies in these gross biomechanical variables, their significance in terms of performance seems to be small as it only explains 20 % of the variance on energetic savings (Hoogkamer et al., 2018). Kinematic and kinetic data may provide further information. To date, only one study has explored this in detail (Hoogkamer et al., 2019). They found no difference in hip and knee kinematics and kinetics but some changes in the ankle and MTP joint. Peak ankle dorsiflexion moment and negative and positive joint work were smaller with AFT shoes, while joint angular velocity was slower during stance. This would imply less metabolic demand on the plantar flexor muscles by reducing the force required to propel forward and decreasing muscle shortening velocity (Kipp et al., 2018; Kram & Taylor, 1990). As for the MTP joint, smaller peak joint dorsiflexion and slower velocity were observed resulting in less negative joint work. Although these changes in kinematics and kinetics could possibly explain some of the performance enhancing effect further, these analyses were done on a group level meaning that individual differences would be hard to observe. Furthermore, differences in individual characteristics were not accounted for which could explain the discrepancy seen between participants.

1.2.4 Individual Characteristics and AFT shoes

Despite observed changes in running performance and mechanics, no research has to our knowledge examined individual differences in anthropometry and neuromuscular characteristics that might explain the discrepancy seen between runners with AFT shoes. Few studies have investigated the effect that specific aspects of AFT have on the muscle-tendon unit (MTU). For instance, increased LBS has been found to decrease the shortening velocity of the gastrocnemius muscle. This may be due to increased contact time as no observational changes in ankle joint moment occurred (Cigoja et al., 2021). The increased contact time would decrease the rate of force generation of the muscle which would therefore reduce the metabolic demand (Kram & Taylor, 1990). Furthermore, increased LBS has also been shown to induce greater energy return from the Achilles tendon (Cigoja et al., 2021), while more

compliant foams could potentially increase the stretch of the tendon (Esposito et al., 2022) and therefore store more energy (Fletcher & MacIntosh, 2015). Runners who exhibit greater energy storage capacity in the Achilles tendon (e.g., increased tendon stiffness) have been shown to perform better (Arampatzis et al., 2006; Kovács et al., 2020). If indeed these changes elicited by the features seen in the new generation shoes can explain the performance enhancing effect, it would make sense that differences between individuals would elicit different outcomes.

1.3 Research Aims and Hypotheses

The aim of this thesis was to investigate the association between individual anthropometrical and neuromuscular characteristics of runners with changes in mechanics while running in AFT shoes. The hypotheses were:

- H₁: Runners with less power in the lower limb will have a greater reduction in knee absorption power with AFT shoes than those with more power
- H₂: Individuals with lower power production ability in the plantar flexor muscles will reduce their ankle propulsive power more with AFT shoes compared to non-AFT shoes than those with higher power production
- H₃: A shorter Achilles tendon moment arm will be more strongly positively correlated with ankle propulsive power changes with AFT shoes compared to non-AFT shoes
- H₄: There will be a significant negative association between vertical stiffness during jumping and step length as well as contact time with AFT shoes compared to non-AFT shoes
- H₅: EUR will be significantly negatively associated with step length and contact time with AFT shoes compared to non-AFT shoes
- H₆: Individuals with greater relative leg length increase due to the AFT shoes will increase their step length and contact time

2 Methodology

2.1 Study Design

This thesis is an experimental cross-sectional study with within-subject design.

2.2 Participants

Eight male endurance runners (age $34,1 \pm 9,1$, height $182,5 \text{ cm} \pm 6,5$, bodyweight $72,7 \text{ kg} \pm 9,3$) were recruited to the study through local running clubs, social media, and personal contacts. Inclusion criteria were: (i) age between 18 and 50, (ii) training volume of at least 30 km per week, (iii) 10-km sub-38-min personal best and (iv) fitting in an EU men's size 42, 43 or 45,5 shoe. Participants were excluded from the study if they had sustained any hip, knee, or foot injury during the past six months. One of the initially recruited participants dropped out of the study due to a lower leg injury sustained before the trial had commenced. Further descriptive data can be found in table 2.1.

Table 2.1. Descriptive participant data (mean \pm standard deviation)

PB 10km [min:sec]	Running/week [h]	Total Volume/week [h]	Days/week
$34:40 \pm 3:15$	$7,3 \pm 2,4$	$9,9 \pm 2,8$	$6,3 \pm 0,8$

PB = personal best

2.3 Ethical Considerations

Due to this study being a master thesis, no ethical approval was required (The Ethical Review Act, 2003:460). However, ethical rules were taken into consideration, and the study was conducted in accordance with the code of the Helsinki Declaration (2013). Prior to participating, written consent was obtained from each participant after being informed both orally and in writing about the purpose of the study. In addition, they were informed about the possibility of withdrawing their participation in the study at any time without being required to state a reason. Following the written consent, each participant completed a health questionnaire to ensure their general well-being. During the trials, each participant was given the opportunity to extend their warm-up if required. All data collected during the trials were coded to allow for anonymization.

2.4 Shoe Conditions

Participants wore two different running shoes: one pair with AFT and one without. These were selected in a randomized order for each participant before each running trial. The selection of running shoes was based on previously performed mechanical tests on energy return characteristics conducted by a research group at KTH. The AFT shoe was selected as it displayed the greatest mechanical energy return, while the non-AFT shoe was selected based

on features seen in more traditional running shoes and their lack of performance during the mechanical testing. Due to the data not yet being publicly available, the shoes were anonymized. Descriptive data of energy return characteristics can be found in table 2.2.

Table 2.2. Shoe characteristics data. Thickness 12% from the heel, Forefoot compression, Rearfoot compression, and Tensile bending stiffness described in relative energy return.

Shoe	Thickness 12% [mm]	Weight [g]	Plate	FRF Comp RER [%]	RF Comp RER [%]	TBS RER [%]
AFT	37	214	Yes	83,9	82	77,6
Non-AFT	28	286	No	63,7	65,4	64,1

FRF = Forefoot, RF = Rearfoot, TBS = Tensile bending stiffness, Comp = Compression, RER = Relative energy return

2.5 Experimental Set-up and Protocol

This study took place at the *Swedish Sports Confederation's Laboratory for Performance Development* at Bosön, Sweden, and comprised of four testing protocols. These were anthropometrics, jumping, running and force-velocity protocols and all were performed during a single visit.

2.5.1 Anthropometric Protocol

The anthropometrical measurements were conducted at the beginning of each session, immediately after the participants had completed the health declaration form. Height (cm) was measured with a standard height rod to the nearest 0,1 cm while body weight (kg) was measured using a force plate with a sampling frequency of 1600 Hz (Kistler Instruments AG, Winterthur, Switzerland). The output from the force plate data was divided by the gravitational constant of $9,81 \text{ m/s}^2$ to obtain the participants' body weight in kg. While in a supine position with a fully extended knee, leg length was measured with a tape measure from the most prominent part of the greater trochanter to the midpoint of the lateral malleolus (Fig. 2.1). The Achilles tendon moment arm was estimated using a modified version of a previously validated method by Scholz et al. (2008). By definition, the distance between the joint axis of the ankle and the shortest line of action to the Achilles tendon can be described as its moment arm. In standing, the horizontal distance between the lateral and medial malleolus and posterior part of the Achilles tendon were measured using a tape measurement (Fig. 2.2). The mean distance from these two measurements were then divided by two and defined as the moment arm of the Achilles tendon.



Figure 2.1. Leg length as measured from the greater trochanter (far left) to the lateral malleoli (far right)



Figure 2.2. Achilles tendon moment arm measured from the apex of the malleoli to the posterior part of the Achilles tendon, perpendicular to the malleoli.

2.5.2 Jumping Protocol

Following the anthropometrical protocol and prior to the jumping protocol, each participant performed a 5-minute running warm-up trial around a 200 m indoor track wearing their own shoes. The participant then completed ten warm-up jumps three times, followed by three maximal vertical jumps with a 1-minute rest in-between. For the ten warm-up jumps, each participant was instructed to jump with as little knee flexion as possible while also minimizing ground contact time. After the warm-up, three different types of vertical jumps were performed on a force plate (Kistler Instruments AG, Winterthur, Switzerland) three times each with a 2-minute rest in-between. These were in the following order: squat jump (SJ), countermovement jump (CMJ) and stiffness jumps. For each type of jump, the participant was instructed to hold their hands at their hips at all times. During the SJ, the participant assumed a squat position of 90° knee flexion and were then told to hold this position isometrically until the test leader told them to jump as high as possible. The trial was discarded if the participant made any countermovement during the propulsive phase, which was screened both visually and through force-time data. For the CMJ, the participant was told to stand upright, then squat to a self-selected depth before directly initiating a maximal vertical jump. Lastly, the stiffness jumps consisted of five continuously performed jumps where the participant was instructed to minimize ground contact time while also aiming to jump for maximum height with as little knee flexion as possible during ground contact.

2.5.3 Running Protocol

After completing the jumping protocol, 43 reflective markers were placed on different anatomical landmarks of the pelvis and legs using double-sided adhesive tape (Fig 2.3). These were attached bilaterally on the ASIS, PSIS, proximal 1/3 of the sacrum, proximal to the apex of the iliac crest laterally, the medial and lateral femoral condyles as well as the medial and lateral malleoli. For the thigh and shank, a cluster of four markers on a plastic plate were used secured with an elastic band and tape. Finally, six markers were attached on each shoe located at the posterior heel, metatarsal joint I and V, lateral cuneiform and dorsal tip of digiti pedis I and IV. The markers on the medial femoral condyles and malleolus were removed after a static calibration trial due to the increased likelihood of them falling off and disturbing the participants during their run. Before the running trials, each participant completed a set of warm-up trials to allow familiarization with the new shoes. The participants only performed 2 to 5 warm-up trials as it has previously been observed that runners quickly adapt their running mechanics in response to changes in running surface (Ferris et al., 1999). Following this, the participants ran across a 15-meter runway embedded with two force plates (Kistler Instruments AG, Winterthur, Switzerland) at a speed of 15 km/h while simultaneously being recorded with a 12-camera three-dimensional motion capture system with a sampling frequency of 200 Hz (Oqus4, Qualisys AB, Gothenburg, Sweden) (Fig. 2.4). The acquired movement data from the marker positions were then synchronized with the GRF-data using the motion analysis software (Qualisys Track Manager, Qualisys AB). Two pairs of timing gates (Smartspeed Pro, Fusion Sport, Coopers Plains, Australia) were placed 5 meters apart and used to monitor running speed with a 5 % acceptable variance. Furthermore, a trial was deemed successful if the participant landed with his right or left foot completely on one of the force plates. The running trials continued until three successful attempts per leg were recorded in each shoe condition.

