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The Influence of Midsole Thickness on Running, Does Size Matter?

by

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Abstract

In 2020, World Athletics amended their footwear regulations to include a maximum midsole thickness of 40-mm to “protect the integrity of sport”. However, there was no evidence to support the restriction therefore, the purposes of this dissertation were to determine; i) the influence of midsole thickness on the energetic cost of running, ii) the influence of midsole thickness on frontal plane ankle angle and performance when running curves, and iii) the influence of midsole thickness on muscle damage associated with a training-style run.

Twenty-one runners participated in the first study, performing five-minute treadmill running trials in four footwear conditions. The footwear conditions were nearly identical except for their midsole which ranged from 35- to 50-mm in increments of 5-mm. Midsole thickness did not influence the energetic cost of running however, it did increase ankle eversion. In conclusion, running on a midsole thicker than 35-mm is inadvisable given that it will not provide a performance advantage but will impact frontal plane ankle angle.

Thirteen recreational athletes participated in the second study testing the impact of two footwear conditions on curved running. Participants performed ten running trials around each of three curves of radii. Midsole thickness did not impact frontal plane ankle angle of the outside leg or performance across any of the three curves.

Sixteen recreational runners with personal best 5-, or 10-km race times shorter than 24-, and 50-minutes, respectively, were recruited to participate in the third study. Participants performed a 60-minute training-style run in two nearly identical footwear conditions that differed only in midsole thickness, before and after which blood draws were performed for markers of muscle damage. Pre-to-post, there was not a statistically significant difference in magnitude of change in concentration of markers of muscle damage between shoes, although the concentration of lactate dehydrogenase did increase more so when running in the 35-mm footwear condition. In conclusion, midsole thickness did not impact the change in concentration of markers of muscle damage during a simulated training-style run.

The results of this dissertation would suggest the World Athletic restriction on midsole thickness is not required and should be reconsidered.

Preface

The following three chapters are based on scientific manuscripts:

Chapter 3: Barrons, Z.B., Wannop, J.W., & Stefanyshyn D.J., The Influence of Footwear Midsole Thickness on Running Biomechanics and Performance in Female and Male Runners, *Footwear Science* (Submitted).

Chapter 4: Barrons, Z.B., Wannop, J.W., & Stefanyshyn D.J., The Influence of Midsole Thickness on Curved Running, *Sports Biomechanics* (Submitted).

Chapter 5: Barrons, Z.B., Tripp, T., & Stefanyshyn D.J., The Influence of Midsole Thickness on Markers of Muscle Damage Following a Training-Style Run, *Journal of Sports Sciences* (Submitted).

All chapters and subchapters were written in a manuscript-based style. Thus, some chapters may contain redundant information, primarily the “introduction” and “methods” sections, when the rationale and methods of the studies were similar.

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Katelyn, thank you for your support and sacrifice. Without you, none of this would have been possible.

To my family, you clearly did not read my Master’s thesis but all the same, everything I said then, holds true now… all of it.

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Darren, thank you for taking a chance on me both as an intern and as a PhD student. Your council has been invaluable.

Committee members, thank you for taking time out of your busy schedules. I know I’m no Stephen King, but I hope the pages weren’t too hard to turn.

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Introduction

On January 31st, 2020, World Athletics (WA), the international governing body for the sport of athletics, announced a rule amendment that restricted the midsole thickness of footwear to be worn in World Athletics sanctioned events to no thicker than 40-mm. This amendment was in response to the burgeoning category of footwear now referred to as advanced footwear technology, that incorporated a forefoot stiffening apparatus, a pronounced rocker profile, and a thick resilient midsole (Frederick, 2022). As described by World Athletics, the rule amendment was intended to "protect the integrity of the sport [(i.e., running)]" (World Athletics Modifies Rules Governing Competition Shoes for Elite Athletes, 2020); however, at the time of amendment, there was no scientific evidence to suggest 40-mm presented a threshold past which sport integrity would be violated. Instead, it appears to have been made to accommodate the thickest midsole on the market (36-mm) at the time. This dissertation aimed to provide information on the role that midsole thickness plays with respect to running biomechanics and performance.

Research has been conducted on footwear with midsole thicknesses in and around 40-mm and found no influence on running economy; however, in addition to the differing midsole thicknesses, the footwear conditions also sported a host of other dissimilarities (e.g., heel-toe drop, mass, midsole material) (Mercer et al., 2018). This made it impossible to determine whether midsole thickness alone affects the metabolic cost of running. Despite these results, it's been proposed that a thicker midsole could positively affect the metabolic cost of running by elongating a runner's leg length (Burns & Tam, 2019). An increased leg length could increase stride length, decrease stride frequency, and increase stance time, all of which could culminate in a decreased rate of force generation, a metabolically beneficial outcome (Fletcher & MacIntosh, 2017; Kram

& Taylor, 1990; Pontzer, 2007). However, an increase in midsole thickness may also have detrimental consequences. Increasing the midsole thickness of a running shoe increases the moment arm about the longitudinal axis of the shoe (Hoogkamer, 2020). When combined with the lateral forces generated during running, the result could be an increased roll moment about the longitudinal axis of the foot, which may cause an increase in ankle eversion. While the topic is complicated to say the least, some have suggested ankle eversion is correlated with an increased risk of running related injuries (Donoghue et al., 2008; Ryan et al., 2009).

While the literature is sparse on research examining the impact of curved running on gait biomechanics, research examining the impact of curved sprinting on gait is more abundant. In comparison to linear sprinting, curved sprinting requires the generation of larger medial forces (Chang & Kram, 2007). If this holds true for curved running, a larger medial force, when combined with the elongated moment arm associated with an increased midsole thickness, could result in an exacerbation of frontal plane ankle angle as compared to linear running. Furthermore, if frontal plane ankle angle is perceived to be compromised by a runner when wearing footwear with a thick midsole, they may slow in order to reduce medial forces and reduce ankle angle. Given enough turns in a race, this could have implications for an athlete’s race outcome.

Regardless of whether the World Athletics rule amendment restricting midsole thickness still stands, athletes perform hundreds of training runs each year unincumbered by World Athletics restrictions. Running, whether training or racing, can cause muscle damage (Quinn & Manley, 2012; Wiewelhove et al., 2016), which can detrimentally impact future training runs and performances (Chen et al., 2009; Hikida et al., 1983; Miyama & Nosaka, 2004). Advanced footwear technology may be able to mitigate this damage (Kirby et al., 2019). The advanced footwear technology attribute responsible for the mitigation and the mechanism through which it does so is unknown. Landing on a soft surface, such as sand, results in less muscle damage than landing on a hard surface, the difference thought to be the result of a discrepancy in eccentric muscle action (Miyama & Nosaka, 2004). Much like sand, a thick midsole can be soft without fear that it will "bottom out" (Kram, 2022). Therefore, a thick compliant midsole may be the mechanism through which advanced footwear technology can reduce muscle damage associated with running.

Therefore, the purposes of this dissertation were to:

1) Determine the influence of midsole thickness on the energetic cost of running.

2) Determine the influence of midsole thickness on frontal plane ankle angle and performance when running curves.

3) Determine the influence of midsole thickness on muscle damage associated with a training-style run.

1.1 - Dissertation Outline

Chapter 2: A review of relevant literature pertaining to the impact of advanced footwear technology on performance, curved locomotion, running related muscle damage, and the mitigation of running related muscle damage by use of footwear.

Chapter 3: An original manuscript examining the impact of midsole thickness on running performance.

Chapter 4: An original manuscript examining the impact of midsole thickness on curved running.

Chapter 5: An original manuscript examining the impact of midsole thickness on pre-to-post changes in concentration of markers of muscle damage.

Chapter 6: A summary of the overall significant findings of this dissertation, with accompanying discussion, limitations, and future directions for research.

A Review of Relevant Literature

1.2 - The Restriction of Midsole Thickness

In 2020, World Athletics, the governing body for the sport of athletics, amended their footwear regulations to “protect the integrity of sport”. Among the amendments was a restriction of midsole thickness to below 40-mm (World Athletics Modifies Rules Governing Competition Shoes for Elite Athletes, 2020); however, at the time of amendment, there was no scientific evidence to suggest 40-mm was a threshold past which sport integrity would be violated (Frederick, 2020). While considerable research has been conducted on other elements of advance footwear technology, far less has examined the impact of midsole thickness, the category of footwear primarily impacted by the amendment, on running gait, and performance in a systematic fashion. While there is evidence and propositions of mechanisms through which increased midsole thickness could positively impact running (Burns & Tam, 2019; Kirby et al., 2019), others have warned of possible detriments (Hoogkamer, 2020). Ultimately the impact of midsole thickness above and beyond 40-mm remains a question that this dissertation sought to answer. In this chapter what is known about the impact of midsole thickness is discussed and its potential implications for racing and training.

1.3 - Advanced Footwear Technology

To be defined as advanced footwear technology, footwear must feature three elements: (i) a forefoot stiffening apparatus, (ii) a pronounced rocker profile, and (iii) a thick resilient midsole (Frederick, 2022). While each of these three elements and their impact on running performance has been studied to an extent, the success with which scientists have isolated each element and determined its contribution to the overall positive impact of advanced footwear technology on running performance is variant.

Increasing forefoot bending stiffness has been shown to improve running economy by approximately 1% (Roy & Stefanyshyn, 2006). There are two proposed mechanisms through which this could be achieved. Firstly, by increasing forefoot bending stiffness, energy loss at the metatarsophalangeal joint is reduced (Stefanyshyn & Nigg, 2000), and secondly, an increase in forefoot bending stiffness increases the moment arm about the ankle, permitting the generation of greater ankle moments given the musculature of the shank is strong enough (Madden et al., 2016; Willwacher et al., 2014). Strength limitations are speculated to be the reason why the relationship between forefoot bending stiffness and improvements in running economy tends to follow a 'U' shape (Farina et al., 2019; Madden et al., 2016). However, by curving the forefoot stiffening apparatus, an energy loss reduction at the metatarsophalangeal joint can be achieved while limiting the increase in ankle joint moment (Farina et al., 2019).

In addition to catering to the curved forefoot stiffening apparatus, the pronounced rocker profile may also have its own performance enhancing effect. Termed the 'teeter-totter effect', the pronounced rocker profile is theorized to permit the curved forefoot apparatus to vault the runner forward as they apply force to the forefoot of the shoe. While exploratory research examining the 'teeter-totter effect' found the centre of pressure to shift posteriorly during toe off, what some might suggest is evidence of a vaulting effect (Subramanium & Nigg, 2021), the metabolic benefits of this theory have yet to be tested.

The resilience of a midsole refers to the proportion of energy stored and returned upon unloading. Although important, equally important is the compliance of a midsole. Compliance refers to the extent to which a material deforms under a given force and is what governs the magnitude of energy stored when loaded. The Nike Vaporfly 4%, when compared to traditional marathon racing shoes on the market in 2017, was found to return considerably more energy (7.46 vs 3.38 and 3.56 joules per step) primarily due to its greater compliance which was twofold greater than the other footwear conditions (Hoogkamer et al., 2017).

The influence of midsole thickness on running performance is unquestionably opaque. Three studies have systematically examined the impact of midsole thickness; however, the ranges of midsole thickness compared never approached that seen in advanced footwear technology. The three ranges were: 6 conditions between 1-, and 29-mm (1-, 5-, 9-, 21-, 25-, and 29-mm) (Law et al., 2018), 6 conditions between barefoot and 16-mm (barefoot, 0-, 2-, 4-, 8-, and 16-mm) (Chambon et al., 2014), and three conditions between 3-, and 24-mm (3-, 14-, and 24-mm) (TenBroek et al., 2014). Overall, significant differences between footwear conditions were primarily limited to initial ground contact. Average and instantaneous vertical loading rates were found to be significantly higher when running in the 1-, and 5-mm conditions as compared to the 4 thicker conditions (Law et al., 2018). Participants were found to be more plantarflexed in both the 3-, and 14- mm conditions at ground contact, with a more extended knee position while running in the 3-mm condition, all as compared to the 24-mm condition (TenBroek et al., 2014). At midstance, participants were found to exhibit greater knee flexion but less ankle eversion when running in the 24-mm as compared to the 3-, and 14-mm conditions and to experience a longer contact time (TenBroek et al., 2014). Unfortunately, the impact of midsole thickness on the metabolic cost of running was not an aspect included in any of these studies; however, the impact of “maximal” shoes, a category of footwear not rigorously defined but featuring a substantial midsole, on metabolic cost has been studied. Participants were found to perform similarly when running in footwear with 35-, and 42-mm thick midsoles (Mercer et al., 2018).

However, the only required shared commonality between maximal shoes is the substantial midsole rendering it impossible to determine whether midsole thickness was responsible for the results or one of a host of other differences (e.g., heel-toe drop, mass, midsole material, etc).

Although there hasn’t been a systematic investigation of the impact of midsole thickness on the metabolic cost of running, a theory has been proposed that explains how an increased midsole thickness could decrease metabolic cost. Burns and Tam (2019) proposed an increase in midsole thickness could decrease the metabolic cost of running by effectively elongating the leg of a runner. They hypothesized, an 8-mm increase in leg length could decrease metabolic cost by ~1%. It would do so, at a given speed, by increasing stride length, which would decrease stride frequency, and increase contact time, all of which would culminate to decrease the required rate of force generation, a metabolically beneficial adaptation (Kram & Taylor, 1990; Pontzer, 2007). However, Hoogkamer (2020) warned that increases in midsole thickness could also have a detrimental effect. Increasing midsole thickness increases the moment arm of the ground reaction force about the longitudinal axis of a shoe. When combined with the medial-lateral forces generated when running, the outcome could be an increased ‘roll’ moment about the longitudinal axis of the shoe. This may increase the peak ankle eversion angle which may increase a runner’s risk of incurring a running related injury (Hannigan & Pollard, 2020). At first glance, the results of TenBroek et al. (2014) would seem to contradict this theory; however, Hannigan and Pollard (2020) found increased ankle eversion among participants when wearing 10-, and 32-mm thick midsoles as compared to 22-mm midsoles. When taken in context with the results of TenBroek et al. (2014), these results might suggest a ‘goldilocks’ effect and that further increases in midsole thickness as seen in advanced footwear technology may further increase ankle eversion as predicted by Hoogkamer (2020).

While the contributions of a forefoot stiffening apparatus, a pronounced rocker profile, and a resilient midsole to improved running economy have been studied, an understanding of the contribution, if any, of midsole thickness to running performance appears a void in the literature. Future research should look to examine the impact of midsole thickness on running to both continue optimizing performance and to minimize risk of injury.

1.4 - Curved Locomotion

Limited research has been conducted examining the influence of curved running on gait biomechanics, that having been conducted being primarily theoretical and/or limited in scope (Greene, 1985; Smith et al., 2006). However, due to its relevance to the sport of track and field, a considerable amount of research has been conducted on curved sprinting. The two legs of a sprinter, when curved sprinting, behave differently leading researchers to conclude they perform different functions (Alt et al., 2015). Finding the inside leg to experience greater ankle eversion, hip adduction and hip external rotation, Alt et al. (2015) concluded the role of the inside leg was to stabilize movement in the frontal plane whereas the role of the outside leg was to control movement in the horizontal plane. In support of this notion, Ishimura & Sakurai (2016) found participants when curved sprinting, to change the direction in which they were sprinting more so during the outside step than the inside step. This they concluded, was due to the difference in centripetal force generated by the two legs. Unlike linear sprinting, curved sprinting necessitates the generation of centripetal force, the force that keeps a runner moving along a curved path (Ishimura & Sakurai, 2016). The generation of centripetal force necessitates the reallocation of force from what otherwise would have been anterior force during linear sprinting, to force partially in the medial-lateral direction (medial in respect to the outside leg, lateral in respect to the inside leg) during curved sprinting. This reallocation of force, when curved running may be problematic when combined with an increased midsole thickness. An increase in midsole thickness elongates the moment arm of the ground reaction force about the longitudinal axis of the shoe (Hoogkamer, 2020). When combined with the reallocated medial-lateral forces during curved running, the result could be an increase in frontal plane ankle angle beyond that seen during linear running (Hannigan & Pollard, 2020). Furthermore, the smaller the turn radii, the greater the centripetal force required to run said curve (Equation 1). This would suggest that curves of smaller radii may result in a further increase frontal plane ankle angle.

$$\text{centripetal force} = \frac{\text{mass} * \text{velocity}^2}{\text{radius}} \qquad \text{Equation 1}$$

When curved sprinting, the outside leg generates greater centripetal force than the inside leg (Ishimura & Sakurai, 2016). The magnitude of medial force generated by the outside leg is larger than the magnitude of lateral force generated by the inside leg (Chang & Kram, 2007). Therefore, it would stand to reason that an increased midsole thickness when curved running, would impact the frontal plane ankle angle of the outside leg more than the frontal plane ankle angle of the inside leg.

The orientation of the resultant ground reaction force with respect to the desired direction of movement can impact performance (Moore et al., 2016; Wannop et al., 2014). If not aligned, the resultant ground reaction force can be reoriented by changing the orientation of the limb generating the force (Wannop et al., 2014). Wannop et al. (2014) reported the horizontal impulse during a cutting movement, could be increased by reducing ankle eversion, which they theorized would increase performance. If instead, when curved running, a thick midsole increased ankle eversion, the result of an elongated moment arm, the difference in orientation of the resultant ground reaction force and direction of movement could result in slower curved running speeds, which would be detrimental for performance.

While the literature on the impact of curved running on gait biomechanics may currently be sparse, in the pursuit of safety and optimal performance it seems important to examine the impact of midsole thickness on peak frontal plane ankle angles and performance when running curves of various radii.

1.5 - Running, Muscle Damage, And Running Footwear Mitigation

At most, a long-distance runner will race only a handful of events each year; however, they'll perform hundreds of training runs. Running, whether intervals or continuous, can cause muscle damage (Quinn & Manley, 2012; Wiewelhove et al., 2016), thought primarily to be the result of eccentric muscle contractions (Black et al., 2022). If substantial enough in magnitude, muscle damage can decrease running economy, alter running gait, and decrease performance for upwards of five days (Chen et al., 2009; Hikida et al., 1983; Miyama & Nosaka, 2004). However, in a comparison of barefoot and shod running, da Silva et al. (2020) found shod running to reduce the perception of delayed onset muscle soreness proceeding a 5-km run suggesting footwear may present an opportunity to mitigate running related muscle damage, improving an athlete's performance during subsequent training runs. Kirby et al. (2019) compared the impact of advanced footwear technology and non-advanced footwear technology on markers of muscle damage, such as white blood cell count, lactate dehydrogenase concentration, and muscle soreness, after a marathon. Participants assigned to wear advanced footwear technology were found to demonstrate fewer markers of muscle damage than participants assigned to wear non-advanced footwear technology. Although a biomechanical analysis was not included as part of the study, researchers speculated the disparity in markers of muscle damage between groups may have been due to differences in midsole softness.

Drop jumps onto a soft sand surface during a study conducted by Miyama and Nosaka (2004), were found to decrease muscle soreness and damage as compared to landing on a hard wood surface, abbreviating recovery. Landings on soft surfaces may reduce the active role an individual plays absorbing the collision, resulting in a reduced peak knee flexion angle, and eccentric muscle contraction (Skinner et al., 2015). Landing on a soft surface can also result in an increased vertical ground reaction force as substantiated by previous literature (Miyama & Nosaka, 2004; Skinner et al., 2015). Similar trends have been observed in running. Participants in a study conducted by Kerdok et al. (2002) displayed 2.5% smaller peak knee angles, and 5% larger vertical ground reaction forces, when running on a soft treadmill surface. Running on the soft surface also reduced participants' metabolic cost by 12% suggest decreased muscle activity and therefore potentially less negative joint work (Blake & Wakeling, 2013).

Midsole softness, the technical term being stiffness, is characterized by the ratio of force to resultant material deformation. An especially soft midsole, as was used by Kirby et al. (2019), must also be of substantial thickness like midsoles typically seen in advanced footwear technology, else it will 'bottom-out' (Kram, 2022). Midsole thickness is therefore a mechanism through which midsole stiffness can be modulated and potentially the characteristic of advanced footwear technology responsible for the reductions in running related muscle soreness, damage, and inflammation reported by Kirby et al. (2019).

While evidence would suggest a thick, soft midsole could reduce running related muscle damage that may be incurred during a training run by decreasing eccentric muscle contractions, to date no study has combined an examination of markers of muscle damage, with a biomechanical analysis of the effects of midsole thickness.

1.6 **- Summary and Statement of Problem**

In 2020, World Athletics amended their footwear regulations, banning all midsoles thicker than 40-mm. The ban wasn't scientifically backed at the time and the influence of midsole thickness on race performance and training remains somewhat of a mystery. This chapter outlined the mechanisms through which midsole thickness could positively and negatively influence running performance and training and this dissertation will seek to address the following related questions:

1) What is the influence of midsole thickness on the energetic cost of running?

2) What is the influence of midsole thickness on frontal plane ankle angle and performance when running curves?

3) What is the influence of midsole thickness on muscle damage associated with a training-style run?

