The Influence of Midsole Properties and Speed on Running Gait

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Abstract

Background: Biomechanical research and footwear engineering have facilitated specific running shoe designs, with a particular focus on the shoe's midsole. The primary aim of the midsole is to facilitate energy absorption (cushioning) from the initial impact of each step incurred during running, while recovering the maximum amount of energy. However, relatively few research articles report the pre-production foam properties or the post-production capability of the shoes' midsole in accordance with established *in vitro* industry standard testing. Moreover, parameters of running gait are often assessed in environments that do not replicate real-world overground running, whereby a limited number of steps are sampled, along with a lack of consideration for different speeds or changes in terrain, creating variation within *in vivo* test results. This highlights the nuanced understanding of how midsole cushioning interacts with the biomechanics of running.

Aims:

1. Assess the *in vitro* mechanical properties of aliphatic thermoplastic polyether polyethylene (ATPU) foam midsoles with varying densities.
2. Evaluate the *in vivo* effects of midsole foam density, within geometrically identical running shoes, on parameters of gait (spatiotemporal, kinetic, and joint kinematics) across different running speeds, with a particular focus on vertical peak impact force and average loading during real-world overground running.

Hypotheses:

1. *In vitro* testing will demonstrate the lower-density ATPU foam midsole to have greater energy absorption and energy recovery.
2. During *in vivo* experimental trials, parameters of running gait related to ground reaction force, specifically vertical peak impact force and average loading rate, will be reduced in the lower-density midsole. It is also expected that increases in running speed will influence spatiotemporal, kinetic, and joint kinematic parameters of gait.

Methods: *In vitro* testing was performed using a modified industry standard test (ISO 20344:2021 (5.17)). The midsole was compressed with 2.2 kN of force, in the vertical direction at a deformation rate of 100 $\text{mm}\cdot\text{min}^{-1}$. Following conditioning, five continuous cycles were performed while recording deformation (mm) and load (kN), from which the final cycle was extracted for analysis.

In vivo trials consisted of 16 recreational to nationally competitive endurance runners. The experimental protocol consisted of shoes classified by the density of the foam's midsole (high-ρ (0.17 $\text{g}\cdot\text{cm}^{-3}$) and mid-ρ (0.14 $\text{g}\cdot\text{cm}^{-3}$)) and three running speeds (12, 14, and 16 $\text{km}\cdot\text{h}^{-1}$). Participants ran 360 m on tarmacadam, at each running speed, paced by a cyclist. LoadSol® insoles were used to collect spatiotemporal and kinetic parameters of running gait, while four AHRS-IMU's attached to the sacrum and right lower limb (shank, femur, and foot) simultaneously recorded joint kinematics.

Results: *In vitro* results demonstrated that the mid-ρ midsole absorbed significantly more energy than the high-ρ midsole ($t_{(30)} = 6.412$, $p < 0.0001$), as well as recovering significantly more energy ($t_{(30)} = 9.052$, $p < 0.0001$).

In vivo trials showed that increases in running speed significantly increased vertical peak impact force ($F_{(2, 30)} = 32.24$, $p < 0.0001$), average loading rate ($F_{(2, 30)} = 38.70$, $p < 0.0001$), peak active force ($F_{(2, 30)} = 78.60$, $p < 0.0001$), stride frequency ($F_{(2, 30)} = 35.08$, $p < 0.0001$), swing phase knee flexion ($F_{(2, 30)} = 3.758$, $p = 0.035$) and extension ($F_{(2, 30)} = 8.363$, $p = 0.0013$), stance phase plantarflexion ($F_{(2, 30)} = 30.81$, $p < 0.0001$), stance phase hip extension ($F_{(2, 30)} = 100.7$, $p < 0.0001$), and swing phase hip flexion ($F_{(2, 30)} = 197.3$, $p < 0.0001$), while decreasing stride duration ($F_{(2, 30)} = 34.95$, $p < 0.0001$), ground contact time ($F_{(2, 30)} = 233.6$, $p < 0.001$), and impulse ($F_{(2, 30)} = 19.64$, $p < 0.0001$). There was no significant main effect of midsole density for vertical peak impact force ($F_{(1, 15)} = 0.01175$, $p = 0.915$), average loading rate ($F_{(1, 15)} = 0.5649$, $p = 0.464$), or any other parameter of running gait, along with no significant interactions.

Conclusion: The ATPU foam materials differed in density and produced significant differences during *in vitro* testing when manufactured into midsoles; however, these differences were not substantial enough to elicit significant changes during the *in vivo* overground running trials. This suggests that a greater level of material difference may be required to produce observable changes in parameters of running gait. It is also plausible that runners adapt their movement patterns in response to variations of midsole cushioning. The practical implications of this study indicate that individuals may not experience changes in running performance solely due to subtle differences in midsole foam properties.

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Abbreviations

A

AFT = Advanced footwear technology

AHRS-IMU = Attitude and Heading Reference System - Inertial Measurement Units

ANOVA = Analysis of variance

ASTM = American Society for Testing and Materials

ATPU = Aliphatic thermoplastic polyether polyethylene

B

BMI = Body mass index

C

CI = Confidence interval

CV % = Coefficient of variation

D

ρ = Density

E

EVA = Ethylene-vinyl acetate

G

g = Peak g-max score

I

ISO = International Organisation for Standardisation

P

PEBA = Polyether-block amide

PU = Polyurethane

S

SATRA = Shoe and Allied Trades Research Association

SD = Standard deviation

spm = Strides per minute

T

TPU = Thermoplastic polyurethane

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Chapter One – Introduction

Running was an essential prerequisite for survival prior to human existence (Kiely & Collins, 2016), and the development of bipedalism over the last five million years (Thorpe et al., 2007) has been a key factor in our evolutionary success as a species (Lieberman, 2007). The adaptations that allowed our hominid ancestors to run have significantly influenced the development of current biological, neurological, and structural characteristics. As a sport, running has undergone remarkable advancements, and the diversity of events has expanded beyond traditional road races and track events to include trail running, ultramarathons, and obstacle courses, attracting a wide range of participants. Globally, from a recreational perspective, it is estimated that more than 600 million people run at some level (Malisoux & Theisen, 2020). The weekly running participation rates in New Zealand for 2023 are reported as 50% in young people and 17% in adults (Sport-New-Zealand, 2024). With growing awareness surrounding the notion of physical activity for a healthy lifestyle, running has become one of the most accessible forms of exercise, supporting both physical and mental well-being (Major, 2001; Penedo & Dahn, 2005; Warburton & Bredin, 2017).

While offering holistic health benefits, the cyclical motion of the running gait cycle generates a shock wave of energy each time the foot makes initial contact with the ground, requiring attenuation to protect vital systems (Hamill et al., 1995; Lafortune et al., 1996; Voloshin et al., 1998; Winter & Challis, 2017). Due to the repetitive nature of running, these passive processes are highly sensitive to factors such as vertical peak impact force and loading rate (Davis et al., 2016). Running at faster speeds further exacerbates these factors (Arampatzis et al., 1999; Dorn et al., 2012; Hamill et al., 1983; Nigg et al., 1987), contributing to the complex and multifaceted nature of the sport.

Since the 1970s, biomechanical research and footwear engineering have facilitated specific running shoe designs (Frederick et al., 2023), with a particular focus on the shoe's midsole. The midsole of a running shoe is a layer of foam between the insole and outsole, providing cushioning through the combination of material properties, structural design features, and chemical modifications to the foam (Chu & Lin, 2007; Ma et al., 2022; Yang et al., 2018). Holistically, the midsole's capability focuses on the energy absorbed and recovered, thereby acting as a fundamental element in managing the amplitude of ground reaction forces that are experienced throughout the running gait cycle (Aerts & De Clercq, 1993; Nigg et al., 1995). Its primary aim is to facilitate energy absorption (cushioning) from the initial impact of each step incurred during running (Sun et al., 2020; Zhang et al., 2022), while recovering the maximum amount of energy (Aimar et al., 2024; Shorten, 1993).

Despite an extensive amount of research focused on the effects of footwear and its influence on biomechanics and running performance, relatively few research articles report the pre-production foam properties or the post-production capability of the shoes' midsole in accordance with established *in vitro* industry standard testing (Baltich et al., 2015; Hoogkamer et al., 2018; Huang, 2019; Worobets et al., 2014). To this end, *in vitro* mechanical tests have demonstrated that midsoles can effectively absorb impact energy (Shorten & Mientjes, 2011), and those studies that do provide test results typically show that softer midsoles have better cushioning properties (Clarke et al., 1983; Komi et al., 1987; Shorten & Mientjes, 2011). Similarly, musculoskeletal and mechanical models consistently predict that impact forces should be attenuated by midsole cushioning (Ly et al., 2010; Nigg & Liu, 1999; Wright et al., 1998; Zadpoor & Nikooyan, 2010). Runners also indicate through subjective self-reports that impacts feel softer in more cushioned shoes (Milani et al., 1997; Sterzing et al., 2013). However, *in vivo* measurements produce varying outcomes when obtained from ground reaction force and correlated with *in vitro* results, where the expectation that the magnitude of vertical peak impact force will be reduced is not achieved (Aerts & De Clercq, 1993; Clarke et al., 1983; Hennig et al., 1993; Nigg et al., 1987; Shorten & Mientjes, 2011). Moreover, parameters of running gait are often assessed in environments that do not replicate a natural running gait, whereby a limited number of steps are sampled, along with a lack of consideration for different running speeds or changes in terrain. Therefore, this thesis will investigate the *in vitro* mechanical properties of aliphatic thermoplastic polyether polyethylene (ATPU) foam, differing in density and manufactured into geometrically identical running shoes, in order to assess the effects on *in vivo* parameters of running gait at different speeds, during real-world overground running.

This thesis will present a contemporary review of the literature identifying reliable knowledge from which the hypotheses will be formulated, to investigate the influence of midsole properties and speed on parameters of running gait. The literature review (Chapter Two) will begin by explaining the running gait cycle and the influence that running speed has on the parameters of gait. Running shoe anatomy and classification will then be explored, followed by a summary of *in vitro* mechanical shoe testing and its limitations. The literature review will then focus on the material properties of midsoles, ultimately leading to an examination of the influence of the midsole material properties on parameters of running gait. Based on the knowledge gained from this literature review, the aims and hypotheses will be explained in Chapter Three. The methods for *in vitro* and *in vivo* experimental protocols will be documented in Chapter Four, and the results of the study will be analysed and presented in Chapter Five. Chapter Six will discuss the study's findings, including supporting literature, limitations, and potential future research directions. Finally, Chapter Seven will provide an overarching conclusion of the study and its practical implications.

Chapter Two – Literature Review

2.1 The Running Gait Cycle

Running is a cyclic activity, whereby a series of movements of the lower extremities causes the body to move in a predictable and recurring pattern (Dicharry, 2010). The running gait cycle is inclusive of two distinct phases (Figure 2.1): the time a single foot spends on the ground (stance phase) and the time in the air (swing phase). The swing phase starts and ends with both feet off the ground, a phenomenon referred to as double float (Novacheck, 1995; Ounpuu, 1990). Typically, 40% of the cycle time is spent in the stance phase, while the swing phase accounts for 60% of time (Figure 2.1A). However, these percentages vary with fluctuations in running speed (Thordarson, 1997) and individual technique (van Oeveren et al., 2024).

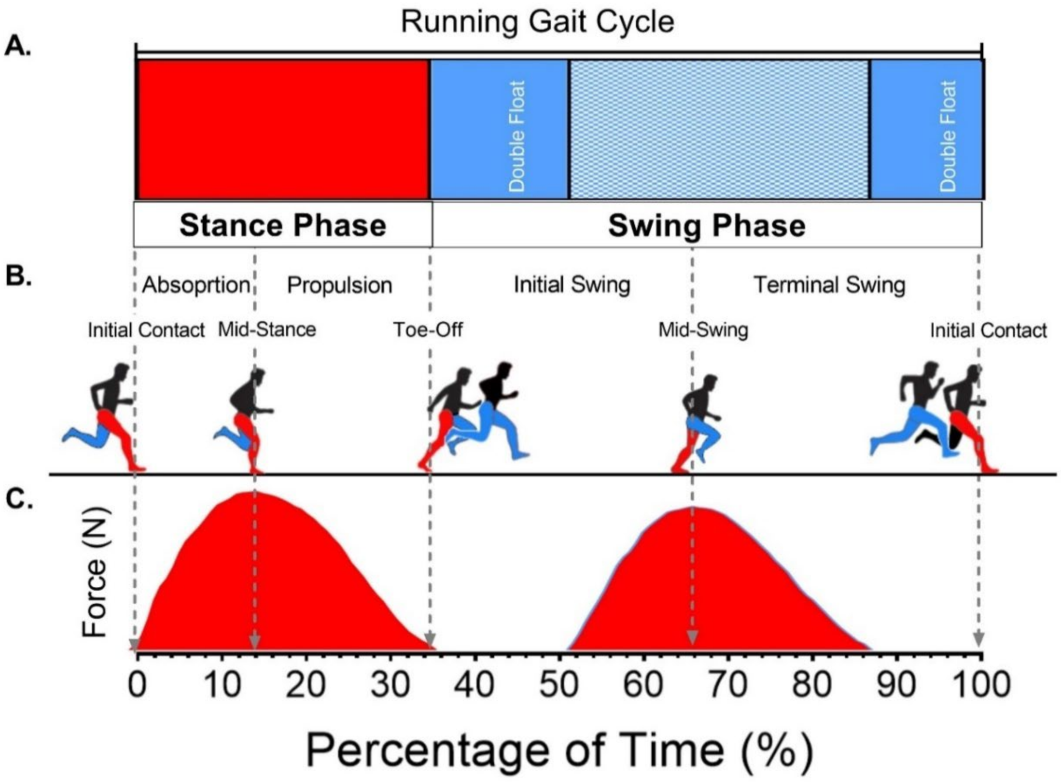

Figure 2.1. The running gait cycle where data were generated from a participant, A. basic schematic of the running gait cycle, B. detailed schematic of phases of the running gait cycle, C. ground reaction force traces for the right and left foot during the gait cycle, (generated from participant data)

The continuous cyclic motion of the running gait cycle indicates that no certain point is assumed to be the beginning or end (Anderson, 1996; Nicola & Jewison, 2012). However, throughout this literature review and thesis, the stance phase will be addressed first.

The running gait cycle consists of two main phases, which are further divided into sub-phases (Figure 2.1B). These phases include the stance phase, which encompasses absorption and propulsion, and the swing phase, which includes the initial and terminal sub-phases. During these phases of the gait cycle, various factors are observed, including spatiotemporal variables (timing and spatial characteristics), kinetic variables (forces that cause or influence motion), and joint kinematics (the movement of joints). The stance phase can be visualised using a ground reaction force trace (Figure 2.1C), which depicts the interaction between the foot and the ground (Richards, 2018). The force is distributed chronologically over the entire contact surface, reflecting the acceleration of the total body's centre of mass (Novacheck, 1998). As the foot makes initial contact with the ground (Figure 2.2), the force increases positively from 0 N and returns to 0 N when the foot leaves the ground, termed toe-off (Miller, 1990). The initial contact, combined with the anatomical aspect of the foot that makes initial contact, is referred to as the strike pattern (Hasegawa et al., 2007). Depending on the running population, current literature suggests that approximately ≥ 80% of runners initially make contact via the posterolateral border of the foot, referred to as a heel strike (Figure 2.2A), while others make initial contact with the ball of the foot (Figure 2.2B), referred to as a forefoot strike (Cavanagh & Lafortune, 1980; de Almeida et al., 2015; Kasmer et al., 2013; Kerr et al., 1983; Thordarson, 1997).

The absorption phase (Figure 2.1B) is characterised by the runner experiencing vertical peak impact force (N). This occurs as a result of the impact of the foot with the ground (Clarke et al., 1983) causing the body's centre of mass to fall, decelerating from its peak height (Novacheck, 1998), and transiting into a stable position for the subsequent phases of movement (Harrold & Abboud, 2018). Vertical peak impact force has been termed as the first peak occurring within 50 ms after initial contact (Chan et al., 2018; Frederick et al., 1981). Nigg et al. (1983), referred to this as the "passive" peak, as it occurs within a time frame too brief for reactive neuromuscular control. The magnitude of this peak reaches values 1.5 to 3 times an individual's body weight (Lieberman et al., 2010), dependent on speed. Further, this impact is considered a significant risk factor for lower limb injuries (Grabowski & Kram, 2008; Logan et al., 2010). However, this peak is not always present within a force trace, as in the case of forefoot strikers (Figure 2.2B). In this instance, the vertical peak impact force has been defined as the force at 13% of the stance time (Blackmore et al., 2016; Chan et al., 2018).

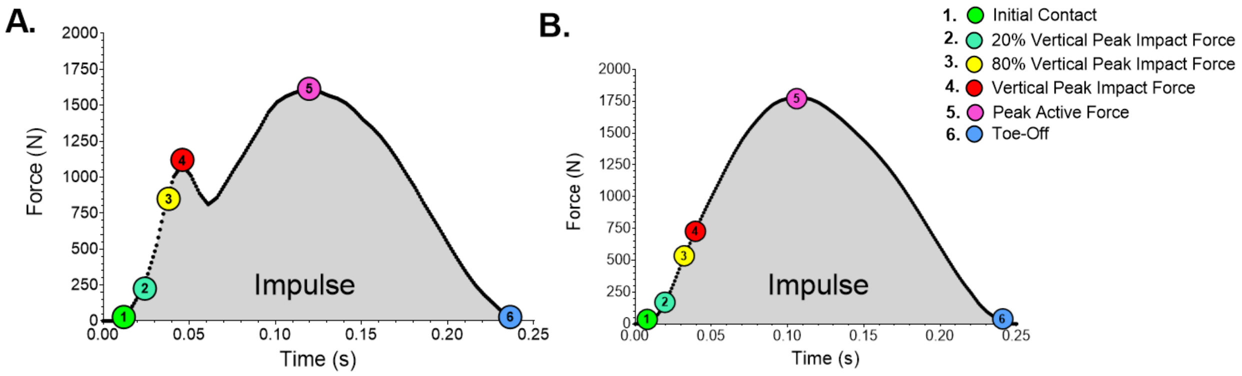

Figure 2.2. Ground reaction force trace during one step, taken from participants' dataset running overground; A. represents heel striking and B. represents a forefoot strike

These two different strike patterns (Figure 2.2) create variations to the ground reaction force trace, and subsequent metrics (Daoud et al., 2012). Heel strikers (Figure 2.2A) generate a rapid, high vertical peak impact force in the ground reaction force trace, during the first part of the stance (Bobbert et al., 1991; De Wit et al., 2000; Laughton et al., 2003; Williams et al., 2000). This creates a greater magnitude and rate of vertical peak impact force compared to forefoot runners (Lieberman et al., 2010), and subsequently an increased risk of injury (Daoud et al., 2012). The speed at which forces are applied to the body during this period, outside of reactive neuromuscular control, is quantified as the loading rate ($N\cdot s^{-1}$). Instantaneously, it is the rate at which peak impact force occurs (Milner et al., 2006), but more holistically, it is associated with the slope of the force trace between time points of 20 and 80% of the vertical peak impact force and is labelled average loading rate (Miller, 1990; Schmida et al., 2022).

Following the absorption phase, the vertical component of the ground reaction force for heel strikers experiences a trough where there is a reduction in force, characterised as the impact peak minimum (Clarke et al., 1983), before continuing to increase to a second peak at midstance (or the only peak for forefoot strikers). This is termed as the peak active force due to its association with the propulsion of the body's centre of mass (Gottschall & Kram, 2005; Shorten & Mientjes, 2011). The timing of this peak occurs when the foot is directly below the centre of mass (Nigg et al., 1987), depicting the mid-stance point of the stance phase (Novacheck, 1998). The time to peak active force refers to the duration from initial contact to the peak (Seiberl et al., 2018).

The combination of the absorption and propulsive phases in relation to the force trace produces an area under the force curve known as impulse (Seiberl et al., 2018) and represents the change in momentum (Winter et al., 2016).

Transitioning into the swing phase enables the foot to clear the ground after toe-off and be repositioned in front of the centre of mass, preparing for the next initial contact (Novacheck, 1998). The limb is accelerated forward during the initial swing (García-Pinillos et al., 2019) and into the double float, where potential energy reaches its peak during the gait cycle (Novacheck, 1998), causing the ground reaction force to become zero. The opposite limb passes the stance limb during mid-swing, before being decelerated in preparation for the next initial contact (terminal swing), where both feet again undergo double float (Adelaar, 1986; Dugan & Bhat, 2005; Novacheck, 1998; Rueterbories et al., 2010). When the limb reaches its reversal point and makes initial contact with the ground again, the stride's length and duration are concluded. The number of these complete gait cycles occurring within a minute is referred to as stride frequency (spm), and is associated with the efficiency of a runner's stride (Thordarson, 1997).