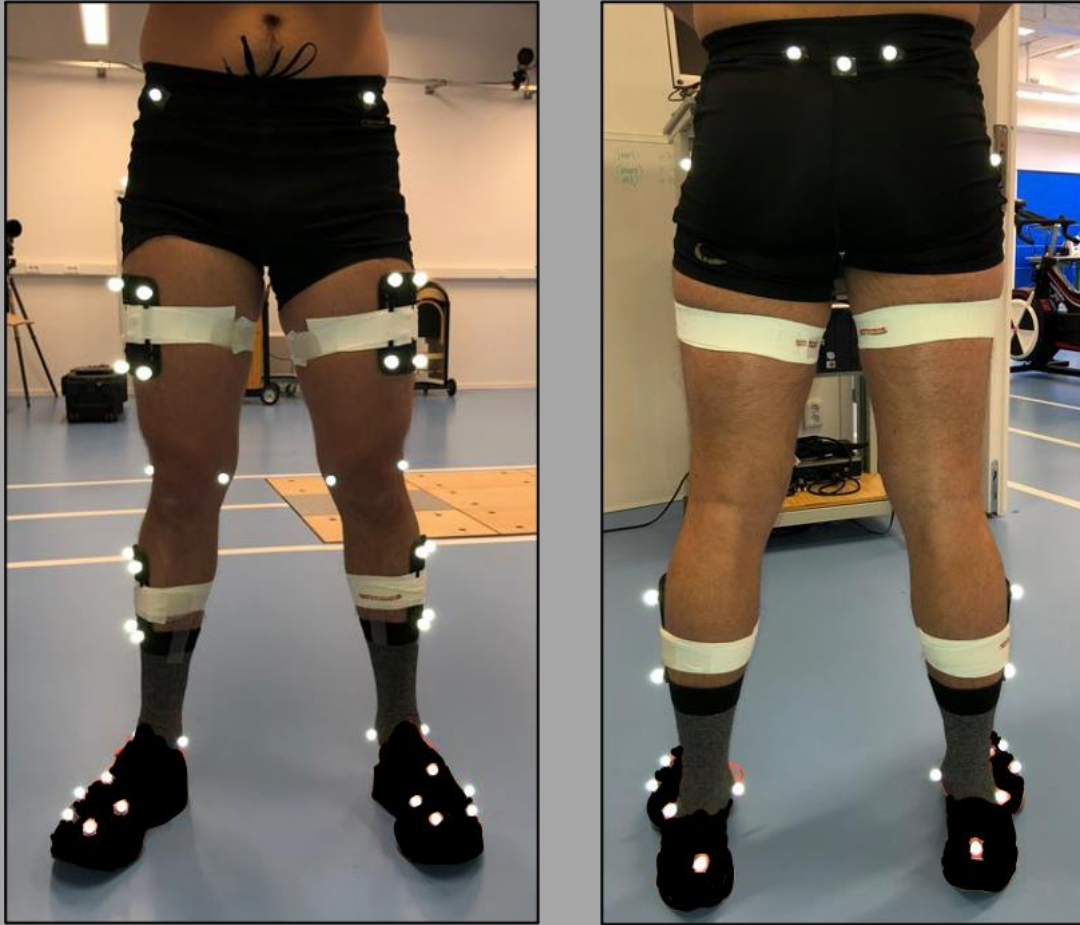


Figure 2.3. Placement of the reflective markers depicted **a)** anteriorly and **b)** posteriorly. This picture was taken during the pilot and the pilot participant used his own personal running shoes.

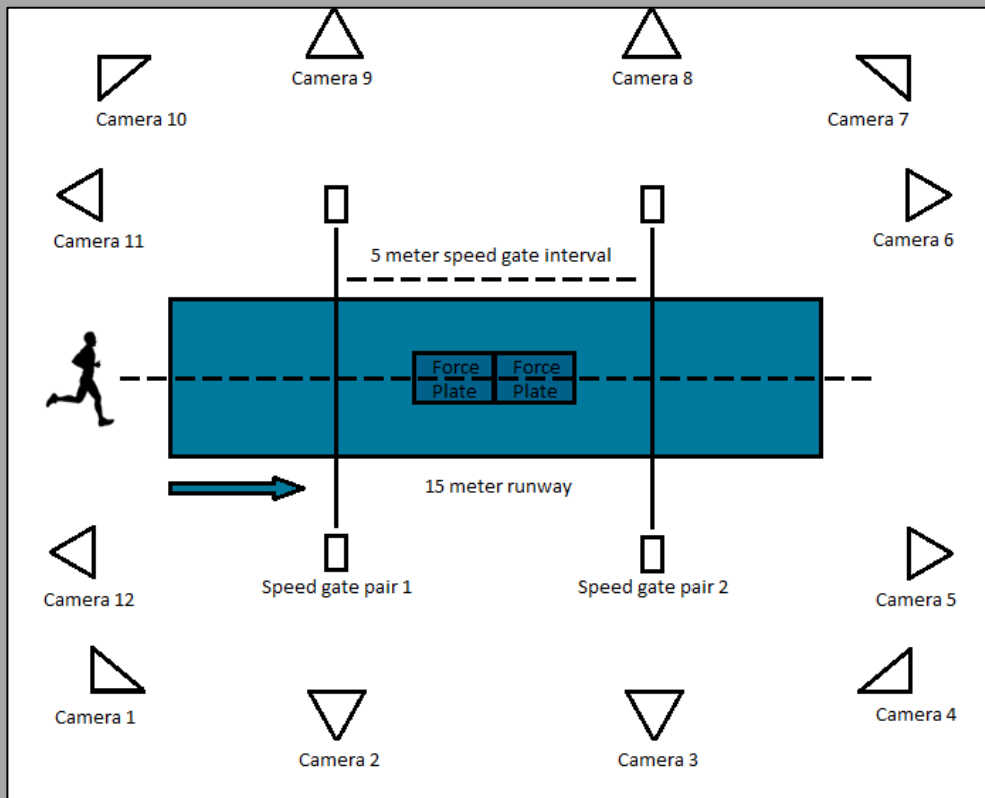


Figure 2.4. Running protocol set-up with a runway of 15 meters, two force plates, two pairs of timing gates and a 12-camera motion capture system.

2.5.4 Force-velocity Protocol

The final protocol completed during the testing session was the force-velocity (F-v) protocol which consisted of calf-raises and back squats. The F-v session was performed in a smith machine with a standardized warm-up of 10 repetitions with the unloaded barbell for each exercise before commencing the trial. Thereafter, all participants completed three repetitions of each exercise at four different loads (30, 50, 70 and 90 % of bodyweight). If the last load was deemed too heavy by the participant, the final repetition was instead reduced to 80 %. The interval between the loads were chosen based on the likelihood of observing differences in velocity with each increase (Jidovtseff et al., 2011). Each set was followed by 2-minutes rest. For the calf-raises, the participants were instructed to raise their heels to maximum height as fast as possible after a signal from the test leader. To ensure they reached maximum height before descending and not bouncing during ground contact, each participant was asked to descend and commence on a signal from the test leader, which took less than 1 second. After completing four sets of three repetitions of calf-raises, back squats were initiated. Before the warm-up, a stop pad was placed at a depth that the thighs were approximately

parallel to the floor to ensure that no countermovement was performed, and that the participant started from the same depth for each trial. The participant was then instructed to descend to the stop pad before performing a concentric squat as fast as possible without lifting the heels. As for the calf-raises, a signal was given from the test leader before commencing the next repetition. The concentric sections of the trials were measured with a linear position transducer (LPT) (GymAware PowerTool, Kinetic Performance Technologies, Canberra, Australia) which measures vertical barbell displacement and has previously been validated for barbell velocity (Banyard et al., 2017). The floor unit of the LPT was positioned on the floor to the far right of the participant while the tether was attached on the barbell vertically from the floor unit using a Velcro strap. The data from the LPT device were then transmitted through Bluetooth to a tablet (iPad; Apple, Inc., Cupertino, CA, USA) and then further analyzed.

2.6 Data Analysis

For the jumping protocol, GRF data were exported to a computational software (Matlab, MathWorks Inc, Natick, MA, USA) for further processing. Using Newton's second law of motion, velocity was calculated during the propulsion phase for the SJ and CMJ by numerically integrating the GRF-time data:

$$V_Y(t) = \int_{t_0}^{tn} \frac{F_Y(t) - mg}{m} dt \quad (1)$$

where F_Y is the GRF, m is body mass and g are the gravitational acceleration constant of $9.81 \text{ m} \times \text{s}^{-1}$. Vertical power was then estimated using the following equation:

$$P_Y = F_Y \times V_Y \quad (2)$$

The peak power ratio between the CMJ and SJ (based on the mean of all three trials) was then used to estimate EUR.

The stiffness jumps were used to measure lower-limb vertical stiffness. For this, we calculated vertical displacement of center of mass (COM) on the last three stiffness jumps during each trial by numerically double-integrating the GRF-data:

$$\Delta COM(t) = \iint_{t_0}^{tn} \frac{F_Y(t) - mg}{g} dt dt \quad (3)$$

From the initial value, the following equation was derived and used in the second integration:

$$V_0 = -\frac{gt_a}{2} \quad (4)$$

where t_a is aerial time. Vertical stiffness was then estimated using the following equation:

$$k_{vert} = \frac{RF_{peak}}{\Delta COM} \quad (5)$$

where RF_{peak} is relative peak force due to stiffness being influenced by body mass (Farley et al., 1993). Force data for both the CMJ and the SJ data as well as for the stiffness jumps were filtered with a fourth order Butterworth low-pass filter with a cut-off frequency of 10 Hz.

For the running protocol, data was collected in Qualisys Track Manager (Qualisys AB, Gothenburg, Sweden). Each marker was labelled after the label list below (fig 2.5) and then either manually added or gap-filled in case a marker disconnected or disappeared during the recording. The data was then exported to Visual 3D (C-Motion, Germantown, USA). The marker data was filtered using a low-pass Butterworth filter with a cutoff frequency of 15 Hz. The stance phase was normalized to percent body weight. To determine touchdown and take-off, a threshold of 5% of body weight based on the GRF data was used. In addition, all trials were controlled visually for any incorrect touchdowns or take-offs after the threshold had been implemented. Knee and ankle joint power were then calculated through Visual 3D using inverse dynamics, ground contact time by calculating the time between touchdown and take-off, and step length by calculating the distance between instances of peak downward velocity of the pelvis. This method has previously been validated to estimate touchdowns regardless of foot-strike type using kinematic data (Milner & Paquette, 2015).

Finally for the F-V protocol velocity and acceleration were calculated from the first and second derivatives of the barbell displacement and force was determined by multiplying the acceleration data with system mass (body weight and external load). Power was then calculated as in Eq 2. Lastly, rate of force development (RFD) was calculated and defined as the steepest part of the force-time curve.