The Influence of Footwear Midsole Thickness on Running Biomechanics and Energetic Cost in Female and Male Runners

1.7 - Introduction

In 2018, Nike Vaporfly 4% running shoes were used to break world records in the 100 km, 42 km (i.e., marathon), 21 km (i.e., half marathon), and 15 km running distances. Reported to improve running economy of both elite and recreational runners (Hoogkamer et al., 2017; Quealy & Katz, 2018) the Vaporfly 4% combined three features that have since become ubiquitous with advanced footwear technology (AFT) or so called "super shoes" (i.e., long distance performance enhancing running shoes): (1) a stiff plate, (2) a midsole material of favorable mechanical properties, and (3) a midsole of substantial thickness (Burns & Tam, 2019).

The use of stiff plates is common across a variety of sporting footwear including sprint spikes, cycling shoes, and football cleats. In running shoes, a stiff plate is thought to increase the longitudinal bending stiffness of a shoe, elongating the moment arm about the ankle, and altering the gearing ratio (the ratio of ground reaction force moment arm to muscle moment arm) of the ankle, knee, and hip (Madden et al., 2016; Willwacher et al., 2014). The performance enhancing effect of this shift may result in up to a 1% improvement in running economy (Roy & Stefanyshyn, 2006).

Two properties characterize a favorable midsole material, compliance, and resilience (Hoogkamer et al., 2017). Compliance refers to the extent to which a material deforms under a given force and governs the magnitude of energy stored when deformed. Resilience refers to the proportion of that energy returned upon unloading. When compared to other running shoes, prototypes of the Vaporfly 4% were found to return considerably more energy (87% vs 75.9% and 65.5%, or 7.46 vs 3.38 and 3.56 joules per step) primarily due to greater compliance.

The impact of midsole thickness on the energetic cost of running is unquestionably less clear. Studies have found midsole thickness to influence running related variables (e.g., contact time, cadence, and stride length (Chambon et al., 2014; Law et al., 2018)) that in turn have been associated with changes in the metabolic cost (De Ruiter et al., 2014; Hunter et al., 2017; Hunter & Smith, 2007). Unfortunately studies directly relating midsole thickness and energetic cost are lacking. One study that compared the influence of a maximal running shoe (i.e., 42-mm midsole) to a neutral running shoe (i.e., 35-mm midsole) found that the maximal midsole did not affect the metabolic cost of running (Mercer et al., 2018). However, midsole thickness was just one of a plethora of differences between the tested shoes (e.g., heel-toe drop, mass, midsole material), rendering it impossible to determine why there wasn’t a difference in running economy (Frederick, 2020).

In response to what was perceived by some as the unfair bequeathment of advantage by these features, unique to the Vaporfly 4% at the time (Kilgore, 2020), suggestions were made as to how to regulate performance enhancing running shoes. Burns and Tam (2019) proposed a midsole thickness restriction. In part, the rationale behind their recommendation was an estimate that a midsole of sufficient height (8 mm) could significantly reduce a runner’s cost-of-transport (~1%) by effectively elongating a runner’s leg. Issue was taken with this aspect of their rationale primarily due to the aforementioned lack of explicit/contradictory evidence of the impact of midsole thickness on running performance (Frederick, 2020; Hoogkamer, 2020; Nigg et al., 2020). Furthermore, it was identified that increases in midsole thickness may be self-governing due to unintended consequences such as an increase in frontal plane ankle angle (Hoogkamer, 2020). This could be especially problematic for populations known to already exhibit greater frontal plane joint movement (e.g., females) due to the association of frontal plane movement with common running related injuries (Ferber et al., 2003; Wouters et al., 2012). Despite World Athletics, the international governing body for sport, amending its rules in 2021 to regulate footwear, which included a midsole thickness limitation of 40-mm, a systematic examination of the effect of midsole thickness on the energetic cost of running has yet to be conducted. Therefore, the purpose of this study was to determine the influence of midsole thickness on running economy.

1.8 - Methods

1.8.1 - Footwear

Four footwear models were tested in this experiment, all of which were provided by adidas along with their mechanical properties. The models were structurally identical in all regards (e.g., US men's size 9, TPEE midsole, curved carbon infused rods, outsole geometry) except midsole thickness (Figure 3.1). The four midsole thicknesses tested were 35-, 40-, 45-, and 50-mm. This range was selected to include a thickness commercially available (i.e., 35-mm), the maximal thickness that still abides by the World Athletics restriction (i.e., 40-mm), and thicknesses that extend well beyond the World Athletics restriction (i.e., 45-, and 50-mm). A consequence of the differing midsole thicknesses was that the mechanical properties of the midsoles (i.e., mass, forefoot bending stiffness, midsole stiffness) also differed (Table 3.1). Measures were taken to mass normalize the conditions (i.e., taping small weights to the external medial side of each necessary shoe) due to the effect mass is known to have on metabolic cost (Franz et al., 2012); however, the remaining mechanical differences were left unaltered.

Forefoot bending stiffness was left unchanged as the structural integrity of the shoes could not be guaranteed if physically altered. Increasing forefoot bending stiffness via carbon fiber plates inserted under the midsole was an option; however, a recent study demonstrated that the location of the stiffness element within a shoe can influence running biomechanics (Flores et al., 2019). Midsole stiffness was left unchanged as evidence has suggested cushioning stiffnesses over 100 N/mm have a similar effect on metabolic cost (Kerdok et al., 2002).

Figure 0.1: The four footwear conditions tested (left – right, 35-, 40-, 45-, and 50-mm).

Table 0.1: Mechanical properties of the different footwear conditions.

	35 mm	40 mm	45 mm	50 mm
Mass (before normalization) (g)	214.5	229.5	241.5	260.5
Rearfoot Stiffness (N/mm)	176.0	155.0	125.0	100.0
Forefoot Stiffness (N/mm)	201.0	172.0	151.0	131.0
Energy Return (%)	83.5	84.0	85.0	86.5
Bending Stiffness (Nm/º)	0.187	0.171	0.160	0.166

1.8.2 - Participants

Twenty-one runners, eleven males (mean ± SD, age: 25.4 ± 4.1, height: 176.6 ± 7.0 cm, mass: 71.6 ± 8.1 kg) and ten females (height: 173.1 ± 8.3 cm, mass: 66.3 ± 8.6 kg), all of whom fit a men's shoe size US9 were recruited for this study. The caliber of runners recruited ranged from recreational, defined as an individual who had run 20+ kilometres per week for at least the previous six months and was free of injury, to collegiate. Informed written consent was obtained from all participants prior to the data collection in accordance with the University of Calgary's Ethics Board.

1.8.3 - Data Collection

Participation in the study comprised of one 90-minute visit to the lab. Each visit (i.e., data collection) started with an incremental speed test, the protocol for which was adopted from previously published methods (Esposito et al., 2022), on a Bertec treadmill (Bertec Corporation, Columbus, Ohio, USA). The results of the incremental test were used to determine a submaximal running speed proportional to the participant's fitness level at which the experimental trials were performed. Starting at an initial speed of 8.85 km/hour, the treadmill speed was increased by 0.8 km/hour every two minutes until the participant reached their anerobic threshold. A participant's anaerobic threshold was visually identified from the output of a Quark cardiopulmonary exercise testing metabolic cart (Cosmed, Rome, Italy) by looking for a combination of excessive CO2 production (Beaver et al., 1986), a respiratory exchange ratio value greater than 1 (Solberg et al., 2005), and/or a nonlinear increase in pulmonary ventilation (Wasserman et al., 1973). Following the incremental test, participants performed a five-minute run in each of the four footwear conditions in a randomized order at 85% of the top speed from the incremental test. During the final two-minutes of each trial metabolic, kinetic, and kinematic data were collected. Participants rested for ten minutes between trials.

Metabolic data was collected on a breath-by-breath basis by the Quark cardiopulmonary exercise testing metabolic cart for the duration of each trial; however, only the final two minutes were analyzed. Kinetic data was collected at a rate of 2400 Hz by the Bertec instrumented treadmill. Kinematic data was collected at a rate of 240 Hz by a nine-camera motion capture system (Vicon, Denver, USA). A total of five sets of four noncolinear retroreflective tracking markers were used in conjunction with the motion capture system to define each participant's pelvis, left thigh, left shank, and left foot segments (Figure 3.2). More specifically, the pelvis segment was defined by four retroreflective markers placed on the left and right, anterior, and posterior iliac crests. The four retroreflective markers that defined each of the thigh and shank segments were placed on the lateral side of each segment in a diamond pattern. The foot segment was defined by permanent markers affixed to each of the four left shoes. Two markers were placed at proximal and distal locations on the heel of the shoe such that they aligned with the Achilles tendon of the participant while the remaining two markers were affixed at differing heights to the lateral side of each shoe. Four markers were glued onto pearl headed pins and inserted into the lateral side of each midsole in a rectangular pattern as described by Clermont et al. (2022). The markers were used to determine the horizontal and vertical deformation of the midsole during the stance phase. Joint center locations were determined by placing additional markers on the following locations: medial and lateral malleolus (to define the ankle joint), and medial and lateral epicondyles of the femur (to define the knee joint).

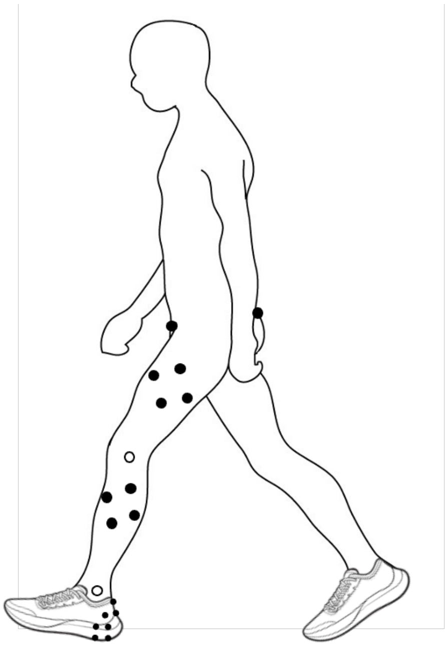

Figure 0.2: Tracking (closed circles), and joint demarcating (open circles) retroreflective markers used in conjunction with the motion capture system.

1.8.4 - Data Analysis

Metabolic data was exported from the Cosmed collection software in the form of Excel spreadsheets (Microsoft Corporation, Seattle, WA, USA). The spreadsheets were imported into MATLAB software (MathWorks, Natick, MA, USA) which was used to calculate both the energy cost of running ($kJ \cdot kg^{-1} \cdot km^{-1}$), as presented by Fletcher et al. (2010), and average VO_2 ($mL \cdot min^{-1} \cdot kg^{-1}$) as presented by Lamarra et al. (1987), of each participant over the final two minutes of each trial.

Kinematic data collected by the Vicon motion capture system was manually tracked using the Vicon Nexus software before being exported and imported to Visual 3D software (C-Motion, Germantown, MD, USA). In Visual 3D, the kinematic data and ground reaction force data were smoothed using a zero-lag, low-pass, 4th order Butterworth filter with a cut-off frequency of 15-Hz. A 20-Newton threshold was used to identify the gait events (i.e., heel-strike and toe-off) of each trial after which Cardan angles, angular velocities, moments, powers, and work of the ankle, knee, and hip were calculated using a four-segment model, including a Coda pelvis (a pelvis segment model in Visual 3D). These were exported from Visual 3D and analyzed (i.e., the identification of peak values, and the calculation of averages) in Excel software.

To calculate midsole deformation and estimate leg length, the data pertaining to the four markers inserted into the lateral side of each midsole and the marker placed on the left anterior superior iliac spine were exported from Vicon Nexus software. Matlab software was then used to calculate peak horizontal and vertical midsole deformation following the methods of Clermont et al. (2022). In short, the relative vertical displacement of the top pair of markers was calculated with respect to the bottom pair of markers, and the relative horizontal displacement of the front pair of markers was calculated with respect to the back pair of markers. The vertical height of the left iliac crest marker was used as a rough estimation of leg length.

1.8.5 - Statistical Analysis

All statistical analysis was performed in SPSS software (IBM, Armonk, NY, USA). The effect of footwear conditions (i.e., 35-, 40-, 45-, and 50-mm midsoles) and interactions between footwear and sex (i.e., males and females) on energetic cost, peak ground reaction forces, contact time, and joint angles, moments, and work were compared using an ANOVA with repeat measures ($p < 0.05$). If a significant difference was detected a pairwise comparison analysis was performed with Bonferroni confidence interval adjustment.

1.9 - **Results**

1.9.1 - Footwear

There were no significant differences in metabolic cost (i.e., average VO_2 or energetic cost), stance time, stride frequency, or stride length between footwear conditions (Table 3.2). There was a significant difference in leg length at heel-strike ($F = 21.5$, $p < 0.001$), midstance ($F = 16.9$, $p < 0.001$), and toe-off ($F = 10.4$, $p < 0.001$). At heel-strike participants had a significantly greater leg length in the 50-mm footwear condition as compared to the 35- ($p < 0.001$), 40- ($p < 0.001$), and 45-mm ($p < 0.001$) conditions and a significantly greater leg length in the 45-mm condition as compared to the 35-mm condition ($p = 0.024$). At mid-stance participants had a significantly greater leg length in the 50-mm footwear condition as compared to the 35- ($p < 0.001$), 40- ($p < 0.001$), and 45-mm ($p < 0.001$) conditions and a significantly greater leg length in the 45-mm condition as compared to the 35-mm condition ($p = 0.004$). Finally, at toe-off participants had a significantly greater leg length in the 50-mm condition as compared to the 35- ($p < 0.001$), 40- ($p < 0.001$), and 45-mm ($p < 0.001$) conditions.

Table 0.2: Metabolic cost, stance time, stride frequency, stride length and leg length when running in each of the four footwear conditions.

					p-value	
	35-mm	40-mm	45-mm	50-mm	Shoe	Shoe x sex
VO_2 (mL·min^{-1}·kg^{-1})	35.2 ± 4.9	35.7 ± 4.0	35.6 ± 4.5	36.1 ± 4.5	0.306	0.550
Energetic Cost (kJ·kg^{-1}·km^{-1})	3.96 ± 0.51	4.01 ± 0.57	3.95 ± 0.49	4.00 ± 0.47	0.261	0.577
Stance Time (s)	0.26 ± 0.03	0.26 ± 0.03	0.26 ± 0.03	0.26 ± 0.03	0.751	0.051
Stride Frequency (per min)	164.5 ± 7.9	164.9 ± 8.5	164.3 ± 9.4	165 ± 8.4	0.345	0.263
Stride Length (m)	1.05 ± 0.14	1.04 ± 0.14	1.05 ± 0.14	1.04 ± 0.14	0.274	0.252
Leg Length Heel Strike (m)	1.04*^ ± 0.06	1.04*^ ± 0.06	1.05* ± 0.06	1.06^ ± 0.07	<0.001	0.736
Leg Length Mid Stance (m)	0.98*^ ± 0.06	0.99* ± 0.06	0.99* ± 0.06	1.00 ± 0.06	<0.001	0.872
Leg Length Toe Off (m)	1.04* ± 0.07	1.04* ± 0.06	1.05* ± 0.06	1.05 ± 0.07	<0.001	0.978

Significant difference as compared to the 50-mm(*), or 45-mm(^).

Significant differences in peak midsole deformation were found in both the horizontal (F = 12.7, $p < 0.001$) and vertical (F = 29.3, $p < 0.001$) directions (Figure 3.2). In the horizontal direction the 45-, and 50-mm conditions were found to displace significantly more than the 35- (p = 0.034, p = 0.007), and 40-mm (p = 0.003, $p < 0.001$) conditions. In the vertical direction the 50-mm condition was found to displace significantly more than the 35-, 40-, and 45- mm ($p < 0.001$, $p < 0.001$, $p < 0.001$) conditions and the 45-mm condition displaced more than the 40-mm condition (p = 0.02). The difference in vertical deformation between the 45- and 35-mm conditions approached significance (p = 0.089).

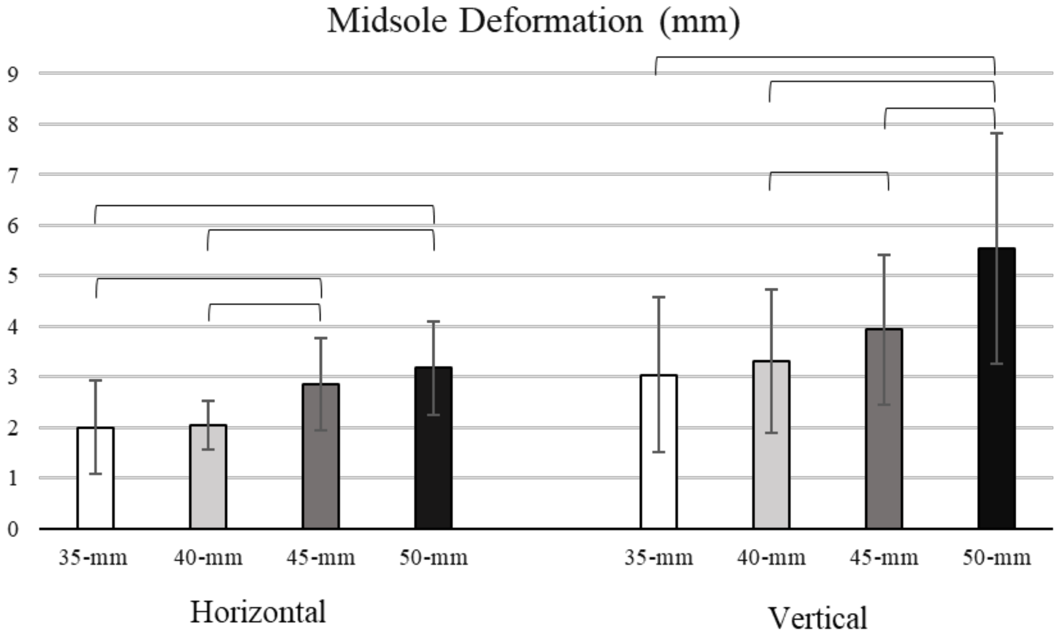

Figure 0.3: Peak horizontal and vertical deformation of the midsole in each of the four footwear conditions. Data represent the mean and standard deviation of all participants with significant differences between conditions denoted by brackets.

Significant differences in kinematic and kinetic variables between footwear conditions were limited to the ankle joint, no differences were found at the knee or hip (Table 3.3). Differences in maximum dorsiflexion ankle angle were found in the sagittal plane (F = 4.70, p = 0.005), participants performed significantly greater dorsiflexion while running in the 40-mm footwear condition as compared to the 50 mm condition (p = 0.037). Participants also performed significantly greater plantarflexion (F = 3.51, p = 0.021) in the 45- , and 50-mm footwear conditions as compared to the 40-mm footwear condition (p = 0.002, and p = 0.027, respectively). Average peak ankle angular velocities, moments, powers, and work can be seen in Figure 3.3. Participants reached significantly greater peak dorsiflexion velocities (F = 6.36, p = 0.001) during midstance when running in the 35-, 40-, and 45-mm conditions as compared to when running in the 50 mm condition (p = 0.047, p = 0.004, and p = 0.002, respectively). At toe-off, participants reach significantly greater peak plantarflexion velocities (F = 11.49, p < 0.00) when running in the

45 mm condition as compared to when running in either the 35 ($p = 0.027$) or 50 mm conditions ($p = 0.019$). In the sagittal plane ($F = 5.04$, $p = 0.004$), participants reach significantly greater peak plantar flexor moments in the 35-, 40-, and 45-mm conditions as compared to when running in the 50-mm condition ($p = 0.047$, $p = 0.006$, and $p = 0.002$, respectively). In the sagittal plane, participants had significantly greater negative ($F = 7.08$, $p < 0.001$) and positive ($F = 8.96$, $p < 0.001$) power at the ankle when running in the 35- and 45-mm conditions as compared to when running in the 50-mm condition ($p = 0.026$, $p = 0.002$, and $p = 0.029$ and $p = 0.001$). Participants performed significantly less negative ankle work ($F = 13.96$, $p < 0.00$) when running in the 50-mm condition as compared to running in the 35- ($p<0.001$), 40- ($p<0.001$), and 45- mm conditions ($p < 0.001$), and significantly less positive ankle work ($F = 11.20$, $p < 0.001$) as compared to running in the 35-, and 45-mm conditions ($p < 0.001$, and $p = 0.002$) in the sagittal plane. In the frontal plane, there was a significant difference in ankle eversion ($F = 5.00$, $p = 0.004$). Participants experienced significantly greater ankle eversion when running in the 45-mm footwear condition as compared to the 35-mm condition ($p = 0.044$). Participants also performed significantly less frontal plane positive work ($F = 3.05$, $p = 0.036$) in the 35-mm condition as compared to the 45-mm conditions ($p = 0.045$) and performed less negative work ($F = 6.30$, $p = 0.001$) as compared to both the 45-, and 50-mm conditions ($p = 0.031$, $p = 0.042$).