2.2 The Influence of Speed on Running Gait

Running speed is the distance travelled per unit of time ($m \cdot s^{-1}$) or the average speed at which the centre of mass travels over a given interval, in the sagittal plane (Yeadon et al., 1999). Speed is susceptible to variation as the body segments accelerate and decelerate with each foot fall (Lee & Farley, 1998), even when running at a controlled pace (Abbiss & Laursen, 2008). This variation can be further influenced by factors such as terrain, environmental conditions, and fatigue (Abbiss & Laursen, 2008; St Gibson et al., 2006).

Both stride length and stride frequency contribute to running speed (Dillman, 1975; Mercer et al., 2005; Williams, 1985), where stride length ($r = 0.92$, $p < 0.05$) and frequency ($r = 0.89$, $p < 0.05$) have been positively correlated with increases in running speed (Mercer et al., 2002). At running speeds less than 7 $m \cdot s^{-1}$, it has been suggested that individuals experience increases in speed through a proportionally greater increase in stride length (Högberg, 1952). Dorn et al. (2012), reported that when running speed changed from slow paced (3.49 ± 0.12 $m \cdot s^{-1}$) to medium-paced (5.17 ± 0.13 $m \cdot s^{-1}$), stride length increased by 32% (from 2.62 ± 0.10 to 3.42 ± 0.13 m), whereas stride frequency only increased by 10% (from 1.31 ± 0.03 to 1.47 ± 0.05 $strides \cdot s^{-1}$). Stride length continued to increase by 17% at fast-paced running (6.96 ± 0.13 $m \cdot s^{-1}$); however, only a modest 3% increase was observed as speed progressed to sprinting (8.99 ± 0.67 $m \cdot s^{-1}$). Concurrently, a significant ($p < 0.01$) shift towards increased stride frequency occurred, with values rising from 1.75 ± 0.10 $strides \cdot s^{-1}$ at fast-paced running to 2.18 ± 0.10 $stride \cdot s^{-1}$ during sprinting. The latter is further supported by Nummela et al. (2007), who found that speeds above 7 $m \cdot s^{-1}$ were achieved by increasing stride frequency, rather than stride length. At high speeds, it is important to achieve rapid leg turnover through angular acceleration of the lower limb joints while minimising the duration of the stance phase (Cavagna et al., 1988; Cavagna et al., 1991; Hunter et al., 2004; Kaneko, 1990; Salo et al., 2011; Weyand et al., 2000). This is essential for maintaining the forward momentum necessary at faster running speeds (Pink et al., 1994).

2.2.1 Stance Phase

As running speed increases, the duration of the stance phase decreases (Dorn et al., 2012; Farley & Gonzalez, 1996; García-Pinillos et al., 2019). Simultaneously, the magnitude of vertical peak impact force during the absorption phase rises, primarily due to greater acceleration of the lower limb segments upon ground contact (Brughelli et al., 2011; Nilsson & Thorstensson, 1989), rather than changes in body mass or segment composition (Dixon et al., 2000; Schache et al., 2014). Nigg et al. (1987) found a linear relationship between vertical peak impact force at 1 m·s^{-1} running speed increments between 3 and 6 m·s^{-1}, where peak impact force increased from 1.33 to 2.17 kN, respectively. Mercer et al. (2002), observed a similar finding, showing a significant correlation between vertical peak impact force and running speed (r = 0.81, p < 0.05). These findings have also been corroborated in our laboratory during an incremental ramp test (Figure 2.3A).

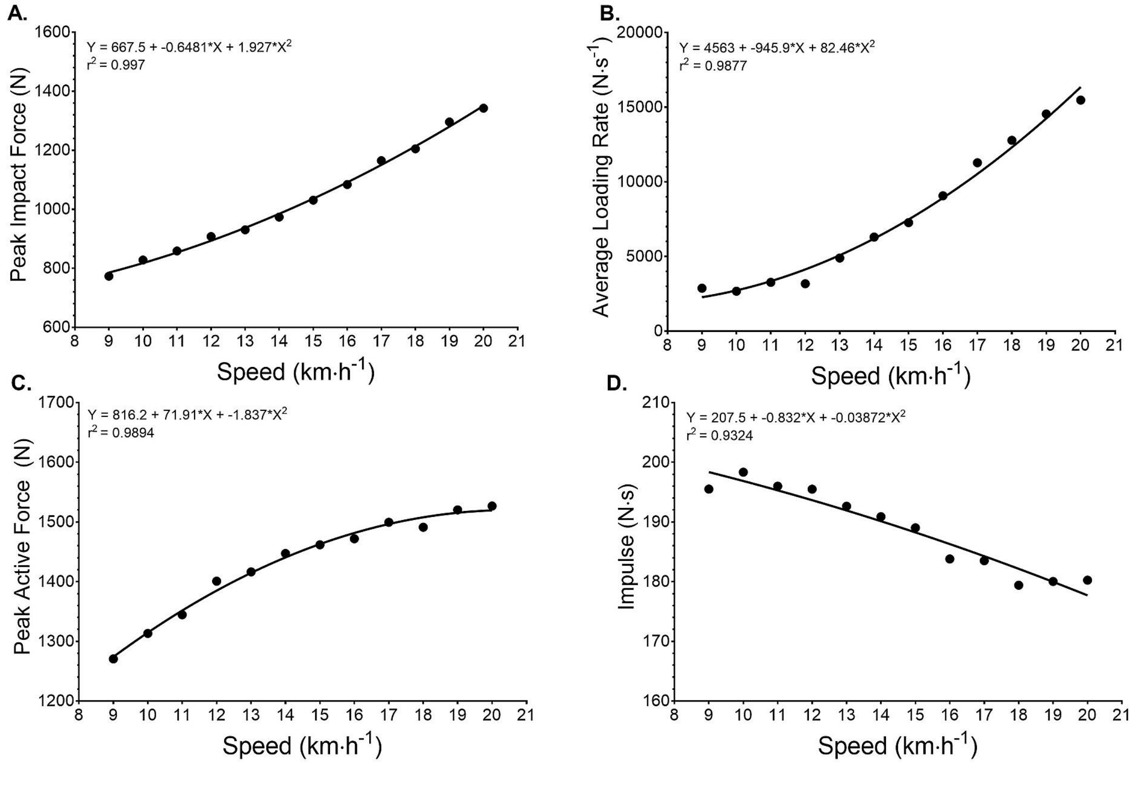

Figure 2.3. Unpublished data, whereby an athlete performed an incremental ramp test on a treadmill, starting at 8 km·h^{-1} and increasing by 1 km·h^{-1} every one minute while wearing LoadSol® insoles. A. peak impact force, B. average loading rate, C. peak active force, D. impulse (Macdermid, 2024)

As vertical peak impact force increases with running speed, so too does the average loading rate, reflecting the rapid application of force over time. The increase in loading rate is a direct consequence of the faster force development, accompanied by shorter ground contact times at higher running speeds (Nummela et al., 2007). Loading rate has been shown to increase from 90 to 233 $kN \cdot s^{-1}$ for 3 to 6 $m \cdot s^{-1}$, respectively (Nigg et al., 1987), with such increases demonstrating a non-linear, quadratic relationship, similar to that observed in our laboratory (Figure 2.3B). Significant correlations for female ($r = 0.687$, $p < 0.001$) and male ($r = 0.639$, $p < 0.001$) runners have also been observed for vertical average loading rate, defined as the average slope between 20 and 80% of the vertical ground reaction force prior to peak impact, with 0.28 $m \cdot s^{-1}$ increments from 2.78 to 4.44 $m \cdot s^{-1}$ (Jiang et al., 2024).

Subsequently, in accordance with Newton's Third Law, when a runner applies more force to the ground, an equal and opposite force propels the body forward (Zatsiorsky, 2002). Faster running speeds require greater propulsive forces but with less time to apply the appropriate force (Derrick et al., 1998; Frederick & Hagy, 1986; Mercer et al., 2005; Mercer et al., 2002; Weyand et al., 2010; Weyand et al., 2000). This is supported by the significant increases ($p < 0.05$) in peak active force from 1.86 kN at 3 $m \cdot s^{-1}$ to 2.26 kN at 6 $m \cdot s^{-1}$ (Nigg et al., 1987), and verified in our laboratory (Figure 2.3C). In contrast, Frederick and Hagy (1986), categorised running participants into three groups based on body mass for comparative analysis. The findings suggest that body mass had a more pronounced effect on the magnitude of peak active force ($r = 0.95$, $p < 0.05$) than speed. In comparison, the correlation coefficient for the effect of speed on peak active force was considered not significant ($r = 0.15$, $p < 0.05$). This underscores why gait variables are typically presented as Newtons per body weight ($N \cdot BW^{-1}$), to enable for the comparison of force related measures across individuals with varying body weights (Little-Letsinger et al., 2025), which could otherwise confound the interpretation of results.

The area under the ground reaction force trace (vertical impulse) has been shown to decrease (Figure 2.3D), as running speed increases (Dorn et al., 2012; Nummela et al., 2007; Weyand et al., 2010; Weyand et al., 2000). Reductions in vertical impulse, as faster running speeds are approached, have been attributed to the decreases in ground contact times, that are larger than the increase in the effective force applied to the ground (Weyand et al., 2000). Macdermid et al. (2025) also showed a decreased main effect of running speed ($p < 0.0001$) for step impulse. Vertical impulse is relevant because although the ground reaction force is always positive in the vertical direction, the horizontal component includes both braking and propulsive forces (Hunter et al., 2005). Early in the stance phase a negative (braking) impulse occurs as the foot strikes the ground, decelerating the body. To maintain a constant overall speed, this deceleration must be offset by an equally large positive (propulsive) impulse during the late stance phase, when the runner pushes off the ground to accelerate forwards (Chang & Kram, 1999). Vertical impulse is proportional to vertical momentum and directly related to the vertical displacement of the centre of mass, commonly referred to as vertical oscillation (Malisoux et al., 2023). Vertical oscillation is the up-and-down movement of a runner's torso that occurs with each step, contributing to the overall dynamics and efficiency of movement (Kyröläinen et al., 2001). At lower speeds of a runner's capability (40-60% of maximum), a runner's vertical oscillation remains relatively constant, but as speed increases beyond this range, vertical oscillation decreases (Brughelli et al., 2011). Reducing vertical displacement may enhance a runner's mechanical efficiency or facilitate faster speeds, by minimising work against gravity (Slawinski & Billat, 2004; Thordarson, 1997).

2.2.2 Swing Phase

As running speed increases, the time spent in the swing phase also increases (Dicharry, 2010; Novacheck, 1998). This is supported by other researchers who suggest that the key to increasing running speed is to reduce stance time and increase ground reaction forces, which in turn lengthens the swing and float phases of gait (Dugan & Bhat, 2005; Mann & Hagy, 1980; Pink et al., 1994). These changes occur due to the equal and opposite reaction forces, which require the leg to move faster to achieve the necessary ground clearance and forward momentum at faster running speeds (Dugan & Bhat, 2005).

The swing phase of gait is influenced by the angles of the joints (Mena et al., 1981), specifically as running speed increases (Novacheck, 1998). The range of motion at the hip, knee, and ankle joints generally increases (Rottier & Allen, 2021), with significant differences ($p < 0.05$) having been observed at speeds of 2.5, 3.5 and 4.5 $m \cdot s^{-1}$, in all three planes of motion (Soltani et al., 2022). Generating greater range of motion and angular velocity contributes to optimising a runner's stride (Caplan et al., 2009; Godges et al., 1993), enabling greater distance to be covered with each step (Smith & Hanley, 2013). This, in turn, reduces the proportion of the gait cycle spent in contact with the ground. Both swing and ground contact times are key determinants that influence a runner's stride length and frequency (Moore, 2016), and these adaptations are critical for maintaining high-speed running mechanics while reducing the energy expenditure over prolonged distances (van Oeveren et al., 2024).

To attenuate the ground reaction forces throughout the gait cycle, particularly at higher speeds, running shoes have evolved over the past 55 years. This evolution is important because each time the foot makes initial contact with the ground, a complex interaction of forces occurs between the surface, the shoe, and the foot.

2.3 Anatomy of a Running Shoe

Since the 1970s, biomechanical research and footwear engineering have facilitated specific running shoe designs focusing on cushioning, comfort, performance, protection, and support (Frederick et al., 2023; Hamill & Bates, 2023). The development of running shoes to address the needs of the wearer has seen cushioned and greater shock-absorbing midsoles regarded as a strategy to mitigate the ground reaction forces experienced throughout the gait cycle (Cavanagh & Lafortune, 1980; Malisoux et al., 2016; Nigg et al., 1987; Sterzing et al., 2013). The primary aim is to provide the wearer with an individualised and preferred movement path while running (Bermon, 2021; Honert et al., 2020; Nigg et al., 2015; Nigg et al., 2017; Winter & Bishop, 1992). The anatomy of a road running shoe is presented in Figure 2.4.

Figure 2.4. Lateral view of the anatomy of a road running shoe

The upper is the part of the shoe that covers the foot (McKenzie et al., 1985) and utilises breathable materials to avoid the accumulation of heat (Reinschmidt & Nigg, 2000). Key aspects of the upper are: the toe box accounting for the front of the shoe, providing adequate room for plantar flexion and dorsiflexion of the toes while running (McKenzie et al., 1985); the laces that secure the shoe to the foot are interlaced and adjusted through eyelets that run alongside the tongue (Caselli, 2006), which covers the dorsal aspect of the foot and provides protection from the laces (McKenzie et al., 1985). The seat region of the shoe includes the heel collar encircling the shoe's opening offering comfort and support, ensuring the foot stays secured and properly positioned; while the heel counter provides structure to the back of the shoe, tending to have a layer of material to lock in the heel when the laces are tied, preventing excessive rotation and slippage (McKenzie et al., 1985).

Located directly under the plantar region is the insole, typically a removable piece of foam providing a layer of comfort above the midsole (Nagano & Begg, 2018). The Strobel board sits directly below the insole, providing a seamless connection between the upper and lower parts of the shoe (Nagano & Begg, 2018). The Strobel board is bonded to the midsole, which is a layer of foam positioned between the insole and the outsole. In a running shoe, the midsole provides cushioning and energy recovery, using various foam materials (Aimar et al., 2024; Caselli, 2006; Shorten, 1993). However, the midsole provides little to no grip on the running surface and would wear out quickly due to the abrasive nature of running. As such, shoes are fitted with an outsole that covers either the whole midsole plantar surface or specific aspects, which is typically made of reinforced rubber to provide durability and traction (Ruello, 2016). The stack height encompasses the total thickness of the sole, including the outsole, midsole, and insole (Frederick et al., 2021). It is typically measured at the base of the calcaneus (heel) and under the ball of the foot (forefoot) (Frederick et al., 2021). According to ASTM (2013) these points correspond to 12 and 75% of the total inside shoe length, respectively. The heel-to-toe drop refers to the difference in stack height between the heel and the forefoot of the shoe (Coetzee et al., 2018; Esculier et al., 2015; Frederick et al., 2021), and with a wide variety of shoe designs available for distance running, this drop can vary from 0 to 12 mm (Richert et al., 2019). The heel-to-toe drop can influence foot strike patterns (Nigg et al., 2021), with a reduced heel-to-toe drop promoting a shift from a rearfoot to a non-rearfoot strike (Chambon et al., 2015; Horvais & Samozino, 2013). This transition is expected to reduce vertical peak impact force and the associated loading rate (Lieberman et al., 2010). However, the expected benefits of this change have not been consistently observed across different studies (Besson et al., 2019; Chambon et al., 2015; Richert et al., 2019).

2.3.1 Running Shoe Classifications

Running shoes are often classified according to specific design features and component technologies, which are manipulated to target various biomechanical needs and performance goals. Common classifications of road running shoes include:

a) Minimalist shoes, defined by their highly flexible sole, low stack height and weight, an absence of heel-to-toe drop and motion control technology (Bonacci et al., 2013). The Minimalist Index (Esculier et al., 2015) considers these attributes to give the shoe a score out of 100, with scores closer to 100 indicating greater barefoot qualities. These shoes are designed to promote barefoot biomechanics by providing minimal interference with the natural movement of the foot (Abshire & Metzler, 2010; Esculier et al., 2015; Jenkins & Cauthon, 2011).

b) Cushioned shoes, characterised by a cushioned and elevated heel and arch (Ridge et al., 2015). These shoes aim to reduce impact upon loading by providing shock absorption (Aguinaldo & Mahar, 2003; Kulmala et al., 2018; Worobets et al., 2014).

c) Motion control shoes, designed to reduce rearfoot eversion throughout the stance phase, enhancing the propulsive efficiency of the foot (Asplund & Brown, 2005; Langley et al., 2019; Rose et al., 2011). Key design features can include firmer midsole density on the medial aspect of the sole (McPoil, 2000), a medial post for enhanced support, or rigid plastic arch inserts (Richards et al., 2009).

d) Racing flats, which were traditionally lightweight and minimal in cushioning, but they have largely been replaced by modern advanced footwear technology (AFT) (Hoogkamer et al., 2018). These ‘supershoes’ combine thick, responsive midsole foams embedded with a carbon fibre plate or another type of stiff element to improve running economy and reduce fatigue (Hébert-Losier & Pamment, 2023; Joubert & Jones, 2022).

2.4 Design and Function of the Midsole

The midsole is defined as the layer of foam located between the insole and the outsole of the shoe, which acts as the primary energy-absorbing mechanism (Sun et al., 2020) outside of the human system, providing cushioning at the foot-ground interface (Zhang et al., 2022). As such, cushioning is defined as the ability to decrease the amplitude of vertical ground reaction forces upon impact (Aerts & De Clercq, 1993; Nigg et al., 1995). This occurs as the cellular structure of the material absorbs energy (Silva et al., 2009) and deforms the midsole. The elastic properties of this process, represented by the cellular structure releasing the stored energy, are referred to as energy returned or recovered (Aimar et al., 2024; Shorten, 1993). The difference between absorbed and recovered energy is the energy lost.

The optimal behaviour of a cushioning system tends to maximise the energy absorbed (Aimar et al., 2024), achieved through the configuration of materials and structural solutions of the midsole foam (Chu & Lin, 2007; Ma et al., 2022). Traditionally, midsoles are made from viscoelastic materials such as ethylene-vinyl acetate (EVA), polyurethane (PU), or thermoplastic polyurethane (TPU) (Asplund & Brown, 2005; McPoil, 2000). EVA is a copolymer that is soft, light, and easy to manipulate (Burns & Joubert, 2024), acting as an impact absorber (Sun et al., 2020). Meanwhile, PU and TPU display similar characteristics to EVA but present greater durability and abrasion resistance (Wang et al., 2010). More recently, polyether-block amide (PEBA) has been used in midsoles and was the first foam to be used in AFT (Hoogkamer et al., 2018). When it is foamed, the chemical becomes a lightweight material with the potential to have a very low density (Burns & Joubert, 2024). This allows PEBA midsoles to have excellent energy absorption properties (Aimar et al., 2024; Ashby & Gibson, 1997), with the ability to reportedly deform twice as much (Hoogkamer et al., 2018) compared to EVA and TPU midsoles (11.9, vs. 6.1, vs. 5.9 mm, respectively).

Changes to midsole foam chemistry allow the physical properties to be manipulated for a specific application (Yang et al., 2018). As such, the material properties of shoes are influenced by microstructural fractures, including the size and shape of cell walls, micro-fillers, along with the type of copolymer (EVA, PU, TPU, and PEBA) used (Aimar et al., 2024), all of which are structural features closely linked to the manufacturing process. Process-induced tortuous cell walls (winding or convoluted path), combined with highly porous (void spaces in a material), and homogeneous microstructure (uniformly distributed), enhance energy absorption while minimising compressive stress (Aimar et al., 2024). Among the samples tested, the PEBA foam with the aforementioned properties demonstrated the best cushioning performance. However, as a result of repeated mechanical test cycling, damage accumulation, which reflects the durability of the foam's mechanical properties, occurred at a faster rate (Aimar et al., 2024).

Density also influences the material properties of the midsole. Foam density is a unit of measure that is calculated from the mass and volume of a foam sample (Roslim et al., 2012), measured as grams per cubic centimetres ($g \cdot cm^{-3}$). The material per se does not define density; rather, density can be manipulated during the foaming process and is a direct representation of porosity and cell size (Pang et al., 2022). Foams with higher porosity and smaller cell size are less dense, due to a higher volume of fraction gas being entrapped within the material (Lunchev et al., 2022). Midsole densities of road running shoes typically range from 0.08 to 0.35 $g \cdot cm^{-3}$ (Kram, 2022). The amount of force required to deform the midsole (compressive stress) and foam density are two important and opposite directional parameters (Lunchev et al., 2022). Ideally, a midsole foam should exhibit a low density while maintaining high compressive strength, making it essential to strike a balance between these two factors (Lunchev et al., 2022). As such, adjusting the density of foams used in the shoe's midsole has become a way of enhancing cushioning (Shimazaki et al., 2016). Lower-density foams tend to be lighter, offering greater energy absorption and recovery (Burns & Joubert, 2024). Conversely, materials exhibiting a very high density tend to deform less, thereby reducing the energy absorbed (Paton et al., 2007). Furthermore, midsole cushioning is also enhanced by incorporating dual-density foams, air, gel, encapsulated gases, or high-density plastic technologies (Asplund & Brown, 2005; Hamill & Bates, 2023; McPoil, 2000). All of these materials exhibit good energy absorption and recovery properties, and when integrated into a shoe's midsole, they enhance cushioning during the initial impact (Shorten & Mientjes, 2011).