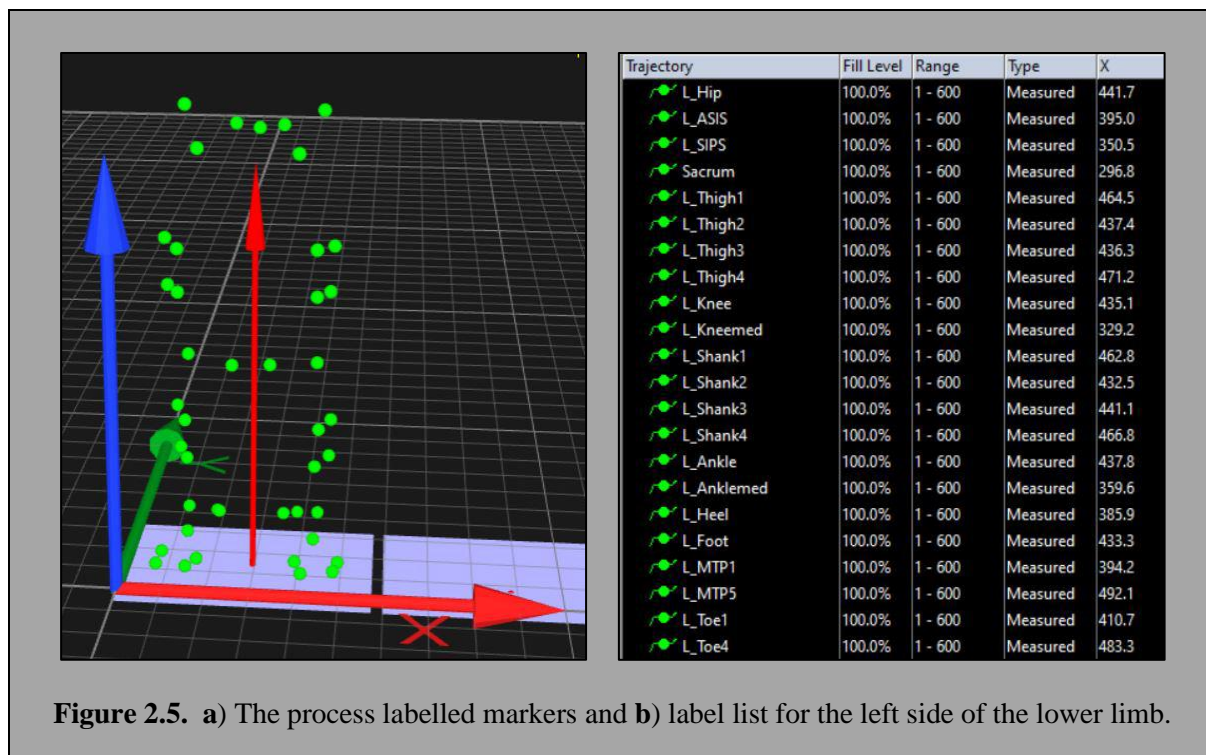


Figure 2.5. a) The process labelled markers and b) label list for the left side of the lower limb.

2.7 Statistics

Descriptive statistics were calculated for each variable of interest and are presented as median and interquartile range (IQR). The assumption of normality for each variable previously mentioned was assessed by performing a Shapiro-Wilk test, assessment of skewness and kurtosis, and visual inspection of histograms. As none of the variables met the criteria for normal distribution, non-parametrical statistics were applied. For the biomechanical differences between the shoes, the Wilcoxon Signed-Rank Test was used, while correlations were analyzed using the Spearman's Rank Correlation Coefficient. This was conducted by using the difference in the biomechanical variable between the shoes as the dependent variable and either the anthropometrical or neuromuscular variable as the independent variable. The biomechanical difference was calculated by subtracting the value of the non-AFT shoe from the value of the AFT shoe. The following interpretation of the Spearman's Rank Correlation coefficient was used: < 0,3 was poor association, 0,3 - 0,5 fair association, 0,6 - 0,7 moderate association, 0,8 - 0,9 very strong association (Akoglu, 2018). The level of significance was set at $p \leq 0,05$. All statistical analyzes were performed with SPSS Statistics version 28.0.1.1 (IBM Corp., Armonk, NY, USA).

3 Results

3.1 Biomechanical Differences

There were no significant differences between the AFT and non-AFT shoes for any of the biomechanical variables. The median and p-values showed a tendency for differences, although not significant, in ground contact time and ankle propulsive power indicating longer contact time and less work done at the ankle joint with the AFT shoe. The complete biomechanical data are shown in Table 3.1.

Table 3.1. Biomechanical measures for each shoe.

		AFT Median (IQR)	non-AFT Median (IQR)	Significant difference (<i>p</i> - value)
Contact time	s	0,210 (0,006)	0,208 (0,007)	0,075
Step Length	m	1,480 (0,168)	1,475 (0,114)	0,484
Knee Absorption Power	W/kg	24,7 (15,2)	25,1 (6,3)	0,401
Ankle Propulsive Power	W/kg	14,3 (1,6)	14,6 (1,9)	0,123

s = second, m = meter, W = Watt

Furthermore, we sought to explore some of the individual differences between the shoes from the observable data (Table 3.2). These showed that contact time and step length were greater in the AFT shoe for most participants, with #1 and #3 showing a shorter contact time and decreased step length. However, the differences were small for contact time where the largest difference was 6,7 ms for participant #6. Step lengths were more variable with participant #6 running with, on average, almost 10 cm shorter step length with the AFT shoe while participant #7 ran with approximately 5 cm longer steps. For knee absorption power, two participants decreased their power substantially with the AFT shoe. Participant #1, for instance, decreased his knee absorption power with 35 % while participant #5 decreased his power with 23 %. The two participants, #2 and #4, that increased their knee absorption power, increased it with 10 %. Finally, most participants reduced their ankle propulsive power with the AFT shoes by an average of 9 % (± 8 %). Participant #2 and #3 increased their ankle propulsive power with the AFT shoe by 1 % and 3 % respectively.

Table 3.2. Individual differences for each participant comparing the biomechanical measures between the shoes. The difference was calculated by subtracting the measured value of the AFT shoe against the non-AFT shoe.

Participant	Contact time (s)	Step Length (m)	Knee Absorption Power (W/kg)	Ankle Propulsive Power (W/kg)
#1	0,0000	- 0,0106	- 7,9886	- 3,5774
#2	0,0025	0,0349	3,3417	0,1671
#3	- 0,0008	0,0378	- 1,8157	0,5157
#4	0,0008	0,0269	3,0740	- 0,6034
#5	0,0058	0,0008	- 5,4109	- 0,1245
#6	0,0067	- 0,0979	- 1,9706	- 2,5229
#7	0,0042	0,0456	0,3289	- 2,1368
#8	0,0000	- 0,0093	- 1,2192	- 0,0809

*The numbers marked in **bold text** represent the measurements where the non-AFT shoe was greater than the AFT shoe.*

3.2 Association with Individual Characteristics

When comparing the correlations between the individual characteristics of the runners and the biomechanical difference between the shoes, only two of the independent variables were found to significantly correlate with the corresponding biomechanical variable. Peak power during the squat was shown to have a very strong negative correlation with peak knee absorption power ($r = -0,905$, $p = 0,005$). This means that those who produced greater power during the squat, reduced their knee absorption power more with the AFT shoe (fig. 3.1). The two participants who produced the lowest peak power during the squat, were also those who increased their knee absorption power with the AFT shoe compared to the non-AFT shoe. Furthermore, vertical stiffness during jumping was found to be moderately negatively correlated with step length ($r = -0,738$, $p = 0,046$), meaning that participants with lower stiffness, increased their step length more in the AFT shoe (fig. 3.2). The three participants who took longer steps with the non-AFT shoe, were also those with the highest vertical stiffness during jumping.

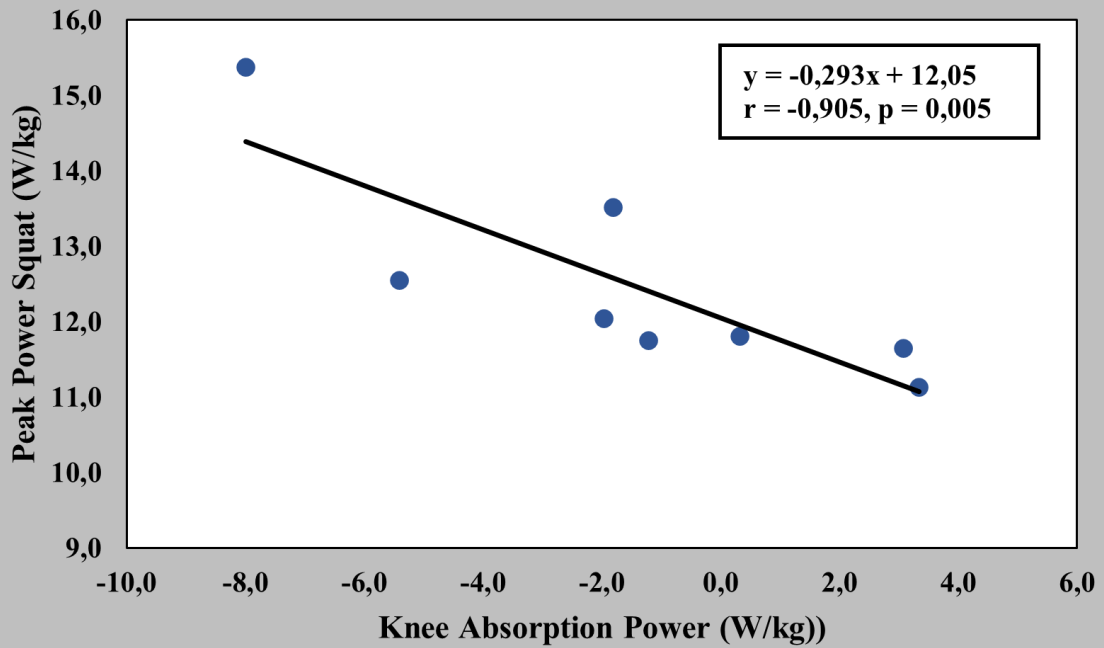


Figure 3.1. Simple linear model of peak power during the squat exercise and knee absorption power difference. Positive values in knee absorption power difference corresponds to increased work rate with the AFT shoes. The solid line represents the slope of the relationship.

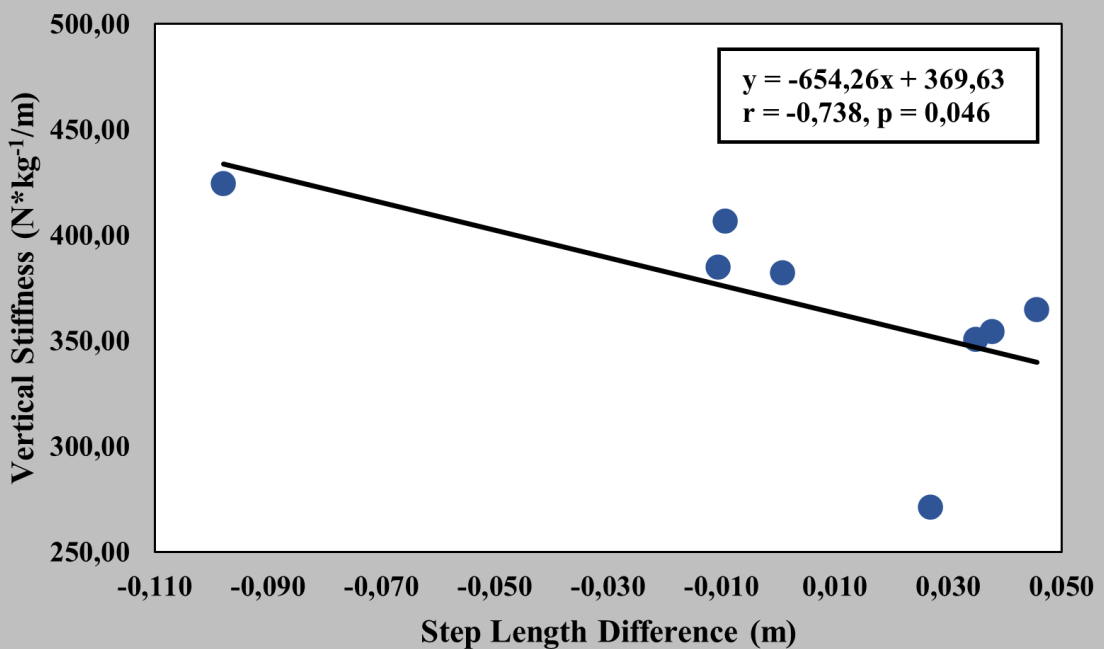


Figure 3.2. Simple linear model of vertical stiffness during jumping and step length difference. Positive values in step length difference corresponds to longer steps with the AFT shoes. The solid line represents the slope of the relationship.