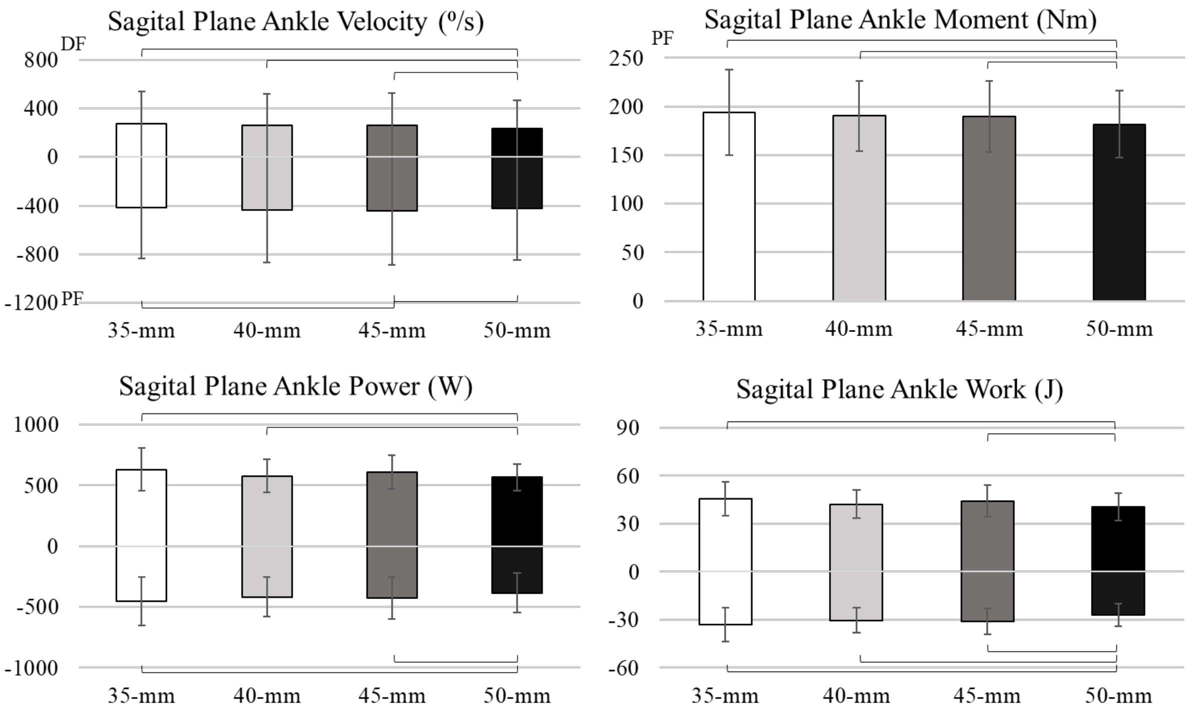

Figure 0.4: Average peak sagittal plane ankle velocities (top left), moments (top right), power (bottom left), and work (bottom right) in each of the four footwear conditions. Data represent the mean and standard deviation of all participants with significant differences between conditions denoted by brackets. DF = dorsiflexion, PF = plantarflexion

Table 0.3: Average peak kinematic and kinetic variables at the ankle, knee and hip.

							p-value	
			35-mm	40-mm	45-mm	50-mm	Shoe	Shoe x sex
Ankle	Angle (º)	Flx	17.3 ± 4.1	17.1 ± 3.1	16.2 ± 3.2	15.3 ± 2.9	0.061	0.143
		Ext	-14.1 ± 6.0	-14.2 ± 4.1	-16.1 ± 4.6	-15.2 ± 4.0	0.050	0.07
	Velocity (º/s)	Flx	271.0 ± 117.1*	260.6 ± 107.2*	262.2 ± 112.2*	234.4 ± 95.5	0.001	0.846
		Ext	-415.9 ± 103.9^	-433.6 ± 105.4	-445.3 ± 104.4*	-424.3 ± 103.3	<0.001	0.100
	Moment (Nm)	Ext	-193.9 ± 43.9*	-190.3 ± 36.4*	-189.5 ± 36.5*	-181.8 ± 34.2	0.015	0.156
	Power (W)	Pos	631.2 ± 200.0*	578.6 ± 160.7*	609.0 ± 172.5	566.2 ± 164.1	0.003	0.817
		Neg	-454.8 ± 175.5*	-417.7 ± 135.7	-425.6 ± 139.4*	-384.2 ± 111.9	<0.001	0.810
	Sagital Plane Work (J)	Pos	45.7 ± 10.6*	42.3 ± 8.6	44.2 ± 10.0*	40.4 ± 8.6	<0.001	0.285
		Neg	-33.1 ± 10.7*	-30.5 ± 7.8*	-30.9 ± 8.2*	-27.2 ± 7.1	<0.001	0.686
	Frontal Plane Work (J)	Pos	2.5 ± 1.8^	2.5 ± 2.0	3.3 ± 2.6	2.9 ± 1.8	0.036	0.538
		Neg	-1.9 ± 1.8*^	-1.8 ± 1.1	-2.4 ± 1.6	-2.3 ± 1.3	< 0.001	0.196
Knee	Angle (º)	Flx	32.1 ± 3.5	32.8 ± 4.8	32.9 ± 4.3	33.1 ± 3.9	0.683	0.254
	Angular Velocity (º/s)	Flx	217.1 ± 46.9	223.9 ± 55.4	229.0 ± 54.2	226.2 ± 53.6	0.110	0.711
	Moment (Nm)	Ext	116.8 ± 28.3	121.3 ±26.1	119.7 ± 20.9	126.9 ± 26.6	0.057	0.075
	Power (W)	Pos	244.7 ± 70.1	237.2 ± 64.7	238.8 ± 58.8	245.0 ± 55.1	0.675	0.517
		Neg	-436.0 ± 186.5	-419.2 ± 153.0	-416.1 ± 138.4	-431.8 ± 170.9	0.830	0.729
	Work (J)	Pos	13.3 ± 4.7	13.4 ± 4.4	12.9 ± 3.4	14.4 ± 4.7	0.399	0.666
		Neg	-17.3 ± 10.2	-15.7 ± 9.3	-16.7 ± 9.7	-17.0 ± 10.7	0.167	0.395
Hip	Angle (º)	Flx	17.3 ± 4.1	17.1 ± 3.1	16.2 ± 3.2	15.4 ± 2.9	0.346	0.065
		Ext	-6.2 ± 3.5	-5.1 ± 3.9	-5.6 ± 4.4	-5.6 ± 3.7	0.305	0.143
	Angular Velocity (º/s)	Ext	-257.5 ± 54.1	-255.9 ± 48.4	-261.5 ± 50.3	-255.9 ± 49.9	0.562	0.178
	Moment (Nm)	Ext	42.6 ± 16.9	48.7 ± 25.0	44.7 ± 21.5	39.9 ± 14.9	0.060	0.179
	Power (W)	Pos	155.2 ± 99.7	168.7 ± 107.6	150.3 ± 88.8	141.2 ± 60.4	0.192	0.501
		Neg	-138.5 ± 71.6	-159.9 ± 103.9	-159.6 ± 96.9	-137.0 ± 59.7	0.311	0.215
	Work (J)	Pos	6.9 ± 4.8	8.1 ± 5.2	7.4 ± 5.4	7.5 ± 5.3	0.227	0.336
		Neg	-9.0 ± 5.5	-8.4 ± 4.8	-8.9 ± 5.7	-9.3 ± 5.3	0.446	0.279

Significant difference as compared to the 50(*), or 45(^).

Flx = flexion, Ext = extension, Pos = positive, Neg = Negative

1.9.2 - Footwear x Sex

Footwear and sex interactions were found in frontal plane ankle angles (F = 0.047, p = 2.81). As can be seen in Figure 3.4, female participants had significantly greater ankle eversion in the 45-mm, and 50-mm conditions as compared to the 40-mm (p = 0.015, and p = 0.005) condition and in the 50-mm conditions as compared to the 35- (p = 0.036) condition. The difference in eversion between the 45-mm and 35-mm condition approached significance (p = 0.08).

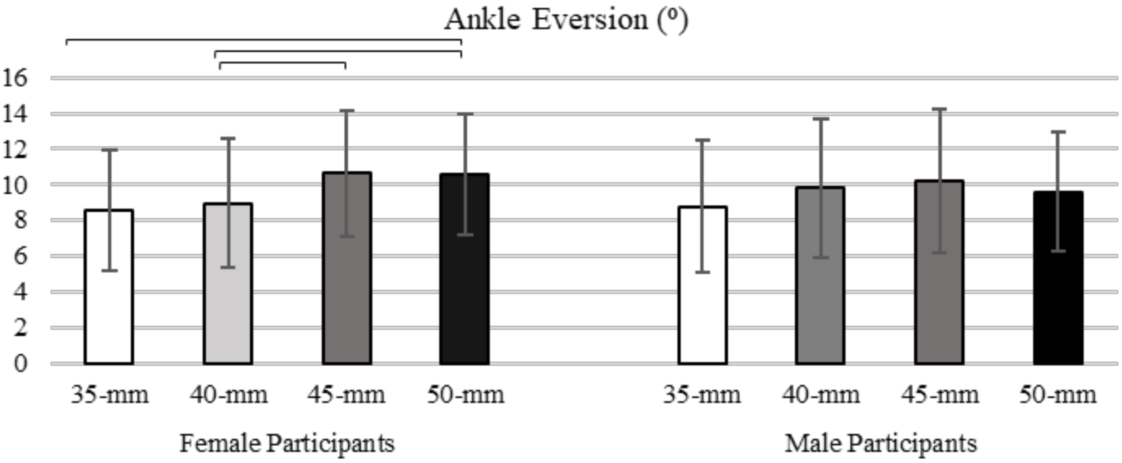

Figure 0.5: Peak Frontal plane ankle angle (i.e., eversion) of female and male participants running in the four footwear conditions. Brackets indicate significant differences ($p < 0.05$).

1.10 - Discussion and Implications

The purpose of this study was to determine the influence of midsole thickness on running the energetic cost of running. Metabolic cost was found to be similar when running in the four footwear conditions. While similar conclusions were published by Mercer et al. (2018) comparing participants' performance in maximal cushioning and neutral footwear, these results were somewhat surprising when taken in context with the significant differences found at the ankle. When running in the 50-mm midsole condition, participants were found to have significantly slower dorsiflexion velocities, lower moments, and powers, and to have performed less work in the sagittal plane. Given that each participant ran at the same speed in all conditions one might anticipate the 50-mm condition to be the footwear in which participants performed best; however, that was not the case. One possible explanation is that participants displayed near significant increases in sagittal plane knee velocity (p = 0.11) and moment (p = 0.057), both metabolically costly adaptations (Fletcher & MacIntosh, 2017; Martin et al., 2000). Any advantage participants gained at the ankle (i.e., decreased velocity, moment, power, work) when running in the 50-mm footwear condition may have been lost at the knee which may, in part, may explain why participants did not perform best in the thickest midsole condition.

In their 2019 editorial "Is it the shoes? A simple proposal for regulating footwear in road running", Burns and Tam proposed midsole thickness could improve running performance by elongating leg length. An elongated leg could increase stride length and contact time and decrease the rate of force production. A lower rate of force production is associated with a lower cost of transport (i.e., metabolic cost) (Kram & Taylor, 1990). This theory was based on the work of Pontzer (2007) who found leg length to explain 98% of observed variance in the metabolic cost of transport across a wide array of species (Pontzer, 2007). Burns and Tam (2019) proposed an 8-mm increase in leg length would decrease the metabolic cost of running by ~1%. On average, at heel-strike, mid-stance, and toe-off, the 50-mm footwear condition elongated the participants' leg lengths by 14.4-, 14.7-, and 11.9-mm, respectively in comparison to the 35-mm footwear. These differences were larger than expected given that undeformed there was a 15-mm difference in midsole thickness and the midsole of the 50-mm condition experienced significantly more vertical deformation during the stance phase. This would suggest that participants may have displayed subtle differences in joint angles in each condition, that individually were not significantly different but when summed and combined with the different midsole thicknesses resulted in differences in effective leg length. This is supported by previous literature that found surfaces of different compliance impact joint angles (Kerdok et al., 2002). The leg elongation, however, did not translate into an increased stride length or contact time. This is consistent with the earlier findings of Law et al. (2018) who found no difference in spatial-temporal variables of participants running in shoes with 22-, and 25-mm midsoles. There was, however, a significant decrease in peak average ankle plantarflexion velocity when participants ran in the 50-mm footwear condition as compared to the 35-, and 45-mm conditions. Joint angular velocity is an effective surrogate of rate of muscle force generation (Martin et al., 2000) suggesting that at least in regard to the muscles responsible for ankle plantarflexion, the 50-mm footwear was metabolically efficient.

An unintended consequence of a thick running shoe midsole may be an increase in frontal plane ankle angle. As outlined by Hoogkamer (2020), an increase in midsole thickness increases the ground reaction force moment arm length about the longitudinal axis of the foot. An increased moment arm combined with the lateral force experienced during running could produce an increased roll-moment about the longitudinal axis of the foot, increasing the frontal plane ankle angle. Evidence of such an effect was presented by Hannigan and Pollard (2020) comparing running shoes with 22- and 33-mm midsoles. They found participants to experience faster, longer, and greater ankle eversion when running in the latter as compared to the former. An increase in frontal plane ankle angle could be hazardous due to its association with common running related injuries at the hip and knee (Wouters et al., 2012). Participants were found to exhibit ~2° greater ankle eversion when running in the 45-, and 50-mm ($p = 0.064$) footwear conditions, and female participants were found to exhibit ~3° more ankle eversion in the 45-, and 50-mm shoe conditions, all as compared to the 35-mm footwear condition, results similar to that found by Hannigan and Pollard (2020). However, there were no significant differences at the hip or knee. The relationship between ankle eversion and risk of running related injury is complicated (Nigg et al., 2019). Some have suggested excessive ankle eversion/pronation to be related to an increased risk of lower leg injuries (Hannigan & Pollard, 2020); however, due to the challenges surrounding quantifying and defining "normal" eversion/pronation there is no clinical definition of "excessive eversion/pronation". Therefore, it is unclear whether a 2-3° increase in ankle eversion puts runners at an increased risk of injury. Due to the lack of performance benefit of the 45- and 50-mm midsole conditions, out of an abundance of caution it is advisable that runners of both sexes avoid running shoes with midsole thicknesses greater than 40-mm.

A second possible explanation as to why participants didn't display a superior performance when running in the 50-mm footwear condition is they exhibited higher levels of antagonist muscle co-contraction. In an examination of the increased metabolic cost of walking among the elderly, Ortega and Farley (2007) found individual limb work not to explain the difference. They postulated greater levels of muscle co-contraction required for gait stabilization may be the responsible culprit. Indeed, when lateral stability is provided from an external source the metabolic cost of walking decreases by ~6% among healthy adults (Donelan et al., 2004). Future research should use electromyography (EMG) to examine the impact of midsole thickness on muscle contractions.

A consequence of altering midsole thickness amongst conditions was differing midsole masses. Evidence would suggest had the footwear conditions been left unaltered, the metabolic cost of running would have increased by 1% for every additional 100 grams in footwear mass difference (Franz et al., 2012). Therefore, running in the 50-mm footwear condition would be 0.46% more costly than running in the 35-mm condition, the mass difference being 46 grams. It is therefore advisable, given the choice of identical footwear models differing only in midsole thickness, the thinnest being 35-mm, a runner should select the 35-mm midsole to optimize metabolic performance.

Beyond the differences in midsole mechanical properties previously discussed, there are a few other limitations to this study. While there is robust evidence that stiff plates increase the forefoot bending stiffness of running footwear, the impact of plates on other midsole behavior are lesser understood, for example whether they impact midsole frontal stability. It is plausible that rods increase frontal plane stability reducing the impact of increases in midsole thickness. It is therefore inadvisable to assume an increase in thickness of a midsole sans plates would have the same impact as that seen in this study. Similarly, this study was performed on a treadmill. Evidence would suggest peak medial ground reaction force to be significantly reduced during treadmill running as compared to overground running (Riley et al., 2008). Larger medial-lateral ground reaction forces may exacerbate the differences in ankle eversion seen in this study further intensifying the rationale for choosing a midsole of lesser thickness.

In conclusion, there is no energetic benefit to running in footwear with a midsole thickness beyond 35-mm, assuming the midsoles are constructed of the same material. These results and this recommendation are based on straight-line running during which the magnitude of lateral force is minimal. Future research should investigate the impact of midsole thickness on curved running during which runners are exposed to substantially greater lateral forces.

The Influence of Midsole Thickness on Curved Running

1.11 - Introduction

For a road running race to be record eligible, World Athletics rule 31.21.2 states “The start and finish points of a course, measured along a theoretical straight line between them, shall not be further apart than 50% of the race distance.” (*COMPETITION RULES, Book C - C.1*, 2021). Although the practical implication of this rule is that road races must feature at least one turn, in practice, record eligible road races, from the 5 to 100 km distances, typically feature numerous turns, an element of a race neglected by the methodologies commonly employed to study advanced footwear technology. Performance-oriented running footwear featuring (i) a forefoot stiffening apparatus, (ii) a pronounced rocker profile and (iii) perhaps most visible, a thick resilient midsole, advanced footwear technology has repeatedly demonstrated to improve treadmill running performance (Heyde et al., 2022; Hoogkamer et al., 2017; Joubert & Jones, 2022). Although statistical models have been used on large publicly sourced data sets adding the external validity of having been collected during actual races featuring turns, they don’t incorporate a biomechanical analysis (Quealy & Katz, 2018, 2019). In a comparison of curved and linear running, Smith et al., (2006) found curved running to require the generation of significantly greater medial-lateral forces than linear running. Increased medial-lateral forces may prove detrimental to the frontal plane ankle angle of runners wearing footwear with substantial midsoles. As outlined by Hoogkamer (2020), as midsole thickness increases so too does the moment arm of the ground reaction force about the longitudinal axis of the foot. When combined with the medial or lateral forces associated with running, an increased moment arm could result in a larger moment and decreased frontal plane stability as evidenced by greater peak frontal plane ankle angles. While a biomechanical analysis was not part of the study conducted by Smith et al. (2006), substantiation of this in linear running was found when comparing midsole thicknesses of 35-, 40-, 45- and 50-mm in Chapter 1. Participants were found to display 2-3° greater ankle eversion (depending on gender) when running in the thickest footwear conditions. If instead, the elongated moment arm of advanced footwear technology was combined with the increased medial forces of curved running, the impact on frontal plane ankle angle could be even greater. This could be detrimental to runners as both increased ankle eversion and inversion have been correlated with in increased risk of injury (Hannigan & Pollard, 2020; Willems et al., 2005). In addition to potentially exposing a runner to an increased risk of injury, ankle eversion may also skew the orientation of the resultant ground reaction force with respect to the desired direction of movement, potentially negatively impacting performance (Moore et al., 2016; Wannop et al., 2014). Wannop et al. (2014) found an increased ankle eversion angle to reduce the horizontal impulse generated during a cutting movement, which they theorized would reduce performance. If true when running curves, a thick midsole could increase ankle eversion and consequently reduce curve running speeds, which would be detrimental for performance. Therefore, the purpose of this study was to determine the impact of midsole thickness on frontal plane ankle angle and performance when running curves.

1.12 - Methods

1.12.1 - Footwear

Two footwear models featuring either a 35-, or 50-mm thick midsole were tested in this experiment (Figure 4.1). The 35-mm condition was selected to represent traditional running footwear while the 50-mm condition represented the upper limit of what is commercially available. The footwear models featured identical uppers, five embedded carbon infused rods, and midsoles constructed of a thermoplastic polyester elastomer (TPEE). A consequence of the differing midsole thicknesses was the footwear models exhibited differences in midsole stiffness, forefoot bending stiffness and mass (Table 4.1). The decision was made to leave each variable as was (i.e., non-normalized) to avoid damaging the footwear, as was the risk with altering forefoot bending stiffness and midsole stiffness, or because the difference was thought to be inconsequential for the purposes of this study as was the case for footwear mass. Although an increase in footwear mass has been demonstrated to decrease running economy, evidence would suggest it does not alter running biomechanics (Rodrigo-Carranza et al., 2020).

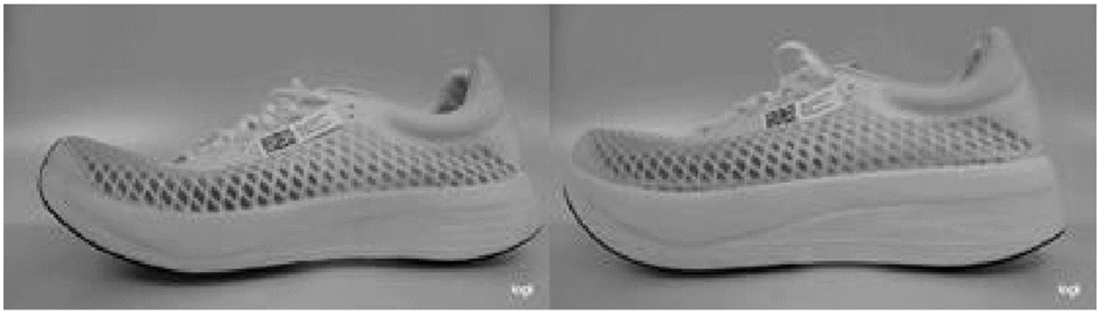

Figure 0.1: The two footwear conditions tested, 35-mm (left), and 50-mm (right)

Table 0.1: Mechanical properties of the different footwear conditions.