However, findings in the literature regarding the midsole's material and mechanical capabilities are somewhat inconclusive, with few research articles reporting in accordance with industry standards (Hoogkamer et al., 2018; Worobets et al., 2014), presenting challenges in making direct comparisons and drawing definitive conclusions.

2.5 *In Vitro* Mechanical Shoe Testing

At an industry level, running shoes are assessed via *in vitro* mechanical tests to determine material capability without the influence of human interference (Wang et al., 2010). This usually involves the determination of the energy absorbed and recovered by the midsole under a prescribed loading rate, for one or more compressive cycles (Matijevich et al., 2022; Shorten, 2024). Each cycle is intended to mimic how materials are expected to behave during *in vivo* running testing (Shorten, 2024).

Footwear industry standards are set by organisations such as: International Organisation for Standardisation (ISO), Shoe and Allied Trades Research Association (SATRA), and American Society for Testing and Materials International (ASTM). Each organisation provides varying methodologies for evaluating and assessing the structural and functional properties of footwear.

There is no specific International Organisation Standardisation (ISO) standard solely focused on the cushioning of athletic shoes. However, ISO 20344:2021 (5.17) Determination of the Energy Absorption of the Seat Region (ISO, 2021), is a safety standard that includes the requirements of energy absorption for the shoe's heel. Regarding running shoes, this includes the insole, midsole and outsole of the seated region. The test requires a compressive test machine (Figure 2.5) capable of measuring compressive forces up to 6 kN, with integrated recording of load (kN) and material deformation (mm). A heel last is fitted into the shoe, placed flush to the heel counter. Compressive load is applied against the bottom unit from inside to the centre of the heel area at a rate of 10 ± 3 mm·min^{-1}, until a force of 5 ± 0.05 kN is obtained.

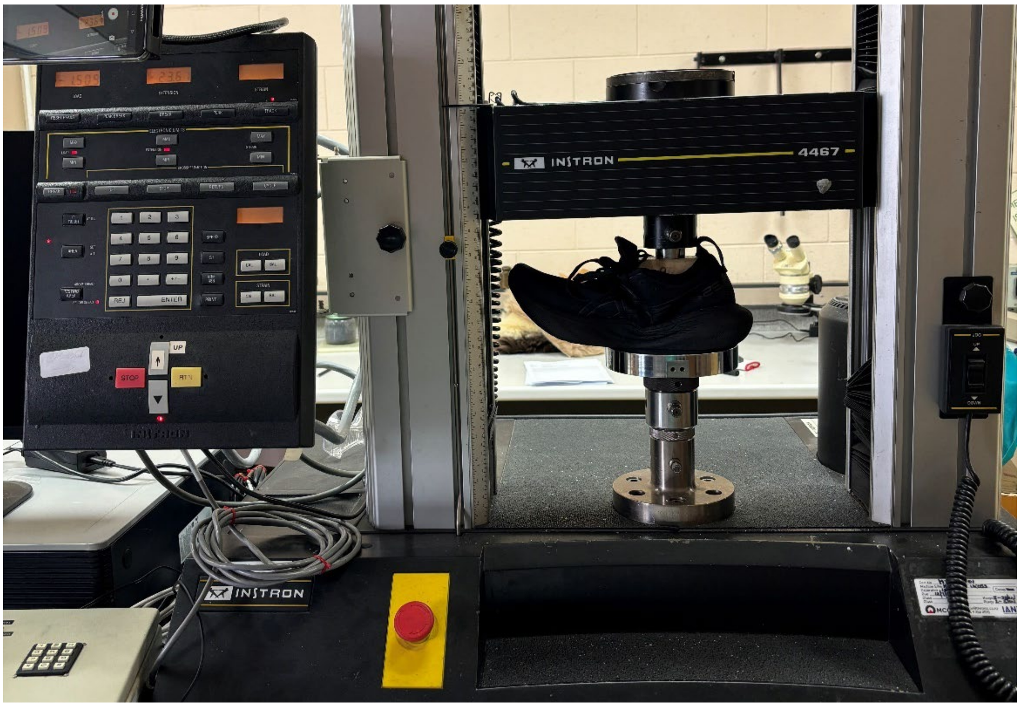

Figure 2.5. International Organisation Standardisation (ISO) 20344:2021 (5.17) Determination of the Energy Absorption of the Seat Region compressive test machine

The Shoe and Allied Trades Research Association (SATRA) Test Method TM183:1998 Whole Shoe Cushion Assessment (SATRA, 1998), is designed to measure the cushioning property of an entire shoe under a typical body weight load. This assessment utilises a compressive testing machine (Figure 2.6) that operates at crosshead speeds of 2 ± 0.5 and 100 ± 5 $\text{mm}\cdot\text{min}^{-1}$, with the capability to measure forces up to 2 kN. A mechanical foot, representative of the size and type of shoe being tested, is attached to the upper jaw of the testing machine. The shoe is positioned centrally on the foot so that the centre of the heel contactor is positioned at 15% of the insole length. The crosshead is then lowered at a speed of 2 ± 0.5 $\text{mm}\cdot\text{min}^{-1}$ until a load of 100 N is reached. Once this load is achieved, the speed is increased to 100 ± 5 $\text{mm}\cdot\text{min}^{-1}$, and the direction of travel is reversed when a load of 700 N is reached. After reaching this load, the shoe is allowed to stand for 30 ± 5 seconds. The procedure is then repeated, and results are recorded to create a force displacement graph.

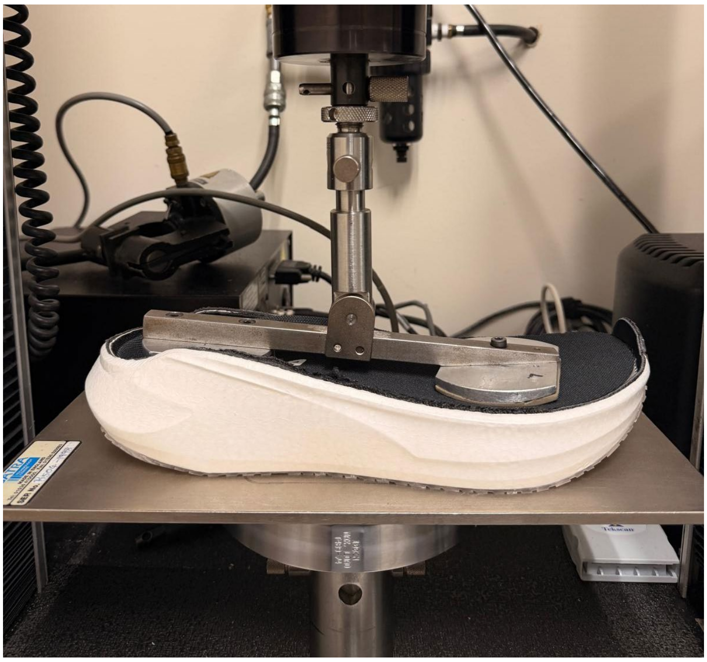

Figure 2.6. Shoe and Allied Trades Research Association (SATRA) Test Method TM183:1998 Whole Shoe Cushion Assessment, compressive testing machine with the upper of shoe removed to shoe removed to show the mechanical foot

The American Society for Testing and Materials International (ASTM) F1976-13, Standard Test Method for Impact Attenuation of Athletic Shoe Cushioning Systems and Materials (ASTM, 2013), provides standardised procedures for assessing the impact attenuation properties of athletic footwear. This method (Figure 2.7) involves dropping a mass of 8.5 ± 0.1 kg from a known height of 30 - 70 mm, delivering a nominal energy input of 5 J, representative of the forces typically encountered during heel and forefoot impacts. To simulate these conditions, the shoe is aligned on the testing apparatus such that the centre of impact aligns with the point located 12% (with a 2 mm tolerance) of the shoe's internal length from the heel for heel impact testing, or 75% (with a of 2mm tolerance) for forefoot testing. This simulates the anticipated peak vertical ground reaction force experienced by the runner on the region of the shoe being compressed, along with a loading duration that reflects the typical ground contact time (185 – 300 ms) of a runner (Hoogkamer et al., 2018; Lippa et al., 2017; Worobets et al., 2014). The test protocol includes 25 dynamic compression cycles (one cycle is complete loading and unloading) to condition the shoe, followed by five additional cycles used for data collection. Key outcome variables include peak acceleration during the impact (*g*-max) where lower values indicate better energy absorption; time to peak acceleration (t-max); peak compressive displacement (x-max); and the amount of energy recovered or lost due to hysteresis (ASTM, 2013).

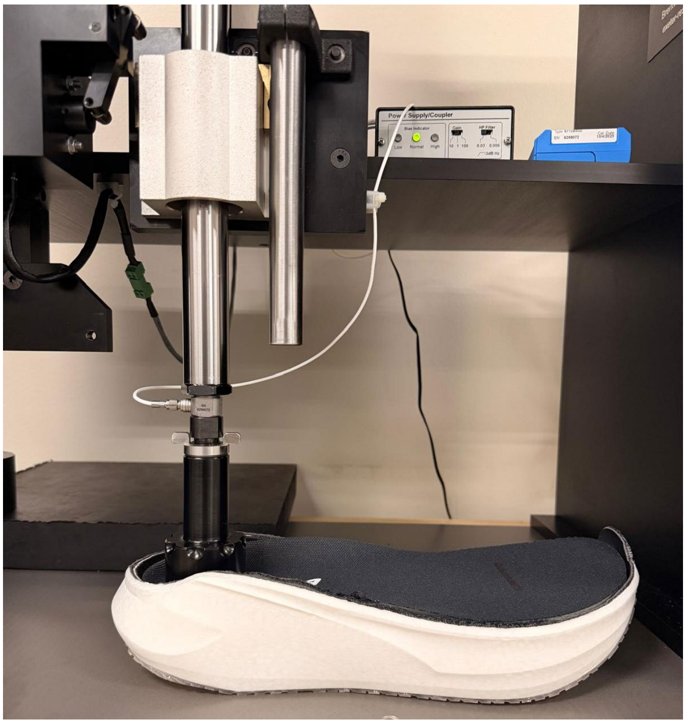

Figure 2.7. Impact tester conforming to the American Society for Testing and Materials International (ASTM) F1976-13, Standard Test Method for Impact Attenuation of Athletic Shoe Cushioning Systems and Materials

Each of these mechanical tests produces a force-displacement hysteresis curve (Figure 2.8), which illustrates the difference between the loading and unloading curves. Displacement (mm) is shown on the X-axis, and force (kN) as a function of displacement on the Y-axis. The energy absorbed by the material is represented by the area under the loading curve. An optimal cushioning system maximises the energy absorbed (Aimar et al., 2024), with higher values representing better cushioning properties of the material. The recovered energy, represented by the area beneath the unloading curve (Hoogkamer et al., 2018; Macdermid et al., 2025), defines the storage and reclamation of the strain energy produced when the shoe's midsole deforms (Frederick et al., 1986; Fuss, 2013; Hamill & Bates, 2023). The energy lost (J) as heat, is represented by the area between the loading and unloading curves (Hoogkamer et al., 2018; Macdermid et al., 2025). Minimising the energy lost requires the appropriate combination of foam material properties (Stefanyshyn & Nigg, 2000).

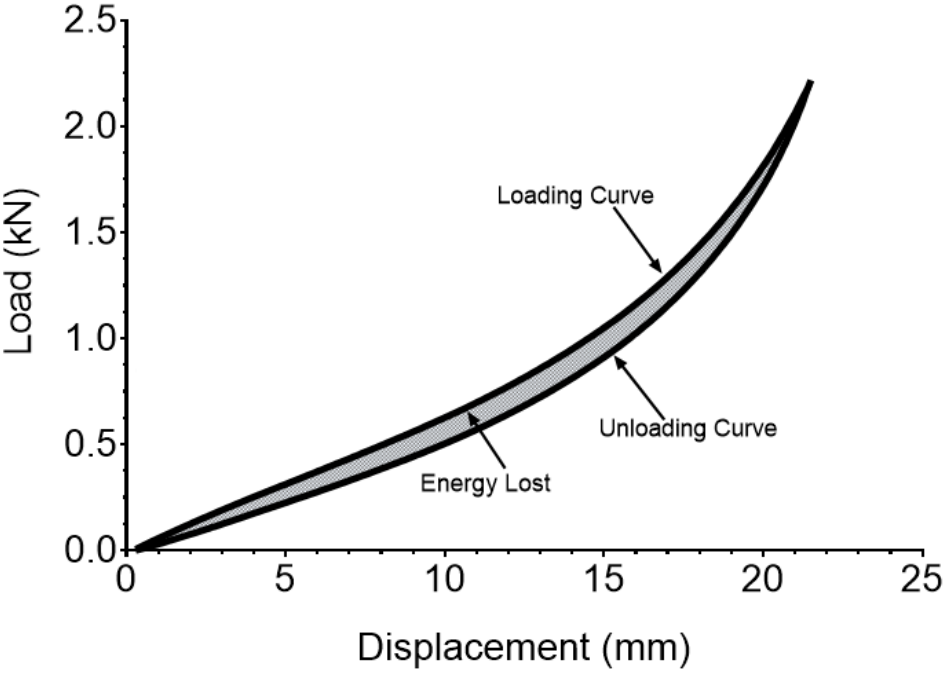

Figure 2.8. Hysteresis curve plotted on a force displacement graph; demonstrating the loading and unloading curves, and the energy lost (shaded area between curves)

These current industry standard tests for running shoes involve applying a standardised energy or a fixed force to ensure consistency across measurements. However, runners do not typically exert the same amount of same force throughout the gait cycle, due to fluctuations in speed (Fuss et al., 2025). This limitation suggests that these tests do not accurately capture the wide range of forces and patterns of application that are experienced during real-world running (Mohammadi & Nourani, 2025; Nigg & Liu, 1999). Such factors must be considered, as they are essential for understanding the stress imposed on midsole materials. Additionally, industry standard tests are often limited to one-dimensional force application over a fixed contact area. However, accurately simulating running would require replicating three-dimensional loading patterns and the ability to vary loading phases by applying pressure to different regions of the midsole, such as the heel and forefoot (Hoogkamer et al., 2018). This highlights the limitations present in controlled testing environments. More recently, custom mechanical testing has been implemented, where specific equipment is designed or industry standard test methods are adjusted to more realistically measure underfoot mechanical energy absorption and recovery. However, this approach can lead to variations in results, which may affect the consistency of the findings. There is a need for standardisation in mechanical shoe testing across industry and academia, particularly as existing copolymers are modified, and new materials are developed.

Other test methods such as SATRA Test Method 205:1999 (SATRA, 1999) determine the hardness of a material using durometers such as Asker C (Figure 2.9A) and Shore A (Figure 2.9B).

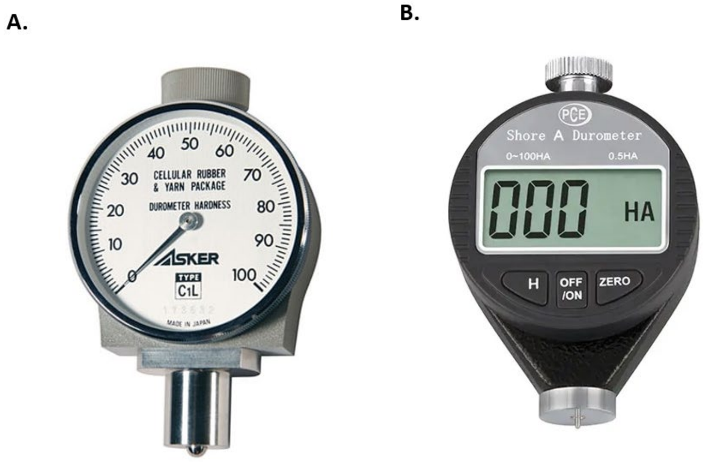

Figure 2.9. A. Asker C durometer and B. Shore A durometer

The Asker C durometer is used for soft materials such as midsole foams, where a small spherical indenter is pressed into the material to displace the head of the indenter. The hardness is indicated on a scale derived from the penetration of the indenter into the surface, ranging from 0 - 100. The higher the value on the Asker scale, the harder the material. The Shore A durometer is used to measure the combined materials of the outsole and midsole. A blunt, cone-shaped indenter is pressed into the foam to gauge resistance to indentation (Figure 2.10). The measure for Shore A is also an arbitrary unit, ranging for 0 – 100, with higher values indicating a harder material.

Figure 2.10. Example of Shore A measurement

Evaluating the indentation hardness using Asker C or Shore A does not fully capture the midsole or the cushioning properties of the foam (Indesteege et al., 1998). These methods are therefore limited in their ability to assess a material's load-bearing capability under dynamic conditions (Indesteege et al., 1998). Additionally, the accuracy of the test results can be affected by the operator's technique, as there is a lack of comprehensive studies detailing how standardised forces are applied or where measurements are taken. This contributes to the variability between testers (Ramsey et al., 2018). Therefore, it is important that measurement locations are marked, with hardness measures recorded at the shoes forefoot and rearfoot, medially and laterally, by making five indents and calculating the average (Ramsey et al., 2018), to account for test-retest repeatability.

Within the current literature relatively few studies report the actual material properties or mechanically test the shoes midsole in accordance with established industry standards. This presents a significant limitation, as it restricts the ability to understand the cause-and-effect relationship of specific midsole material properties, particularly when making comparisons between studies. Additionally, the pre-production process of materials prior to shoe manufacturing is often overlooked (Isherwood et al., 2021), as is its impact on the midsole's mechanical performance.

2.6 Midsoles Material Properties

Accurate characterisation of midsole materials properties is essential in biomechanical research. The peer-reviewed literature frequently reports the use of EVA, PU, TPU, and PEBA foams, while other studies do not disclose the specific copolymer used in the midsole. Understanding the copolymer material used is important as it contributes midsoles' capability to absorb and recover energy (Chang et al., 2023; Mills et al., 2003; Shimazaki et al., 2016). However, the structural properties (porosity, cell wall structure, and microstructure) of the foam are rarely reported, and only a select few studies report the foam's actual density (Aimar et al., 2024; Huang, 2019; Mey et al., 2018; Wang et al., 2012; Wang et al., 2010). This may be due to proprietary constraints on manufacturing details or an absence of sustained research interest. Providing the density of the foam used in the midsole should be standard practice, because it allows for a transparent assessment of the material properties that influence energy absorption and recovery of the shoe's midsole. Currently, the lack of such information creates challenges when comparing different midsoles, therefore making it difficult to accurately assess their performance across various materials. However, mechanical shoe testing in alignment with industry standards is inconsistently used, meaning there is a dearth of information regarding the capability of the midsole's materials.

While limited due to the inability to provide a comprehensive understanding of the midsoles' cushioning capability under dynamic conditions, Asker C is an easy and accessible test to assess the hardness of the midsole. Studies using Asker C to assess EVA midsoles (De Wit et al., 1995; Flores et al., 2019; Isherwood et al., 2021; Nigg & Gérin-Lajoie, 2011; Play et al., 2024; Wang et al., 2012; Wang et al., 2010) have reported values between C-40 to C-71 on the Asker scale. These values assist in classifying shoes as soft, medium, or hard. Early evaluation of midsole material properties was conducted using a mechanical impact tester, in which a known mass was dropped from a known height while recording force and displacement (Clarke et al., 1983). When implementing this test on an EVA midsole Frederick et al. (1986) reported a higher peak max-*g* and less energy recovered, when compared to a PU midsole. More recently, assessing the mechanical properties of an EVA foam midsole via the ATSM industry standard demonstrated greater cushioning properties and energy recovered (Wang et al., 2012) at a density of 0.20 $g \cdot cm^{-3}$. While no differences in peak *g*-max scores (11.47 ± 0.42 vs. 12.0 ± 0.33 g) have been observed before and after 20 km of running (Mey et al., 2018), significant differences in impact peak force have been interpreted as a reflection of the energy absorbing capability, between 0 and 500 km (918.2 – 968.0 N), respectively (Wang et al., 2010). EVA midsoles categorised by hardness (soft, medium, and hard) demonstrated peak *g*-max scores of 12.83, 13.49, and 13.95 *g*, along with energy recovered percentages of 67.31, 66.38, and 62.36%, respectively (Isherwood et al., 2021). Furthermore, peak *g*-max values of 37, 40.5, and 47.5 *g*, were reported for soft, medium, and hard shoes, respectively (Play et al., 2024). Subsequently, shoe conditions representing the 8th, 57th, and 96th percentile of heel peak impact shock values of commercially available running shoe cushioning properties between 2008 to 2010, showed peak *g*-max values ranging from 25, 15.1, 12.3 *g*, respectively (Shorten & Mientjes, 2011), indicating that increased midsole cushioning is associated with lower peak *g*-max values.