Table 3.3. Correlation matrix with the biomechanical difference as dependent variable and the individual characteristic of the runner as independent. The biomechanical difference was calculated by subtracting the value measured with the AFT shoe against the non-AFT shoe. A positive value means that the greater the independent variable, the less negative or greater positive difference in the dependent variable. A dashed line means that no correlation analysis was performed.

	Ankle Propulsive Power	Knee Absorption Power	Step Length	Contact Time
RFD CR	- 0,405	-	-	-
PP CR	- 0,095	-	-	-
Moment arm	- 0,714	-	-	-
RFD SQ	-	- 0,476	-	-
PP SQ	-	- 0,905 **	-	-
EUR	-	-	0,143	-0,048
Vertical Stiffness	-	-	- 0,738 *	-0,252
RLLI	-	-	- 0,386	0,448

Note. * $p < .05$, ** $p < .01$

RFD = rate of force development, PP = peak power, CR = calf raise, SQ = squat, RLLI = relative leg length increase

4 Discussion

The present thesis' overall objective was to investigate the association between individual characteristics of runners and changes in mechanics while running in AFT shoes. The results indicate, in direct contradiction with hypothesis #1, that those participants with higher power production capabilities in the lower limb produced less knee absorption power with the AFT shoes than in non-AFT shoes. Furthermore, the results indicated that the participants with less vertical stiffness during jumping in the lower limb took longer steps with the AFT shoes than in non-AFT shoes. This may indicate that these individuals benefited more from the spring-like behavior of the shoe and therefore hypothesis #4 was accepted. We found no association between calf muscle power capabilities and achilles tendon moment arm length with ankle propulsive power, relative leg length increase and EUR with contact time and step length, and vertical stiffness during jumping with contact time. Thus, the remaining hypotheses were rejected.

4.1 Knee Absorption Power

During the initial stance phase of running, the knee extensors contract eccentrically while the knee flexes, acting as shock absorbers (Hamner & Delp, 2013; Hamner et al., 2010; Novacheck, 1998). Biomechanical factors that influence shock absorption during running include step length, knee flexion and vertical impact speed (Clarke et al., 1985; Nigg et al., 1995). Furthermore, external cushioning, as in surfaces and shoes, may reduce the demand on the leg muscles to cushion the impact and therefore reduce the energetic cost (Tung et al., 2014). Because of this, it was hypothesised that the knee absorption power would be reduced while running in the AFT shoes and that those with less power production capabilities in the lower limbs would benefit more due to a more favourable force-velocity relationship and improved effective mechanical advantage (EMA) at the knee joint. In contrast to this, the results showed that those with a greater power production ability reduced their knee absorption power more, while those with less power in the lower limb increased their knee absorption power with the AFT shoes. This could be related to the increased step length that the shoe contributed to and therefore increased impact forces during the initial phase of ground contact (Clarke et al., 1985; Derrick et al., 1998). Earlier studies have shown that with greater step length, peak vertical GRF increases and as a result, the knee extension moment increases (Schubert et al., 2014). The participants who increased their knee absorption power in this study, also increased their step length with the AFT shoes. In addition, these individuals ran with greater peak knee flexion, as opposed to those who reduced their knee absorption power who ran with less peak knee flexion. Spencer et al. (2020) found a significant negative relationship between knee extensor muscle strength and knee flexion during running, indicating that individuals with less quadriceps strength flexed their knees more. As a result of the increase in step length, the impact forces for these runners may have cancelled the potential benefits the shoe's cushioning could have at the knee joint with decreased knee flexion, and therefore increased leg stiffness.

The amount of cushioning could also have played a role in why some individuals increased their knee absorption power, and while some decreased it. Tung et al. (2014) speculated that there might be an optimal cushioning for performance, as they found considerable variation between individuals in metabolic demand while running on different cushioned surfaces. This is probably due to several different factors including foot strike pattern and body weight. Foot strike patterns, increased midsole thickness, and hence footwear cushioning, have been shown to promote rearfoot striking (RFS) (Chambon et al., 2014; Squadrone et al., 2015). This can potentially affect knee kinematics and kinetics for

non-rearfoot strikers (NRFS) as acute changes from RFS to NRFS have been shown to reduce peak knee flexion and knee extension moment (Anderson et al., 2020). However, because foot strike pattern was not measured or controlled for in this study, it cannot be said for certain whether this had any effect on the results.

4.2 Ankle Propulsive Power

For hypotheses #2 and #3, it was hypothesised that the increased LBS, induced by the carbon fiber plate, would reduce the ankle propulsive power more for those with lower power production ability and shorter moment arm. The theory behind this was that the increased LBS and shorter moment arm would decrease the muscle shortening velocity by an increase in gear ratio and thus optimizing the force-velocity relationship. However, both these hypotheses were rejected as there were no significant correlations between these variables. There are many possible reasons for this, e.g., the interplay of the force-length relationship of the calf muscle. The level of muscle activation is dependent on both the force-velocity ratio and the force-length relationship. This is expressed as the operating length of the muscle as it works in a state to optimize force production during contraction, which is modulated by the interaction between the myofilaments in the muscle's sarcomeres (Gordon et al., 1966). The calf muscles' operating length, as well as velocity, are mainly mediated by the lever arm of the Achilles tendon, MTU gearing (ratio of MTU and muscle fascicle velocity), and the range of motion (ROM) of the ankle joint (Rassier et al., 1999; Scholz et al., 2008; Wakeling et al., 2011). During running, smaller ankle joint ROM in the stance phase may decrease muscle fiber length changes and velocity (Rassier et al., 1999). Williams & Cavanagh (1987) found that runners who ran with a smaller ankle joint ROM, were also those with better running economy. This was also confirmed in a recent study where a greater angular velocity and ankle joint ROM led to less economical running (Bohm et al., 2019). In this thesis, participant #1, who reduced his propulsive power more, also reduced his ankle angular velocity and peak dorsiflexion the most. However, no other observations could be concluded for the other participants, which may be due to the complex interplay between the muscles, the tendon and ankle joint kinematics as explained before.

The reason for the non-significant difference between the AFT shoe and non-AFT shoe in terms of ankle propulsive power could have been due to optimal LBS. Recent research suggests that there is such a thing as optimal LBS and that this is dependent on both running speed and individual characteristics. McLeod et al. (2020) found that optimal

stiffness values varied between individuals and for rearfoot strikers, optimal stiffness was higher at faster speeds (16 km/h) than during slower speeds (10,7 km/h). In addition, they found that for some individuals the optimal LBS was outside the range of stiffness tested, which was particularly noticeable during faster speeds. Similarly, Day and Hahn (2020) found no difference in performance between the control (5,9 Nm/rad) and the stiff shoe (10,5 Nm/rad) when running at two different speeds (14 km/h and 17 km/h). However, between the two speed conditions, they found that more participants exhibited improved performance during the faster speed with the stiff shoes. In this thesis, the participants performed their running trials at approximately 15 km/h. This may have been too slow for some participants to elicit any significant changes in running mechanics with the increased LBS. Recently, Day and Hahn (2021) investigated the effects on running kinematics and kinetics on different speeds and LBS. In the ankle joint, they only found significant changes at 17 km/h with decreased negative ankle work with the stiffest shoe, further suggesting that running speed might have been too slow for some participants. This could also have affected the correlation analysis as the dependent variable used was the biomechanical difference between the shoes.

The curvature of the plate also seems to be of importance. Previous studies that have shown a reduction in muscle shortening velocity, have all used straight plates (Cigoja et al., 2020; Cigoja et al., 2021; Ray & Takahashi, 2020; Takahashi et al., 2016). Recently, Farina et al (2019) found that shoes with a stiff carbon-fiber plate, embedded in the midsole, increased peak ankle moment in comparison with control shoes. However, shoes with a curved plate did not produce any significant changes in the ankle joint. In this thesis, we used an AFT shoe with a curved plate. The curved plate might not have had the same effect on the moment arm as the straight plate had, and therefore not inducing sufficient changes in gearing ratio and subsequently ankle propulsive power.

Other possible reasons for the absence of change may be due to the test used to measure power and RFD in this thesis. This is discussed in detail below under “Methodological Considerations”.

4.3 Step Length and Contact Time

It was hypothesized that runners with lower vertical stiffness during jumping and EUR would benefit more from the spring-like properties of the AFT shoe by taking longer steps and decreasing their contact time. However, we only found an association between lower vertical stiffness and increased step length and therefore the remaining hypotheses were rejected.

Running with greater vertical stiffness is thought to improve performance by aiding the lower body's ability to withstand large excursions of COM while also increase the propulsive force during the stance phase (Brughelli & Cronin, 2008). In this thesis, the reason for the greater step length for those with lower vertical stiffness during jumping could be because these individuals benefitted more from the spring-like behavior of the shoe than those who are already considered to have the ability to utilize their elastic leg spring more. The energy return characteristics from the earlier mentioned unpublished data from the FRF and RF mechanical test (table 2.2), where the sole is compressed vertically, show that the AFT shoe returned significantly more energy than the non-AFT shoe (83,9 % and 82 % respectively for the AFT shoe and 63,7 % and 65,4 % respectively for the non-AFT shoe). This is also true for the TBS test where the AFT shoe returned 77,6 % of the stored energy while the non-AFT shoe returned 64,1 %. Our results showed that those who increased their step length with the AFT shoe, were also the ones who increased their peak vertical GRF. The reverse was seen in those who ran with shorter steps. A similar result was not seen for anterior GRF. Furthermore, these differences in peak vertical GRF may suggest that the spring-like mechanics changed for those individuals with lower vertical stiffness during jumping. In previous studies, the spring-like behavior during running has been shown to be affected by factors such as surface material and midsole foam (Kerdok et al., 2002; Kulmala et al., 2018). Kulmala et al. (2018) investigated whether highly cushioned shoes would increase leg stiffness more than traditional shoes while running at slower (10 km/h) and faster speeds (14,5 km/h). They found that the leg stiffness increased in the highly cushioned shoes at both speeds, but that the change was more pronounced during the faster speed. This was mainly due to a change in peak vertical GRF as the leg compression did not change between the speeds. As mentioned earlier, the participants who increased their step length, also increased their peak vertical GRF. However, most of these participants also increased their knee flexion with the AFT shoes, suggesting that vertical stiffness and leg stiffness during running might not have changed that much. This has recently been demonstrated by Hata et al (2022) where they found no change in leg stiffness while running in AFT shoes. Furthermore, what also might indicate that the shoes did not affect stiffness for these runners was that contact time did not change. Contact time has previously been shown to be inversely related to vertical stiffness (Farley & González, 1996).