	35-mm	50-mm
Mass (g)	214.5	260.5
Rearfoot Stiffness (N/mm)	176	100
Forefoot Stiffness (N/mm)	201	131
Energy Return (%)	83.5	86.5
Bending Stiffness (Nm/º)	0.187	0.166

1.12.2 - Participants

Thirteen recreational athletes, four females and nine males (mean ± SD, age: 24.3 ± 3.3, height: 172.9 ± 5.1 cm, mass: 66.9 ± 5.3 kg), all of whom fit a men's shoe size US9 were recruited for this study. Informed written consent was obtained from all participants prior to the data collection in accordance with the University of Calgary's Ethics Board.

1.12.3 - Data Collection

Participants performed ten successful over ground running trials around three curves of different radii (Figure 4.2) in two footwear conditions (i.e., 30 trials per shoe). The radii of the three curves were 3-, 6-, and 9-m and were selected based on the tightest curves observed on Abbot World Marathon course maps, and pilot testing. Each curve was taped on the floor of the lab, their paths intersecting over a Kistler force plate (Kistler Group, Winterthur, Switzerland) that collected at 2400 Hz. A successful trial was defined as one in which participants i) accurately followed the path as laid out on the floor (i.e., no cut corners) as visually determined by the tester, ii) hit the force plate in stride with their right foot (i.e., no stutter steps), and iii) entered the turn moving between 4 and 5 m/s. Turn entrance speed was determined using a pair of Brower timing lights (Brower Timing Systems, Draper, USA) positioned one meter apart at the entrance of the turn and was selected based on the work of Chang and Kram (2007) who found 4.49 ± 0.07 m/s to be the fastest speed around which participants could sprint a 3-meter radii circle. Participants were instructed to attempt to maintain running speed for the duration of the curve. Following the completion of ten successful trials, the timing lights were moved to the next turn. The decision was made for participants to strike the force plate with their outside leg (i.e., their right foot) because Chang and Kram (2007) determined that to be the leg that generates higher medial forces and, therefore, that which might experience a greater frontal plane ankle angle as a result. Participants performed five warm-up trials before each new shoe-curve combination and were permitted to start each trial a distance away from the turn of their choosing as long as they started the turn running between 4 and 5 m/s.

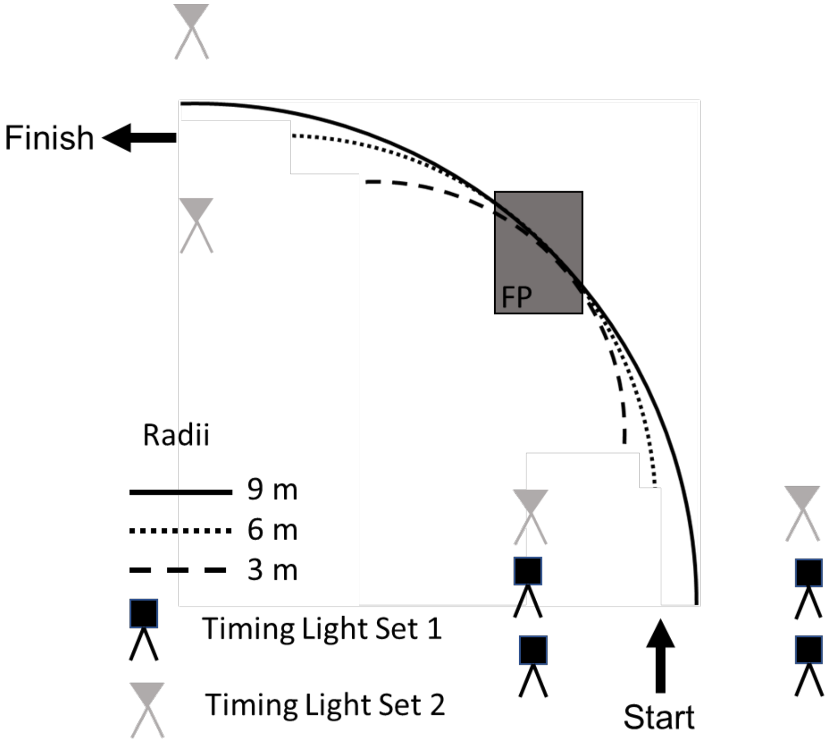

Figure 0.2: A diagram of the three curves (3-, 6-, and 9-m radii) and two sets of timing light positions.

Positioned around the three curves was an eight camera Vicon motion capture system (Vicon, Denver, USA) collecting at 240 Hz. Used in conjunction with the motion capture camera system were four sets of four non-collinear retroreflective tracking markers. Each set was used to define one of four segments: a pelvis, right thigh, right shank, and right foot. The pelvis segment was defined by four retroreflective markers placed on the left and right, anterior, and posterior iliac crests, while the thigh and shank segments were defined by two marker sets arranged in diamond patterns. The right foot segment was defined by markers affixed to each of the two right shoes. Two markers were placed at proximal and distal locations on the heel of each shoe such that they aligned with the Achilles tendon of the participant while the remaining two markers were affixed at varying heights to the lateral side of each shoe. Joint center locations of the ankle and knee were determined by placing additional markers on the following locations: medial and lateral malleolus (to define the ankle joint), and medial and lateral epicondyles of the femur (to define the knee joint). The hip joint was defined during the data analysis process in Visual 3D using a Coda pelvis and the method as outlined by (Bell et al., 1989). A second set of timing lights synchronized with the motion capture system and positioned at the start and end of each curve signalled the motion capture system to start recording as participants entered the curve and stopped the recording as participants exited the curve, thereby both operating the camera system and timing each trail.

1.12.4 - Data Analysis

Motion capture data was manually tracked using Vicon Nexus software before being exported and imported into Visual 3D software (C-Motion, Germantown, MD, USA). Once imported, ground reaction forces and kinematic data were smoothed using a zero-lag, low-pass, 4th order Butterworth filter with a cut-off frequency of 15-Hz. Ground reaction forces were then rotated to be in reference to the participants foot (as opposed to the force plate) before gait events (i.e., heel-strike and toe-off) in each trial were identified using a 20-Newton threshold after which Cardan angles, moments, powers, and work of the ankle, knee, and hip were calculated using a four-segment model. These were exported from Visual 3D and analyzed (i.e., the identification of peak values, and the calculation of averages) in Excel software. To determine the time it took each participant to run each curve, referred to as “time to completion”, and peak centre of mass velocity, force and motion capture data were exported from Nexus directly to Matlab. Time to completion was determined by calculating the duration of each trial (number of frames/sampling rate). Centre of mass velocity was calculated by first smoothing the force and motion capture data and determining gait events in the same manner as in Visual 3D. The centre of mass location for every frame of each trial was then determined as the centre of the pelvis, equidistance from the left and right anterior superior iliac spines and posterior superior iliac spines. The velocity was then calculated between gait events (i.e., heel-strike and toe-off) as determined using a 20 N threshold for each trial using the first central difference method after which the peak velocity was identified.

1.12.5 - Statistical Analysis

All statistical analysis was performed in SPSS software (IBM, Armonk, NY, USA) using a two-way repeated measures ANOVA ($p < 0.05$) with within-participant factors of footwear conditions (two-levels, 35-, and 50-mm midsoles) and curve (three levels, 3-, 6-, and 9-m). Interactions between footwear and curve were also analyzed. The main outcome variables were peak centre of mass velocity, time-to-completion, contact time, peak ground reaction forces, joint angles, velocities, moments, and work. If a significant difference was detected a pairwise comparison analysis was performed with Bonferroni confidence interval adjustment ($p < 0.05$).

1.13 - Results

1.13.1 - Footwear

The influence of footwear condition across all curves is shown in Table 4.2. When running in the 35-mm footwear condition participants were found to generate larger propulsive forces ($p = 0.03$), plantarflexion moments ($p = 0.01$), and magnitudes of positive ($p < 0.01$), and negative ($p = 0.02$) ankle power. Participants were also found to perform more positive ($p < 0.01$), and negative ($p < 0.01$) ankle work. While no differences were found at the knee, participants generated larger internal hip rotation moments while wearing the 35-mm footwear condition ($p = 0.01$).

Table 0.2: Running related variables when running in the 35-, and 50-mm footwear conditions across all curves.

			Footwear			
			35-mm	50-mm	F-value	p-value
	Velocity (m/s)		4.4 ± 0.5	4.4 ± 0.5	0.31	0.59
	Time to Completion (s)		2.2 ± 0.1	2.2 ± 0.1	0.02	0.89
	Stance Time (s)		0.20 ± 0.02	0.20 ± 0.02	0.06	0.81
Peak Forces	Braking (BW)		0.6 ± 0.1	0.6 ± 0.1	0.10	0.76
	Propulsive (BW)		**-0.28 ± 0.07**	**-0.26 ± 0.08**	**8.45**	**<0.01**
	Medial (BW)		-0.7 ± 0.2	-0.7 ± 0.2	0.06	0.81
	Vertical (BW)		2.6 ± 0.3	2.6 ± 0.3	0.10	0.76
	Resultant (BW)		2.8 ± 0.2	2.8 ± 0.2	0.01	0.92
Foot	Peak Angle (º)	Internal roll	-25.7 ± 4.8	-25.6 ± 4.4	<0.01	0.94
Ankle	Peak Angle (º)	Dorsiflexion	10.0 ± 2.7	9.5 ± 3.0	0.78	0.40
		Plantarflexion	-10.0 ± 3.4	-9.4 ± 2.8	0.81	0.39
		Inversion	5.8 ± 3.0	5.3 ± 2.9	0.95	0.35
		External rot.	-17.7 ± 5.4	-17.6 ± 6.7	<0.01	0.96
	Peak Velocity (º/s)	Dorsiflexion	247.2 ± 88.0	229.2 ± 104.7	1.86	0.20
		Plantarflexion	-354.0 ± 61.7	-352.0 ± 77.5	0.14	0.72
		Inversion	70.6 ± 27.0	80.8 ± 32.4	3.07	0.11
		Eversion	-87.8 ± 32.9	-84.1 ± 33.8	0.98	0.34
	Peak Moment (Nm)	Plantarflexion	**-193.1 ± 28.6**	**-182.6 ± 25.2**	**8.23**	**0.01**
		Eversion	-22.1 ± 11.8	-23.5 ± 13.0	0.35	0.57
		Inversion	10.1 ± 10.8	9.6 ± 11.1	0.05	0.82
		External rot.	-23.6 ± 10.8	-22.5 ± 8.4	0.53	0.48
		Internal rot.	2.2 ± 2.1	1.9 ± 1.4	1.04	0.33
	Sagital Power (W)	Positive	**860.8 ± 202.0**	**757.0 ± 187.7**	**8.03**	**0.02**
		Negative	**-590.9 ± 204.2**	**-511.2 ± 209.4**	**23.21**	**<0.01**
	Sagital Work (J)	Positive	**50.2 ± 9.1**	**45.1 ± 10.5**	**17.42**	**<0.01**
		Negative	**-36.8 ± 12.3**	**-30.8 ± 11.2**	**22.80**	**<0.01**
		Net	14.8 ± 14.6	16.2 ± 11.2	0.97	0.34
Knee	Peak Angle (º)	Flexion	40.8 ± 4.6	42.6 ± 4.4	3.86	0.07
		Abduction	-3.8 ± 4.5	-3.5 ± 4.0	0.11	0.75
		Adduction	3.0 ± 4.1	2.9 ± 3.2	0.02	0.89
		External rot.	-7.6 ± 6.2	-9.4 ± 4.5	1.11	0.31
		Internal rot.	8.9 ± 7.1	7.7 ± 6.2	0.63	0.44
	Peak Velocity (º/s)	Flexion	544.3 ± 83.3	536.1 ± 90.6	0.15	0.71
		Extension	-304.8 ± 68.0	-308.2 ± 82.4	0.15	0.71
	Peak Moment (Nm)	Extension	-207.6 ± 41.2	-215.4 ± 36.6	2.97	0.11
		Abduction	-48.1 ± 32.3	-44.2 ± 28.7	0.68	0.43
		Adduction	13.6 ± 15.0	16.0 ± 12.7	1.33	0.27
		Internal rot.	32.3 ± 9.1	32.1 ± 7.8	0.06	0.82
	Sagital Power (W)	Positive	661.1 ± 304.7	681.5 ± 250.1	0.16	0.69
		Negative	-1,269.8 ± 584.8	-1,223.6 ± 495.5	0.22	0.65
	Sagital Work (J)	Positive	34.9 ± 12.6	36.5 ± 11.2	0.65	0.44
		Negative	-48.0 ± 17.8	-50.6 ± 16.0	1.04	0.33
		Net	-15.3 ± 14.1	-14.5 ± 9.5	0.96	0.34
Hip	Peak Angle (º)	Flexion	38.2 ± 6.6	39.0 ± 6.7	0.57	0.47
		Extension	-9.4 ± 6.4	-7.7 ± 7.5	2.68	0.13
		Abduction	-3.7 ± 4.7	-4.5 ± 3.8	2.28	0.16
		Adduction	5.2 ± 6.1	4.2 ± 6.1	4.75	0.05
		External rot.	-7.3 ± 8.5	-6.5 ± 6.7	0.19	0.68
	Peak Extension Velocity (º/s)		-419.3 ± 75.1	-420.8 ± 75.5	0.02	0.89
	Peak Moment (Nm)	Extension	-108.2 ± 28.8	-112.2 ± 27.5	1.52	0.24
		Flexion	60.8 ± 16.5	61.4 ± 15.8	0.10	0.75
		Abduction	-115.3 ± 25.5	-111.1 ± 21.9	1.96	0.19
		External rot.	-35.8 ± 10.5	-35.5 ± 10.8	0.28	0.87
		Internal rot.	**11.5 ± 8.1**	**8.7 ± 5.8**	**9.00**	**0.01**
	Sagital Power (W)	Positive	197.6 ± 94.9	200.4 ± 100.0	0.03	0.87
		Negative	-359.0 ± 111.9	-346.1 ± 91.7	0.87	0.37
	Sagital Work (J)	Positive	7.1 ± 4.1	7.5 ± 4.2	0.62	0.45
		Negative	-28.9 ± 7.6	-28.1 ± 7.5	0.51	0.49
		Net	-21.4 ± 10.1	-19.5 ± 10.8	2.48	0.14

Bolded numbers indicate significant differences.

1.13.2 - Curves

In a comparison of curved running, there were significant main effects observed in performance, ground reaction forces, and kinetic and kinematic variables of the ankle, knee, and hip (Table 4.3). Participants ran at faster peak velocities (6-m vs. 3-m, 9-m vs. 3-m, 9-m vs. 6-m, $p < 0.01$, $p < 0.01$, $p < 0.01$)), and had shorter stance times ($F = 43.43$, $p < 0.01$) as curve radii increased. Participants also took less time to run the 6-, and 9-m curves (i.e., time to completion) than they did the 3-m curve ($p = 0.01$, $p = 0.01$). Participants generated larger vertical ground reaction forces ($F = 43.58$, $p < 0.01$), and propulsive forces ($F = 44.136$, $p < 0.01$), as curve radii increased but conversely generated smaller braking forces ($F = 44.136$, $p < 0.01$), and medial forces ($F = 42.631$, $p < 0.01$) (Figure 4.3).

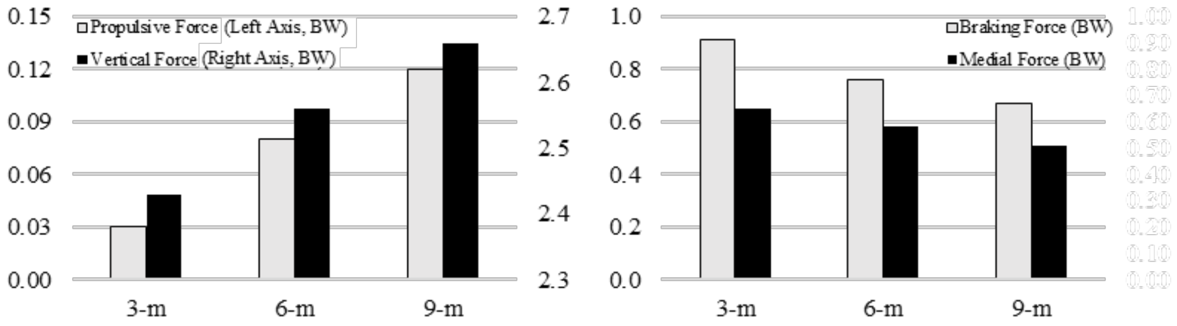

Figure 0.3: Peak propulsive and Vertical Forces (Left) and peak Braking and Medial Force (Right) during 3-, 6-, and 9-m curved runs) in units of body weight (BW).

At the foot, in the frontal plane, participants experienced greater internal roll about the longitudinal axis of the foot as curve radii increased (3-m vs. 6-m, 3-m vs. 9-m, 6-m vs. 9-m, $p < 0.01$, $p < 0.01$, $p < 0.01$).

At the ankle, in the sagittal plane, participants experienced greater dorsiflexion (3-m vs. 6-m, 3-m vs. 9-m, 6-m vs. 9-m, $p < 0.01$, $p < 0.01$, $p < 0.01$), and increased plantarflexion velocities

($p < 0.01$, $p < 0.01$, $p = 0.04$) as curve radii increased. However, participants only generated greater plantarflexion moments (3-m vs. 6-m, 3-m vs. 9-m, $p < 0.01$, $p < 0.01$), and positive power ($p < 0.01$, $p < 0.01$), and only performed greater positive ($p < 0.01$, $p < 0.01$) and negative work ($p = 0.02$, $p = 0.04$) when running the 6- and 9-m curves as compared to the 3-m curve. In the frontal plane participants experienced greater ankle inversion angles ($p < 0.01$) and ankle eversion velocity ($p = 0.02$) when running the 3-m as compared to the 9-m curve. While participants generated decreased eversion moments as curve radii increased (3-m vs. 6-m, 3-m vs. 9-m, 6-m vs. 9-m, $p < 0.01$, $p < 0.01$, $p = 0.01$), they generated greater inversion moments when running the 6-, and 9-m curves as compared to the 3-m curve (3-m vs. 6-m, 3-m vs. 9-m, $p < 0.01$, $p < 0.01$). Participants generated greater positive power and work when running the 6- and 9-m curve as compared to the 3-m curve ($p < 0.01$, $p < 0.01$, $p < 0.01$, $p < 0.01$), but only greater negative ($p < 0.01$) and net work ($p = 0.02$) when running the 6-m curve as compared to the 3-m curve. In the transverse plane, participants experienced greater external ankle rotation when running the 3-m curve as compared to the 6- ($p = 0.01$), and 9-m ($p < 0.01$) curves but greater internal rotation ankle moments as compared to the 6-m curve ($p =0.03$).

At the knee, in the sagittal plane, participants experienced greater extension velocity ($p < 0.01$, $p < 0.01$), and generated greater positive power ($p = 0.01$, $p = 0.01$) when running the 6-, and 9-m curves as compared to the 3-m. In the frontal plane, participants generated greater abduction moments when running the 9-m curve, as compared to the 3- ($p = 0.04$), and 6-m ($p = 0.03$) curves, and lesser adduction moments when running in the 6- ($p < 0.01$), and 9-m ($p = 0.02$) curves as compared to the 3-m curve. In the transverse plane, participants generated greater internal rotation moments as curve radii increased (3-m vs. 6-m, 3-m vs. 9-m, 6-m vs. 9-m, $p < 0.01$, $p < 0.01$, $p = 0.014$).

At the hip, in the sagittal plane, participants had greater hip extension ($p < 0.01$, $p = 0.01$) when running 6-, and 9-m curve as compared to the 3-m curve and experienced increased hip extension velocity with increasing curve radii (3-m vs. 6-m, 3-m vs. 9-m, 6-m vs. 9-m, $p = 0.01$, $p < 0.01$, $p = 0.01$). Participants generated more negative power when running the 9-m corner as compared to the 3- ($p < 0.01$), and 6-m ($p = 0.01$) and performed more negative work when running the 9-m curve as compared to the 3-m curve ($p = 0.02$). In the frontal plane, as curve radii increased, hip abduction decreased (3-m vs. 6-m, 3-m vs. 9-m, 6-m vs. 9-m, $p < 0.01$, $p < 0.01$, $p < 0.01$), and hip adduction (3-m vs. 6-m, 3-m vs. 9-m, 6-m vs. 9-m, $p < 0.01$, $p < 0.01$, $p < 0.01$) and abduction moments (3-m vs. 6-m, 3-m vs. 9-m, 6-m vs. 9-m, $p < 0.01$, $p < 0.01$, $p < 0.01$) increased. In the transverse plane, as curve radii increased, so too did hip external rotation moments (3-m vs. 6-m, 3-m vs. 9-m, 6-m vs. 9-m, $p < 0.01$, $p < 0.01$, $p < 0.01$).

Table 0.3: Running related variables when running the 3-, 6-, and 9-m curves.