Using Asker C to assess indentation hardness, Wang et al. (2012) evaluated two PU foam midsoles (PU-1 and PU-2), which were classified as C-55 and C-60, respectively. These foams had densities of 0.28 and 0.38 $g \cdot cm^{-3}$, indicating greater hardness relative to the EVA foam that was also examined. When mechanically tested, the PU-1 foam, with a lower density, exhibited lower peak force before and after 500 km of running (909.6 – 972.9 N) and demonstrated a superior energy recovery (40.1 – 44.0%) compared to the PU-2 foam with a higher density (983.0 – 1105.6 N; 39.6 – 42.3%). These findings indicate that of these two copolymers the midsole with the lowest density had greater cushioning properties (Wang et al., 2012). Notably the EVA foam used in the same study and the PU-1 demonstrated the lowest peak forces, but the EVA midsole had a higher energy recovery (50.1 – 51.7%) than both PU-1 and PU-2 (Wang et al., 2012). However, others that have reported higher energy recovery for PU midsoles; for instance, Flores et al. (2019) demonstrated that a PU midsole recovered 29% more energy than the EVA midsole. Similarly, Frederick et al. (1986) demonstrated from mechanical impact testing, that a PU midsole containing 1 cm of air cushioning had a 13% lower peak *g*-max score and a 2.3 mm increase in midsole deformation, while energy recovery was 7% greater compared to that of the EVA midsole.

Building on these comparisons of foam midsole properties, further studies have investigated the mechanical performance of TPU midsoles using protocols designed to replicate real-world running forces. For example, Worobets et al. (2014) conducted mechanical testing using a custom hydraulic machine, applying 20 consecutive loading and unloading cycles. Each cycle compressed the shoe at a rate of 4250 $N \cdot s^{-1}$ to a peak load of 1700 N, with such values reflecting the vertical ground reaction forces experienced during running. The TPU midsole displayed a stiffness of 129.7 $N \cdot mm^{-1}$ and a hysteresis value of 22.3%, demonstrating superior cushioning properties compared to EVA midsoles, which showed greater stiffness (186.1 $N \cdot mm^{-1}$) and energy loss (32.3%). In a separate study Hoogkamer et al. (2018) assessed a TPU midsole using a material testing machine (Instron 8800 Series Servohydraulic System, Norwood, MA, USA) by applying a vertical compressive force of 2000 N over 185 ms, with such parameters representative of mid-stance loading at 18 $km \cdot h^{-1}$. Under these conditions, the TPU midsole deformed 5.9 mm and recovered 75.9% of input energy. This deformation was less than that observed in PEBA (11.9 mm) and EVA (6.1 mm) midsoles tested under identical conditions. The relatively limited TPU deformation could reflect either the material's high resistance to compression or that the applied force was insufficient to exploit its elastic potential fully. However, the lack of information on the density of each midsole limits the interpretation of these findings. Therefore, future research should investigate various copolymers of equivalent densities to establish a cause.

Recent investigations have focused on PEBA foams, due to its use in high-performance footwear. PEBA foams used in midsoles, all of which also contained a carbon fibre plate, were tested according to industry standard ASTM F1976-13, with the peak *g*-max scores for the different shoes tested being 8.43, 8.79, 9.45, and 9.89 *g* (Isherwood et al., 2024). However, without knowing the densities of the PEBA foams, it is challenging to draw conclusions about what caused the observed difference in peak *g*-max values. Since foam density affects the mechanical capability of the shoe's midsole, the lack of this information limits interpretation, as differences could be due to microstructural properties of the foam, or other design factors. PEBA has been shown to deform twice as much as EVA and TPU midsoles (11.9 vs. 6.1 vs. 5.9 mm, respectively), while also recovering more energy (87.0 vs. 65.5 vs 75.9%, respectively), when tested using a custom mechanical testing machine (Hoogkamer et al., 2018). However, the PEBA midsole had a stiff embedded plate, likely contributing to the differences observed. In terms of durability, a study examining PEBA midsole foam properties with a carbon fibre plate before and after 450 km of running, reported a significant difference in energy recovery and longitudinal bending stiffness between the new and worn conditions (35.5 ± 1.8 vs. 21.6 ± 1.3 $N \cdot mm^{-1}$, respectively) (Rodrigo-Carranza et al., 2024). Although previous studies investigating PEBA midsoles have not reported density values, PEBA foams tend to be less dense, causing greater compression of the cells (Verdejo & Mills, 2004). This characteristic is why such foams are often embedded with a carbon fibre plate to create an interaction with the midsole material (Rodrigo-Carranza et al., 2023). This interaction assists to stabilise the foam, allowing it to function like a spring by absorbing, recovering, and minimising energy lost during ground contact (Ghanbari et al., 2025), thereby enhancing the runners forward propulsion (Nigg et al., 2021).

Despite these insights, a recurring limitation in the literature is the inconsistent reporting of midsole material characteristics. Many studies have failed to specify the exact copolymer or the density of the midsole foams, relying instead on indirect metrics such as Shore A (Hardin et al., 2004; Nigg et al., 1987) or Asker C (Baltich et al., 2015; Meardon et al., 2018; Nigg et al., 2012; Theisen et al., 2014). Others have applied industry-standard testing (Meardon et al., 2018; Theisen et al., 2014), custom mechanical protocols (Clarke et al., 1983; Cook et al., 1985; Macdermid et al., 2025), or provided no methodological details

(Nigg et al., 2017). Failing to report the copolymer or the density of the material compromises the ability to compare results across studies, as the quantification of material properties is essential to understanding the midsole's capability under specific forces and speeds.

There is clear evidence that different copolymers exhibit different material capabilities and properties. However, without the implementation of standardised testing methods and with a lack of reporting on the structural properties or foam density, it becomes increasingly difficult to draw meaningful conclusions when comparing different midsoles. This underscores the need for *in vitro* standardisation within industry and academia. Equally important is recognising that when the shoe is placed upon the runner's foot, it becomes a dynamic and functional element (Bates et al., 1978). This highlights the necessity of evaluating midsole performance not only through mechanical laboratory testing in both pre- and post-shoe construction, but also under *in vivo* conditions. Individual interactions with footwear are influenced by neuromechanical responses to balance and movement demands, which can vary significantly between users (Pink & Jobe, 1997). Accordingly, *in vivo* experimental trials should be conducted in an environment that replicates real-world overground running, to ensure ecologically valid and translational findings.

2.7 Influence of Midsole Material Properties on Parameters of Running Gait

Considering running shoe research has been published in peer-reviewed journals since the 1970s (Hamill & Bates, 2023), it is surprising that there is a shortage of work considering the midsole material properties when investigating *in vivo* parameters of running gait. Within the industry more recently, as a result of advent AFT, there has been an increased interest in material cushioning properties, aiming to provide greater attenuation of impact forces, overall comfort, and improved running performance (Hamill & Bates, 2023; Lafortune et al., 1996). As such, this section focuses on those studies that have tested the material properties of the midsole *in vitro* and *in vivo*, via the collection of parameters of running gait.

At a holistic gait cycle level, no changes have been observed for stride duration as a result of shoe cushioning (Macdermid et al., 2025). Accordingly, stride time ($p = 0.66$) and stance time ($p = 0.08$) did not differ between shoe conditions classified by their impact shock scores as soft (9.3 *g*-max), medium (10.3 *g*-max), and hard (12.0 *g*-max) (Meardon et al., 2018). The participants ran at a self-selected speeds, with a tolerance of five percent, over a force plate, with the speeds for the soft, medium, and hard conditions being 3.69 ± 0.45, 3.70 ± 0.43, and 3.69 ± 0.44 $m \cdot s^{-1}$, respectively, with no significant differences ($p = 0.84$) observed between these running speeds (Meardon et al., 2018). In contrast, stride frequency has been shown to be significantly ($p = 0.024$) lower (Flores et al., 2019) along with step frequencies (Hoogkamer et al., 2018), in shoes with greater levels of cushioning and energy recovery. This suggested that longer steps were taken, whereby shoes with high energy recovery properties induced a significantly greater ground contact time ($p = 0.017$) compared to the low energy return shoes (Flores et al., 2019). Furthermore, a PEBA midsole with a stiff embedded carbon fibre plate, which deformed twice as much (11.9 vs. 6.1 mm), showed a 0.6% longer ground contact time than the EVA midsole ($p = 0.020$). Increased ground contact time has been proposed as a response to the increased energy absorption component of midsole deformation (Addison & Lieberman, 2015), with authors suggesting that due to the materials capability to absorb more energy it then requires longer to recover during the propulsive phase (Flores et al., 2019; Hoogkamer et al., 2018). However, other studies have highlighted that ground contact time is unaltered between shoes of differing cushioning properties (Clarke et al., 1983; Isherwood et al., 2021; Macdermid et al., 2025; Malisoux et al., 2021; Play et al., 2024; Shorten & Mientjes, 2011). Consequently, events occurring at the ground level exert an influence on those taking place in the air (Knuesel et al., 2005; Novacheck, 1998). Specifically, Play et al. (2024) categorised midsoles as soft, medium, and hard, with peak acceleration *g*-max scores of 37, 40.5, and 47.5 *g*, respectively, where the soft midsole condition exhibited a significantly lower swing time ($p = 0.047$). The authors attributed their findings to a greater dorsiflexed ankle at initial contact, contributing to a more pronounced heel strike, which enabled for shock absorption at impact and a more efficient propulsive phase (Play et al., 2024). However, swing time has also been observed not to vary between shoe conditions (Macdermid et al., 2025; Malisoux et al., 2021), leading to the plausible assumption that participants' technique remained relatively unchanged.

Understanding strategies to attenuate ground reaction forces that runners experience throughout the cyclic motion of the running gait cycle is critical, especially as speed increases (Arampatzis et al., 1999). As such, midsole cushioning has been attributed to assisting with impact attenuation, in particular, the energy absorption and recovery of the midsole's foam material properties (Shorten, 1993, 2024). In relation to the absorption phase of the running gait cycle, *in vitro* test results lead to the expectation that the magnitude of vertical peak impact force will be reduced (Clarke et al., 1983; Komi et al., 1987; Shorten & Mientjes, 2011). Similarly, musculoskeletal and mechanical models consistently predict that impact forces should be attenuated by midsole cushioning (Ly et al., 2010; Nigg & Liu, 1999; Wright et al., 1998; Zadpoor & Nikooyan, 2010). Runners also indicate through subjective self-reports that impacts feel softer in more cushioned shoes (Milani et al., 1997; Sterzing et al., 2013). However, *in vivo* measurements frequently do not meet this expectation when obtained from ground reaction force or accelerometer data and correlated with *in vitro* results (Aerts & De Clercq, 1993; Clarke et al., 1983; Hennig et al., 1993; Nigg et al., 1987; Shorten & Mientjes, 2011). In spite of this, other attributes of vertical peak impact force are more consistent with *in vitro* test results and theoretical predictions. Specifically, midsoles characterised as having greater cushioning have been shown to delay the time at which vertical peak impact force occurs (Clarke et al., 1983; Isherwood et al., 2024; Malisoux et al., 2021) and to reduce loading rate, even when the peak's magnitude remains unaffected (Clarke et al., 1983; De Wit et al., 1995; Heidenfelder et al., 2010).

Seminal research indicated that midsole cushioning did not significantly reduce the magnitude of vertical peak impact force (Clarke et al., 1983; Nigg et al., 1987). Clarke et al. (1983) examined the effects of cushioning upon the vertical force patterns during running, using two shoes, with mechanical impact scores indicating that the softer shoe had 50% more cushioning. Participants were required to run at a speed of 4.5 $m \cdot s^{-1}$, with a tolerance of five per cent over a force plate, collecting five right footfalls in each shoe condition. Results showed no difference in the magnitude of vertical peak impact force, hard = 2.30 $N \cdot BW^{-1}$ vs. soft = 2.34 $N \cdot BW^{-1}$. While a shoe deemed to have 50% more cushioning would be expected to decrease the magnitude of peak impact force, the absence of material property data makes it challenging to interpret the cause of this result. In accord Nigg et al. (1987), required participants to complete 12 trials at 3, 4, 5, and 6 ± 2 $m \cdot s^{-1}$ over a force plate in three identical shoes, except for the hardness of the midsole, that was quantified by using Shore A measurement (25, 35, and 45 Shore). Findings demonstrated that a change in midsole hardness resulted in a slight decrease in impact force peaks of less than 10% of the maximum impact forces for increasing shore values; however, this decrease was not significant ($p > 0.05$). Similarly, seven participants conducted five trials over a force plate positioned 40 m along an indoor runway at a speed of 4.5 ± 0.1 $m \cdot s^{-1}$ (De Wit et al., 1995), utilising shoes categorised as soft (Asker C-40) and hard (Asker C-65). The results demonstrated that the hard shoe significantly reduced vertical peak impact force ($p < 0.05$). Although it may be presumed that a softer midsole will absorb more energy, Shore A and Asker C values solely indicate the material's hardness and, thus, do not necessarily reflect the midsole's cushioning capability under dynamic or varying loads.

Subsequent research conducted by Shorten and Mientjes (2011) tested a minimal control shoe alongside three distinct shoe conditions (S1, S2, and S3), representing the 96th, 57th, and 8th percentile of heel peak impact *g*-max shock scores. The corresponding *g*-max shock scores for the minimal control shoe and the three distinct shoe conditions were 25, 15.1, 12.3, and 6.9 *g*, respectively. Participants completed four trials, landing with their right foot on a force plate at a speed of 4.0 ± 0.2 $m \cdot s^{-1}$. The three cushioned shoes attenuated peak impact force by 7-11%, relative to the minimal control shoe. The mean peak impact force for the minimal control shoe (2.20 $N \cdot BW^{-1}$) was significantly greater ($p < 0.05$) than that observed in the three cushioned shoes. However, the shoe condition deemed to be the most cushioned (S3) elicited a significantly greater peak impact force (2.04 $N \cdot BW^{-1}$) compared to S1 and S2, recorded at 1.95 and 1.97 $N \cdot BW^{-1}$, respectively. These shoes accounted for 90% of the commercially available running shoe cushioning properties from 2008 to 2010, with a peak impact force difference of only 2.2%. When compared to the minimal control shoe condition, the cushioned shoes reduced peak impact force by an average 10%, whereas *in vitro* impact attenuation reached 51% (Shorten & Mientjes, 2011). Further, shoes characterised as hard and soft, distinguished by a 35.4% difference in heel global stiffness (94.9 ± 5.9 vs. 61.3 ± 2.7 $N \cdot mm^{-1}$, respectively), were utilised by 848 participants (Malisoux et al., 2021). Biomechanical running analysis was conducted on an instrumented force-plated treadmill, with participants running at a self-selected speed (soft: 2.72 ± 0.47; hard:

2.75 ± 0.47 $m \cdot s^{-1}$) for a 2-minute data collection phase. Notably, the soft shoe group exhibited a significantly higher vertical impact peak force compared to the hard shoe group (95% confidence interval (CI): 0.07 – 0.13 BW), contradicting the expectation that softer cushioning system would attenuate impact peaks (Shorten & Mientjes, 2011). Additionally, Isherwood et al. (2024) examined advanced footwear technology, encompassing shoes classified as an innovation model, a current market model and a market frontrunner, all of which incorporated a carbon fibre plate. Peak max-*g* scores for each shoe model ranged from 8.43 - 8.79; 9.30 - 9.46; and 9.45 - 9.89 *g*, respectively, with energy recovery values of 69.4 - 69.43; 50.24 - 50.45; and 68.42 - 69.98%. Recreational runners completed eight right foot trials per shoe condition, landing on a force plate situated along a 40 m indoor asphalt runway at speeds between 3.5 and 3.89 $m \cdot s^{-1}$, allowing for a tolerance of five per cent. Significant effects were observed for both vertical peak impact force ($p < 0.001$) and time to reach vertical peak impact force ($p = 0.004$). Both the innovation model and the market frontrunner demonstrated a significantly higher and longer time to vertical peak impact force compared to the market model shoe. Although these models were perceived to have superior cushioning *in vitro*, this did not translate into a reduction in vertical peak impact force during the *in vivo* trials.

Equivocal findings have been referred to as the 'impact peak anomaly' which proposes that the vertical impact peak force is inclusive of a high-frequency 'true' impact load and a lower-frequency load (Shorten & Mientjes, 2011). Consequently, the high-frequency load, and the addition of a low-frequency component mask the true impact-related component, therefore contributing to incorrect quantification of the impact event itself. However, in contrast to prior findings, Macdermid et al. (2025) provided clear evidence that increased midsole cushioning, with 690% greater energy absorption, significantly attenuated peak impact force by 12% during treadmill running at controlled speeds of 2.78 and 3.89 $m \cdot s^{-1}$ ($p = 0.009$ and $p = 0.005$, respectively). These results were obtained using pressure-sensitive insoles across consecutive steps ($n = 23 \pm 2$). Further, shoes defined as maximally cushioned, without providing *in vitro* results, decreased in-shoe overall plantar loading forces as well as those at the forefoot (Ogston, 2019). Nevertheless, no clear relationship has been established between plantar pressure and impact force across minimalist and maximally cushioned shoes.

The lack of correlation between *in vitro* and *in vivo* results related to vertical peak impact force has generally been attributed to kinematic adjustments brought about by adaptation mechanisms (Clarke et al., 1983; Nigg et al., 1987). However, only one study has highlighted that technique is adapted, specifically as the midsole cushioning increases, ankle and knee joint stiffness also increase (Baltich et al., 2015). Recreational runners performed five heel striking running trials (3.33 ± 0.15 $m \cdot s^{-1}$), landing on a force plate in three different shoe conditions, that only differed in midsole hardness, classified as: Asker C-40 (soft), Asker C-52 (medium), and Asker C-65 (hard). A motion capture system with eight cameras operating at 240 Hz, collected kinematic data using 12 retro-reflective markers mounted on the pelvis and right lower extremity. There was a significant main effect of midsole hardness for the vertical impact peak ($p < 0.001$) and post-hoc comparisons revealed that all midsole conditions were significantly different ($p < 0.001$). The mean vertical peak impact increased as the midsole hardness decreased (soft 1.70, medium 1.64, and hard 1.54 $N \cdot BW^{-1}$). There was also a significant main effect of midsoles for the apparent ankle joint stiffness ($p < 0.001$), as the midsole hardness decreased apparent ankle joint stiffness increased (all $p < 0.001$). Increased joint stiffness may be required to compensate for and effectively control movements with a softer midsole, leading to a greater decelerated mass upon impact, which potentially explains the increased vertical impact peak observed in the softer midsole (Baltich et al., 2015). However, this study did not provide insight into the material capabilities of the shoes' midsoles. While it could be assumed that a midsole defined as being softer will absorb more energy, there is currently no existing research directly correlating Asker C values with mechanical energy absorption. As such, further research is required to establish definitive conclusions.

It has been suggested that runners naturally adapt their movement patterns in response to variations in the impact-absorbing properties of the running surface (Dixon et al., 2000) and changes in the level of midsole cushioning (Baltich et al., 2015). Adaptive changes align with the proposed theory that the human body will tend to follow the same movement pattern for a specific task, referred to as the preferred movement path (Nigg, 2001; Nigg, 2010; Nigg et al., 2017), to maintain a consistent overall loading pattern, regardless of external changes (Isherwood et al., 2021; Nigg et al., 2017; Play et al., 2024). As a result, it is assumed that runners operate within a personalised bandwidth, adapting their running technique (joint kinematics) to manage and respond to the cyclic ground reaction forces experienced throughout the running gait cycle (McNair & Marshall, 1994).

Furthermore, midsole cushioning of running shoes has been proposed to decrease loading rates by dispersing the impact force over a longer time period (Reinschmidt & Nigg, 2000). As such, the time to vertical peak impact force was significantly longer in the soft shoe (26.6 ms) compared to 22.5 ms in the hard shoe (Clarke et al., 1983), with De Wit et al. (1995), Malisoux et al. (2021), and Nigg et al. (1987) observing similar findings when comparing shoes defined as soft and hard. Average loading rate has been shown to decrease significantly by 11% (Macdermid et al., 2025) in a cushioned shoe at speeds of 2.78 and 3.89 $m \cdot s^{-1}$ ($p = 0.008$ and $p = 0.004$, respectively). Moreover, aligning with *in vitro* results, significant reductions from 131.28 to 138.40 and 139.54 $BW \cdot s^{-1}$, in maximal vertical loading rates were observed in shoes defined as soft, medium, and hard (Isherwood et al., 2021). These were accompanied by peak *g*-max rearfoot accelerations of 12.83, 13.49, and 13.95 *g*, and corresponding energy recovery percentages of 67.31, 66.38, and 62.36%, (Isherwood et al., 2021). However, other studies have found no differences in vertical average (Malisoux et al., 2021; Play et al., 2024), instantaneous (Malisoux et al., 2021), or maximal loading rate (Nigg et al., 1987) between different shoe conditions. Meanwhile, maximum loading rate was significantly ($p < 0.05$) higher in the shoes with the lowest midsole density (0.035 $g \cdot cm^{-3}$), compared to any other densities tested (Huang, 2019), suggesting that the proposed beneficial effect of midsole cushioning cannot be explained by a decrease in loading rate alone.