We found no associations of EUR with step length and contact time. This may be because the outcome measure is not sufficiently sensitive or applicable to endurance runners. Previous studies have shown strong correlation between vertical jumping

performance (SJ and CMJ) and sprint running (Loturco et al., 2015), but not for endurance running (Barnes et al., 2014; Lanferdini et al., 2020). Since running is usually related to the spring-mass model (Farley et al., 1991), it is possible that the outcome measure of stiffness was more specific to the current population than EUR.

For relative leg length increase, no association was found between step length and contact time. The relative increase in leg length seen between shoes was approximately 1% for each runner, while the relative increase between individuals was max 0,62 % with the AFT shoe. This might explain why we did not observe any significant changes or associations.

4.4 Methodological Considerations

One of the major limitations with this thesis is the small sample size. A small sample size results in low statistical power, which then reduces the likelihood of declaring a true association or difference as statistically significant. This also applies for observed significant effects and associations where the probability decreases that they actually reflect a true value (Button et al., 2013). The small sample size also led to a lack of diversity in the participant group with all the eight participants being Caucasian European males. This makes it more difficult to extrapolate the results from this thesis to the general population of runners. Furthermore, due to the sample size and the amount of set variables measured, we used a simple linear correlation analysis. This can make the interpretation of the results somewhat difficult as the correlation analysis only shows us the association between the two chosen variables, not causation (Bewick et al., 2003). There could, for instance, be a third variable related to both the variables investigated that confounds the results. For this, a multiple regression analysis would be more suitable but due to the small sample size, we opted for a simple linear correlation analysis instead.

Another potential methodological limitation with this thesis is with some of the tests used to measure the variables in question. For instance, during the stiffness jumps, we observed that some of the participants had difficulty coordinating the jumps. The consequence of this may have been that the measured value did not reflect the participant's true value as the individual lacked the ability to produce the amount of force that he was capable of. For the running protocol, the visible force platforms might have influenced the results. This has earlier been shown to potentially alter running gait in some individuals where they, consciously or unconsciously, try to hit the platforms as they run over them (Challis, 2001).

Furthermore, the distance which the participants ran during the running protocol was limited to 15-20 m. The relative short distance and acceleration phase makes it more difficult to consistently maintain the same velocity throughout the running trials. Although we allowed a 5 % variance from the target speed of 15 km/h, in accordance with Li et al. (2021), we could not ascertain whether they had achieved steady state running or if they were still accelerating when crossing the platforms. This could potentially have implications on the running kinematics and kinetics. For this, an instrumented force-measuring treadmill would have been more appropriate as the velocity could be controlled and more data recorded. This would ensure that each participant reached steady state running and reduce the likelihood of changes in running mechanics due to environmental factors.

Finally, the F-V test performed for the calf muscles could have been improved. Firstly, the load applied to each set might have been either too low or too high. Typically, during the F-V test, a steady decrease in velocity is seen with each increase in load. In contrast, we saw only small changes in velocity between the loads, with some even increasing at the end. The applied loads used during the tests were derived from % of body weight, but perhaps using % of 1 repetition maximum (RM) would have been more appropriate. We opted for % body weight due to time constraints. Secondly, the ROM used during the test may also have influenced the outcome. Each participant was placed in a neutral starting position before commencing the ascend. It might have been more suitable to start them in certain degrees of dorsiflexion as the ankle joint reaches approximately 25 degrees of dorsiflexion just before the propulsion phase begins (Novacheck, 1998), which would mimic the movement during running more. An improved F-V test is envisaged in future research.

4.5 Practical Implications

The practical implications of the results of this thesis show that runners with lower vertical stiffness in the lower limbs during jumping may benefit more from the spring-like behavior induced by these AFT shoes, as we found significant moderate correlation between vertical stiffness and step length. However, the increased step length experienced by these runners may increase the knee absorption power for those with insufficient lower limb strength, due to a strong significant correlation between them two. This could potentially nullify or reduce the metabolic savings these shoes induce as an increased negative work performed at a joint leads to more eccentric work required by the muscles, and thus requiring more energy (Cigoja et al., 2022). This could also affect fatigue as the cost of force generation is higher in these muscles

compared to more distally located muscles such as the triceps surae (Biewener & Roberts, 2000). Additionally, the calf muscle's ability to produce power may be of less importance with these shoes as we found no correlation with ankle propulsive power, and instead morphology of the muscle and tendons may be more significant.

4.6 Future Research

Future research exploring biomechanical differences between different AFT shoes and non-AFT shoes and how they relate to individual characteristics is needed. For instance, follow-up studies should investigate how muscle activation and fascicle shortening velocities are affected while running with these shoes, and if this is influenced by the morphology of the runner. Furthermore, tendon energy storage and return may be of interest as both midsole cushioning (Esposito et al., 2022) and LBS (Cigoja et al., 2021) have been found to influence this during running. Comparing this with individual tendon stiffness and length might explain some of the mechanisms of these shoes. Follow-up studies investigating joint re-distribution work may also be of interest to ascertain if certain individuals may be more prone to fatigue or vice versa during prolonged running in AFT shoes. Finally, how these variables compare to the shoes mechanical energy return tests earlier mentioned and performance metrics such as time trials and running economy will be addressed in follow-up studies. This could clarify why some individuals improve their running performance with these shoes and why some do not. These follow-up studies should include a larger and more diverse participant group so that it becomes more relevant to the running community.

4.7 Conclusion

In conclusion, our findings indicate that runners with lower vertical stiffness in the lower limb during jumping take longer steps while running in AFT shoes. Additionally, we found that those with lower power production capabilities in the lower limb had higher knee absorption power, potentially explained by the higher vertical GRF induced by the greater step length. However, we found no association between anthropometrical measurements or calf muscle ability with running mechanics. This might indicate that these individual characteristics may not be of great importance for the performance enhancing effect these shoes elicit, but other characteristics such as calf muscle and Achilles tendon morphology may be of importance. Due to the low statistical power, the generalization of these results should be done with caution and further investigation is required.

5 Acknowledgement

First and foremost, I would like to thank my thesis supervisors Professor Toni Arndt and Dr Johanna Rosén for their patience, guidance, and support throughout this project. I would also like to thank my research group, Kalle, Johanna and Franziska. Without their assistance and support, this thesis would have never been accomplished. A special thanks to the Swedish Sports Confederation and their staff for providing the facilities needed for data collection. Finally, I would like to express my profound gratitude to my wife, Sarah, and my family for their unconditional support and encouragement throughout the writing of this thesis. This accomplishment would never have been possible without them. Thank you.

6 References

- A. Freedman, R., & D. Young, H. (2015) *University Physics with modern physics*. Pearson Education.
- Active Lives Survey. (2021). *Active Lives Adult Survey Maj 2020/21 Report*.
<https://sportengland-production-files.s3.eu-west-2.amazonaws.com/s3fs-public/2021-10/Active%20Lives%20Adult%20Survey%20May%202020-21%20Report.pdf?VersionId=YcsnWYZSKx4n12TH0cKpY392hBkRdA8N>
- Akoglu, H. (2018). User's guide to correlation coefficients. *Turk J Emerg Med*, 18(3), 91-93.
<https://doi.org/10.1016/j.tjem.2018.08.001>
- 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 Med*, 50(5), 885-917. <https://doi.org/10.1007/s40279-019-01238-y>
- Arampatzis, A., De Monte, G., Karamanidis, K., Morey-Klapsing, G., Stafilidis, S., & Brüggemann, G. P. (2006). Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. *J Exp Biol*, 209(Pt 17), 3345-3357.
<https://doi.org/10.1242/jeb.02340>
- Banyard, H. G., Nosaka, K., Sato, K., & Haff, G. G. (2017). Validity of Various Methods for Determining Velocity, Force, and Power in the Back Squat. *Int J Sports Physiol Perform*, 12(9), 1170-1176. <https://doi.org/10.1123/ijsp.2016-0627>
- Barnes, K., & Kilding, A. (2019). A Randomized Crossover Study Investigating the Running Economy of Highly-Trained Male and Female Distance Runners in Marathon Racing Shoes versus Track Spikes. *Sports Medicine*, 49(2), 331-342.
<https://doi.org/10.1007/s40279-018-1012-3>
- Barnes, K. R., & Kilding, A. E. (2015). Running economy: measurement, norms, and determining factors. *Sports Med Open*, 1(1), 8. <https://doi.org/10.1186/s40798-015-0007-y>
- Barnes, K. R., & Kilding, A. E. (2019). A Randomized Crossover Study Investigating the Running Economy of Highly-Trained Male and Female Distance Runners in Marathon Racing Shoes versus Track Spikes. *Sports Med*, 49(2), 331-342.
<https://doi.org/10.1007/s40279-018-1012-3>
- Barnes, K. R., McGuigan, M. R., & Kilding, A. E. (2014). Lower-body determinants of running economy in male and female distance runners. *J Strength Cond Res*, 28(5), 1289-1297. <https://doi.org/10.1519/jsc.0000000000000267>
- Baron, K. (January 2020). *HOKA ONE ONE: The Anatomy Of Sports Fastest Growing (Crisis-Proof) Sneaker Star*.
<https://www.forbes.com/sites/katiebaron/2020/06/26/hoka-one-one-the-anatomy-of-sports-fastest-growing-crisis-proof-sneaker-star/?sh=4a8bcff6287a>
- Bermon, S., Garrandes, F., Szabo, A., Berkovics, I., & Adami, P. E. (2021). Effect of Advanced Shoe Technology on the Evolution of Road Race Times in Male and Female Elite Runners. *Front Sports Act Living*, 3, 653173.
<https://doi.org/10.3389/fspor.2021.653173>
- Bewick, V., Cheek, L., & Ball, J. (2003). Statistics review 7: Correlation and regression. *Crit Care*, 7(6), 451-459. <https://doi.org/10.1186/cc2401>
- Biewener, A. A. (1989). Scaling body support in mammals: limb posture and muscle mechanics. *Science*, 245(4913), 45-48. <https://doi.org/10.1126/science.2740914>