			Curves				
			3-m	**6-m**	**9-m**	**F-Value**	**p-value**
	Velocity (m/s)		**4.0 ± 0.3**	**4.5 ± 0.3**	**4.8 ± 0.5**	**53.09**	**<0.01**^{d}
	Time to Completion (s)		**2.29 ± 0.1**	**2.19 ± 0.1**	**2.17 ± 0.1**	**8.72**	**0.01**^{ab}
	Stance Time (s)		**0.23 ± 0.02**	**0.22 ± 0.02**	**0.21 ± 0.02**	**43.43**	**<0.01**^{d}
Peak Forces	Braking (BW)		**0.63 ± 0.10**	**0.56 ± 0.09**	**0.54 ± 0.12**	**43.58**	**<0.01**^{d}
	Propulsive (BW)		**-0.20 ± 0.08**	**-0.29 ± 0.10**	**-0.32 ± 0.11**	**97.85**	**<0.01**^{d}
	Medial (BW)		**-0.9 ± 0.1**	**-0.7 ± 0.1**	**-0.6 ± 0.1**	**111.77**	**<0.01**^{d}
	Vertical (BW)		**2.4 ± 0.3**	**2.6 ± 0.3**	**2.7 ± 0.2**	**43.58**	**<0.01**^{d}
	Resultant (BW)		2.7 ± 0.3	2.7 ± 0.7	2.8 ± 0.2	2.34	0.12
Foot	Peak Angle (°)	Internal roll	**-21.2 ± 3.2**	**-26.3 ± 3.1**	**-29.5 ± 3.2**	**154.62**	**<0.01**^{d}
Ankle	Peak Angle (°)	Dorsiflexion	**9.0 ± 3.0**	**9.9 ± 2.0**	**10.3 ± 2.8**	**15.36**	**<0.01**^{d}
		Plantarflexion	-9.6 ± 3.6	-10.0 ± 2.5	-9.5 ± 3.1	0.90	0.42
		Inversion	**5.8 ± 3.0**	**5.4 ± 2.9**	**5.3 ± 2.9**	**4.30**	**0.04**^{b}
		External rot.	**-19.7 ± 5.7**	**-16.5 ± 6.6**	**-16.8 ± 5.4**	**7.32**	**<0.01**^{ab}
	Peak Velocity (°/s)	Dorsiflexion	235.9 ± 108.9	256.4 ± 95.3	229.7 ± 84.6	0.69	0.51
		Plantarflexion	**-307.0 ± 65.1**	**-366.4 ± 58.2**	**-385.6 ± 61.1**	**31.23**	**<0.01**^{d}
		Inversion	71.7 ± 27.7	76.9 ± 32.1	78.4 ± 30.3	0.37	0.69
		Eversion	**-75.7 ± 21.1**	**-87.5 ± 37.8**	**-94.7 ± 35.9**	**5.08**	**0.014**^{b}
	Peak Moment (Nm)	Plantarflexion	**-176.0 ± 27.7**	**-192.9 ± 25.8**	**-194.6 ± 24.9**	**34.82**	**<0.01**^{ab}
		Eversion	**-31.3 ± 13.2**	**-20.5 ± 9.2**	**-16.6 ± 9.4**	**17.30**	**<0.01**^{d}
		Inversion	**3.9 ± 6.8**	**10.3 ± 10.2**	**16.2 ± 11.6**	**41.00**	**<0.01**^{ab}
		External rot.	-22.9 ± 11.3	-23.4 ± 9.5	-22.7 ± 7.9	0.18	0.83
		Internal rot.	**2.6 ± 2.4**	**1.7 ± 1.4**	**1.8 ± 1.2**	**3.75**	**0.04**^{ab}
	Power (W)	Positive	**699.0 ± 171.8**	**836.3 ± 184.1**	**882.9 ± 199.8**	**33.09**	**<0.01**^{ab}
		Negative	-509.9 ± 228.1	-559.9 ± 186.7	-583.4 ± 208.3	2.69	0.11
	Work (J)	Positive	**43.1 ± 10.2**	**50.0 ± 9.6**	**49.9 ± 9.0**	**21.89**	**<0.01**^{ab}
		Negative	**-31.4 ± 12.3**	**-35.0 ± 11.4**	**-34.0 ± 12.3**	**5.15**	**0.01**^{a}
		Net	**13.1 ± 14.0**	**16.7 ± 15.1**	**16.7 ± 15.2**	**4.99**	**0.02**^{a}
Knee	Peak Angle (°)	Flexion	41.4 ± 4.8	41.95 ± 4.2	-41.8 ± 4.8	0.39	0.68
		Abduction	-3.9 ± 4.4	-3.5 ± 4.1	-3.6 ± 4.2	1.14	0.34
		Adduction	3.0 ± 3.6	2.7 ± 3.7	3.2 ± 37.	1.95	0.16
		External rot.	-8.6 ± 6.1	-8.6 ± 5.1	-8.3 ± 5.3	0.43	0.66
		Internal rot.	7.8 ± 6.5	8.4 ± 6.7	8.5 ± 6.8	1.99	0.16
	Peak Velocity (°/s)	Flexion	539.7 ± 79.5	540.3 ± 61.6	540.6 ± 112.5	<0.01	0.99
		Extension	**-261.6 ± 75.4**	**-322.6 ± 60.7**	**-336.0 ± 68.0**	**13.47**	**<0.01**^{ab}
	Peak Moment (Nm)	Extension	-205.0 ± 40.4	-210.7 ± 37.2	-215.4 ± 39.0	2.09	0.15
		Abduction	**-43.4 ± 30.3**	**-44.8 ± 29.6**	**-50.3 ± 31.4**	**3.92**	**0.03**^{ac}
		Adduction	**19.5 ± 18.2**	**12.5 ± 11.4**	**12.4 ± 9.6**	**7.69**	**< 0.01**^{ab}
		Internal rot.	**28.3 ± 6.9**	**32.8 ± 7.3**	**35.6 ± 9.3**	**19.24**	**<0.001**^{d}
	Sagital Power (W)	Positive	**590.7 ± 267.7**	**685.5 ± 253.7**	**726.5 ± 295.2**	**7.77**	**<0.01**^{ab}
		Negative	-1,248.5 ± 526.4	-1,191.7 ± 427.1	-1,300.0 ± 646.1	0.37	0.70
	Sagital Work (J)	Positive	33.8 ± 12.5	36.9 ± 10.8	36.3 ± 12.2	1.79	0.20
		Negative	-49.4 ± 17.5	-48.6 ± 14.9	-49.9 ± 18.3	0.07	0.94
		Net	**-17.4 ± 12.7**	**-12.8 ± 13.4**	**-14.5 ± 15.0**	**4.99**	**0.02**^{ac}
Hip	Peak Angle (°)	Flexion	37.9 ± 6.7	37.8 ± 6.4	39.7 ± 6.8	2.98	0.07
		Extension	**-6.8 ± 7.8**	**-9.4 ± 6.0**	**-9.5 ± 6.8**	**8.92**	**<0.01**^{ab}
		Abduction	**-6.6 ± 4.2**	**-3.35 ± 3.72**	**-2.4 ± 3.7**	**46.37**	**<0.01**^{d}
		Adduction	**-0.3 ± 5.0**	**5.76 ± 5.00**	**8.6 ± 4.7**	**136.89**	**<0.01**^{d}
		External rot.	**-8.7 ± 7.5**	**-6.14 ± 7.42**	**-5.9 ± 7.6**	**21.77**	**<0.01**^{ab}
	Peak Extension Velocity (°/s)		**-376.3 ± 54.9**	**-425.6 ± 61.1**	**-458.3 ± 82.8**	**16.05**	**<0.01**^{d}
	Peak Moment (Nm)	Extension	-109.4 ± 30.2	-108.3 ± 29.8	-113.0 ± 24.1	0.77	0.47
		Flexion	65.6 ± 19.3	59.3 ± 13.2	58.5 ± 14.4	2.46	0.11
		Abduction	**-95.1 ± 19.6**	**-116.2 ± 19.2**	**-128.3 ± 19.9**	**62.31**	**<0.01**^{d}
		External rot.	**-28.8 ± 8.6**	**-36.0 ± 9.0**	**-42.1 ± 9.9**	**20.77**	**<0.01**^{d}
		Internal rot.	10.5 ± 7.4	10.0 ± 6.8	9.9 ± 7.4	0.09	0.91
	Sagital Power (W)	Positive	202.8 ± 105.2	171.9 ± 100.1	218.3 ± 80.7	2.65	0.09
		Negative	**-300.1 ± 81.1**	**-347.8 ± 81.2**	**-409.7 ± 110.9**	**9.99**	**<0.01**^{ab}
	Sagital Work (J)	Positive	7.9 ± 4.8	6.7 ± 4.4	7.2 ± 3.1	0.93	0.41
		Negative	**-25.9 ± 6.8**	**-28.5 ± 6.4**	**-31.1 ± 8.5**	**5.22**	**0.01**^{b}
		Net	**-17.1 ± 9.2**	**-21.1 ± 9.9**	**-23.1 ± 11.3**	**4.22**	**0.03**^{b}

Bolded numbers indicate significant differences.

[a] Indicates a significant difference between the 3- and 6-m curves.

[b] Indicates a significant difference between the 3- and 9-m curves.

[c] Indicates a significant difference between the 6- and 9-m curves.

[d] Indicates a significant difference between all curves.

*1.13.3 - Footwear * Curve*

Statistically significant interactions between curves and footwear were observed at the ankle, knee, and hip and can be seen in Table 4.4. When running the 3-m radii curve, while wearing the 50-mm footwear condition, participants experienced slower plantarflexion velocities ($p = 0.01$) and generated smaller plantarflexion moments ($p < 0.01$), while exhibiting less peak hip extension ($p = 0.03$).

When running the 9-m radii curve, while wearing the 50-mm footwear condition, participants experienced faster knee extension velocities than when wearing the 35-mm footwear condition ($p = 0.04$).

While wearing the 35-mm footwear condition, participants experienced faster plantarflexion ($p < 0.001$, $p < 0.001$), and knee extension velocities ($p < 0.01$, $p < 0.01$), while generating larger plantarflexion moments ($p < 0.01$, $p < 0.01$) when running the 6-, and 9-m curves as compared to the 3-m curve. Participants also performed more frontal plane positive work while wearing the 35-mm footwear condition and running the 3- ($p = 0.04$), and 6-m ($p < 0.01$) curves as compared to the 9-m curve.

While wearing the 50-mm footwear condition, participants experienced faster plantarflexion and knee extension as curve radii increased (3-m vs. 6-m, 3-m vs. 9-m, 6-m vs. 9-m, $p < 0.01$, $p < 0.01$, $p = 0.04$) and experienced greater peak hip extension when running the 6-

($p < 0.01$), and 9-m ($p < 0.01$) curves as compared to the 3-m. Participants also generated larger plantarflexion moments when running the 6- ($p < 0.01$), and 9-m ($p < 0.01$) curves as compared to the 3-m curve.

Table 0.4: Running related variables when wearing the 35-, and 50-mm footwear conditions and running the 3-, 6-, and 9-m curves.

			3-m		**6-m**		**9-m**			
			35-mm	**50-mm**	**35-mm**	**50-mm**	**35-mm**	**50-mm**	F-Value	p-value
	Velocity (m/s)		3.97 ± 0.31	3.93 ± 0.32	4.43 ± 0.43	4.51 ± 0.33	4.76 ± 0.52	4.78 ± 0.51	1.85	0.18
	Time to Completion (s)		2.24 ± 0.07	2.26 ± 0.10	2.20 ± 0.10	2.19 ± 0.09	2.17 ± 0.11	2.17 ± 0.13	1.57	0.23
	Stance Time (s)		0.23 ± 0.02	0.23 ± 0.02	0.22 ± 0.02	0.22 ± 0.02	0.21 ± 0.02	0.21 ± 0.02	1.72	0.20
Peak Forces	Braking (BW)		0.63 ± 0.14	0.64 ± 0.12	0.56 ± 0.10	0.55 ± 0.11	0.55 ± 0.14	0.52 ± 0.11	0.64	0.54
	Propulsive (BW)		-0.22 ± 0.10	-0.18 ± 0.13	-0.30 ± 0.12	-0.27 ± 0.11	-0.32 ± 0.10	0.31 ± 0.14	1.23	0.31
	Medial (BW)		-0.90 ± 0.12	-0.88 ± 0.11	-0.70 ± 0.10	-0.74 ± 0.14	-0.57 ± 0.14	-0.57 ± 0.11	3.09	0.06
	Vertical (BW)		2.42 ± 0.32	2.44 ± 0.34	2.59 ± 0.33	2.57 ± 0.21	2.65 ± 0.24	2.67 ± 0.24	0.64	0.54
	Resultant (BW)		2.73 ± 0.21	2.74 ± 0.31	2.74 ± 0.22	2.74 ± 0.23	2.83 ± 0.22	2.82 ± 0.20	0.16	0.86
Foot	Peak Angle (°)	Internal roll	**-20.8 ± 3.2**	**-21.6 ± 3.1**	**-26.7 ± 3.1**	**-25.9 ± 2.9**	**-29.5 ± 3.3**	**-29.5 ± 3.0**	**9.32**	**<0.01**^{abcdef}
Ankle	Peak Angle (°)	Dorsiflexion	9.3 ± 2.9	8.7 ± 3.0	10.2 ± 9.5	9.5 ± 2.8	10.5 ± 2.6	10.1 ± 2.9	0.27	0.77
		Plantarflexion	-10.2 ± 4.0	-9.0 ± 2.9	-10.3 ± 2.7	-9.7 ± 2.3	-9.6 ± 3.2	-9.4 ± 3.0	2.28	0.13
		Inversion	6.0 ± 3.1	5.5 ± 2.8	5.6 ± 2.9	5.2 ± 3.0	5.6 ± 2.8	5.1 ± 2.9	0.07	0.94
		External rot.	-18.8 ± 6.8	-20.7 ± 4.1	-16.9 ± 4.9	-16.0 ± 8.0	-17.4 ± 3.8	-16.2 ± 6.5	0.83	0.45
	Peak Velocity (°/s)	Dorsiflexion	241.9 ± 98.7	230.0 ± 118.0	257.6 ± 87.5	240.4 ± 101.8	242.1 ± 75.2	217.2 ± 91.2	0.24	0.79
		Plantarflexion	**-318.9 ± 60.5**	**-295.0 ± 67.3**	**-364.7 ± 54.9**	**-368.1 ± 61.4**	**-378.2 ± 53.1**	**-393.0 ± 67.3**	**8.60**	**<0.01**^{abdefg}
		Inversion	66.4 ± 26.9	77.1 ± 27.4	73.3 ± 32.1	80.4 ± 31.8	72.0 ± 20.1	84.8 ± 36.8	0.23	0.80
		Eversion	-77.0 ± 20.6	-74.5 ± 21.5	-89.8 ± 35.9	-85.0 ± 39.3	-96.5 ± 36.4	-92.8 ± 35.2	0.04	0.96
	Peak Moment (Nm)	Plantarflexion	**183.6 ± 28.8**	**168.4 ± 24.4**	**197.5 ± 26.2**	**188.2 ± 24.4**	**198.1 ± 28.5**	**191.1 ± 20.2**	**3.54**	**0.04**^{abdeg}
		Eversion	31.1 ± 11.9	31.4 ± 14.5	18.3 ± 8.6	22.8 ± 9.2	16.9 ± 9.1	16.2 ± 9.6	2.23	0.13
		Inversion	3.7 ± 6.4	4.1 ± 7.2	10.2 ± 10.1	8.8 ± 10.2	16. 3 ± 11.3	16.0 ± 11.9	0.43	0.66
		External rot.	-23.7 ± 12.2	-22.2 ± 10.3	-23.3 ± 11.1	-23.6 ± 7.6	-23.8 ± 8.7	-21.7 ± 6.8	1.09	0.35
		Internal rot.	2.7 ± 2.8	2.4 ± 1.9	1.7 ± 1.6	1.7 ± 1.1	2.0 ± 1.4	1.6 ± 1.0	0.25	0.78
	Power (W)	Positive	759.2 ± 174.1	639.5 ± 146.3	900.2 ± 177.2	790.0 ± 173.3	924.9 ± 209.7	841.0 ± 180.0	0.56	0.58
		Negative	-558.8 ± 220.4	-461.0 ± 225.1	-590.2 ± 168.7	-529.6 ± 198.5	-623.8 ± 214.2	-543.0 ± 194.1	0.76	0.48
	Work (J)	Positive	46.4 ± 9.4	39.8 ± 10.0	52.5 ± 8.9	47.5 ± 9.7	51.8 ± 7.8	48.1 ± 9.7	1.55	0.23
		Negative	-34.6 ± 12.0	-28.2 ± 11.8	-38.0 ± 11.2	-32.0 ± 10.8	-37.9 ± 13.2	-32.1 ± 10.6	0.08	0.92
		Net	13.0 ± 14.3	13.1 ± 13.8	16.1 ± 14.9	17.4 ± 15.1	15.5 ± 14.5	18.0 ± 15.8	1.06	0.36
Knee	Peak Angle (°)	Flexion	40.1 ± 5.1	42.6 ± 4.1	41.0 ± 3.9	42.9 ± 4.2	41.2 ± 4.7	42.3 ± 4.7	2.25	0.13
		Abduction	-4.0 ± 4.6	-3.8 ± 4.2	-3.5 ± 4.3	-3.4 ± 3.9	-3.8 ± 4.5	-3.4 ± 3.8	0.83	0.45
		Adduction	2.9 ± 4.1	3.1 ± 3.2	2.9 ± 4.1	2.5 ± 3.2	3.2 ± 4.2	3.1 ± 3.1	1.59	0.22
		External rot.	-7.6 ± 7.0	-9.5 ± 4.8	-7.8 ± 5.5	-9.5 ± 4.5	-7.3 ± 6.0	-9.2 ± 4.4	0.20	0.82
		Internal rot.	8.4 ± 7.1	7.2 ± 5.8	8.7 ± 7.1	8.1 ± 6.2	9.4 ± 7.0	7.6 ± 6.6	2.52	0.10
	Peak Velocity (°/s)	Flexion	532.8 ± 68.3	546.6 ± 88.7	546.8 ± 48.5	533.3 ± 71.7	553.3 ± 116.5	527.8 ± 106.9	1.16	0.33
		Extension	**-273.5 ± 62.2**	**-249.7 ± 85.0**	**-314.7 ± 65.4**	**-329.2 ± 54.7**	**-326.2 ± 64.6**	**-345.8 ± 70.0**	**6.36**	**0.01**^{abdefh}
	Peak Moment (Nm)	Extension	-199.9 ± 43.6	-209.9 ± 36.2	-209.9 ± 39.2	-218.4 ± 34.6	-213.0 ± 39.5	-217.7 ± 38.4	0.59	0.56
		Abduction	-44.7 ± 31.2	-42.0 ± 29.4	-45.9 ± 30.9	-43.6 ± 28.1	-53.6 ± 33.8	-47.0 ± 28.5	0.74	0.49
		Adduction	16.6 ± 19.7	22.4 ± 16.0	12.2 ± 12.2	12.8 ± 10.5	12.1 ± 11.1	12.7 ± 7.6	1.76	0.19
		Internal rot.	28.3 ± 7.7	28.2 ± 6.1	32.7 ± 7.6	32.8 ± 7.1	36.0 ± 10.2	35.2 ± 8.4	0.16	0.86
	Sagital Power (W)	Positive	587.6 ± 290.2	593.8 ± 243.1	668.5 ± 259.4	725.2 ± 244.5	727.3 ± 342.1	725.6 ± 239.3	0.85	0.44
		Negative	-1200.0 ± 574.4	-1296.9 ± 468.5	-1216.6 ± 467.2	-1166.7 ± 381.1	-1392.8 ± 674.4	-1207.2 ± 602.4	2.36	0.12
	Sagital Work (J)	Positive	33.1 ± 13.2	34.5 ± 11.9	35.8 ± 11.6	38.0 ± 9.8	35.8 ± 12.8	36.8 ± 11.5	0.32	0.73
		Negative	-46.3 ± 18.7	-52.4 ± 15.6	-47.0 ± 15.8	-50.1 ± 13.8	-50.6 ± 18.4	-49.1 ± 18.2	1.92	0.17
		Net	-15.4 ± 14.0	-19.4 ± 10.7	-13.8 ± 15.2	-11.9 ± 11.2	-17.0 ± 12.9	-12.3 ± 16.6	0.06	0.91
Hip	Peak Angle (°)	Flexion	37.4 ± 6.8	38.5 ± 6.5	37.8 ± 6.1	38.7 ± 6.7	39.4 ± 6.7	39.9 ± 6.8	0.35	0.71
		Extension	**-8.7 ± 7.4**	**-4.9 ± 7.7**	**-9.6 ± 5.6**	**-9.1 + 6.4**	**-9.8 ± 5.9**	**-9.1 + 7.6**	**5.60**	**0.01**^{deg}
		Abduction	-6.3 ± 4.5	-6.9 ± 3.9	-2.9 ± 4.6	-3.8 ± 2.5	-2.0 ± 4.0	-2.7 ± 3.5	0.10	0.91
		Adduction	0.2 ± 4.7	-0.7 ± 5.2	6.2 ± 5.2	5.3 ± 4.7	9.3 ± 4.3	8.0 ± 4.9	0.12	0.89
		External rot.	-9.1 ± 8.2	-8.3 ± 6.8	-6.5 ± 8.4	-5.8 ± 6.3	-6.3 ± 8.5	-5.5 ± 6.6	0.02	0.99
	Peak Extension Velocity (°/s)		-382.5 ± 50.3	-370.1 ± 58.5	-418.0 ± 63.1	-433.1 ± 58.1	-457.5 ± 87.1	-459.1 ± 78.3	2.35	0.12
	Peak Moment (Nm)	Extension	-107.9 ± 36.1	-110.8 ± 22.7	-104.2 ± 24.2	-112.5 ± 34.0	-112.5 ± 23.8	-113.4 ± 24.3	0.38	0.69
		Flexion	64.4 ± 19.2	66.7 ± 19.2	58.8 ± 14.0	59.9 ± 12.3	59.2 ± 15.1	57.8 ± 13.7	0.64	0.44
		Abduction	-96.4 ± 18.6	-93.7 ± 20.4	-118.3 ± 21.7	-114.0 ± 16.0	-131.1 ± 22.9	-125.5 ± 15.9	0.19	0.83
		External rot.	-28.7 ± 7.0	-29.0 ± 9.9	-35.5 ± 8.5	-36.4 ± 9.4	-43.1 ± 10.1	-41.1 ± 9.6	1.29	0.29
		Internal rot.	12.3 ± 8.4	8.7 ± 5.6	11.8 ± 8.1	8.1 ± 4.4	10.4 ± 7.8	9.4 ± 7.0	1.03	0.37
	Sagital Power (W)	Positive	172.1 ± 75.0	209.3 ± 98.8	163.6 ± 65.3	171.7 ± 57.8	231.4 ± 86.0	205.2 ± 72.6	0.68	0.52
		Negative	-307.3 ± 70.2	-292.8 ± 90.1	-347.4 ± 95.9	-348.1 ± 63.2	-422.1 ± 129.0	-397.3 ± 87.5	0.83	0.45
	Sagital Work (J)	Positive	8.2 ± 5.9	7.5 ± 3.3	6.0 ± 2.8	7.5 ± 5.5	6.9 ± 2.6	7.5 ± 3.5	0.65	0.53
		Negative	-25.8 ± 6.9	-25.9 ± 6.7	-28.8 ± 0.7	-28.2 ± 6.6	-32.0 ± 8.3	-30.2 ± 8.6	0.75	0.48
		Net	-16.8 ± 10.4	-17.5 ± 7.8	-22.7 ± 7.7	-19.6 ± 11.5	-24.7 ± 10.2	-21.5 ± 12.2	2.82	0.08

Bolded numbers indicate significant differences.