The kinetic parameter related to propulsion within the stance phase, peak active force, has been shown to occur at a similar time point (Clarke et al., 1983), while others (Shorten & Mientjes, 2011) have highlighted a non-significant trend for its time occurrence being shorter in the minimal control shoe (95 ms) than in the other shoe conditions (103 ms). In magnitude, vertical peak active force has been observed to be significantly greater in soft shoes (2.83 $N \cdot BW^{-1}$), defined as having 50% more cushioning, than 2.73 $N \cdot BW^{-1}$ in the hard shoes (Clarke et al., 1983). Furthermore, when participants completed five minute trials at speeds of 3.88, 4.44, or 5 $m \cdot s^{-1}$ on a force-measuring treadmill, shoes with a PEBA midsole that deformed twice as much as the EVA and TPU midsoles (11.9, 6.1, and 5.9 mm, respectively), while also recovering substantially more mechanical energy (PEBA 87%, TPU 75.9%, and EVA 65.5%). Vertical peak force was, however, 1.1% greater in the PEBA midsole compared to the EVA midsole ($p = 0.002$), and increased at faster running speeds across all midsoles (all $p < 0.001$) (Hoogkamer et al., 2018). Other studies have demonstrated no significant main effect of footwear on peak active force ($p = 0.084$), as observed by Macdermid et al. (2025), which supports the findings of Malisoux et al. (2021), Isherwood et al. (2021) and Shorten and Mientjes (2011). The absence of the influence of midsole cushioning on peak active force has been ascribed to the vertical oscillation of the centre of mass remaining unaffected, as evidenced by the unchanged vertical impulse (Clarke et al., 1983; Flores et al., 2019; Macdermid et al., 2025; Malisoux et al., 2021). Another possible explanation is that muscle activation, which typically increases with running speed (Kyröläinen et al., 2001), may be reduced when running in footwear with greater cushioning properties. Conversely, the 50-ms passive impulse (the impulse generated by the vertical ground reaction force within 50 ms post-landing), exhibited a significant difference ($p < 0.05$) across different shoe hardnesses levels (Huang, 2019). Specifically, it was markedly higher in footwear with the lowest density ($0.035\ g{\cdot}cm^{-3}$) relative to other hardnesses, due to the earliest occurrence of the first peak force in the vertical direction.

2.7.1 Methodological Considerations

Inconclusive findings regarding the influence of the midsole material properties on parameters of gait may be limited to the method of measurement or by the protocols used. While force plates are recognised as the gold standard for measuring ground reaction forces (Higginson, 2009; Seiberl et al., 2018), they are typically restricted to use in the laboratory setting, where participants must anticipate landing on a designated sampling area, potentially altering their gait mechanics (Paolini et al., 2007). Acquiring 20 - 64 consecutive steps from each participant has been proposed to increase the likelihood of achieving stability and statistical power for parameters of running gait (Belli et al., 1995; Oliveira & Pirscoveanu, 2021; Riazati et al., 2019). Others have suggested that research practices should use trials lasting a minimum of four minutes (Burns & Joubert, 2024), with data averaged over the last one to two minutes (Saunders et al., 2004). Despite these recommendations, many studies frequently continue to rely on ten or fewer steps per participant, in conditions that do not replicate real-world overground running. Consequently, claims that midsole cushioning does not attenuate impact are difficult to justify (Shorten & Mientjes, 2011).

One critical issue is that force plate measurements reflect whole-body acceleration rather than isolating lower limb segmental forces, limiting their precision in assessing foot-strike dynamics (Shorten & Mientjes, 2011). It is often assumed that peak impact force is determined by heel strike intensity; however, the measured force is actually proportional to the acceleration of the body's centre of mass and is therefore influenced by the motion of all body segments (Bobbert et al., 1991). Moreover, studies have accepted variability of ± 5 to 10% around the prescribed running speed during overground force plate trials (Almonroeder & Benson, 2017; Riazati et al., 2019; Riley et al., 2008; Sinclair et al., 2013), potentially introducing error in the measurement of gait parameters. Given that running speed significantly influences vertical peak impact force (Section 2.2.1), careful consideration should be given to both the selection and enforcement of consistent running speeds during experimental trials.

The use of instrumented treadmills for collecting ground reaction forces enables continuous data acquisition at a relatively constant speed (Riazati et al., 2019). However, this approach does not accurately replicate the natural variability of biomechanical pattens observed during overground running (Brand & Crowninshield, 1981; Fellin et al., 2010). As an alternative, pressure-sensitive insoles offer a more ecologically valid method for assessing ground reaction forces during locomotion (Renner et al., 2019). These devices are placed directly inside the shoe, allowing for the measurement of forces acting on the plantar surface of the foot, rather than on the external sole of the shoe, as occurs with traditional force plates (Dixon, 2008). This enables for the assessment of shoe design upon foot loading between similar shoes (Clinghan et al., 2008) and over repeated impact cycles (Verdejo & Mills, 2004). Therefore, assessing parameters of gait during real-world overground running, while controlling for experimental running speeds, would enhance the ecological validity of research outcomes. This is particularly important as novel midsole materials emerge, with the potential to influence running gait.

2.8 Summary

Despite a substantial body of research examining the effects of footwear on biomechanics and running performance, relatively few research articles report the actual material properties of the midsole or test them in accordance with established industry standards (Baltich et al., 2015; Hoogkamer et al., 2018; Huang, 2019; Worobets et al., 2014). The absence of standardised cushioning data represents a significant limitation within the existing body of literature and is further compounded by limited transparency from shoe manufacturers regarding midsole material specifications. This lack of consistent and objective reporting underscores the need for standardisation and improved transparency in both academic and industry setting.

While *in vitro* studies generally indicate the softer midsoles exhibit superior cushioning properties, *in vivo* findings remain inconsistent. Much of the existing research is conducted under laboratory conditions that do not adequately replicate real-world overground running. These studies are often constrained by a limited number of steps sampled, a lack of variation in running speeds, and minimal consideration of terrain effects. Such limitations hinder a comprehensive understanding of how midsole cushioning influences running biomechanics in practical settings. Therefore, to advance the understanding in this area, the present thesis investigates the *in vitro* properties of aliphatic thermoplastic polyether polyethylene (ATPU) foam, with controlled variations in density, manufactured into geometrically identical running shoes. It evaluates the influence of these midsoles on *in vivo* spatiotemporal, kinetic, and joint kinematic gait parameters across different running speeds. *In vivo* experimental trials will be conducted during real-world overground running, thereby enhancing ecological validity. By integrating rigorous material-level testing with biomechanical analysis in a representative running environment, this research aims to address the methodological limitations identified in previous studies. The following chapter outlines the specific research aims and hypotheses that underpin this thesis.

Chapter Three – Research Aims and Hypotheses

The literature review presented in Chapter Two explored the running gait cycle and its relationship with running speed. Additionally, it examined contemporary research on midsole design and function, mechanical testing methods, material properties, and the effects of the midsole on parameters of running gait. The equivocal findings reported across studies are often attributed to methodologies involving a limited number of steps in highly controlled laboratory settings, with limited consideration given to variations in running speed and terrain. These limitations highlight the complex and context-dependent relationship between midsole cushioning and running biomechanics. To date, no study has examined the interaction between *in vitro* midsole material properties of geometrically identical running shoes, differing only in density, and *in vivo* parameters of running gait at different running speeds in a real-world overground environment. Accordingly, the following aims and hypotheses were developed for this study.

3.1 Aims

This thesis aimed to:

1. Assess the *in vitro* mechanical properties of aliphatic thermoplastic polyether polyethylene (ATPU) foam midsoles of varying densities.

2. Evaluate the *in vivo* effects of midsole foam density, within geometrically identical running shoes, on parameters of gait (spatiotemporal, kinetic, and joint kinematics) across different running speeds, with a particular focus on vertical peak impact force and average loading during real-world overground running.

3.2 Hypotheses

It is hypothesised that:

1. *In vitro* testing will demonstrate the lower-density ATPU foam midsole to have greater energy absorption and energy recovery.

2. During *in vivo* experimental trials, parameters of running gait related to ground reaction force, specifically vertical peak impact force and average loading rate, will be reduced in the lower-density midsole. It is also expected that increases in running speed will influence spatiotemporal, kinetic, and joint kinematic parameters of gait.

Chapter Four – Methods

4.1 Participants

Sixteen recreational to nationally competitive endurance runners (mean ± standard deviation (SD); age (32 ± 10 years), height (172.8 ± 7.8 cm), body mass (64.0 ± 7.8 kg), body mass index (21.36 ± 1.2 $kg \cdot m^2$), and who were free of injury participated in this study. The average weekly running kilometres of participants from the past two months was 67.8 ± 18.4 km.

Participants read the study information sheet (Appendix One) and were informed of the study's aims, experimental protocols, requirements, risks, and benefits of the research. All participants completed the health screening questionnaire (Appendix Two) and provided written informed consent (Appendix Three). The study was approved in accordance with the Massey University Human Ethics Committee, Ohu Matatika 1, application 24/44 (Appendix Four).

4.2 Priori Statistics

Sample size was determined based on a priori statistic (G*power V 3.1.9.7, Heinrich-Heine University, Dusseldorf, Germany) using the analysis of variance (ANOVA) repeated measures within-factors test. The alpha value was set at 0.05, power 0.95, with one group and a total of nine measurements including three shoes and three speeds. Correlation among repeated measures was set to 0.5 and non-sphericity correction was set at 1.0. Effect size (Cohen's f = 0.457) for differences between peak impact force ($N \cdot kg^{-1}$) whilst running in shoes with midsole densities similar to those proposed for this study ($\rho = 0.079$ vs 0.181) estimated a total sample size requirement of seven (Huang, 2019). However, application of the same criteria and methodology to the work of Baltich et al. (2015) who investigated soft and hard midsoles (Asker C 40 vs 65) whilst running over a force plate reported peak impact forces increased (f = 0.275) in softer shoes compared to the hard shoes and estimated a total sample size of 18 would be required.

4.3 Shoes

Previous research has highlighted the importance of controlling for shoe characteristics, particularly the upper and design features, as variations in these components may confound biomechanical comparisons between footwear conditions (Hannigan & Pollard, 2020). Therefore, the shoes provided by Altra, in kind, and used for *in vitro* and *in vivo* experimental protocols were geometrically identical. The only variation was the density of the foam's midsole, as specified by the manufacturer. These shoes are presented in Figure 4.1, along with their respective density specifications. Throughout this thesis, Shoe A will be referred to as the high-ρ midsole, Shoe B as the mid-ρ midsole, and Shoe C as the low-ρ midsole, where ρ represents density.

Figure 4.1. The three geometrically identical shoes used for the in vitro and in vivo experimental protocols, identified as Shoe A: high-ρ midsole, Shoe B: mid-ρ midsole, and Shoe C: low-ρ midsole, including the manufacturer's density specifications for each midsole

The geometrically identical midsoles had a 38 mm heel stack height (12% from heel) and a 32 mm forefoot stack height (75% from heel), featuring a single layer of ATPU supercritical bead foam cushioning. Supercritical foaming involves blending carbon dioxide or nitrogen with polymers to produce foam without the need for chemical additives or the creation of additional compounds (Kumar & Suh, 1990), eliminating the toxic or hazardous chemicals involved in traditional foaming methods (Zhou et al., 2023). ATPU is microcellular aliphatic TPU, produced using aliphatic TPU as the substrate with clean supercritical carbon dioxide as the blowing agent to form a large number of microcells in the matrix (Hsiao et al., 2021). Such foams have the ability to maintain their cushioning and energy recovery properties over time, allowing for running performance and comfort to be enhanced (Tsivintzelis et al., 2016; Zhou et al., 2023).

4.4 *In Vitro* Experimental Protocol

In vitro mechanical shoe testing was performed on 16 right shoes (Thomson et al., 1999) prior to their use for data collection during the *in vivo* experimental trials. Testing multiple pairs of shoes allows for an accurate assessment of material properties, along with indicating reproducible results from machine loading (Cook et al., 1985). The shoes were placed in the laboratory for 48 hours to condition the materials prior to testing. Environmental conditions were controlled at a temperature of 23 ± 2°C and a relative humidity of 50%, in accordance with the industry standard (ISO, 2021).

The *in vitro* experimental protocol involved using a modified industry standard test (ISO 20344:2021 (5.17)) (ISO, 2021). The Instron (4467, Instron, Norwood, MA, USA) was fitted with a two-thousand-kilogram load cell and programmed to compress the midsole in a vertical direction at a deformation rate of 100 $\mathrm{mm{\cdot}min^{-1}}$. A force of 2.2 kN was applied via a fitted heel-sized last, through a steel indenter. Following 20 conditioning cycles, the number of cycles required to achieve a steady-state hysteresis (Worobets et al., 2014), five continuous cycles were then performed while recording deformation (mm) and load (kN), from which the final cycle was extracted for analysis.

A live force-displacement hysteresis curve was produced during each cycle, with deformation (mm) on the X-axis and load (kN) on the Y-axis. This simplified testing approach offers a general characterisation of midsole mechanical energy absorption and recovery capabilities in a direction relevant to the spring-mass dynamics of runners (McMahon & Cheng, 1990).

4.5 *In Vivo* Equipment

4.5.1 Pressure Sensitive Insoles

Deformable, textile, and ultra-thin pressure-sensitive insoles (LoadSol® insoles, Novel GmbH, Munich, Germany), are designed to record the measurement of the ground reaction force on the plantar surface of the foot, through linear sensitive capacitor sensors (Seiberl et al., 2018). LoadSol® Pro-t (Figure 4.2) were used in this study, measuring at a frequency of 200 Hz, to determine total spatiotemporal (stride duration, stride frequency, ground contact time, and swing time) and kinetic variables (vertical peak impact force, average loading rate, peak active force, and impulse).

Figure 4.2. The LoadSol® Pro-t insoles (Loadsol® - Mobile force measurement for real-world applications, 2025)

Force plates have been recognised as the gold standard for measuring ground reaction forces (Higginson, 2009; Seiberl et al., 2018), however, they are limited in the number of steps that can be sampled and are typically restricted to use in a laboratory setting. Their relatively small size imposes constraints on foot placement, where individuals must anticipate landing on the designated sampling area, potentially altering their gait mechanics (Paolini et al., 2007). Pressure-sensitive insoles are lightweight, portable, and an easy-to-use alternative in which to analyse running gait. LoadSol® insoles have demonstrated excellent accuracy and reliability, with an intraclass correction coefficient (ICC) of > 0.76 when compared with force plates (Renner et al., 2019). Since the device is fitted into the shoe (Figure 4.3), loads acting upon the surface of the foot are measured directly, as opposed to the force acting on the sole of the shoe with a standard force plate (Dixon, 2008). This enables the assessment of shoe design under foot loading between similar shoes (Clinghan et al., 2008), and between shoes of different midsole designs (Dixon, 2008). They also enable for the evaluation of a shoe's absorption capabilities over repeated impact cycles (Verdejo & Mills, 2004), all within a setting that replicates a natural running gait. Seiberl et al. (2018) indicated that LoadSol® insoles provided high accuracy for ground contact time, impulse, and peak active force, with mean bias ranging from 0.6 to 3.4%. Furthermore, LoadSol® insoles measuring at a sampling frequency of 200 Hz improves the validity of ICC values (Renner et al., 2019). However, due to the highly dynamic nature of ground reaction forces, discrepancies between LoadSol® and force plate measurements have been reported, and are related to the influence of sampling rates (Seiberl et al., 2018).

Figure 4.3. The LoadSol® insoles fitted into a shoe, with the battery box attached to the top of the shoe (Loadsol® - Mobile force measurement for real-world applications, 2025)

4.5.2 Attitude and Heading Reference System - Inertial Measurement Units (AHRS-IMU's)

AHRS-IMU (WitMotion WT9011DCL-BT5.0), with four inertial sensors, each comprising a triaxial accelerometer (± 16 *g*), a triaxial gyroscope (± 2000 $°\cdot s^{-1}$), and a triaxial magnetometer (± 2 Gs), was used simultaneously with the LoadSol® Pro-t insoles. Measurement was sampled at a frequency of 100 Hz.

The AHRS-IMU sensors integrate a high-precision gyroscope, accelerometer, and geomagnetic field sensor. They use a high-performance microprocessor along with advanced dynamic calculation and Kalman filtering algorithm to calculate the three-axis angle data. This advanced filtering technology can accurately output the current attitude of the sensor in the dynamic environment, with an attitude measurement accuracy of 0.2°, making the stability very high (*WitMotion WT9011DCL-BT5.0 Bluetooth Ahrs IMU senso: Instruction manual*, 2025). Such filtering improves measurement efficiency and reduces noise interference (Ahmed & Tahir, 2017).

Traditionally, motion capture has been the gold standard for three-dimensional kinematic measurements (Colyer et al., 2018; Maynard et al., 2003). However, conventional marker-based capture is expensive, localised to a laboratory, and requires skilled operators (Lopes et al., 2018; Reinking et al., 2018). Therefore, when compared to the gold standard, accelerometers paired with gyroscopes have been shown to yield joint angles, angular velocity, and angular acceleration similar to those derived from motion capture systems (Mayagoitia et al., 2002). Furthermore, Chung and Ng (2012), showed that when used in gait assessment the accelerometer and three-dimensional motion analysis have good reliability, although the ICC value for accelerometer (0.779; $p < 0.001$) was higher than that of the three-dimensional motion analysis (0.542; $p < 0.001$). Good test-retest reliability has been reported for accelerometer recordings in previous studies, with ICC values ranging from 0.7 to 0.97 (Armstrong et al., 2010; Henriksen et al., 2004; Moe-Nilssen, 1998). Measurement at a frequency of 100 Hz has also been validated for dynamic data collection during running, in which precise measurements and acceptable accuracy have been acquired (Provot et al., 2017). Beyond a range of 100 Hz, the response quality becomes insufficient for accurate interpretation of results (Provot et al., 2017).

4.6 *In Vivo* Experimental Protocol

The experimental protocol consisted of shoes classified by the density of the foam's midsole (Figure 4.1) and three running speeds (3.33, 3.89, and 4.44 $m \cdot s^{-1}$). For simplicity of reading, throughout this thesis, the speeds will be referred to as 12, 14, and 16 $km \cdot h^{-1}$. These speeds have been shown to produce significant differences in vertical ground reaction forces (Arampatzis et al., 1999), thus facilitating a comprehensive examination of the effects of speed on running gait.

The experimental protocol was completed in a single session on the same day, with an one-hour time commitment (Burns & Joubert, 2024). Testing was performed in a counterbalanced order of midsole density conditions, while the order of running speed for each midsole density condition was kept constant, progressing from 12 to 14 to 16 $km \cdot h^{-1}$. The order of running speeds was not randomised as it can be challenging and potentially unsafe, especially when attempting to reach higher running speeds, without gradually increasing from slower speeds (Chang & Cen, 2024; Dorris et al., 2024).

Upon arrival at Dairy Farm Road, Massey University, Palmerston North, New Zealand, participants' body weight and height were recorded using a set of scales (Tanita BC-533, Tokyo, Japan) and a stadiometer (SECA 213, Hamburg, Germany). The order of midsole density conditions was selected for the participant, and the appropriate footwear was fitted with LoadSol® insoles (Novel GmbH, Munich, Germany), with the battery box attached to the top of the shoe (Figure 4.3). Each insole (left and right) was configured for the specific participant, following the manufacturer's bipedal calibration process. LoadSol® insoles are Bluetooth operated and controlled via a smartphone device application for data collection of both the right and left insoles. Between each midsole density condition, the LoadSol® insoles were both zeroed.

AHRS-IMU's log data in all three axes (X-Y-Z), inclusive of sensor angles, angular velocity, and angular acceleration, operated on a Bluetooth 5.0 wireless transmission, via a smartphone device application. Each AHRS-IMU sensor was calibrated for multiple sensors, including the accelerometer and magnetometer, prior to being affixed to the participant. AHRS-IMU's were attached to the participants' right lower limb using elastic straps, and once affixed, the sensors were covered in medical tape (Universal Specialities Limited (USL) Sport

Healthcare Foam Underwrap and USL Sport Game Day Rigid Tape, New Zealand) to reduce movement and noise (Nüesch et al., 2017; Wolski et al., 2024). The AHRS-IMU foot sensor was attached to the shoe using a flat bracelet, interlaced tightly with the shoelace and also secured with USL Sport Game Day Rigid Tape to reduce vibration (Florenciano Restoy et al., 2021; Mo & Chow, 2018). AHRS-IMU placement was defined from previously described techniques (Mo & Chow, 2018; Nüesch et al., 2017), and is visually presented in Figure 4.4:

Sacrum - affixed to a point between the fifth lumbar vertebra and the superior aspect of the median sacral crest of the sacrum.

Femur - affixed laterally to the distal aspect of the femur and superior to the lateral condyle of the femur, where soft tissue is least. Sensor placement is aligned between the greater trochanter and the lateral condyle.

Shank - affixed laterally to the distal aspect of the fibula and superior to the lateral malleolus. Sensor placement is aligned between the lateral condyle and the malleolus.

Foot - interlaced on the distal surface of the shoe, above the metatarsal bones, pointing distally from the body’s midline.