- Biewener, A. A., & Roberts, T. J. (2000). Muscle and tendon contributions to force, work, and elastic energy savings: a comparative perspective. *Exerc Sport Sci Rev*, 28(3), 99-107.
- Black, M. I., Kranen, S. H., Kadach, S., Vanhatalo, A., Winn, B., Farina, E. M., . . . Jones, A. M. (2022). Highly Cushioned Shoes Improve Running Performance in Both the Absence and Presence of Muscle Damage. *Med Sci Sports Exerc*, 54(4), 633-645. <https://doi.org/10.1249/mss.0000000000002832>
- Bohm, S., Mersmann, F., Santuz, A., & Arampatzis, A. (2019). The force-length-velocity potential of the human soleus muscle is related to the energetic cost of running. *Proc Biol Sci*, 286(1917), 20192560. <https://doi.org/10.1098/rspb.2019.2560>
- Boyer, K. A., & Andriacchi, T. P. (2009). Changes in running kinematics and kinetics in response to a rockered shoe intervention. *Clin Biomech (Bristol, Avon)*, 24(10), 872-876. <https://doi.org/10.1016/j.clinbiomech.2009.08.003>
- Brazier, J., Maloney, S., Bishop, C., Read, P. J., & Turner, A. N. (2019). Lower Extremity Stiffness: Considerations for Testing, Performance Enhancement, and Injury Risk. *J Strength Cond Res*, 33(4), 1156-1166. <https://doi.org/10.1519/jsc.0000000000002283>
- Brooks. (2021). *Our History*. https://www.brooksrunning.com.au/meet_brooks/our_history
- Brughelli, M., & Cronin, J. (2008). Influence of running velocity on vertical, leg and joint stiffness : modelling and recommendations for future research. *Sports Med*, 38(8), 647-657. <https://doi.org/10.2165/00007256-200838080-00003>
- Burns, G. T., & Tam, N. (2020). Is it the shoes? A simple proposal for regulating footwear in road running. In *Br J Sports Med* (Vol. 54, pp. 439-440). <https://doi.org/10.1136/bjsports-2018-100480>
- Button, K. S., Ioannidis, J. P., Mokrysz, C., Nosek, B. A., Flint, J., Robinson, E. S., & Munafò, M. R. (2013). Power failure: why small sample size undermines the reliability of neuroscience. In *Nat Rev Neurosci* (Vol. 14, pp. 365-376). <https://doi.org/10.1038/nrn3475>
- Carrier, D. R., Heglund, N. C., & Earls, K. D. (1994). Variable gearing during locomotion in the human musculoskeletal system. *Science*, 265(5172), 651-653. <https://doi.org/10.1126/science.8036513>
- Challis, J. H. (2001). The Variability in Running Gait Caused by Force Plate Targeting. *Journal of Applied Biomechanics*, 17(1), 77-83. <https://doi.org/10.1123/jab.17.1.77>
- Chambon, N., Delattre, N., Guéguen, N., Berton, E., & Rao, G. (2014). Is midsole thickness a key parameter for the running pattern? *Gait Posture*, 40(1), 58-63. <https://doi.org/10.1016/j.gaitpost.2014.02.005>
- Cigoja, S., Asmussen, M. J., Firminger, C. R., Fletcher, J. R., Edwards, W. B., & Nigg, B. M. (2020). The Effects of Increased Midsole Bending Stiffness of Sport Shoes on Muscle-Tendon Unit Shortening and Shortening Velocity: a Randomised Crossover Trial in Recreational Male Runners. *Sports Med Open*, 6(1), 9. <https://doi.org/10.1186/s40798-020-0241-9>
- Cigoja, S., Firminger, C., Asmussen, M. J., Fletcher, J. R., Edwards, B., & Nigg, B. (2019). Effects of midsole bending stiffness on arch deformation of the human foot during running [Article]. *Footwear Science*, 11, S181-S182. <https://doi.org/10.1080/19424280.2019.1606318>
- Cigoja, S., Fletcher, J. R., Esposito, M., Stefanyshyn, D. J., & Nigg, B. M. (2021). Increasing the midsole bending stiffness of shoes alters gastrocnemius medialis muscle function during running. *Sci Rep*, 11(1), 749. <https://doi.org/10.1038/s41598-020-80791-3>
- Cigoja, S., Fletcher, J. R., & Nigg, B. M. (2022). Can changes in midsole bending stiffness of shoes affect the onset of joint work redistribution during a prolonged run? *J Sport Health Sci*, 11(3), 293-302. <https://doi.org/10.1016/j.jshs.2020.12.007>

- Clarke, T. E., Cooper, L. B., Hamill, C. L., & Clark, D. E. (1985). The effect of varied stride rate upon shank deceleration in running. *J Sports Sci*, 3(1), 41-49. <https://doi.org/10.1080/02640418508729731>
- Connolly, T. J., & Cannon, W. J. (1999). Comments on “America's Oldest Basketry”. *Radiocarbon*, 41(3), 309-313. <https://doi.org/10.1017/S0033822200057167>
- Dalleau, G., Belli, A., Bourdin, M., & Lacour, J. R. (1998). The spring-mass model and the energy cost of treadmill running. *Eur J Appl Physiol Occup Physiol*, 77(3), 257-263. <https://doi.org/10.1007/s004210050330>
- Day, E., & Hahn, M. (2020). Optimal footwear longitudinal bending stiffness to improve running economy is speed dependent. *Footwear Science*, 12(1), 3-13. <https://doi.org/10.1080/19424280.2019.1696897>
- Day, E. M., & Hahn, M. E. (2021). Does running speed affect the response of joint level mechanics in non-rearfoot strike runners to footwear of varying longitudinal bending stiffness? *Gait Posture*, 84, 187-191. <https://doi.org/10.1016/j.gaitpost.2020.11.029>
- Derrick, T. R., Hamill, J., & Caldwell, G. E. (1998). Energy absorption of impacts during running at various stride lengths. *Med Sci Sports Exerc*, 30(1), 128-135. <https://doi.org/10.1097/00005768-199801000-00018>
- Durussel, J., Daskalaki, E., Anderson, M., Chatterji, T., Wondimu, D. H., Padmanabhan, N., . . . Pitsiladis, Y. P. (2013). Haemoglobin mass and running time trial performance after recombinant human erythropoietin administration in trained men. *PLoS One*, 8(2), e56151. <https://doi.org/10.1371/journal.pone.0056151>
- Dyer, B. (2020). A Pragmatic Approach to Resolving Technological Unfairness: the Case of Nike's Vaporfly and Alphafly Running Footwear. *Sports Med Open*, 6(1), 21. <https://doi.org/10.1186/s40798-020-00250-1>
- Esposito, M., Wannop, J. W., & Stefanyshyn, D. J. (2022). Effects of midsole cushioning stiffness on Achilles tendon stretch during running. *Sci Rep*, 12(1), 4193. <https://doi.org/10.1038/s41598-022-07719-x>
- Farina, E. M., Haight, D., & Luo, G. (2019). Creating footwear for performance running. *Footwear Science*, 11(sup1), S134-S135. <https://doi.org/10.1080/19424280.2019.1606119>
- Farley, C. T., Blickhan, R., Saito, J., & Taylor, C. R. (1991). Hopping frequency in humans: a test of how springs set stride frequency in bouncing gaits. *J Appl Physiol (1985)*, 71(6), 2127-2132. <https://doi.org/10.1152/jappl.1991.71.6.2127>
- Farley, C. T., Glasheen, J., & McMahon, T. A. (1993). Running springs: speed and animal size. *J Exp Biol*, 185, 71-86. <https://doi.org/10.1242/jeb.185.1.71>
- Farley, C. T., & González, O. (1996). Leg stiffness and stride frequency in human running. *J Biomech*, 29(2), 181-186. [https://doi.org/10.1016/0021-9290\(95\)00029-1](https://doi.org/10.1016/0021-9290(95)00029-1)
- Ferris, D. P., Liang, K., & Farley, C. T. (1999). Runners adjust leg stiffness for their first step on a new running surface. *J Biomech*, 32(8), 787-794. [https://doi.org/10.1016/s0021-9290\(99\)00078-0](https://doi.org/10.1016/s0021-9290(99)00078-0)
- Ferris, D. P., Louie, M., & Farley, C. T. (1998). Running in the real world: adjusting leg stiffness for different surfaces. *Proc Biol Sci*, 265(1400), 989-994. <https://doi.org/10.1098/rspb.1998.0388>
- Fletcher, J. R., Groves, E. M., Pfister, T. R., & Macintosh, B. R. (2013). Can muscle shortening alone, explain the energy cost of muscle contraction in vivo? *Eur J Appl Physiol*, 113(9), 2313-2322. <https://doi.org/10.1007/s00421-013-2665-0>
- Fletcher, J. R., & MacIntosh, B. R. (2015). Achilles tendon strain energy in distance running: consider the muscle energy cost. *J Appl Physiol (1985)*, 118(2), 193-199. <https://doi.org/10.1152/japplphysiol.00732.2014>

- Fletcher, J. R., & MacIntosh, B. R. (2018). Theoretical considerations for muscle-energy savings during distance running. *J Biomech*, *73*, 73-79. <https://doi.org/10.1016/j.jbiomech.2018.03.023>
- Flores, N., Le Gendre, E., Rao, G., Berton, E., & Delattre, N. (2019). Relationships between biomechanics, anthropometrics, and running economy as a function of shoe mechanical feature variations. *Footwear Science*, *11*, S48 - S49.
- Franz, J. R., Wierzbinski, C. M., & Kram, R. (2012). Metabolic cost of running barefoot versus shod: is lighter better? *Med Sci Sports Exerc*, *44*(8), 1519-1525. <https://doi.org/10.1249/MSS.0b013e3182514a88>
- Frederick, E. C. (2020). No evidence of a performance advantage attributable to midsole thickness. *Footwear Science*, *12*(1), 1-2. <https://doi.org/10.1080/19424280.2019.1690327>
- Gordon, A. M., Huxley, A. F., & Julian, F. J. (1966). The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *J Physiol*, *184*(1), 170-192. <https://doi.org/10.1113/jphysiol.1966.sp007909>
- Haile, D. W., Durussel, J., Mekonen, W., Ongaro, N., Anjila, E., Mooses, M., . . . Pitsiladis, Y. P. (2019). Effects of EPO on Blood Parameters and Running Performance in Kenyan Athletes. *Med Sci Sports Exerc*, *51*(2), 299-307. <https://doi.org/10.1249/mss.0000000000001777>
- Hamner, S. R., & Delp, S. L. (2013). Muscle contributions to fore-aft and vertical body mass center accelerations over a range of running speeds. *J Biomech*, *46*(4), 780-787. <https://doi.org/10.1016/j.jbiomech.2012.11.024>
- Hamner, S. R., Seth, A., & Delp, S. L. (2010). Muscle contributions to propulsion and support during running. *J Biomech*, *43*(14), 2709-2716. <https://doi.org/10.1016/j.jbiomech.2010.06.025>
- Hata, K., Noro, H., Takeshita, T., Yamazaki, Y., & Yanagiya, T. (2022). Leg stiffness during running in highly cushioned shoes with a carbon-fiber plate and traditional shoes. *Gait Posture*, *95*, 9-14. <https://doi.org/10.1016/j.gaitpost.2022.03.021>
- Hébert-Losier, K., Finlayson, S. J., Driller, M. W., Dubois, B., Esculier, J. F., & Beaven, C. M. (2022). Metabolic and performance responses of male runners wearing 3 types of footwear: Nike Vaporfly 4%, Saucony Endorphin racing flats, and their own shoes. *J Sport Health Sci*, *11*(3), 275-284. <https://doi.org/10.1016/j.jshs.2020.11.012>
- Helsinki Declaration. (2013). World medical association declaration of Helsinki: ethical principles for medical research involving human subjects. [http://www.wma.net/en/30publications/10policies/b3/index.html.pdf?print-mediatype&footer-right=\[page\]/\[toPage\]](http://www.wma.net/en/30publications/10policies/b3/index.html.pdf?print-mediatype&footer-right=[page]/[toPage])
- Hill, A. V. (1938). The Heat of Shortening and the Dynamic Constants of Muscle. *Proceedings of the Royal Society of London. Series B, Biological Sciences (1934-1990)*, *126*(843), 136-195. <https://doi.org/10.1098/rspb.1938.0050>
- Hoogkamer, W. (2020). More isn't always better [Article]. *Footwear Science*, *12*(2), 75-77. <https://doi.org/10.1080/19424280.2019.1710579>
- Hoogkamer, W., Kipp, S., Frank, J., Farina, E., Luo, G., & Kram, R. (2018). A Comparison of the Energetic Cost of Running in Marathon Racing Shoes. *Sports Medicine*, *48*(4), 1009-1019. <https://doi.org/10.1007/s40279-017-0811-2>
- Hoogkamer, W., Kipp, S., & Kram, R. (2019). The Biomechanics of Competitive Male Runners in Three Marathon Racing Shoes: A Randomized Crossover Study. *Sports Med*, *49*(1), 133-143. <https://doi.org/10.1007/s40279-018-1024-z>
- Hoogkamer, W., Kipp, S., Spiering, B. A., & Kram, R. (2016). Altered Running Economy Directly Translates to Altered Distance-Running Performance. *Med Sci Sports Exerc*, *48*(11), 2175-2180. <https://doi.org/10.1249/mss.0000000000001012>