[a] Indicates a significant difference between the 3-, and 6-m curves while wearing the 35-mm footwear condition

[b] Indicates a significant difference between the 3-, and 9-m curves while wearing the 35-mm footwear condition

[c] Indicates a significant difference between the 6-, and 9-m curves while wearing the 35-mm footwear condition

[d] Indicates a significant difference between the 3-, and 6-m curves while wearing the 50-mm footwear condition

[e] Indicates a significant difference between the 3-, and 9-m curves while wearing the 50-mm footwear condition

[f] Indicates a significant difference between the 6-, and 9-m curves while wearing the 50-mm footwear condition

[g] Indicates a significant difference between the 35-, and 50-mm footwear conditions when running the 3-m curve.

[h] Indicates a significant difference between the 35-, and 50-mm footwear conditions when running the 9-m curve.

1.14 - Discussion

The purpose of this study was to examine the influence of midsole thickness on frontal plane ankle angle and performance when running curves of 3-, 6-, and 9-m radii. Overall, when running in the 50-mm footwear condition, participants did not experience a greater frontal plane ankle angle, as evidenced by peak frontal plane ankle angles. This is in contrast with the results of Chapter 3 and previous research that examined linear running and found participants to experience ~3° greater ankle eversion when running in shoes with a thicker midsole (33- vs. 22-mm and 50 vs. 35-mm) (Hannigan & Pollard, 2020). These results also oppose the theory that combining the increased medial forces associated with curved sprinting (Chang & Kram, 2007), with the elongated moment arm about the longitudinal axis of the foot associated with an increased midsole thickness (Hoogkamer, 2020) would result in an exacerbation of frontal plane ankle angles. In comparison to the medial and lateral forces measured during linear running (medial and lateral, 0.127 and 0.145 BW (McClay & Cavanagh, 1994)), participants produced much higher medial forces in both pairs of footwear across all curves (35- and 50-mm footwear, 3-, 6-, and 9-m curves; 0.67, 0.64, 0.57, 0.59, 0.50, 0.51 BW). Seeing as how the medial forces during curved running were as predicted (i.e., higher than linear running), one possible explanation as to why there was no difference in frontal plane angle between conditions is that curved running altered footwear midsole cushioning geometry. Throughout the stance phase in both footwear conditions, participants’ feet were internally rolled, suggesting the geometry of the midsole cushioning was effectively altered, with participants converting the midsole into a laterally banked surface. Previous research has demonstrated a laterally banked surface to reduce ankle inversion (Wannop et al., 2014). Participants in a study conducted by Schroeder et al. (2021), were found to exhibit 14° less ankle inversion when running a replica softball basepath with a base, a laterally banked surface, as opposed to without. As to why in the current study, there were no differences in ankle inversion between the two footwear conditions, the explanation may be that participants turned both footwear conditions into approximately the same banked surface (i.e., there were no significant differences in frontal plane foot angles found between conditions). In this way, despite the 50-mm footwear condition having an elongated moment arm about the longitudinal axis of the foot, it did not exacerbate frontal plane ankle angle.

Participant curve running performance, quantified as peak velocity when in contact with the force plate, or time-to-completion, were similar between footwear conditions. These results are in agreement with the average maximum velocities found when sprinting curves of similar radii (Chang and Kram, 2007). Given that participants did not experience greater ankle eversion but instead may have compressed both midsole conditions into laterally banked surfaces, this refutes the theory that participants’ running speeds around corners may be reduced due to misalignment between the direction of movement and the resultant ground reaction force.

While wearing the 50-mm footwear condition, participants generated less propulsive force, peak plantarflexion moments, and ankle power (positive and negative) and performed less ankle work (positive and negative), especially when running the 3-m curve. These results are consistent with the results reported in Chapter 3. In that study, the differences in ankle velocity, moments, power, and work didn’t translate into a reduced energetic cost when running in the 50-mm footwear condition (as compared to a 35-mm footwear condition) which authors postulated may be due to increases in knee velocity and moments, two metabolically costly alterations (Donelan et al., 2002; Fletcher & MacIntosh, 2017; Martin et al., 2000). In the current study, while participants experienced differences in knee extension velocities while wearing the 50-mm footwear condition and running the 3-, and 9-m radii curves that were or approached significance as compared to when wearing the 35-mm footwear condition, there were no differences in knee moment.

When running curves of differing radii participants displayed a host of differences. Perhaps most intuitive, participants exhibited faster peak velocities and shorter times-to-completion as curve radii increased, a result supported by previous literature (Chang & Kram, 2007; Taboga & Kram, 2019). Also supported by the literature, running at different speeds resulted in changes in lower limb kinematic and kinetic variables (Guo et al., 2006; Sundström et al., 2021). It was with this in mind that Alt et al. (2015) elected to control sprint speed when examining the impact of curved versus linear sprinting, finding differences in kinematic variables to be limited to the frontal, and transverse planes. In comparison, Churchill et al., (2015), who chose not to control curve sprint speed, found differences in kinematic variables in the sagittal plane. These results would suggest the differences in sagittal plane variables found in the current study may be the result of the faster running speeds permitted by the larger radii rather than alterations in gait due to the differing radii themselves (not to say differences in frontal, and transverse plane variables could not also be due to changes in running velocity). In fact, all the sagittal plane variables found to differ between curves in this study have been previously identified to be correlated with changes in speed during linear running and/or sprinting. This includes increased vertical (Weyand et al., 2000), and propulsive (Belli et al., 2002) ground reaction forces, increased joint angular velocities (e.g., plantarflexion, knee extension, and hip extension velocities) (Belli et al., 2002; de David et al., 2015), and increased joint power and work (Belli et al., 2002; Orendurff et al., 2018; Schache et al., 2011).

Curved sprinting is slower than straight sprinting, at least in part, because curved sprinting requires the generation of larger medial forces (Alt et al., 2015). This necessitates a reduction in the other components of the resultant force (i.e., anterior-posterior, and vertical) (Chang & Kram, 2007) and is achieved by altering a runners movement pattern (in comparison to straight sprinting) to increase their orientation towards the centre of the curve. This is accomplished, as demonstrated by Alt et al. (2015) on a 36.5-m radius curve, by increasing ankle inversion, and external rotation, and decreasing hip adduction. The results of the current study support these findings and suggest as curve radii decreases, the change in these variables is magnified.

Chang and Kram (2007) found curved sprinting to require larger medial forces than when linear sprinting. They did not however, find differences in medial force when sprinting curves of increasingly smaller radii (i.e., 6 – 1-m), a trend seen in the current study. A possible explanation for this discrepancy is that participants in the current study may have generated horizontal forces (i.e., anterior-posterior, and medial-lateral) in a pattern more similar to that seen when performing lateral cuts, especially when running the 3-, and 6-m curves. The performance of a lateral cut, as seen in a sport such as basketball, is characterized by proportionally higher braking (~ 1 BW), and medial (~ 1 BW) forces, as compared to propulsive force (~ 0.2 BW) (Mcclay et al., 1994). In the current study, as curve radii decreased, braking force increased (0.54, 0.56, and 0.63 BW), medial force increased (0.6, 0.7, and 0.9 BW), but propulsive force decreased (0.32, 0.29, and 0.20 BW). Indeed, a similar theory was proposed by Churchill et al. (2015) when contrasting the sprinting of large radii curves vs small radii curves.

This study examined the impact of midsole thickness on the outside leg when running curves due to its known association with higher medial force during curved sprinting (as compared to the inside leg) (Chang & Kram, 2007). However, the two legs of a sprinter (outside and inside) perform asymmetrically (Ishimura & Sakurai, 2016) and previous literature has found the inside leg to experience significantly greater frontal plane ankle eversion, a movement that can be exacerbated by an increased midsole thickness in linear running and may increase the risk of running related injuries (Hannigan & Pollard, 2020; Viellehner et al., 2016). Future research should look to examine the impact of midsole thickness on frontal plane ankle kinematics of the inside leg during curved running.

The decision was made to leave the differing mechanical qualities of the midsole as was (i.e., non-normalized) including the differing levels of midsole stiffness. The rearfoot and forefoot stiffnesses of the shoes differed by 76 and 70 N/mm, respectively. If the laterally banked surface explanation of ankle inversion minimization is true, participants may have only been able to achieve similar bank angles while wearing each because of the differing stiffnesses. Had they had the same stiffness, the same bank may not have been achieved which may have impacted peak frontal plane ankle angles. Seeing as how the midsoles were constructed of the same material, increases in midsole thickness go hand-in-hand with decreases in midsole stiffness; however, footwear manufacturers should keep this in mind when increasing the midsole thickness of footwear with midsoles of differing midsole materials.

In conclusion, this study sought to determine the impact of midsole stiffness on frontal plane ankle angle, performance, and gait when running curves of 3-, 6- and 9-m. Frontal plane ankle angles and centre of mass velocity were not found to be impacted by midsole thickness across any of the three curves. These results shed light on an understudied aspect of advanced shoe technology and an unavoidable element of road racing, curves. Future research should look to examine the impact of midsole thickness on the frontal plane ankle angle of the inside leg.

The Influence of Midsole Thickness on Markers of Muscle Damage Following a Training-Style Run

1.15 - Introduction

Even if it weren't in violation of World Athletics rules, racing in advanced footwear technology equipped with a midsole thicker than 40-mm, may not enhance performance as reported in Chapter 3. However, while a long-distance runner may only compete in a handful of races each year, they perform countless training runs. Running, whether long distances or intervals, can cause muscle damage (Quinn & Manley, 2012; Wiewelhove et al., 2016), the negative consequences (i.e., decreased running economy, altered gait, and decreased performance (Chen et al., 2009; Hikida et al., 1983; Miyama & Nosaka, 2004)) of which can last upwards of five days (Chen et al., 2009; Kyröläinen et al., 2000). Advanced footwear technology may present an opportunity to mitigate the deleterious effects of a training run, which could potentially improve subsequent runs, as reported by Kirby et al. (2019). In a comparison of advanced and non-advanced footwear technology, Kirby et al. (2019) found advanced footwear technology to reduce running related muscle soreness, damage, and inflammation. Although a mechanistic determination of the reductions was not included as part of the study (e.g., a biomechanical analysis), authors highlighted previous research that found soft surfaces to lessen delayed onset muscle soreness (Brown et al., 2017; Skinner et al., 2015).

Landing from a drop-jump onto a soft surface such as sand, has been found to decrease muscle soreness and damage, abbreviating recovery (Miyama & Nosaka, 2004). While landing on a soft surface, the role an individual must play actively absorbing the collision is thought to be reduced, permitting a straighter knee posture and consequently, less eccentric muscle contraction, (i.e., negative mechanical work), a major contributant of muscle damage (Black et al., 2022;

Skinner et al., 2015). Counterintuitively, landing on a soft surface can, as reported by Miyama and Nosaka (2004), result in a larger peak vertical ground reaction force than when landing on a hard surface. While there may appear a discrepancy between drop jump landings, and landings during running, similar results in regards to the effect of surface stiffness on knee posture and vertical ground reaction force have been found in both. Kerdok et al. (2002) reported a 2.5% decrease in peak knee flexion angle, and a 5% increase in peak vertical ground reaction force when participants ran on a soft surface as compared to a hard surface. While the study didn't calculate joint work, the metabolic cost of participants when running on the soft surface was found to be 12% lower, suggesting reduced muscle activity.

Although midsole stiffness, defined as the ratio of force to resultant material deformation and colloquially referred to as softness, is a material property and therefore independent of size, an especially soft midsole, as seen in advanced footwear technology, requires the midsole to be of substantial thickness else it risk "bottoming out" and becoming infinitely stiff (Kram, 2022). Midsole thickness is therefore a mechanism through which midsole stiffness can be modulated and potentially the characteristic of advanced footwear technology responsible for the reductions in running related muscle soreness, damage, and inflammation reported by Kirby et al. (2019). However, this remains speculation. Therefore, the purpose of this study was to determine the influence of midsole thickness on muscle damage that may occur during a prolonged training run.

1.16 - Methods

1.16.1 - Participants

Sixteen recreational runners, fourteen male and two female (mean ± SD, age: 28.5 ± 6.2, height: 1.74 ± 0.06 m, mass: 66.67 ± 6.62 kg), all of whom fit a men's size nine (US) shoe were recruited for this study. A recreational runner was defined as an individual with an official 5-, or

10-km race time less than 24-, or 50-minutes, respectively, within the previous 3-months. Informed written consent was obtained from all participants prior to the data collection in accordance with the University of Calgary's Ethics Board.

1.16.2 - Footwear

Two footwear models were used in this study (Figure 5.1). The models were identical (e.g., men's size nine (US), thermoplastic polyester elastomer (TPEE) midsole, curved carbon infused rods, outsole geometry) except for their midsole thicknesses which were 35-, and 50-mm. A consequence of the footwear models' differing midsole thicknesses were that they had differing mechanical properties (Table 0.1). While the difference in midsole stiffness was desired (as previously discussed), the other differences were less so. The decision was made to leave the masses of the footwear conditions as was because the difference in mass was an unavoidable consequence of the difference in volume of midsole material (i.e., it's impossible to make a thicker midsole of the same material without an increase in mass). The decision was made to leave the forefoot bending stiffness of the conditions as was because the structural integrity of the shoes could not be guaranteed if physically altered, and increasing the forefoot bending stiffness via carbon fiber plates inserted under the midsole was to exchange one uncontrolled variable (i.e., forefoot bending stiffness) for another (i.e., stiffness element location), which can influence running biomechanics (Flores, Rao, et al., 2019).

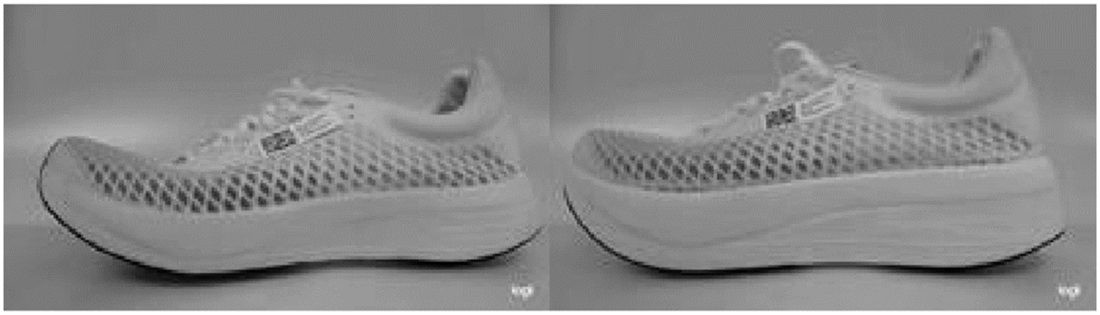

Figure 0.1: The two footwear conditions tested, 35-mm (left), and 50-mm (right).

Table 0.1: Mechanical properties of the two footwear conditions.

	35-mm	50-mm
Mass (before normalization) (g)	214.5	260.5
Midsole Stiffness (N/mm)	176.0	100.0
Energy Return (%)	83.5	86.5
Bending Stiffness (Nm/º)	0.187	0.166

1.16.3 - Data Collection

5.2.3.1 - Running Protocol. Participation in this study entailed two 90-minute instrumented treadmill sessions (Bertec Coporation, Columbus, USA), performed a minimum of two weeks apart. Each session comprised of a 5-minute warm-up followed by 60-minutes of continuous running in one of the two footwear conditions, performed in a randomized order. The 60-minutes of continuous running was performed at either approximately 86% of a participant's most recent 5-km race speed, or 89% of a participants most recent 10-km race speed. The intensity and duration were selected to simulate a training run performed by an athlete once or twice a week, mid-season. These percentages were based on a data set of race times compiled by Stephan Seiler and John Peters, culled from the IAAF.org performance database and available on researchgate.net. To be included in the data set, athletes were required to: 1) have raced each of the following distances in a single year between 2014-2018: 5-km, 10-km, 21.1 km (i.e., a half-marathon), and 42.2-km (i.e., a marathon), and 2) have ranked within the top 500 individuals at each distance during the specified time period. For the current study, the average percentage of 5- and 10-km speed at which the top 38 athletes, those that had run half-marathons in approximately 60-minutes, ran their half-marathons were calculated (i.e., 93% and 97%, respectively) and reduced after pilot testing. Furthermore, although participants performed both 5-minute treadmill warm-ups at the prescribed speed, they were permitted to increase or decrease the speed at which the 60-minute continuous running trials were performed based on their understanding of their own fitness as to better achieve the goal outcome of simulating a training run. Regardless, both trials (i.e., performances in 35-, and 50-mm footwear conditions) were completed at the same speed. If, during the first session, participants were unable to complete 60-minutes of continuous running at the target speed, they were able to request drops in speed in a half-a-kilometre per hour increment. Eleven of seventeen participants were able to complete all 60-minutes of continuous running at their target speed while the remaining six required at least one drop in speed, two of whom elected to end testing prematurely (i.e., before reaching 60-minutes). All participants returned for the second session during which all drops in speed and premature terminations of testing were mirrored from the first session.

In addition to the ground reaction forces collected at 2400 Hz by the instrumented treadmill, 60 seconds of kinematic data was collected at a rate of 240 Hz by an eight-camera motion capture camera system (Vicon, Denver, USA) starting at the 1st, 10th, 20th, 30th, 40th, 50th, and 59th minute. The initial capture, termed T1, taken immediately after the treadmill had reached the target speed (i.e., the 1st minute), was used as a baseline value with which to compare all proceeding timepoints. Each subsequent collection was termed T2-T7. Twenty-four retroreflective markers were used in conjunction with the motion capture system to define each participant's pelvis, left thigh, left shank, and left foot segments. The pelvis segment was defined by a total of four markers placed on the right and left anterior and posterior iliac crests. The left thigh and shank were defined by two sets of four non-colinear markers arranged in a diamond pattern on the lateral side of each segment. The foot segment was defined by four markers permanently affixed to each left shoe. Two markers were placed on the heel of each shoe, one proximal and the other distal, such that they aligned with the Achilles tendon of the participant, while the remaining two markers were affixed at differing heights to the lateral side of the shoe. Joint center locations were determined by placing additional markers on the following locations: medial and lateral malleolus (to define the ankle joint), and medial and lateral epicondyles of the femur (to define the knee joint).

Participants also wore a heart rate monitor (4iiii, Cochrane, Canada) that collected continuously at a rate of six samples per minute.