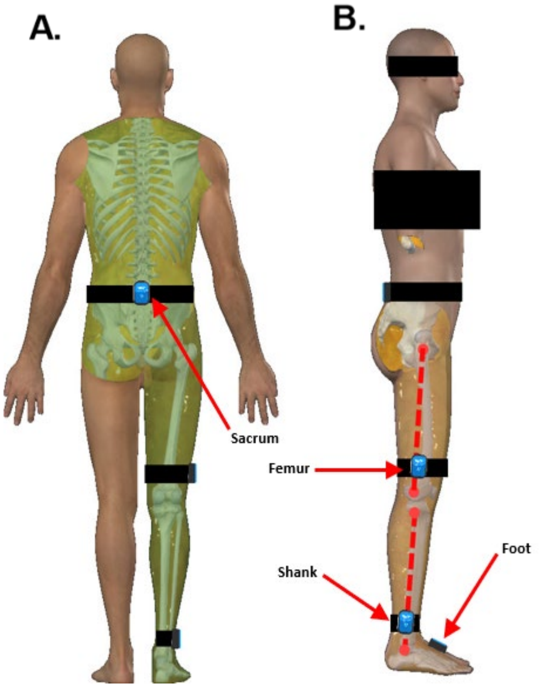

Figure 4.4. AHRS-IMU placement locations. A. dorsal view of the placement of sacrum; B. lateral view of the placement locations for femur, shank, and foot

Once affixed to the aforementioned positions (Figure 4.4), the sensors were accelerometer calibrated and reference angled with the participant standing still in the anatomical position, facing the direction of travel, for a total of 40 seconds. The reference angle defined the orientation of the sensor and was used to calculate any deviation from this angle. Between each midsole density condition, the sensors were accelerometer-calibrated, and reference-angled, ensuring that data were consistent and comparable across different conditions.

Each midsole density intervention began with a familiarisation warm-up over a distance of 720 m, performed at a running speed of 10 km·h^{-1} on the road to be used during experimental trials. The length of the road was surfaced with tarmacadam, faced easterly aspect, and sheltered from prevailing wind by a 15 m high evergreen hedge (Figure 4.5). Environmental conditions (air temperature and relative humidity) were recorded pre- and post-trials from data obtained via a local weather station website (*Palmy weather*, 2025). The average air temperature and relative humidity over the 16 trials were 17.5 ± 2.8°C and 65.3 ± 12.0%, respectively. Trials were not performed in the presence of headwinds, tailwinds, rain, or if the tarmacadam surface was wet, as these conditions have previously been shown to affect the cushioning capabilities of the midsole (Cook et al., 1985). The start point altitude was 29.8 m, decreasing to an end point altitude of 27.6 m, with slight fluctuations, ranging between a maximum of 26.8 m and a minimum of 31.2 m (Figure 4.6).

Figure 4.5. Dairy Farm Road, Massey University, Palmerston North, New Zealand, demonstrating the start point and the end point of the experimental trials

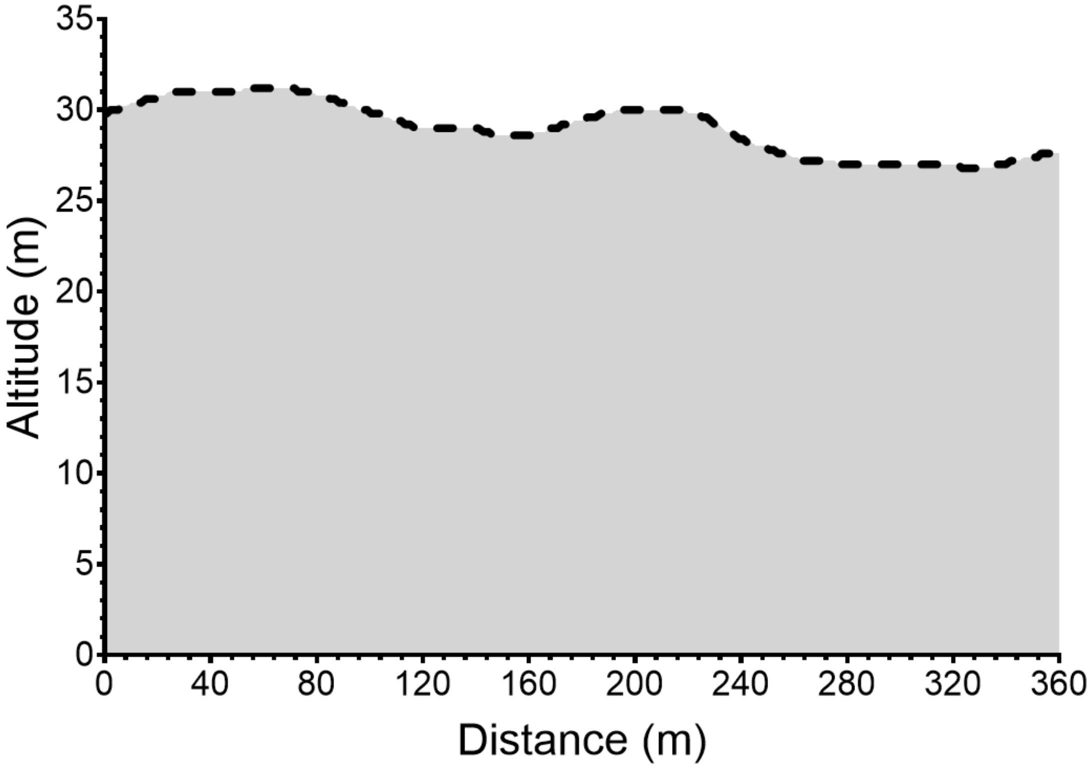

Figure 4.6. Dairy Farm Road, Massey University, Palmerston North, New Zealand, altitude profile from the start point to the end point (360 m)

Throughout the entire trial, running speed was paced by a cyclist (Merida Juliet 7 40 MD 27.5”) using a compatible speed sensor (GSC + 10, Garmin), connected to Garmin Forerunner 735 XT sports watch (Garmin, Schaffhausen, Switzerland). From the start point (Figure 4.5) data logging commenced, where the participant ran to the end point (360 m), at which point data logging was stopped. The participant returned to the start point at a speed of 10 km·h^{-1}, and the same procedure was repeated for the remaining running speeds before changing shoes. Between each midsole density condition, there was a 10-minute period to change shoes, zero the LoadSol® insoles, accelerometer calibrate, and reference angle each AHRS-IMU. Throughout the experimental trials, participants were blind to the midsole density intervention and any dependent variables being measured.

4.7 Data Processing

4.7.1 *In Vitro* Data Processing

Raw data were transferred to an Excel file (version 2410, Microsoft, Redmond, Washington, USA), from which the final cycle of the continuous test, following steady-state hysteresis, was extracted for analysis. Using MATLAB (R2024a, MathWorks, Inc., Natick, MA, USA), dependent variables were calculated.

Figure 4.7 demonstrates the hysteresis curve plotted on a force displacement graph, where energy absorption (J) was calculated as the area under the loading curve, until peak extension was met. Recovered energy (J) was calculated as the area beneath the unloading curve, from the peak extension to the return of zero extension. The energy lost (J) as heat is represented by the area between the loading and unloading curves (Hoogkamer et al., 2018; Macdermid et al., 2025). As a percentage, the energy recovered (%) is calculated as (recovered energy ÷ energy absorbed) *100 (Hoogkamer et al., 2018; Macdermid et al., 2025).

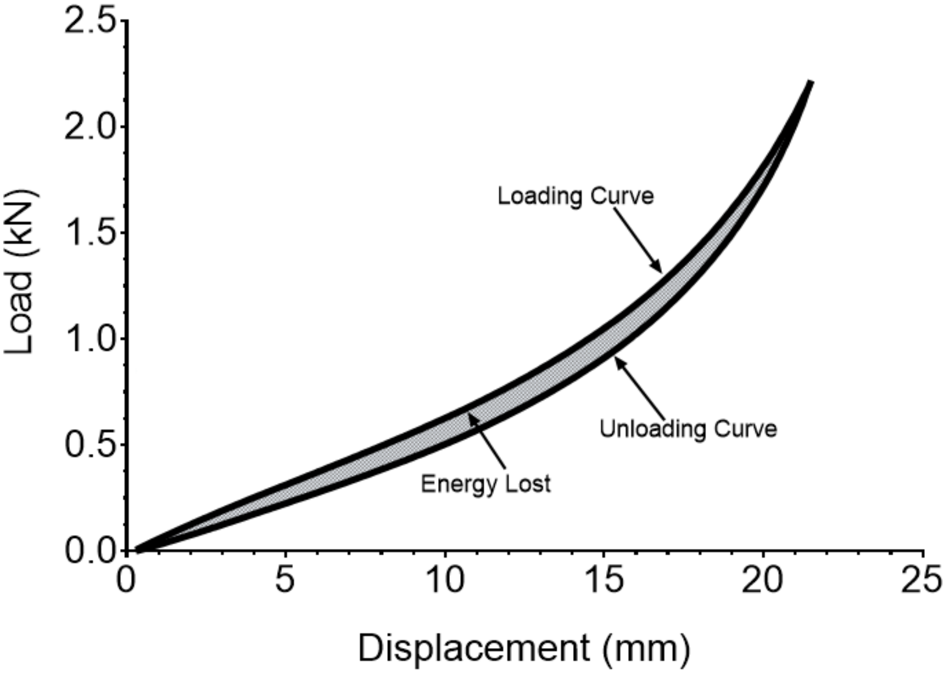

Figure 4.7. Hysteresis curve plotted on a force displacement graph; demonstrating the loading and unloading curves, and the energy lost (shaded area between curves)

4.7.2 *In Vivo* Data Processing

4.7.2.1 Running Speed

Running speed data were downloaded from the Garmin Connect app (Garmin, Schaffhausen, Switzerland), and transferred to GoldenCheetah application (version 3.6, Cycling Power Analysis Software). The data were converted to comma separated values (CSV) files for subsequent analysis, with the first 20 and last five seconds of each data recording removed. Speeds for all participants were grouped for each midsole density.

4.7.2.2 Spatiotemporal and Kinetic Variables

Prior to data processing, the first 20 and last five steps were removed from analysis to account for acceleration/deceleration speed zones, ensuring that the steps analysed were at a constant speed (Melvin et al., 2014).

The precise identification of initial contact and toe-off in running gait analysis is critical for accurately determining gait phases, estimating spatiotemporal parameters, and understanding joint movement characteristics (Mo & Chow, 2018; Sinclair et al., 2011).

LoadSol® time and force data (200 Hz) was uploaded into MATLAB (R2024a, MathWorks, Inc., Natick, MA, USA), re-sampled to 1,000 Hz, and processed using force threshold values of 5 and 10 N to determine initial foot contact and toe-off (Macdermid et al., 2025; Wright et al., 1998). From these outputs, the following dependent variables were calculated and identified using previously described techniques, expressed as force per body weight ($N \cdot BW^{-1}$) where appropriate (Chan et al., 2018; Macdermid et al., 2025):

a) Vertical peak impact force ($N \cdot BW^{-1}$) was identified as the first peak between initial contact and the active peak. If no first peak was present (forefoot strike) it was defined as the force at 13% of the stance phase (Blackmore et al., 2016; Chan et al., 2018).

b) Average loading rate ($N \cdot BW^{-1} \cdot s^{-1}$) was the difference between forces at 20% and 80% of the peak impact force, divided by the corresponding time interval (s) between these two points.

c) Peak active force ($N \cdot BW^{-1}$) was the second peak for heel strikers, or the highest force recorded in each step for forefoot strikers. In running, this point (mid-stance) occurs when the foot is directly beneath the centre of mass.

d) Impulse ($N \cdot s \cdot BW^{-1}$), the area under the force-time curve, where the analysis identified the initial impact and toe-off phases for each step based on filtered indices derived from force data. After determining the number of steps, an empty array was created to store impulse values. For each step, the corresponding force-time data between the filtered initial impact and toe-off was extracted. Impulse was then calculated using the trapezoidal numerical integration over this interval, summing the force applied over time.

e) Ground contact time (s) was the time during which the foot was in contact with the ground.

f) Swing time (s) was the time the foot had no contact with the ground.

g) Stride duration (s) was the time from one initial impact to the next initial impact of the same foot.

h) Stride frequency (spm) was the number of strides completed per minute.

4.7.2.3 Joint Kinematic Variables

AHRS-IMU data (100 Hz) was uploaded into MATLAB (R2024a, MathWorks, Inc., Natick, MA, USA), separated based on anatomical position and re-sampled to 1,000 Hz. To determine initial contact and toe-off, two methods were used, via the incorporation of accelerometer data. The S-method (Figure 4.8A) identifies key events using total accelerations of the foot to determine initial contact (Strohrmann et al., 2012). The M-method (Figure 4.8B) uses the vertical acceleration at the shank where the minimum before peak vertical acceleration was identified as initial contact, and that in the region of interest was identified as toe-off (Mercer et al., 2003). Both of these methods have been deemed best practice (Mo & Chow, 2018).

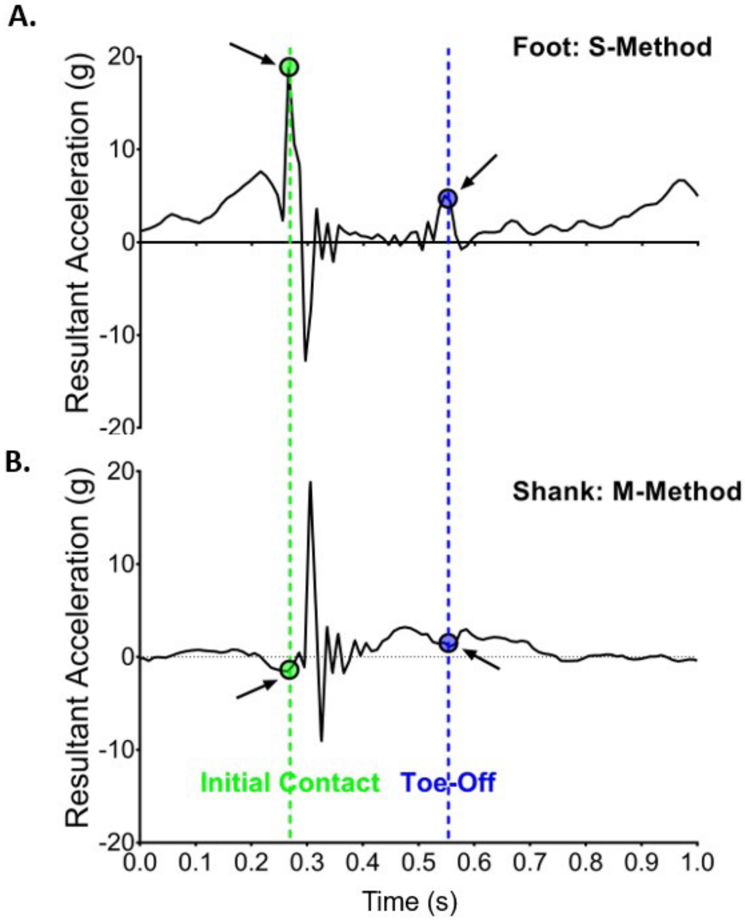

Figure 4.8. Methods for determining initial contact and toe-off are illustrated, with arrows indicating these points for each method. A. S-method, B. M-method

As the AHRS-IMU's used in this study incorporate embedded Kalman filters, real-time sensor fusion was performed to smooth the raw data by integrating accelerometer, gyroscope, and magnetometer inputs. To further mitigate residual artifacts, a low-pass filter (cutoff 5 Hz) was applied to remove high-frequency noise, and a high-pass filter (cutoff 0.1 Hz) was used to removed low-frequency drift. As such, the following dependent variables were calculated based on the reference angle, derived the strategic anatomical positioning of the sensors, and are all expressed as range of motion (°):

a) Stance phase knee flexion, providing insight into the amount of flexion upon impact.

b) Stance phase knee extension, providing insight into the amount of knee extension during toe-off.

c) Swing phase knee flexion, identified as the greatest knee flexion during the first half of the swing phase (initial swing).

d) Swing phase knee extension, identified as the greatest knee extension during the second half of the swing phase (terminal swing).

e) Stance phase dorsiflexion, identified during the first half of the stance phase (absorption).

f) Stance phase plantarflexion, identified during the second half of the stance phase (propulsion).

g) Stance phase hip extension, inclusive of stance and the initial swing phase, if the hip is still extending.

h) Swing phase hip flexion, identified as occurring during this phase of gait.

Summary data for all dependent variables were exported to an Excel file (version 2410, Microsoft, Redmond, Washington, USA), which included mean ± SD and the coefficient of variation (CV %) for each parameter of gait.

4.8 Statistical Analysis

4.8.1 *In Vitro* Statistical Analysis

All statistics were conducted and graphed using GraphPad Prism (version 8.4.3, GraphPad Software, San Diego, CA, USA). Dependent variables are reported as the overall mean ± SD for each independent variable. An unpaired t-test was used to assess differences between the midsole densities. Significance was set at $p < 0.05$.

4.8.2 *In Vivo* Statistical Analysis

4.8.2.1 Running Speed

All statistics were conducted and graphed using GraphPad Prism (version 8.4.3, GraphPad Software, San Diego, CA, USA). Speeds obtained throughout the trials are reported for each midsole density, as overall mean ± SD, with the coefficient of variation (CV %) presented as the mean ± SD. A one-sample t-test was used to verify whether each trial achieved the prescribed speed (12, 14, or 16 $km \cdot h^{-1}$), ensuring correct pacing. Subsequently, a paired t-test was used to assess differences between midsole density trials at each prescribed speed. Statistical significance was set at $p < 0.05$.

4.8.2.2 Spatiotemporal, Kinetic, and Joint Kinematic Variables

To reduce the complexity of the statistical analyses, only data from the right limb was analysed (Nüesch et al., 2017). All dependent variables were calculated per step, with the number of steps, overall mean ± SD, and the mean ± SD of the CV % per independent variable reported. Differences between running speeds and midsole density were analysed using a two-way repeated-measures ANOVA, with two within-subject variables (speed*midsole density). Where significant differences were identified, Sidak's post-hoc multiple comparisons testing was performed. Post-hoc results are reported as the mean difference ± standard error difference (mean ± SE), to provide clarity and an understanding of the magnitude of these differences. A two-way repeated-measures ANOVA was used to assess the effects of midsole density, speed, and their interaction on the dependent variables, allowing for the determination of statistically significant differences (Godin et al., 2024). Reporting the CV % per trial at a group level provides a measure of absolute reliability and addresses potential bias due to error in measurement (Godin et al., 2024). All statistical analyses and data visualisations were performed using GraphPad Prism (version 8.4.3, GraphPad Software, San Diego, CA, USA). Statistical significance was set at $p < 0.05$.

Disclaimer

Currently, this thesis has outlined methods and procedures as if they applied to all three midsole density shoes conditions. However, due to unforeseen manufacturing issues, the production of low-ρ midsole (Shoe C) was unsuccessful. Given the time constraints associated with completing this thesis, data collection and analysis were conducted solely using only high-ρ midsole (Shoe A) and mid-ρ midsole (Shoe B), both of which were successfully manufactured. As a result, all subsequent analyses and discussions will be based exclusively on findings from the high-ρ and mid-ρ midsole conditions.

Chapter Five – Results

5.1 *In Vitro* Experimental Results

The energy absorption (Figure 5.1) during *in vitro* testing showed a significant difference between the high-ρ and mid-ρ midsole ($t_{(30)} = 6.412$, $p < 0.0001$), where the mid-ρ midsole absorbed more energy than the high-ρ midsole (19.37 ± 0.52 vs. 18.19 ± 0.53 J, respectively).

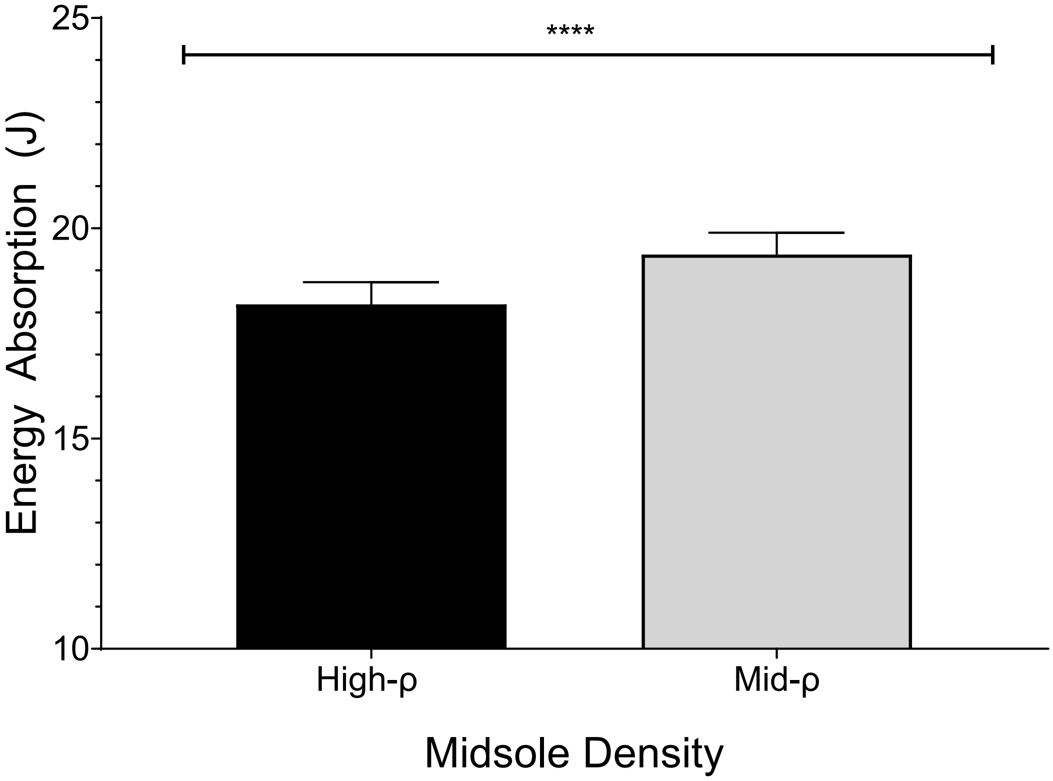

*Figure 5.1. Mean ± SD of energy absorption (J) for the for the high-ρ midsole (black) and mid-ρ midsole (grey). **** p < 0.0001 indicates level of significance*

The maximum deformation (Figure 5.2) presented a significant difference between the high-ρ and mid-ρ midsole ($t_{(30)} = 2.495$, $p = 0.0183$), whereby the mid-ρ midsole resulted in greater deformation compared to the high-ρ midsole (24.13 ± 0.68 vs. 23.32 ± 1.11 mm, respectively).