- Hunter, I., McLeod, A., Valentine, D., Low, T., Ward, J., & Hager, R. (2019). Running economy, mechanics, and marathon racing shoes. *J Sports Sci*, 37(20), 2367-2373. <https://doi.org/10.1080/02640414.2019.1633837>
- INEOS. (2019). *THE INEOS 1:59 PERFORMANCE BLUEPRINT*. <https://www.ineos159challenge.com/>
- Jidovtseff, B., Harris, N. K., Crielaard, J. M., & Cronin, J. B. (2011). Using the load-velocity relationship for 1RM prediction. *J Strength Cond Res*, 25(1), 267-270. <https://doi.org/10.1519/JSC.0b013e3181b62c5f>
- Joubert, D. P., & Jones, G. P. (2022). A comparison of running economy across seven highly cushioned racing shoes with carbon-fibre plates. *Footwear Science*, 14(2), 71-83. <https://doi.org/10.1080/19424280.2022.2038691>
- Joyner, M. J., Hunter, S. K., Lucia, A., & Jones, A. M. (2020). Physiology and fast marathons. *J Appl Physiol (1985)*, 128(4), 1065-1068. <https://doi.org/10.1152/jappphysiol.00793.2019>
- Kerdok, A. E., Biewener, A. A., McMahan, T. A., Weyand, P. G., & Herr, H. M. (2002). Energetics and mechanics of human running on surfaces of different stiffnesses. *J Appl Physiol (1985)*, 92(2), 469-478. <https://doi.org/10.1152/jappphysiol.01164.2000>
- Kipp, S., Grabowski, A. M., & Kram, R. (2018). What determines the metabolic cost of human running across a wide range of velocities? *J Exp Biol*, 221(Pt 18). <https://doi.org/10.1242/jeb.184218>
- Knapik, J. J., Pope, R., Orr, R., & Grier, T. (2015). Injuries and Footwear (Part 1): Athletic Shoe History and Injuries in Relation to Foot Arch Height and Training in Boots. *J Spec Oper Med*, 15(4), 102-108. <https://doi.org/10.55460/ktp0-xu4q>
- Kovács, B., Kóbor, I., Gyimes, Z., Sebestyén, Ö., & Tihanyi, J. (2020). Lower leg muscle-tendon unit characteristics are related to marathon running performance. *Sci Rep*, 10(1), 17870. <https://doi.org/10.1038/s41598-020-73742-5>
- Kram, R., & Taylor, C. R. (1990). Energetics of running: a new perspective. *Nature*, 346(6281), 265-267. <https://doi.org/10.1038/346265a0>
- Kulmala, J. P., Kosonen, J., Nurminen, J., & Avela, J. (2018). Running in highly cushioned shoes increases leg stiffness and amplifies impact loading. *Sci Rep*, 8(1), 17496. <https://doi.org/10.1038/s41598-018-35980-6>
- Lanferdini, F. J., Silva, E. S., Machado, E., Fischer, G., & Peyré-Tartaruga, L. A. (2020). Physiological Predictors of Maximal Incremental Running Performance. *Front Physiol*, 11, 979. <https://doi.org/10.3389/fphys.2020.00979>
- Li, F., Newton, R. U., Shi, Y., Sutton, D., & Ding, H. (2021). Correlation of Eccentric Strength, Reactive Strength, and Leg Stiffness With Running Economy in Well-Trained Distance Runners. *J Strength Cond Res*, 35(6), 1491-1499. <https://doi.org/10.1519/jsc.0000000000003446>
- Loturco, I., Pereira, L. A., Cal Abad, C. C., D'Angelo, R. A., Fernandes, V., Kitamura, K., . . . Nakamura, F. Y. (2015). Vertical and Horizontal Jump Tests Are Strongly Associated With Competitive Performance in 100-m Dash Events. *J Strength Cond Res*, 29(7), 1966-1971. <https://doi.org/10.1519/jsc.0000000000000849>
- Lucia, A., Esteve-Lanao, J., Oliván, J., Gómez-Gallego, F., San Juan, A. F., Santiago, C., . . . Foster, C. (2006). Physiological characteristics of the best Eritrean runners-exceptional running economy. *Appl Physiol Nutr Metab*, 31(5), 530-540. <https://doi.org/10.1139/h06-029>
- Madden, R., Sakaguchi, M., Tomaras, E. K., Wannop, J. W., & Stefanyshyn, D. (2016). Forefoot bending stiffness, running economy and kinematics during overground running [Article]. *Footwear Science*, 8(2), 91-98. <https://doi.org/10.1080/19424280.2015.1130754>

- McDougall, C., & Nilsson, J. (2012). *Born to run : jakten på löpningens själ*. Mån-pocket.
- McGuigan, M. R., Doyle, T. L., Newton, M., Edwards, D. J., Nimphius, S., & Newton, R. U. (2006). Eccentric utilization ratio: effect of sport and phase of training. *J Strength Cond Res*, 20(4), 992-995. <https://doi.org/10.1519/r-19165.1>
- McLeod, A. R., Bruening, D., Johnson, A. W., Ward, J., & Hunter, I. (2020). Improving running economy through altered shoe bending stiffness across speeds. *Footwear Science*, 12(2), 79-89. <https://doi.org/10.1080/19424280.2020.1734870>
- Megroz, G. (December 2013). *The Clown Shoe That's Changing Minimalist Running*. <https://www.outsideonline.com/outdoor-gear/run/clown-shoe-thats-changing-minimalist-running/>
- Milner, C. E., & Paquette, M. R. (2015). A kinematic method to detect foot contact during running for all foot strike patterns. *J Biomech*, 48(12), 3502-3505. <https://doi.org/10.1016/j.jbiomech.2015.07.036>
- Mooses, M., Mooses, K., Haile, D. W., Durussel, J., Kaasik, P., & Pitsiladis, Y. P. (2015). Dissociation between running economy and running performance in elite Kenyan distance runners. *J Sports Sci*, 33(2), 136-144. <https://doi.org/10.1080/02640414.2014.926384>
- Morales, A. T., Tamayo Fajardo, J. A., & González-García, H. (2019). High-Speed Swimsuits and Their Historical Development in Competitive Swimming. *Front Psychol*, 10, 2639. <https://doi.org/10.3389/fpsyg.2019.02639>
- Morin, J. B., Dalleau, G., Kyröläinen, H., Jeannin, T., & Belli, A. (2005). A simple method for measuring stiffness during running. *J Appl Biomech*, 21(2), 167-180. <https://doi.org/10.1123/jab.21.2.167>
- Muniz-Pardos, B., Sutehall, S., Angeloudis, K., Guppy, F. M., Bosch, A., & Pitsiladis, Y. (2021). Recent Improvements in Marathon Run Times Are Likely Technological, Not Physiological. *Sports Med*, 51(3), 371-378. <https://doi.org/10.1007/s40279-020-01420-7>
- Nagano, A., & Komura, T. (2003). Longer moment arm results in smaller joint moment development, power and work outputs in fast motions. *J Biomech*, 36(11), 1675-1681. [https://doi.org/10.1016/s0021-9290\(03\)00171-4](https://doi.org/10.1016/s0021-9290(03)00171-4)
- New York Times. (2018). *Nike says its \$250 running shoes will make you run much faster. What if that's actually true?* <https://www.nytimes.com/interactive/2018/07/18/upshot/nike-vaporfly-shoe-strava.html>
- Nigg, B. M., Cigoja, S., & Nigg, S. R. (2020). Effects of running shoe construction on performance in long distance running. *Footwear Science*, 12(3), 133-138. <https://doi.org/10.1080/19424280.2020.1778799>
- Nigg, B. M., Cigoja, S., & Nigg, S. R. (2021). Teeter-totter effect: a new mechanism to understand shoe-related improvements in long-distance running. In *Br J Sports Med* (Vol. 55, pp. 462-463). <https://doi.org/10.1136/bjsports-2020-102550>
- Nigg, B. M., Cole, G. K., & Brüggemann, G.-P. (1995). Impact Forces during Heel-Toe Running. *Journal of Applied Biomechanics*, 11(4), 407-432. <https://doi.org/10.1123/jab.11.4.407>
- Novacheck, T. F. (1998). The biomechanics of running. *Gait & Posture*, 7(1), 77-95. [https://doi.org/https://doi.org/10.1016/S0966-6362\(97\)00038-6](https://doi.org/https://doi.org/10.1016/S0966-6362(97)00038-6)
- Oh, K., & Park, S. (2017). The bending stiffness of shoes is beneficial to running energetics if it does not disturb the natural MTP joint flexion. *J Biomech*, 53, 127-135. <https://doi.org/10.1016/j.jbiomech.2017.01.014>