5.2.3.2 – Blood Collection Protocol. Four blood draws were performed by a certified phlebotomist, one at the start of each data collection session and one 72-96 hours post-exercise for each of the two data collection sessions (Hyatt & Clarkson, 1998). Effort was taken to ensure the times between the runs and the post-run blood draws were similar. Participants were instructed to abstain from any vigorous and novel physical activity from 72-hours pre-exercise until the post-collection blood draw was performed, to avoid sustaining muscle damage that was not the direct result of the testing protocol. Blood was collected in a 6 mL ethylenediaminetetraacetic acid (EDTA) vacutainer, after which it was immediately placed in a cooled centrifuge (4° Celsius) and spun at 3000 rpm for 15 minutes. Separated blood plasma was then aliquoted into two separate microcentrifuge tubes and stored at –30 °C until further analysis.

1.16.4 - Data Analysis

Motion capture data collected by the Vicon camera system was manually tracked using the Vicon Nexus software before being exported and imported to Visual 3D software (C-Motion, Germantown, MD, USA). Once in Visual 3D, ground reaction forces and kinematic data were filtered using a zero-lag, low-pass, 4th order Butterworth filter with a cut-off frequency of 15-Hz. A 20-Newton threshold was used to identify gait events (i.e., heel-strike and toe-off) of each trial after which Cardan angles, angular velocities, moments, powers, and work of the ankle, knee, and hip were calculated using a four-segment model, including a Coda pelvis (a pelvis segment model in Visual 3D). These were exported from Visual 3D and analyzed (i.e., the identification of peak values, and the calculation of averages) in Excel software.

To account for the participants who did not complete the full 60-minutes of running and, therefore, only had five data collections (as opposed to seven), two of the seven collections of the remaining 14 participants were removed (T2 and T4) for the kinematic and kinetic comparisons. This was done to approximately normalize the points at which data was collected (i.e., ~ every 25-30% of a session) relative to each participants total duration of running. Hence forth, only five data collections will be referred to: T1 (~0% trial completion), T2 (~ 25-30% completion), T3 (~50-60% trial completion), T4 (75 – 90% trial completion), and T5 (~ 100% completion).

Heart rate data was exported from the 4iiii iPhone application in a .fit file format before being converted into .xlsx files using a Python script. The 10 data points which corresponded to each of the five 60-second segments during which kinematic and kinetic data were collected were manually identified and averaged. The time point collected during the 10th minute (originally termed T2) but removed for the kinetic and kinematic analysis was used as the baseline for the heart rate analysis because participants heart rates had not stabilized during T1. Therefore, the two participants that did not complete the full 60-minutes of running were excluded from the heart rate analysis. Each participant's maximum heart rate was estimated using the equation published by Gellish et al., (2007).

$$\text{Maximum Heart Rate} = 207 - \text{Age} * 0.7$$

The concentrations of creatine kinase (CKM; ab264617, abcam, Cambridge, United Kingdom) and lactate dehydrogenase (LDH-B; ab183367, abcam) in EDTA blood plasma samples were determined using enzyme-linked immunosorbent assay (ELISA) kits and a Spectra Max i3 spectrophotometer (Molecular Devices, San Jose, USA), following manufacturer protocols with the following modification to optimize for the equipment to be used: 30-minute incubation time with the colourimetric development solution, prior to addition of the stop solution. Sample concentrations were calculated using an 8-point standard curve fit with a 4-parameter function in SoftMax Pro software (Molecular Devices, San Jose, USA). All samples underwent two freeze-thaw cycles prior to running on the plate – once to dilute samples into the working range of the assays (1/80 for CKM and 1/16 for LDH-B), and once on the day of the ELISA experiments. As CKM and LDH-B are cytoplasmatic enzymes, their presence in the blood is indicative of a disrupted muscle membrane, as they cannot otherwise cross the muscle membrane (Callegari et al., 2017).

1.16.5 - Statistical Analysis

All statistical analysis was performed in SPSS software (IBM, Armonk, NY, USA). The effect of footwear on change in lactate dehydrogenase, and creatine kinase were compared using a paired t-test ($p < 0.05$). Effect size was calculated as previously reported (Lakens, 2013). The effect of footwear conditions (i.e., 35-, and 50-mm midsoles), time-points (i.e., T1, t2, t3, t4, and t5) and interactions between footwear and time-point on contact time, peak ground reaction forces, and joint angles, velocities, moments, and work were compared using an ANOVA with repeated measures ($p < 0.05$). If a significant difference was detected a pairwise comparison analysis was performed with Bonferroni confidence interval adjustment.

1.17 - Results

1.17.1 - Lactate Dehydrogenase and Creatine Kinase Results

Pre to post run, there was not a statistically significant difference in magnitude of change in concentration of lactate dehydrogenase (p = 0.061, effect size = 0.52) or creatine kinase (p = 0.52, effect size = 0.2) when running in the two footwear conditions (Figure 5.2).

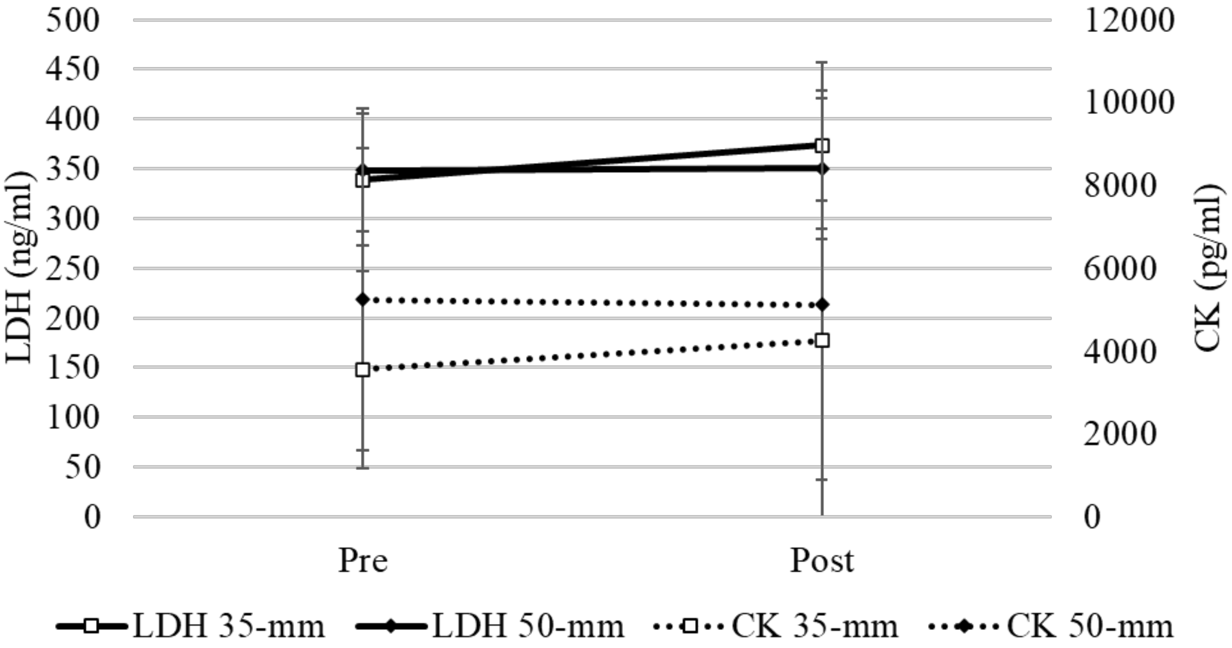

Figure 0.2: Concentrations of Lactate Dehydrogenase (LDH), and Creatine Kinase (CK), pre-run and post-run while wearing the 35-, and 50-mm footwear conditions.

1.17.2 - Kinematic and Kinetic Variables

No main interaction effects were found between footwear and time (Table 5.2). Significant main shoe effects were found in braking (F = 5.668, p = 0.008), and lateral (F = 9.347, p = 0.008) forces and both main shoe and timepoint effects were found in propulsive force (F = 7.547, p = 0.015, and F = 5.554, p < 0.001, respectively). Participants generated greater forces (i.e., braking and propulsive) while wearing the 35-mm footwear condition compared to the 50-mm footwear condition and produced less propulsive force compared to T1 at T4 (p = 0.045), and T5 (p = 0.012). No main shoe effect was found for stance time (p = 0.900); however, a main time effect was found (F = 13.821, p < 0.001). Compared to T1, participants stance time increased at every time point (T2, T3, T4, T5, p = 0.044, p = 0.002, p = 0.002, p < 0.001, respectively), and increased compared to the preceding time point at T2 (p = 0.044), T3 (p = 0.001), and T5 (p = 0.025).

At the ankle, main shoe, and time effects were found in peak ankle eversion (F = 5.78, p = 0.030, and F = 6.44, p = 0.005, respectively), peak dorsiflexion velocity (F = 10.07, p = 0.006, and F = 6.88, p = 0.049, respectively), peak plantarflexion moment (F = 16.58, p = 0.001, and F = 6.21, p < 0.001, respectively), negative (F = 28.371, p < 0.001, and F = 3.105, p = 0.022, respectively), and positive (F = 41.42, p < 0.001, and F = 19.81, p < 0.001, respectively) power and in positive work (F = 72.28, p < 0.001, F = 24.53, p < 0.001, respectively). Furthermore, main shoe effects were found in peak dorsiflexion angle (F = 12.95, p = 0.003), and in negative work (F = 38.87, p < 0.001), and main time effects were found in peak plantarflexion angle (F = 20.04, p < 0.001), and in peak plantarflexion velocity (F = 4.92, p = 0.019). While running in the 35-mm footwear condition participants exhibited a greater peak dorsiflexion angle, a higher peak velocity (i.e., dorsiflexion velocity), all while generating greater peak plantarflexion moments, greater positive and negative power and performing more positive and negative work. While running in the 50-mm footwear condition, participants exhibited greater peak ankle eversion angles.

As compared to T1 participants exhibited greater peak ankle eversion angles, slower peak dorsiflexion velocities, generated less positive ankle power and performed less positive ankle work after T2 (T2, T3, T4, T5, p = 0.025, p < 0.001, p < 0.001, p < 0.001, and p = 0.021, p = 0.018, p = 0.005, p = 0.007, and p < 0.001, p < 0.001, p < 0.001, p < 0.001, and p < 0.001, p < 0.001, p < 0.001, p < 0.001, respectively). After T3, participants exhibited lower peak ankle plantarflexion angles (T3, T4, T5 $p = 0.004$, $p < 0.001$, $p < 0.001$, respectively), while after T4, participants generated lower peak plantarflexion moments (T4, T5, $p = 0.048$, $p = 0.011$, respectively). However, while participants exhibited greater peak ankle eversion angles, generated less positive ankle power and performed less positive ankle work at each timepoint as compared to the immediately preceding timepoint (T2, T3, T4, T5, $p = 0.025$, $p = 0.016$, $p = 0.022$, $p = 0.032$, and $p < 0.001$, $p = 0.025$, $p = 0.013$, $p = 0.001$, and $p < 0.001$, $p = 0.049$, $p = 0.005$, $p = 0.007$), participants only exhibited slower peak dorsiflexion velocities at T2 ($p = 0.021$), and T4 ($p = 0.036$) as compared to T1 and T3, respectively, less peak ankle plantarflexion at T3 ($p = 0.004$), and T4 ($p = 0.036$), as compared to T4, and T5 respectively, slower peak plantarflexion velocity ($p = 0.036$) as compared to T3, and generated lower peak plantarflexion moments and negative power at T4 ($p = 0.022$, $p = 0.029$, respectively), and T5 ($p = 0.016$, $p = 0.005$), as compared to time points T3, and T4, respectively.

At the knee, a main shoe effect was found for extension velocity ($F = 8.57$, $p = 0.010$). Participants exhibited significantly faster knee extension velocities when running in the 50-mm footwear condition as compared to the 35-mm footwear condition.

At the hip, while no main shoe effects were found, main time effects were found for positive power ($F = 7.121$, $p = 0.003$), positive work ($F = 15.17$, $p < 0.001$), negative work ($F = 5.41$, $p = 0.006$), and extension velocity ($F = 5.24$, $p = 0.014$). As compared to T1, participants exhibited greater positive power and performed more positive work after T2 (T2, T3, T4, T5, $p = 0.010$, $p = 0.001$, $p = 0.016$, $p = 0.005$, and $p < 0.001$, $p < 0.001$, $p < 0.001$, $p < 0.001$, respectively), with a second significant increase happening after T2 (i.e., as compared to T3, $p = 0.002$ (power), and $p = 0.004$ (work)). Hip extension slowed after T4, as compared to T1 (T4, T5, $p = 0.038$, $p = 0.014$).

Table 0.2: Kinematic and kinetic Variables at the ankle, knee, and hip.

			T1		T2		T3		T4		T5		Footwear		Time	
			35-mm	**50-mm**	**35-mm**	**50-mm**	**35-mm**	**50-mm**	**35-mm**	**50-mm**	**35-mm**	**50-mm**	**F-value**	**p-value**	**F-value**	**p-value**
Ankle	Peak Angle (º)	Dorsiflexion	-20.2 ± 3.4	-20.2 ± 2.9	-19.8 ± 3.2	-19.3 ± 3.4	-19.2 ± 3.5	-18.8 ± 3.2	-17.9 ± 4.2	-18.4 ± 3.3	-17.9 ± 3.6	-17.7 ± 3.6	12.95	0.003	3.93	0.051
		Plantarflexion	19.4 ± 2.6	17.7 ± 2.4	19.5 ± 2.3	17.9 ± 2.7	**20.1 ± 2.2**	**18.3 ± 2.7**	**20.4 ± 2.5**	**18.3 ± 2.7**	**20.3 ± 2.5**	**18.3 ± 2.6**	0.04	0.844	20.04	<0.001
		Sagital ROM	39.6 ± 2.7	37.9 ± 3.4	39.5 ± 2.6	37.2 ± 3.4	39.3 ± 3	37.1 ± 3.3	**38.6 ± 2.8**	**36.6 ± 2.9**	**38.3 ± 2.6**	**36 ± 3.1**	31.60	<0.001	5.93	<0.001
		Eversion	9.2 ± 2.7	9.4 ± 3.0	**9.8 ± 2.9**	**10.9 ± 3.1**	**10.4 ± 2.7**	**12 ± 2.5**	**9.3 ± 4.3**	**11.6 ± 3.5**	**10.7 ± 3.2**	**12.4 ± 3.5**	5.78	0.030	6.44	0.005
	Peak Velocity (º/s)	Dorsiflexion	416.7 ± 167.9	382.5 ± 139.0	**387.8 ± 142.1**	**348.7 ± 117.8**	**385.1 ± 139.2**	**343.2 ± 121.6**	**374 ± 129.5**	**339.2 ± 118.2**	**381.6 ± 128.3**	**333 ± 108.1**	10.07	0.006	6.88	0.049
		Plantarflexion	-659.5 ± 108.4	-654.1 ± 129.8	-668.4 ± 116.7	-655.6 ± 124.5	-654.8 ± 112.2	-643.9 ± 117.3	-634 ± 115.2	-633.9 ± 102.5	-632.8 ± 99.7	-625.6 ± 104.8	0.62	0.444	4.92	0.019
	Peak Moment (Nm)	Plantarflexion	-230.8 ± 21.5	-220.7 ± 23.6	-228 ± 23.1	-218.7 ± 21.0	-227.2 ± 21.2	-217.7 ± 19.8	**-223.3 ± 18.7**	**-215.2 ± 20.0**	**-219 ± 19.4**	**-212.2 ± 19.1**	16.58	0.001	6.21	<0.001
	Sagital Power (W)	Positive	923.6 ± 157.1	838.2 ± 154.7	**875.9 ± 175.1**	**779 ± 138.1**	**848.1 ± 154.9**	**758.6 ± 137.5**	**800.8 ± 147.4**	**739.1 ± 123.3**	**779.1 ± 148.9**	**710.2 ± 127.9**	41.42	<0.001	19.81	<0.001
		Negative	-693.4 ± 154.4	-626.4 ± 157.2	-696.1 ± 177.9	-620.3 ± 149.2	-687.2 ± 154.1	-619.6 ± 146.9	-666.2 ± 135.9	-603.2 ± 140.1	-650.5 ± 135.6	-585 ± 129.3	28.37	<0.001	3.11	0.022
	Sagital Work (J)	Positive	58.4 ± 6.3	53.1 ± 6.1	**55.7 ± 6.5**	**49.5 ± 5.8**	**54.6 ± 6.2**	**48.6 ± 6.0**	**51.7 ± 6.1**	**47.5 ± 5.7**	**50.9 ± 5.8**	**46.1 ± 5.9**	72.28	<0.001	24.53	<0.001
		Negative	-47.3 ± 10.9	-41.8 ± 10.2	-47.6 ± 10.9	-40.8 ± 8.7	-47.6 ± 10.1	-40.8 ± 8.6	-46.5 ± 8.7	-40 ± 8.3	-46.4 ± 8.4	-38.8 ± 7.9	38.87	<0.001	1.58	0.192
Knee	Peak Angle (º)	Flexion	-35.2 ± 2.9	-35.3 ± 3.7	-35.4 ± 2.8	-35.5 ± 3.3	-36 ± 3.2	-35.9 ± 3.3	-37 ± 6.2	-35.8 ± 3.3	-35.9 ± 3.4	-36 ± 3.4	0.07	0.796	1.51	0.210
	Peak Velocity (º/s)	Flexion	-447.1 ± 47.5	-441.5 ± 52.9	-434.3 ± 39.9	-446.9 ± 55.8	-444.6 ± 40.3	-436.6 ± 44.4	-419 ± 55.8	-433.7 ± 46.7	-436.8 ± 46.7	-434.8 ± 43.8	0.06	0.810	1.15	0.342
		Extension	275.2 ± 70.3	291.7 ± 83.6	285.9 ± 70.2	303.9 ± 81.4	279.8 ± 65.9	302.8 ± 76.9	265.4 ± 71.8	297.6 ± 69.2	266.7 ± 67.6	290.7 ± 68.4	8.57	0.010	2.54	0.112
	Peak Moment (Nm)	Extension	131.3 ± 16.4	133.4 ± 23.0	135 ± 16.8	136.8 ± 24.9	139.2 ± 18.5	138.7 ± 21.8	138.8 ± 20.2	139.6 ± 23.7	140 ± 20.4	139.9 ± 22.2	0.02	0.899	3.55	0.051
	Sagital Power (W)	Positive	270.2 ± 74.3	245.2 ± 73.6	277.9 ± 80.5	247.8 ± 79.9	281.8 ± 94	248.1 ± 86.1	269.8 ± 97.1	247 ± 78.8	276.6 ± 76.7	239.9 ± 62.5	2.63	0.126	0.21	0.806
		Negative	-517.1 ± 188.3	-466.9 ± 158.5	-542.6 ± 162.6	-496.4 ± 151.5	-557.4 ± 180.1	-479.7 ± 148.8	-529.5 ± 165.1	-488.2 ± 142.4	-525.4 ± 154.6	-477.3 ± 144.1	2.90	0.109	0.61	0.516
	Sagital Work (J)	Positive	14.8 ± 2.8	14.1 ± 4.2	15.2 ± 2.7	14.3 ± 4.1	15.6 ± 2.8	14.6 ± 3.9	15.1 ± 3.4	14.5 ± 3.7	15.4 ± 2.7	14.5 ± 3.4	0.95	0.344	0.62	0.653
		Negative	-20.7 ± 5.4	-19.9 ± 5.2	-21.4 ± 4.2	-21 ± 5.7	-21.5 ± 4.6	-20.1 ± 5.2	-20.6 ± 5.3	-20.6 ± 5.1	-20.7 ± 4.8	-20 ± 5.1	0.43	0.522	0.98	0.397
Hip	Peak Angle (º)	Flexion	33.9 ± 6.3	33.1 ± 6.1	34.0 ± 5.3	34.3 ± 5.1	34.8 ± 5.6	34.6 ± 5.2	35.9 ± 8.4	34.6 ± 5.1	34.7 ± 5.3	35.0 ± 4.8	0.34	0.568	1.79	0.188
		Extension	-8.9 ± 5.5	-9.2 ± 4.8	-10.2 ± 4.3	-9.4 ± 4	-9.6 ± 4.8	-9.7 ± 4	-8.6 ± 6.4	-9.6 ± 4.3	-9.7 ± 4.9	-9.2 ± 4.6	0.07	0.800	1.85	0.168
	Peak Velocity (º/s)	Extension	-340.8 ± 61.4	-335.4 ± 57.3	-340.4 ± 62.1	-329.7 ± 59.5	-328.4 ± 54.7	-321.2 ± 55.2	**-322.1 ± 52.1**	**-312.2 ± 46.8**	**-316.5 ± 54.3**	**-306.6 ± 44.9**	0.40	0.536	5.24	0.014
	Peak Moment (Nm)	Extension	-97.6 ± 20.1	-97.7 ± 18.1	-98.7 ± 18.1	-101.9 ± 20.4	-103 ± 18.7	-101.4 ± 21.9	-104.8 ± 24.3	-97.9 ± 20.8	-101.8 ± 18.8	-98.3 ± 20.3	0.85	0.374	2.00	0.109
		Flexion	52.8 ± 21.2	50.3 ± 18.6	54.6 ± 21.6	49.6 ± 17.5	52.5 ± 22.4	49.6 ± 20.9	53.1 ± 20.1	49.5 ± 22.1	53.9 ± 19.9	47.6 ± 21.4	3.78	0.074	0.24	0.691
	Sagital Power (W)	Positive	199.7 ± 97.3	183.6 ± 63.8	**222.7 ± 117.4**	**214.7 ± 76.5**	**247 ± 125.1**	**227.4 ± 83.6**	**258.7 ± 159.9**	**210.5 ± 87.8**	**239.3 ± 114.4**	**219.1 ± 77.6**	0.98	0.340	7.12	0.003
		Negative	-183 ± 71.9	-197 ± 77.6	-185 ± 75.2	-189.5 ± 88.2	-177.6 ± 67.4	-182.3 ± 75.6	-175.2 ± 62.9	-177.7 ± 76	-176.4 ± 54.9	-168.4 ± 69.6	0.31	0.590	1.57	0.232
	Sagital Work (J)	Positive	8.9 ± 4.1	8.7 ± 5.2	**10.2 ± 4.7**	**10.4 ± 5.7**	**11.4 ± 5.1**	**11.4 ± 5.9**	**10.5 ± 4.2**	**11 ± 6.2**	**11.2 ± 4.6**	**11.6 ± 6.3**	0.05	0.833	15.17	<0.001
		Negative	-15.3 ± 6.0	-15.2 ± 5.1	-15.1 ± 5.6	-14.4 ± 4.7	-14 ± 5.1	-13.8 ± 4.4	**-13.4 ± 5.2**	**-13.5 ± 3.9**	**-13.8 ± 3.4**	**-12.9 ± 4.2**	0.66	0.431	5.41	0.006

Bolded text indicates a significant difference as compared to T1 and underlined text indicates a significant difference as compared to the immediately previous time point.