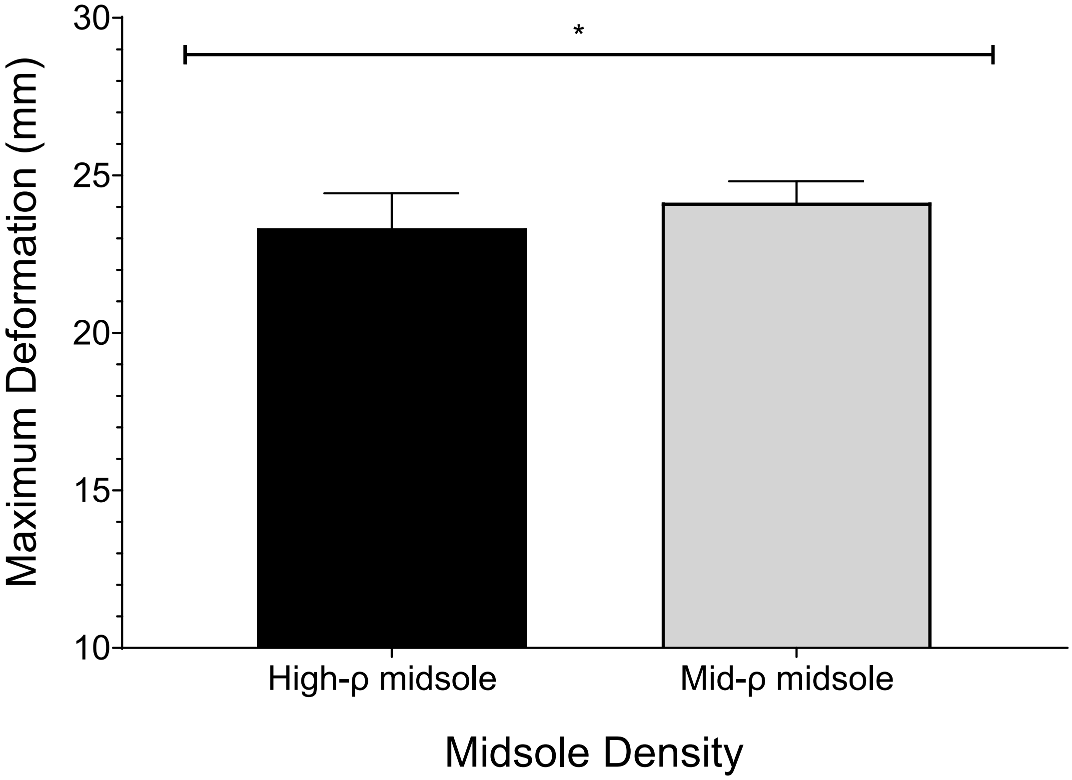

*Figure 5.2. Mean ± SD of maximum deformation (mm) for the high-ρ midsole (black) and mid-ρ midsole (grey). * p < 0.05 indicates level of significance*

The energy recovered (Figure 5.3) showed a significant difference between the high-ρ and mid-ρ midsole ($t_{(30)} = 9.052$, $p < 0.0001$), resulting in the mid-ρ midsole recovering more energy than that of the high-ρ midsole (17.07 ± 0.42 vs. 15.75 ± 0.39 J, respectively).

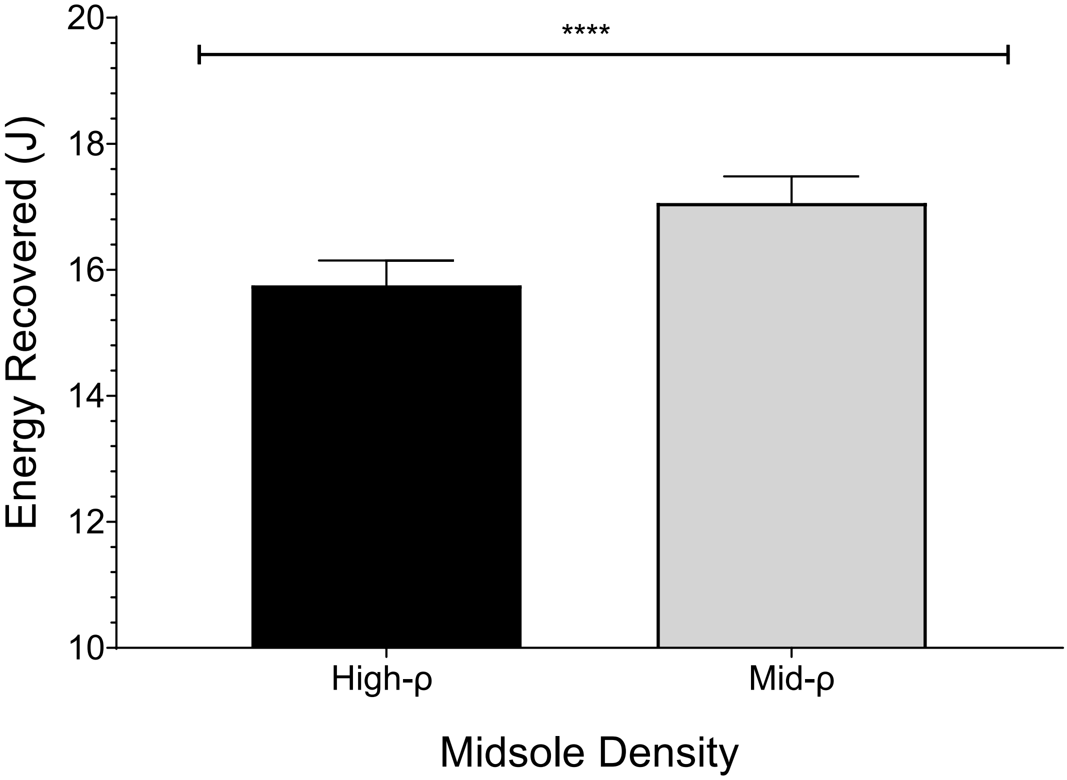

*Figure 5.3. Mean ± SD of energy recovered (J) for the high-ρ midsole (black) and mid-ρ midsole (grey). **** p < 0.0001 indicates level of significance*

The energy recovered as a percentage of energy absorbed (Figure 5.4) reported a significant difference between high-ρ and mid-ρ midsole ($t_{(30)} = 7.957$, $p < 0.0001$), where the mid-ρ midsole had a greater percentage of energy recovered compared to the high-ρ midsole (88.06 ± 0.44 vs. 86.62 ± 0.58%, respectively).

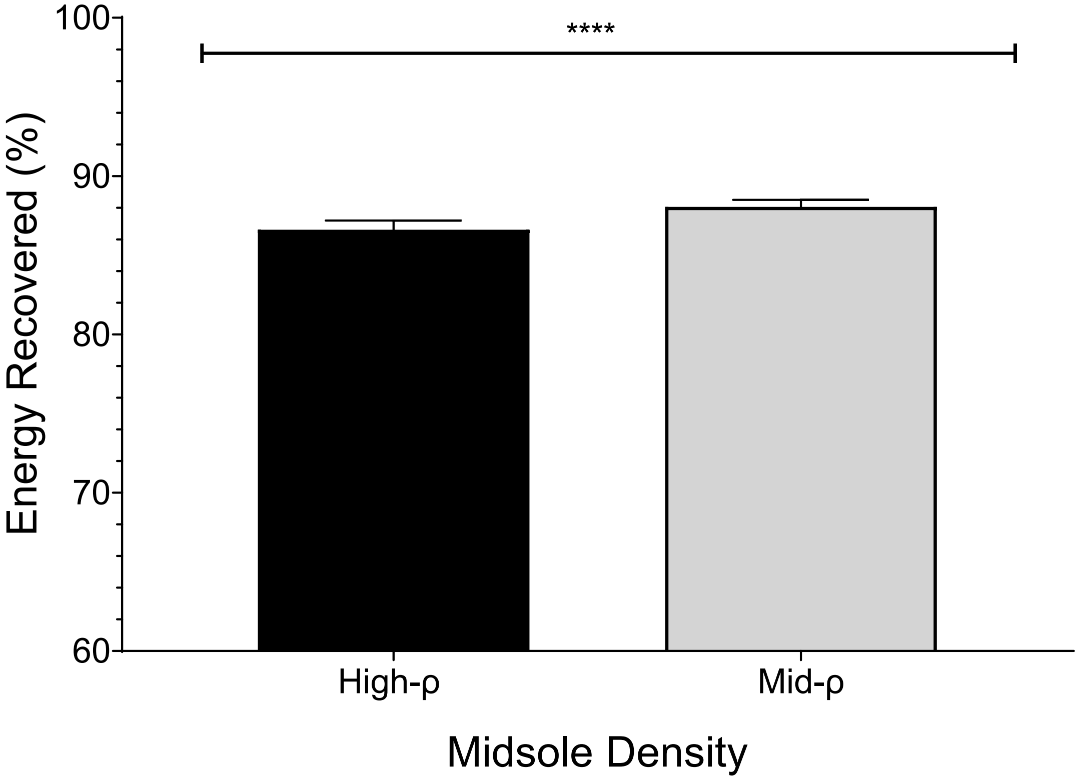

*Figure 5.4. Mean ± SD of energy recovered as a percentage (%) for the high-ρ midsole (black) and mid-ρ midsole (grey). **** p < 0.0001 indicates level of significance*

The energy lost (Figure 5.5) between the high-ρ and mid-ρ midsole presented a significant difference ($t_{(30)} = 2.389$, $p = 0.0234$), resulting in the high-ρ midsole losing more energy than the mid-ρ midsole (2.44 ± 0.16 vs. 2.32 ± 0.13 J, respectively).

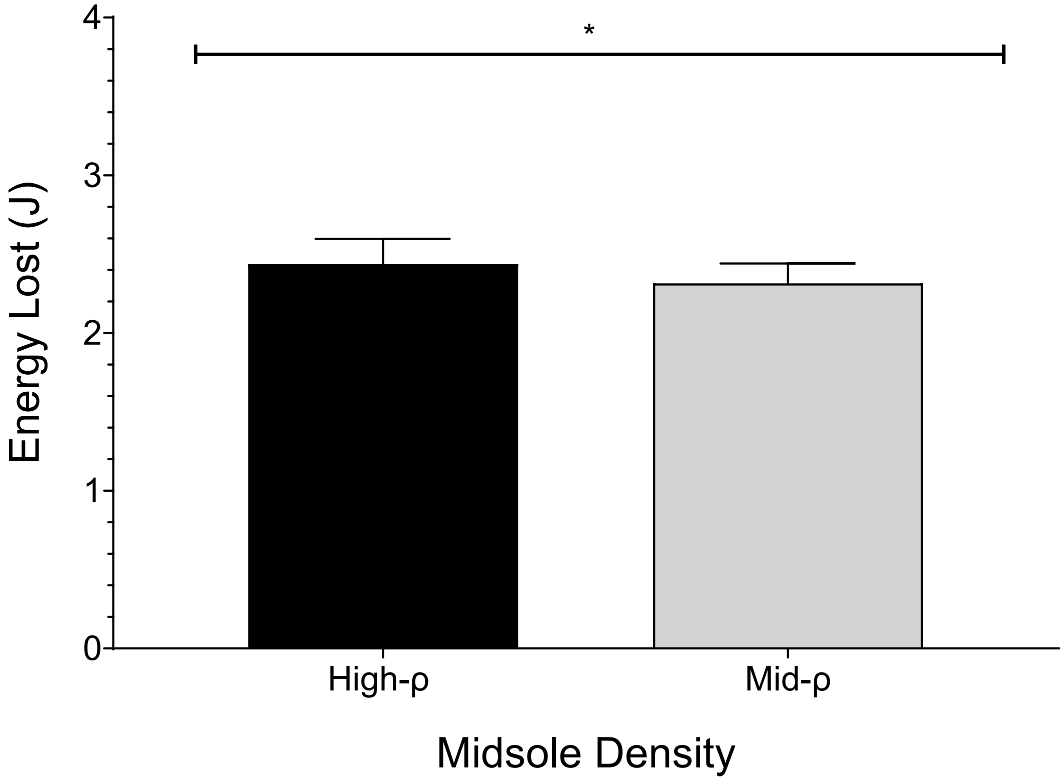

*Figure 5.5. Mean ± SD of energy lost (J) for the high-ρ midsole (black) and mid-ρ midsole (grey). * p < 0.05 indicates level of significance*

5.2 *In Vivo* Experimental Results

5.2.1 Running Speed

The objective of the *in vivo* trials was to collect data at running speeds of 12, 14, and 16 km·h^{-1}. One sample t-test showed no significant difference for either the high-ρ or mid-ρ midsoles at 12 (12.06 ± 0.26, $t_{(15)} = 0.91$, $p = 0.377$ vs. 12.03 ± 0.26, $t_{(15)} = 0.462$, $p = 0.651$) or 14 km·h^{-1} (13.93 ± 0.17, $t_{(15)} = 1.688$, $p = 0.112$ vs. 13.9 ± 0.21, $t_{(15)} = 1.904$, $p = 0.076$). However, there was a difference between the prescribed running speed and actual speed at 16 km·h^{-1} (15.81 ± 0.19, $t_{(15)} = 3.966$, $p = 0.001$ vs. 15.78 ± 0.24, $t_{(15)} = 3.548$, $p = 0.0003$). Further analysis of this dataset resulted in no significant differences within speeds (12, 14, 16 km·h^{-1}, Figure 5.6) when comparing the high-ρ and mid-ρ midsoles ($t_{(15)} = 0.463$, $p = 0.650$; $t_{(15)} = 0.668$, $p = 0.514$; and $t_{(15)} = 0.897$, $p = 0.384$), respectively.

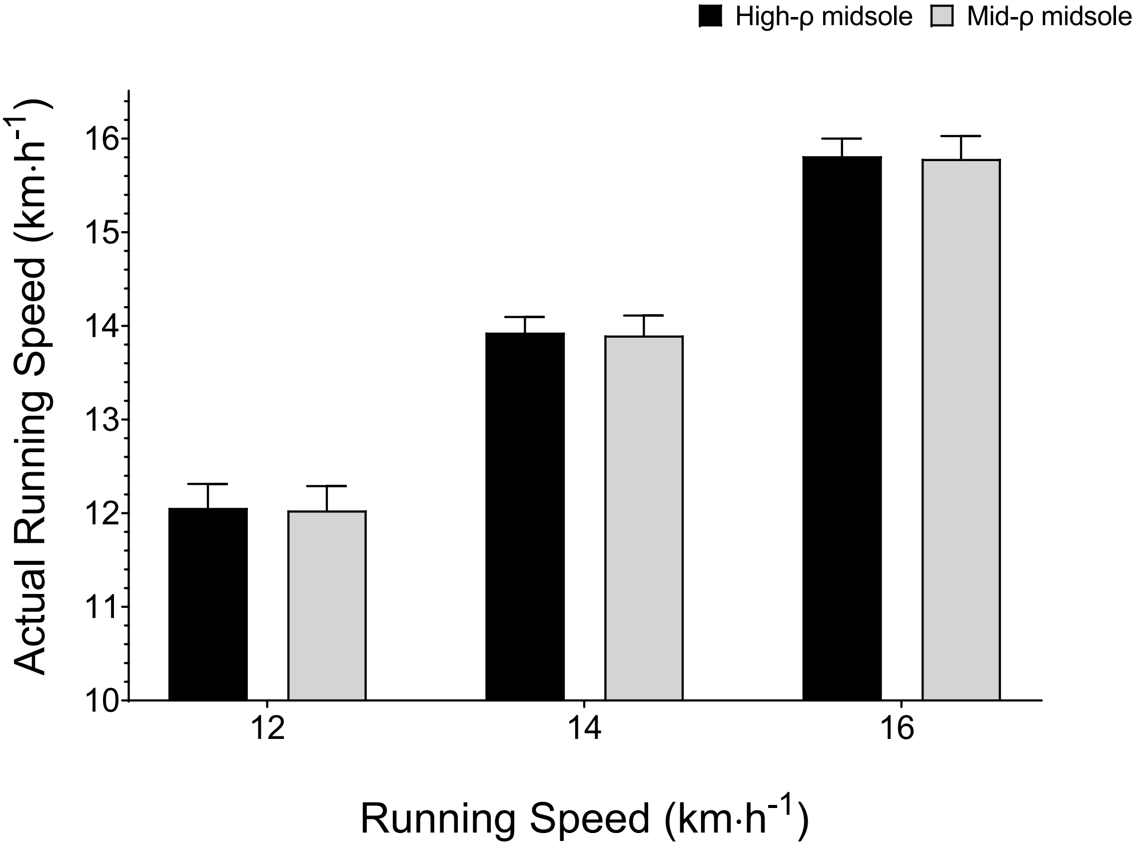

Figure 5.6. Mean ± SD of actual running speeds (km·h^{-1}) achieved in the high-ρ midsole (black) and mid-ρ midsole (grey), from the prescribed speeds of 12, 14, and 16 km·h^{-1}

5.2.1.1 Running Speeds CV %

Actual running speeds CV % mean ± SD for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} were 2.19 ± 0.30 vs. 2.41 ± 0.43; 2.11 ± 0.37 vs. 2.09 ± 0.41; 1.90 ± 0.37 vs. 1.95 ± 0.46%, respectively. Additional examination of this dataset resulted in no significant differences within speeds (12, 14, 16 km·h^{-1}) when comparing the high-ρ and mid-ρ midsoles ($t_{(15)} = 1.722$, $p = 0.106$; $t_{(15)} = 0.217$, $p = 0.831$; and $t_{(15)} = 0.338$, $p = 0.740$), respectively.

5.2.2 Spatiotemporal Variables

The number of steps taken during the trials did not show a significant speed*midsole density interaction (F $_{(2, 30)}$ = 0.571, p = 0.571) or main effect of midsole density (F $_{(1, 15)}$ = 1.059, p = 0.320), but speed had a significant main effect (127 ± 1, 108 ± 0, and 96 ± 1 steps, F $_{(2, 30)}$ = 492.4, p <0.0001) on the number of steps taken by participants at 12, 14, and 16 km·h^{-1}, respectively.

Stride duration for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 0.708 ± 0.035 vs. 0.710 ± 0.034; 0.696 ± 0.037 vs. 0.701 ± 0.038; and 0.679 ± 0.038 vs. 0.683 ± 0.041 s, respectively (Figure 5.7). There was no significant speed*midsole density interaction (F $_{(2, 30)}$ = 0.7472, p = 0.482) or main effect of midsole density (F $_{(1, 15)}$ = 2.699, p = 0.121). There was a significant main effect of speed, with stride duration decreasing as speed increased (F $_{(2, 30)}$ = 34.95, p < 0.0001). Post-hoc multiple comparisons between speeds indicated significance between 12 vs. 14 km·h^{-1} (0.010 ± 0.003, p = 0.0194); 12 vs. 16 km·h^{-1} (0.028 ± 0.003, p < 0.0001); and 14 vs. 16 km·h^{-1} (0.018 ± 0.003, p < 0.0001).