- Pinhasi, R., Gasparian, B., Areshian, G., Zardaryan, D., Smith, A., Bar-Oz, G., & Higham, T. (2010). First direct evidence of chalcolithic footwear from the near eastern highlands. *PLoS One*, *5*(6), e10984. <https://doi.org/10.1371/journal.pone.0010984>
- Pontzer, H. (2007). Effective limb length and the scaling of locomotor cost in terrestrial animals. *J Exp Biol*, *210*(Pt 10), 1752-1761. <https://doi.org/10.1242/jeb.002246>
- Rassier, D. E., MacIntosh, B. R., & Herzog, W. (1999). Length dependence of active force production in skeletal muscle. *J Appl Physiol (1985)*, *86*(5), 1445-1457. <https://doi.org/10.1152/jappl.1999.86.5.1445>
- Ray, S. F., & Takahashi, K. Z. (2020). Gearing Up the Human Ankle-Foot System to Reduce Energy Cost of Fast Walking. *Sci Rep*, *10*(1), 8793. <https://doi.org/10.1038/s41598-020-65626-5>
- Roberts, T. J., Kram, R., Weyand, P. G., & Taylor, C. R. (1998). Energetics of bipedal running. I. Metabolic cost of generating force. *J Exp Biol*, *201*(Pt 19), 2745-2751. <https://doi.org/10.1242/jeb.201.19.2745>
- Rogers, S. A., Whatman, C. S., Pearson, S. N., & Kilding, A. E. (2017). Assessments of Mechanical Stiffness and Relationships to Performance Determinants in Middle-Distance Runners. *Int J Sports Physiol Perform*, *12*(10), 1329-1334. <https://doi.org/10.1123/ijsp.2016-0594>
- Roy, J. P., & Stefanyshyn, D. J. (2006). Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. *Med Sci Sports Exerc*, *38*(3), 562-569. <https://doi.org/10.1249/01.mss.0000193562.22001.e8>
- Running USA. (2019). *U.S. Running Trends*. https://www.wpr.org/sites/default/files/running_usa_trends_report_2019-r4.pdf
- Runners World. (October 2018). *Nike's Air Tailwind Is Retro Running Royalty You Can Wear Today*. <https://www.runnersworld.com/gear/a23801919/nike-air-tailwind/>
- RunRepeat. (2021). *Pronation 101: Running Shoe Choices, DIY Analysis, Injuries*. <https://www.runrepeat.com/guides/pronation-running-shoes-diy-analysis-injuries>
- Saunders, P. U., Pyne, D. B., Telford, R. D., & Hawley, J. A. (2004). Factors affecting running economy in trained distance runners. *Sports Med*, *34*(7), 465-485. <https://doi.org/10.2165/00007256-200434070-00005>
- Scholz, M. N., Bobbert, M. F., van Soest, A. J., Clark, J. R., & van Heerden, J. (2008). Running biomechanics: shorter heels, better economy. *J Exp Biol*, *211*(Pt 20), 3266-3271. <https://doi.org/10.1242/jeb.018812>
- Schubert, A. G., Kempf, J., & Heiderscheidt, B. C. (2014). Influence of stride frequency and length on running mechanics: a systematic review. *Sports Health*, *6*(3), 210-217. <https://doi.org/10.1177/1941738113508544>
- Senefeld, J. W., Haischer, M. H., Jones, A. M., Wiggins, C. C., Beilfuss, R., Joyner, M. J., & Hunter, S. K. (2021). Technological advances in elite marathon performance. *J Appl Physiol (1985)*, *130*(6), 2002-2008. <https://doi.org/10.1152/japplphysiol.00002.2021>
- Shorten, M. R. (1993). The energetics of running and running shoes. *J Biomech*, *26 Suppl 1*, 41-51. [https://doi.org/10.1016/0021-9290\(93\)90078-s](https://doi.org/10.1016/0021-9290(93)90078-s)
- Sleivert, G. G., & Rowlands, D. S. (1996). Physical and physiological factors associated with success in the triathlon. *Sports Med*, *22*(1), 8-18. <https://doi.org/10.2165/00007256-199622010-00002>
- Sobhani, S., Hijmans, J., van den Heuvel, E., Zwerver, J., Dekker, R., & Postema, K. (2013). Biomechanics of slow running and walking with a rocker shoe. *Gait Posture*, *38*(4), 998-1004. <https://doi.org/10.1016/j.gaitpost.2013.05.008>
- Sobhani, S., van den Heuvel, E. R., Dekker, R., Postema, K., Kluitenberg, B., Bredeweg, S. W., & Hijmans, J. M. (2017). Biomechanics of running with rocker shoes. *J Sci Med Sport*, *20*(1), 38-44. <https://doi.org/10.1016/j.jsams.2016.04.008>

- Sobhani, S., Zwerver, J., van den Heuvel, E., Postema, K., Dekker, R., & Hijmans, J. M. (2015). Rocker shoes reduce Achilles tendon load in running and walking in patients with chronic Achilles tendinopathy. *J Sci Med Sport*, 18(2), 133-138. <https://doi.org/10.1016/j.jsams.2014.02.008>
- Spencer, A., Davis, K., Jacobs, C., Johnson, D., Ireland, M. L., & Noehren, B. (2020). Decreased quadriceps force steadiness following anterior cruciate ligament reconstruction is associated with altered running kinematics. *Clin Biomech (Bristol, Avon)*, 72, 58-62. <https://doi.org/10.1016/j.clinbiomech.2019.11.021>
- Squadrone, R., Rodano, R., Hamill, J., & Preatoni, E. (2015). Acute effect of different minimalist shoes on foot strike pattern and kinematics in rearfoot strikers during running. *J Sports Sci*, 33(11), 1196-1204. <https://doi.org/10.1080/02640414.2014.989534>
- Studel-Numbers, K. L., Weaver, T. D., & Wall-Scheffler, C. M. (2007). The evolution of human running: effects of changes in lower-limb length on locomotor economy. *J Hum Evol*, 53(2), 191-196. <https://doi.org/10.1016/j.jhevol.2007.04.001>
- Sun, X., Lam, W. K., Zhang, X., Wang, J., & Fu, W. (2020). Systematic Review of the Role of Footwear Constructions in Running Biomechanics: Implications for Running-Related Injury and Performance. *J Sports Sci Med*, 19(1), 20-37.
- Takahashi, K. Z., Gross, M. T., van Werkhoven, H., Piazza, S. J., & Sawicki, G. S. (2016). Adding Stiffness to the Foot Modulates Soleus Force-Velocity Behaviour during Human Walking. *Sci Rep*, 6, 29870. <https://doi.org/10.1038/srep29870>
- The Ethical Review Act. (2003:460). Utbildningsdepartementet. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/lag-2003460-om-etikprovning-av-forskning-som_sfs-2003-460
- Trinkaus, E., & Shang, H. (2008). Anatomical evidence for the antiquity of human footwear: Tianyuan and Sunghir. *Journal of Archaeological Science*, 35(7), 1928-1933. <https://doi.org/https://doi.org/10.1016/j.jas.2007.12.002>
- Tung, K. D., Franz, J. R., & Kram, R. (2014). A test of the metabolic cost of cushioning hypothesis during unshod and shod running. *Med Sci Sports Exerc*, 46(2), 324-329. <https://doi.org/10.1249/MSS.0b013e3182a63b81>
- Vanderbilt, T., & Sjögren, F. (2001). *Gympadojan : från sportsko till ikon*. Ordfront.
- Wakeling, J. M., Blake, O. M., Wong, I., Rana, M., & Lee, S. S. (2011). Movement mechanics as a determinate of muscle structure, recruitment and coordination. *Philos Trans R Soc Lond B Biol Sci*, 366(1570), 1554-1564. <https://doi.org/10.1098/rstb.2010.0294>
- Williams, K. R., & Cavanagh, P. R. (1987). Relationship between distance running mechanics, running economy, and performance. *J Appl Physiol* (1985), 63(3), 1236-1245. <https://doi.org/10.1152/jappl.1987.63.3.1236>
- Willwacher, S., Kurz, M., Menne, C., Schrödter, E., & Brüggemann, G.-P. (2016). Biomechanical response to altered footwear longitudinal bending stiffness in the early acceleration phase of sprinting [Article]. *Footwear Science*, 8(2), 99-108. <https://doi.org/10.1080/19424280.2016.1144653>
- Willwacher, S., König, M., Braunstein, B., Goldmann, J. P., & Brüggemann, G. P. (2014). The gearing function of running shoe longitudinal bending stiffness. *Gait Posture*, 40(3), 386-390. <https://doi.org/10.1016/j.gaitpost.2014.05.005>
- Willwacher, S., König, M., Potthast, W., & Brüggemann, G. P. (2013). Does specific footwear facilitate energy storage and return at the metatarsophalangeal joint in running? *J Appl Biomech*, 29(5), 583-592. <https://doi.org/10.1123/jab.29.5.583>
- World Athletic. (2020a). *Technical Rules 2020*. <https://www.worldathletics.org/about-iaaf/documents/technical-information#collapsemanuals>

- World Athletic. (2020b). *World athletics modifies rules governing competition shoes for elite athletes* <https://www.worldathletics.org/news/press-release/modified-rules-shoes>
- Worobets, J., Wannop, J. W., Tomaras, E., & Stefanyshyn, D. (2014). Softer and more resilient running shoe cushioning properties enhance running economy. *Footwear Science*, 6(3), 147-153. <https://doi.org/10.1080/19424280.2014.918184>
- Yin, L., Hu, X., Lai, Z., Liu, K., & Wang, L. (2020). Leg Stiffness and Vertical Stiffness of Habitual Forefoot and Rearfoot Strikers during Running. *Appl Bionics Biomech*, 2020, 8866340. <https://doi.org/10.1155/2020/8866340>

Appendix 1

Litteratursökning

I bilagan Litteratursökning ska du återge de sökningar du har gjort för att hitta tidigare forskning inom ditt ämnesområde. Se Uppsatsguiden för exempel på hur bilagan kan fyllas i.

Syfte och frågeställningar:

- | |
|--|
| <ul style="list-style-type: none">- Vilken effekt har löpskor på prestation och löpekonomi?- Vilken effekt har löpskor på spatiotemporal parametrar samt kinematik och kinetik?- Hur påverkar löpskornas funktioner individuella egenskaper hos löparen? |
|--|

Vilka sökord har du använt?

Ämnesord och synonymer svenska	Ämnesord och synonymer engelska
	<i>Running, Shoe, Footwear, Performance, Economy, Muscle, Strength, Tendon, Muscle-tendon Unit, Anthropometry, Neuromuscular, Biomechanics, Mechanics, Kinematics, Kinetics</i>

Var och hur har du sökt?

Databaser och andra källor	Sökkombination
PubMed SportsDiscus	runn* AND (footwear OR shoe) AND (performance OR economy) NOT (ortho* OR pain OR injury) runn* AND (footwear OR shoe) AND (muscle OR strength OR tendon OR "muscle-tendon unit" OR anthropometric* OR neuromuscular) NOT (ortho* OR pain OR injury) runn* AND (footwear OR shoe) AND (biomechanic* OR *mechanic* OR kinematic* OR kinetic*) NOT (ortho* OR pain OR injury)

Kommentarer

Google och Twitter har varit till stor hjälp för att hitta populärvetenskapliga artiklar på området samt pre-prints. Utöver detta har jag även tagit hjälp av diverse funktioner på PubMed och SportsDiscus som "similar articles"-funktionen samt granskat och förkovrat mig i de referenser som artiklarna jag hittat refererat till.