1.17.3 - Heart Rate

A main time effect (F = 23.283, $p < 0.001$) was found for heart rate while there was no main shoe ($p = 0.630$) or shoe, time interaction effect ($p = 0.11$) (Figure 5.3). As compared to T1, participants exhibited an increased heart rate after every timepoint (T2, T3, T4, T5, $p < 0.001$, respectively). Participants heart rates continued to increase between T2 and T3 ($p < 0.001$), and T4 and T5 ($p = 0.046$).

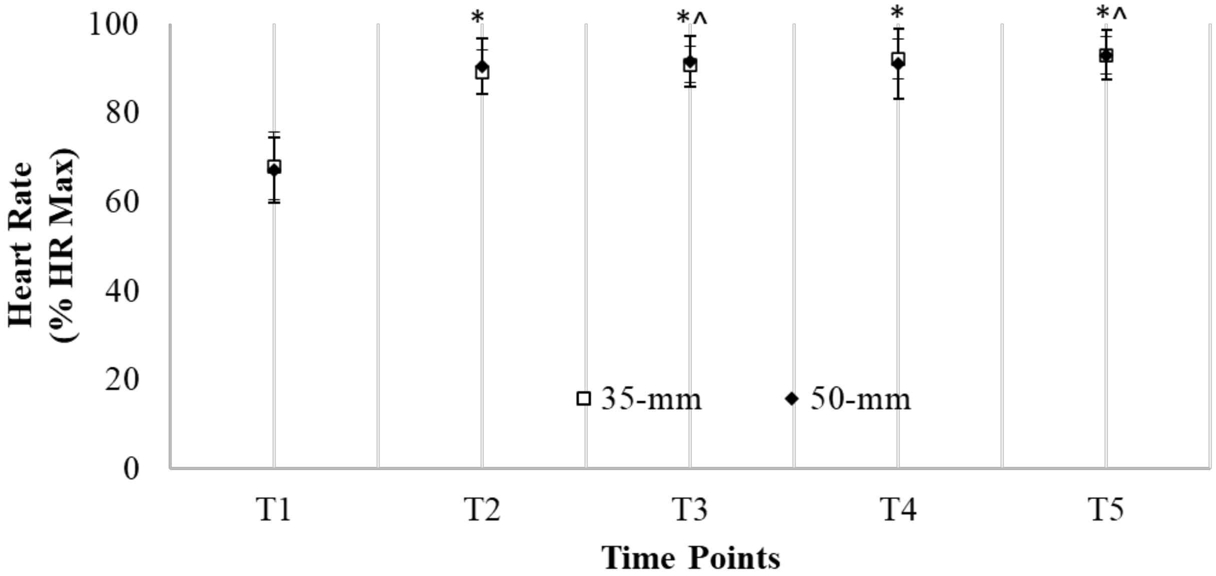

Figure 0.3: Average heart rate as a percentage of participant max heart rate. An asterisk (*) denotes a significant difference as compared to T1, and a circumflex (^) denotes a significant difference as compared to the previous timepoint.

1.18 - **Discussion**

The purpose of this study was to determine the influence of midsole thickness on muscle damage that may occur during a prolonged training-style run. Pre to post run, the concentration of lactate dehydrogenase increased more when running in the 35-mm condition as compared to the 50-mm condition. However, the difference was not significant (p = 0.06), nor was the difference in exercise-induced change in creatine kinase concentration. In comparison to previous literature, the pre to post change in serum concentration of both lactate dehydrogenase and creatine kinase were much smaller (i.e., 35-mm-LDH: 9.8%, 50-mm-LDH: 0.52%, 35-mm-CK: 17.9%, 50-mm-CK: -2.54%) than those measured 72-96 hours post-marathon by Kobayashi et al. (2005) (i.e., LDH: 200%, CK: 300%). This may be a product of both the difference in participant fitness and run duration. Noakes (1987) concluded post-exercise increases in enzyme activity to be greater among individuals of lesser training and following exercise of longer duration. Participants recruited by Kobayashi et al. (2005) were described by researchers as "not dedicated runners", running 50-km/week in training in preparation for the marathon which lasted 240 ± 12 minutes. Comparatively, participants in the current study consisted of collegiate track and field athletes, and dedicated runners with 5-km race personal bests ranging from 16 – 21 minutes, who ran, on average, 65.5 ± 22.1 km per week and who only had to run for 60-minutes.

As to why there was a noticeable increase in lactate dehydrogenase (ES = 0.52) but not in creatine kinase (ES = 0.20), this may be the result of the difference in the rate with which concentrations of the two enzymes dissipate. As previously reported (Kobayashi et al., 2005), after peaking within the first 24-hours, the concentration of creatine kinase decreases in an exponential manner whereas the concentration of lactate dehydrogenase decreases in a more linear fashion. This might suggest, in the current study, concentrations of both enzymes probably peaked within 24-hours of testing (though at a much lower level than would be expected after a 4–6-hour race); however, while an elevated level of lactate dehydrogenase was still present 72-96 hours after each run, creatine kinase concentrations had returned to pre-run levels.

The soft surface of a thick midsole was proposed to decrease the magnitude of eccentric muscle contraction by reducing the active roll an individual had to play in absorbing the collision during a landing and permitting a straighter knee posture. This proved not to be the case. No significant differences between footwear conditions were detected in peak joint angle or negative work at the knee, nor in peak vertical ground reaction force, another previously reported hallmark of a landing on a soft surface (Kerdok et al., 2002; Miyama & Nosaka, 2004). While Kerdok et al. (2002) reported both significant differences in peak knee angle and vertical ground reaction forces when running on surfaces of different stiffness, the differences were only between their softest condition (75.5 kN/m) and the remaining conditions (97.5, 216.8, 454.2, and 945.7 kN/m). Future research should look to explore the impact of softer midsoles (i.e., below 100 N/mm) on markers of muscle damage.

An alternative explanation for the increase in concentration of lactase dehydrogenase when running in the 35-mm footwear condition may be that participants required greater triceps surae muscle activation to generate a greater plantarflexion moment (Fukunaga et al., 2001), with which to rotate their ankle through a larger range of motion (i.e., from peak dorsiflexion to peak plantarflexion). Logic would dictate more active muscle would increase the opportunity for muscle damage and previous literature has demonstrated that larger ranges of motion induce greater muscle damage (Baroni et al., 2017).

Regardless of why lactate dehydrogenase was slightly elevated 72-96 hours after running in the 35-mm footwear condition, it's unlikely that midsole thickness would have impacted future training runs. In a study conducted by Quinn and Manley (2012), participants performed a 23-km "training run" at a prescribed intensity of 60-75% of their maximum heart rate. Participants ended up covering the distance in 125.5 ± 13.7 minutes at 79.3 ± 7.1% of their maximum heart rate. Post-run, participants returned to the lab once every 24-hours for 3-days at which time their blood was drawn and their running economy tested. Despite researchers finding elevated creatine kinase concentrations 24-, 48-, and 72-hours post run (as compared to T1), participants running economy remained unchanged. If, as concluded by Noakes (1987) and Kobayashi et al. (2005), duration is a major contributant to elevated enzyme activity and concentrations, based on the results of Quinn and Manley (2012) it seems unlikely that a 60-minute training in either footwear condition would induce levels of muscle damage sufficient to impair future running economy.

Plasma concentrations of creatine kinase, and lactate dehydrogenase are markers of muscle damage (Callegari et al., 2017) and some have cast doubt on whether or not concentrations of creatine kinase relate to the magnitude of sustained muscle damage (Nosaka & Clarkson, 1992). Furthermore, training status, as suggested by Noakes (1997) and Sanno et al. (2018) may impact an individual's response to prolonged running. Future research should look to examine the impact of midsole thickness on muscle damage in more homogeneous populations using methods perhaps more directly indicative of muscle damage such as muscle force generation capacity, biopsies, or with ultrasound.

In summary, pre to post, running in the 35-mm midsole condition elicited a small increase in lactate dehydrogenase that was not present after running in the 50-mm footwear condition; however, the magnitude of change when running for 60-minutes in either condition makes it unlikely to impact future training.

Discussion

1.19 - Summary

In Chapter One, the rationale for the studies that compose this dissertation were outlined. In 2020, when World Athletics amended their rules governing footwear to include a maximum midsole thickness of 40-mm, there was no evidence to suggest 40-mm presented a threshold past which sport integrity would be violated. In fact, although numerous individuals have presented theories detailing the theoretical benefits (i.e., a reduced energetic cost) (Burns & Tam, 2019), and detriments (i.e., increased ankle eversion) (Hoogkamer, 2020), the impact of midsole thicknesses above and beyond 40-mm on running performance and biomechanics remained an unanswered question. Therefore, the purpose of this dissertation was threefold:

1. To determine the influence of midsole thickness on the energetic cost of running.
2. To determine the influence of midsole thickness on frontal plane ankle angle and performance when running curves.
3. To determine the influence of midsole thickness on the muscle damage associated with a training-style run.

In Chapter two, a review of pertinent literature was presented. Advanced footwear technology (i.e., performance enhancing running shoes) features three key elements; (i) a forefoot stiffening apparatus, (ii) a pronounced rocker profile, and (iii) a thick resilient midsole (Frederick, 2022). While research has been conducted examining the influence of a forefoot stiffening apparatus (Madden et al., 2016; Oh & Park, 2017; Roy & Stefanyshyn, 2006), and a pronounced rocker profile (Farina et al., 2019; Subramanium & Nigg, 2021) on running, a systematic examination of the influence of midsole thicknesses at and above 40-mm on running had yet to be performed. An increased midsole thickness has been proposed to bequeath its wearer a performance enhancing advantage by elongating leg length (Burns & Tam, 2019); however, the increase in thickness may also come with consequences. Increasing midsole thickness also increases the ground reaction force moment arm about the longitudinal axis of the foot (Hoogkamer, 2020), which could result in an increase in frontal plane ankle angle. This increase in frontal plane ankle angle could be further exacerbated when combined with the greater medial-lateral forces required to run curves (Smith et al., 2006). The impact on frontal plane ankle angle and the World Athletics ban aside, a thick midsole may present an opportunity to improve run training by reducing the muscle damage it inflicts (Kirby et al., 2019), and therefore abbreviating recovery (Miyama & Nosaka, 2004). For all these reasons, a thorough examination of the influence of midsole thickness on running performance and biomechanics was warranted.

In Chapter 3, the first study was presented, the purpose of which was to determine the influence of midsole thickness on the energetic cost of running. The study tested four nearly identical footwear conditions ranging in midsole thickness from 35- to 50-mm, in increments of 5-mm. Midsole thickness was found to not impact the energetic cost of running, contradicting the theory that a longer leg length would be energetically beneficial (Burns & Tam, 2019). This may have been, at least in part, due to the fact that an increase in leg length was not accompanied by an increase in stride length or contact time. An increase in midsole thickness did, as predicted (Hoogkamer, 2020), increase frontal plane ankle angle. This was found to be especially true among female participants.

Based on these results, the recommendation was made that purchasing running shoes with a midsole thicker than 35-mm is inadvisable given that it may not improve performance but may increase a runner's frontal plane ankle angle.

In Chapter 4, the second study was presented, the purpose of which was to determine the influence of midsole thickness on frontal plane ankle angle and performance when running curves. Two nearly identical footwear conditions were tested with midsole thicknesses of 35-, and 50-mm while running curves of 3-, 6-, and 9-m radii. Midsole thickness was found to not increase frontal plane ankle angle, as indicated by peak frontal plane ankle angles, or impact curve running performance, as measured by peak velocity or time-to-completion. These results may be the product of participants compressing the medial side of both footwear conditions into the same laterally banked surface. By doing so, participants avoided an increase in frontal plane ankle angle and decrements in performance, when running in the 50-mm footwear condition.

Based on these results it was concluded, there is no need to consider midsole thickness and its impact on running curves when selecting a running shoe.

In Chapter 5, the third and final study was presented, the purpose of which was to determine the influence of midsole thickness on pre-to-post changes in markers of muscle damage that may occur during a training-style run. Two nearly identical footwear conditions were tested with midsole thicknesses of 35-, and 50-mm while running for 60-minutes. The concentration of the blood markers of muscle damage lactate dehydrogenase and creatine kinase were tested before and after each run. Pre-to-post, the concentration of lactate dehydrogenase was found to increase more when running in the 35-mm footwear condition than when running in the 50-mm footwear condition; however, the difference was not significant and appeared to not be due to differences in eccentric muscle contraction (i.e., there were no significant differences in peak joint angles, or negative work). Based on previous literature (Quinn & Manley, 2012) it was concluded that completing a 60-minute training run was unlikely to be sufficient to incur enough muscle damage to impact subsequent training runs and that two midsole stiffnesses stiffer than 100 N/mm may not induce sufficient changes in joint angles to significantly increase eccentric muscle contractions.

Based on these results, it was concluded there is no need to consider midsole thickness when selecting a running shoe for training runs.

1.20 - Limitations and Future Directions

The research presented in this dissertation does not come without limitations. This section will discuss the main limitations of each study and future directions for research.

1.20.1 - The consequence of an increased midsole thickness

An unavoidable consequence of altering the thickness of a midsole is that the mechanical properties of the midsole, including mass, stiffness, and forefoot bending stiffness are also altered. Evidence would suggest each of these mechanical properties can impact the energetic cost of running (Franz et al., 2012; Kerdok et al., 2002; Roy & Stefanyshyn, 2006); however, in this dissertation, the conclusion was drawn that only mass could be normalized using a previously establish method (Esposito et al., 2022). Physically altering the stiffnesses of the footwear midsoles and forefeet was a risky proposition given that there was only one pair of each footwear condition, and the conditions were prototypes (i.e., not available for purchase). Had a condition been irreparably damaged it would have been irreplaceable. Previous research would suggest that the difference in midsole stiffness (i.e., ~ 70 N/mm) may not have been sufficiently large as to result in significant differences in performance and gait between conditions given that the most compliant condition (i.e., 35-mm) had a stiffness of 100 N/mm. That research, however, modulated floor stiffness, which may or may not have the same impact on running that midsole stiffness does. Therefore, it's impossible to know if differences in midsole stiffness contaminated this dissertations examination of midsole thickness and future research should look to examine the impact of footwear with differing midsole thicknesses but uniform midsole stiffnesses on running. While there wasn't an alternative method to normalize midsole stiffness beyond physical alteration, there was an alternative avenue to normalize forefoot bending stiffness. Forefoot bending stiffness can be modulated by inserting carbon fiber plates under the insole (Cigoja et al., 2022); however, previous research has demonstrated the location of a forefoot stiffening apparatus can impact running biomechanics (Flores, Delattre, et al., 2019). To have used carbon fiber plates under the insole would have been to trade one uncontrolled variable for another. Furthermore, to do so would have been to introduce two forefoot stiffening apparati in parallel, the impact of which is unclear. Future research should look to examine the impact of footwear with differing midsole thicknesses but uniform forefoot bending stiffnesses on running.

1.20.2 - The Influence of forefoot stiffening apparati

The footwear tested in this study were examples of advanced footwear technology, featuring among other elements forefoot stiffening apparati composed of five nominally parallel curved, carbon infused rods. While numerous studies have concluded forefoot stiffening apparati reduce the range of motion at the metatarsophalangeal joint (Madden et al., 2016; Oh & Park, 2017), their impact on other midsole behavior is lesser understood. It is plausible that the forefoot stiffening apparati, in addition to stiffening the forefoot, acted as structural support in the midsole reducing frontal plane angle. If so, footwear featuring 45-, and 50-mm thick midsoles but without forefoot stiffening apparati may not behave in the same manner as the footwear tested in this dissertation. It is therefore inadvisable to assume an increase in midsole thickness sans forefoot stiffening apparati would have the same impact on frontal plane angle.

Similarly, although the forefoot stiffening apparati in the footwear tested in this dissertation were five separate rods, presumably capable of moving independently of one another, other examples of advanced footwear technology contain only a single carbon fiber plate. It's unclear what the impact of differences in form of forefoot stiffening apparati would have on performance and frontal plane ankle angle in midsoles of different thickness. Future research should look to examine the impact of midsole thickness sans forefoot stiffening apparati and with forefoot stiffening apparati of different forms on running performance and frontal plane ankle angle.

1.20.3 - The influence of treadmill running

As indicated in Chapters Three and Five, studies one and three were conducted on a treadmill. Evidence would suggest peak medial ground reaction forces when treadmill running to be significantly reduced as compared to overground running (Riley et al., 2008). Given that members of both sexes saw decreases in frontal plane ankle angle when treadmill running on a thick midsole, the larger medial forces associated with over ground running could exacerbate increases in frontal plane ankle angle potentially increasing the risk of incurring a running related injury (Hannigan & Pollard, 2020). Future research should look to examine the impact of midsole thickness on frontal plane ankle angle when over ground running.

1.20.4 - The inside versus outside leg during curved running

In study 2 (i.e., Chapter 4), the choice was made to examine the impact of midsole thickness on the outside leg of a runner when curved running due to its known association with higher medial forces during curved sprinting (as compared to the inside leg) (Chang & Kram, 2007). However, the inside and outside leg of sprinters perform asymmetric functions when curved sprinting (Ishimura & Sakurai, 2016) therefore, future research should look to examine the impact of midsole thickness on frontal plane ankle kinematics of the inside leg during curved running.

1.20.5 - The influence of midsole stiffness on curved running

In study 2 (i.e., Chapter 4), the decision was made to leave the differing mechanical qualities of the midsole as was (i.e., non-normalized) including midsole stiffness. The rearfoot and forefoot stiffnesses of the two shoes tested differed by 76 and 70 N/mm, respectively. If participants did, as proposed, compress the midsole of both footwear conditions into similarly laterally banked surfaces, this was despite differences in midsole stiffness. Had the midsoles been of a similar stiffness, perhaps participants would not have been able to compress both footwear conditions in the same extent. Therefore, future research should look to examine the impact of footwear with different midsole thicknesses but the same midsole stiffness on curved running.

1.20.6 - Markers of muscle damage

In study 3 (i.e., Chapter 5), pre-to-post changes in concentration of lactate dehydrogenase and creatine kinase were assessed because they are widely accepted markers of muscle damage (Callegari et al., 2017). However, concern has been expressed as to whether or not concentrations of creatine kinase relate to the magnitude of sustained muscle damage (Nosaka & Clarkson, 1992). Furthermore, training status, as suggested by Noakes (1997) and Sanno et al. (2018) may impact an individual’s response to prolonged running. Future research should look to examine the impact of midsole thickness on muscle damage in a variety of homogeneous populations using methods perhaps more directly indicative of muscle damage such as muscle force generation capacity, muscle soreness, biopsies, or with ultrasound.

1.20.7 - Training-Style Run

While midsole thickness did not impact the pre-to-post change in concentration of markers of muscle damage caused by a 60-minute training style run, there are numerous styles of run a runner can employ that vary in speed, and duration such as intervals, hill runs, and long runs. Future research should examine the impact of midsole thickness on muscle damage associated with different styles of training runs.

1.21 - **Conclusion**

In 2020, when World Athletics amended their footwear rules restricting midsole thickness to a maximum of 40-mm (World Athletics Modifies Rules Governing Competition Shoes for Elite Athletes, 2020), there was no scientific evidence to support the amendment. This dissertation sought to determine the influence of midsole thickness on performance and running biomechanics and therefore determine whether the amendment was necessary. Midsole thickness was found to have no influence on running performance, curved running, or changes in markers of muscle damage following a training-style run. Increases in midsole thickness above 40-mm however, were found to increase ankle eversion. This would suggest the World Athletics footwear rule amendment was unnecessary and that midsole thickness may be self-governing given the supposed correlation between ankle eversion and an increased risk of running related injuries.

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