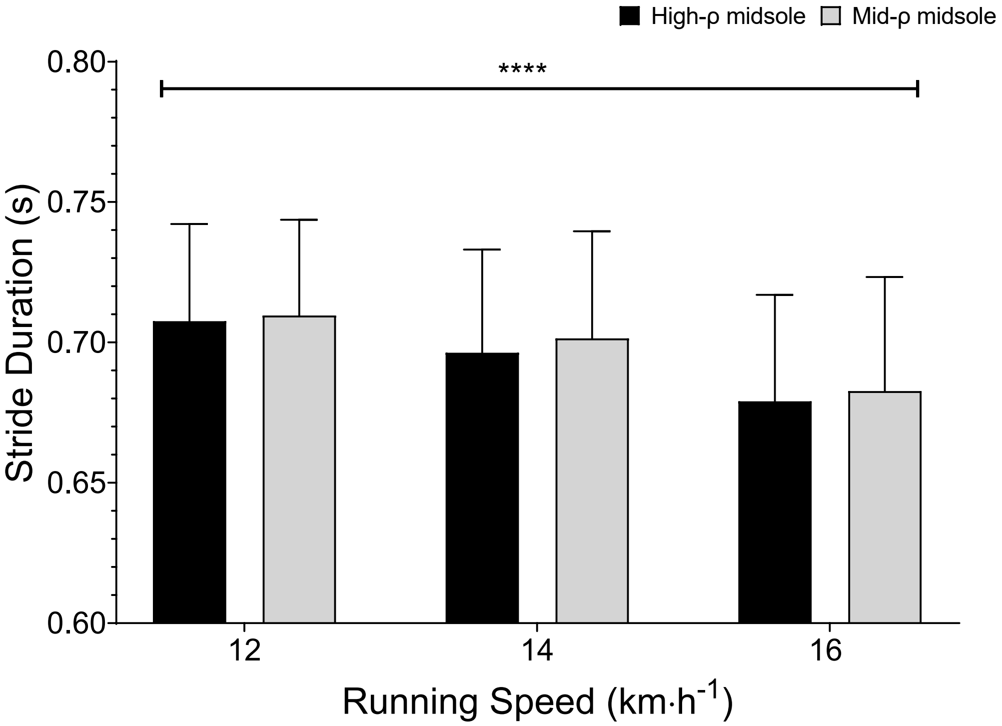

*Figure 5.7. Mean ± SD of stride duration (s) at each running speed (12, 14, and 16 km·h^{-1}) for the high-ρ midsole (black) and mid-ρ midsole (grey). **** p < 0.0001 indicates level of significance*

Stride frequency for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 84.88 ± 4.13 vs. 84.72 ± 4.14; 86.34 ± 4.74 vs. 85.99 ± 4.77; and 88.63 ± 4.98 vs. 88.14 ± 5.16 spm, respectively (Figure 5.8). As a result of stride duration, there was no significant speed*midsole density interaction ($F_{(2, 30)} = 0.6724$, $p = 0.518$) for stride frequency, or main effect of midsole density ($F_{(1, 15)} = 1.608$, $p = 0.224$). There was, however, a significant main effect of speed, with stride frequency increasing as speed increased ($F_{(2, 30)} = 35.08$, $p < 0.0001$). Post-hoc multiple comparisons between speeds indicated stride frequency to be significantly greater at faster running speeds; 12 vs. 14 km·h^{-1} (-1.37 ± 0.43, $p = 0.0097$); 12 vs. 16 km·h^{-1} (-3.59 ± 0.43, $p < 0.0001$); and 14 vs. 16 km·h^{-1} (-2.22 ± 0.43, $p < 0.0001$).

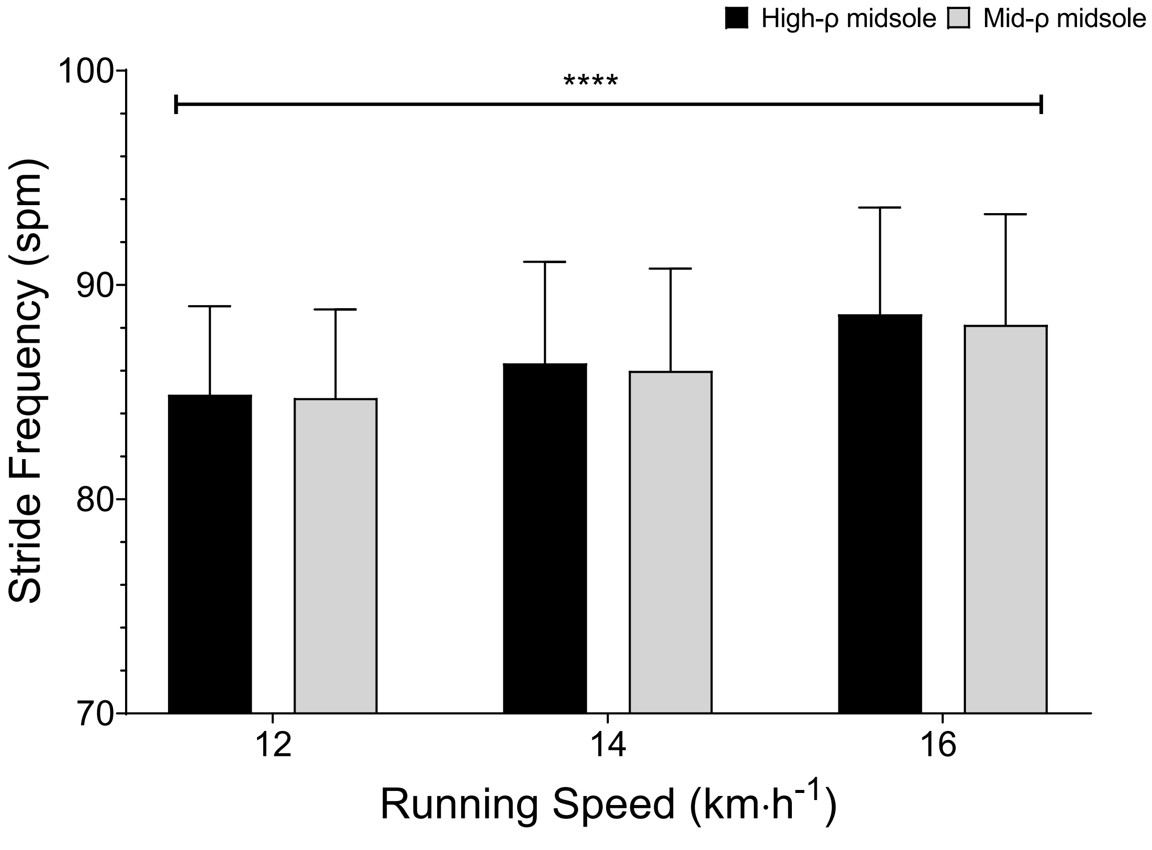

*Figure 5.8. Mean ± SD of stride frequency (spm) at each running speed (12, 14, and 16 km·h^{-1}) for the high-ρ midsole (black) and mid-ρ midsole (grey). **** $p < 0.0001$ indicates level of significance*

Ground contact time for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 0.237 ± 0.015 vs. 0.237 ± 0.016; 0.219 ± 0.015 vs. 0.219 ± 0.016; and 0.206 ± 0.016 vs. 0.205 ± 0.015 s, respectively (Figure 5.9). No significant interaction was observed ($F_{(2, 30)} = 0.05151$, $p = 0.950$), along with no main effect of midsole density ($F_{(1, 15)} = 0.1479$, $p = 0.706$). However, there was a significant main effect of speed, with ground contact time decreasing as speed increased ($F_{(2, 30)} = 233.6$, $p < 0.001$). Post-hoc multiple comparisons between speeds indicated that ground contact time significantly decreased between 12 vs. 14 km·h^{-1} (0.018 ± 0.001, $p < 0.0001$); 12 vs. 16 km·h^{-1} (0.032 ± 0.001, $p < 0.0001$); and 14 vs. 16 km·h^{-1} (0.014 ± 0.001, $p < 0.0001$).

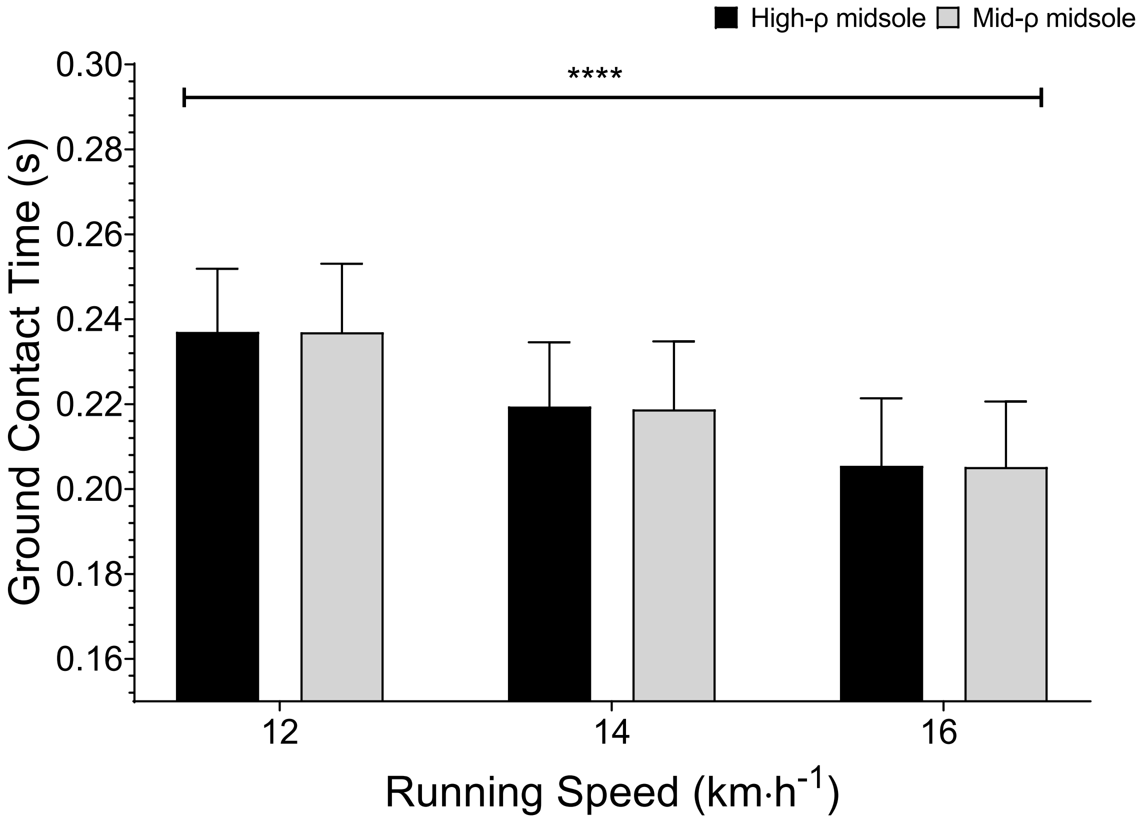

*Figure 5.9. Mean ± SD of ground contact time (s) at each running speed (12, 14, and 16 km·h^{-1}) for the high-ρ midsole (black) and mid-ρ midsole (grey). **** $p < 0.0001$ indicates level of significance*

Swing time for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 0.471 ± 0.038 vs. 0.474 ± 0.035; 0.478 ± 0.037 vs. 0.481 ± 0.037; and 0.474 ± 0.037 vs. 0.479 ± 0.038 s, respectively (Figure 5.10). There was no significant interaction ($F_{(2, 30)}$ = 0.1446, p = 0.866) or main effect of midsole density ($F_{(1, 15)}$ = 2.381, p = 0.144). There was, however, a significant main effect of speed ($F_{(2, 30)}$ = 4.141, p = 0.026). Post-hoc multiple comparisons between speeds indicated swing time to be significant between 12 vs. 14 km·h^{-1} (-0.007 ± 0.002, p = 0.020), but not between 12 vs. 16 km·h^{-1} (-0.004 ± 0.002, p = 0.213); or 14 vs. 16 km·h^{-1} (0.003 ± 0.002, p = 0.501).

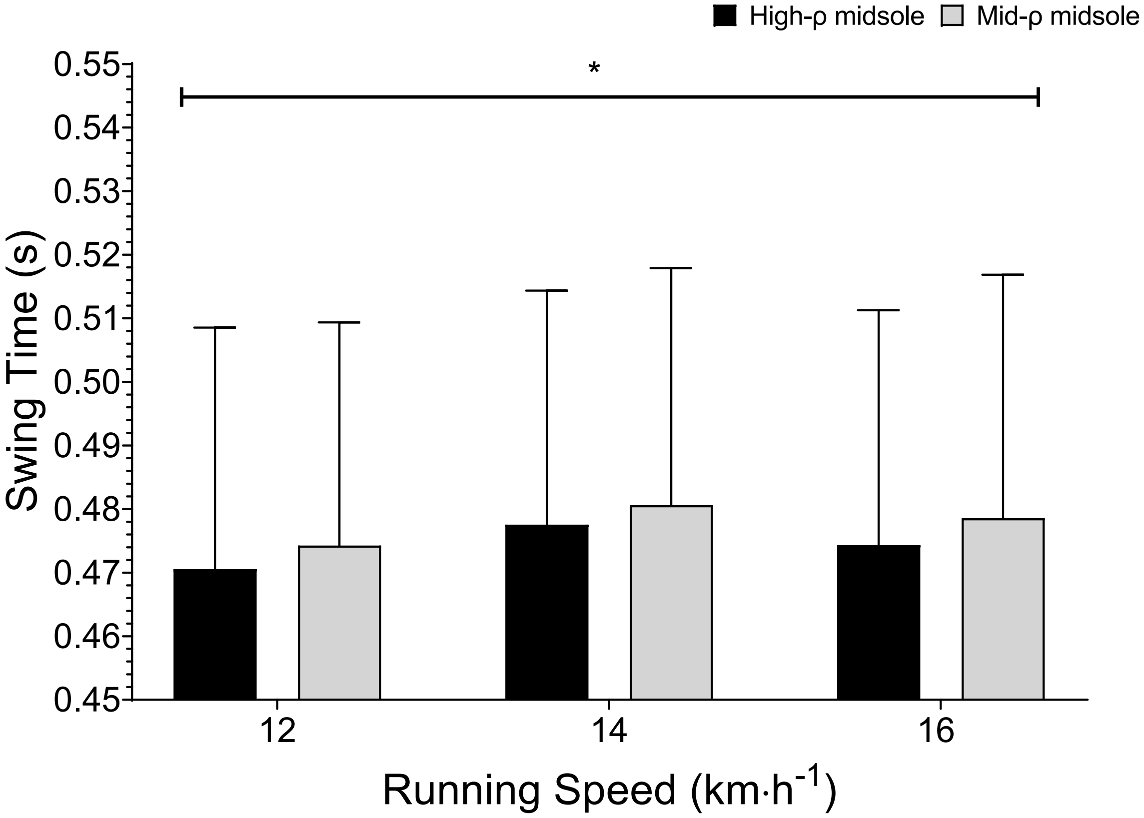

*Figure 5.10. Mean ± SD of swing time (s) at each running speed (12, 14, and 16 km·h^{-1}) for the high-ρ midsole (black) and mid-ρ midsole (grey). * $p < 0.05$ indicates level of significance*

5.2.2.1 Spatiotemporal Variables CV %

As each participants specific trials included between 96 – 127 right steps on average, it is important to highlight the variation across trials. The CV % of spatiotemporal variables, expressed as mean ± SD, are illustrated in Table 5.1.

There was no significant interaction (speed*midsole density) for stride duration CV % ($F_{(2, 30)} = 1.002$, $p = 0.379$), no main effect of midsole density ($F_{(1, 15)} = 0.632$, $p = 0.439$) or speed ($F_{(2, 30)} = 2.032$, $p = 0.149$). Stride frequency CV % also showed no significant interaction ($F_{(2, 30)} = 1.150$, $p = 0.330$), with no main effect of midsole density ($F_{(1, 15)} = 0.744$, $p = 0.402$) or speed ($F_{(2, 30)} = 2.234$, $p = 0.125$). Further, there was no significant interaction ($F_{(2, 30)} = 0.662$, $p = 0.523$) for ground contact time CV %, with no main effect of midsole density ($F_{(1, 15)} = 3.216$, $p = 0.093$) or speed ($F_{(2, 30)} = 1.773$, $p = 0.187$). There was also no interaction ($F_{(2, 30)} = 0.853$, $p = 0.436$), main effect of midsole density $F_{(1, 15)} = 0.031$, $p = 0.864$) or speed ($F_{(2, 30)} = 1.998$, $p = 0.153$) observed for swing time CV %.

Table 5.1. Mean ± SD of the CV % for spatiotemporal variables, expressed as a percentage

Midsole Density	**High-ρ**	**Mid-ρ**	**High-ρ**	**Mid-ρ**	**High-ρ**	**Mid-ρ**
Speed (km·h^{-1})	*12*	*12*	*14*	*14*	*16*	*16*
Stride Duration	1.35 ± 0.25	1.27 ± 0.27	1.32 ± 0.24	1.32 ± 0.29	1.39 ± 0.29	1.39 ± 0.27
Stride Frequency	1.36 ± 0.27	1.27 ± 0.27	1.32 ± 0.24	1.32 ± 0.29	1.4 ± 0.31	1.4 ± 0.27
Ground Contact Time	2.43 ± 0.42	2.25 ± 0.31	2.24 ± 0.41	2.37 ± 0.31	2.51 ± 0.29	2.49 ± 0.23
Swing Time	1.95 ± 0.30	1.88 ± 0.33	1.78 ± 0.38	1.81 ± 0.36	1.86 ±0.42	1.88 ± 0.38

5.2.3 Kinetic Variables

Vertical peak impact force for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 1.67 ± 0.29 vs. 1.67 ± 0.26; 1.85 ± 0.37 vs. 1.85 ± 0.36; and 2.00 ± 0.43 vs. 1.99 ± 0.42 N·BW^{-1}, respectively (Figure 5.11). There was no significant speed*midsole density interaction for vertical peak impact force ($F_{(2, 30)} = 0.1182$, $p = 0.889$) or main effect of midsole density ($F_{(1, 15)} = 0.01175$, $p = 0.915$). There was, however, a significant main effect of speed, with vertical peak impact force increasing as speed increased ($F_{(2, 30)} = 32.24$, $p < 0.0001$). Post-hoc multiple comparisons between speeds indicated vertical peak impact force to be significantly greater between 12 vs. 14 km·h^{-1} (-0.18 ± 0.04, $p = 0.0003$); 12 vs. 16 km·h^{-1} (-0.32 ± 0.04, $p < 0.0001$); and 14 vs. 16 km·h^{-1} (-0.14 ± 0.04, $p = 0.0038$).

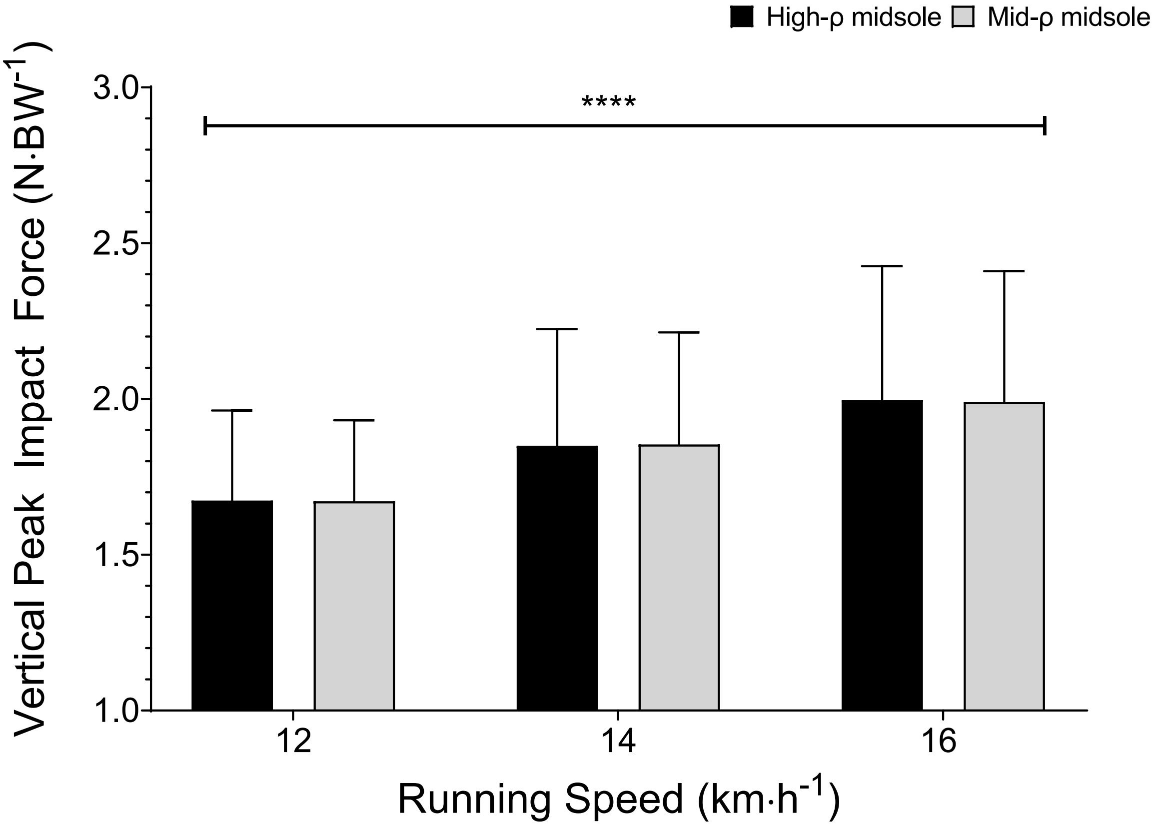

*Figure 5.11. Mean ± SD of vertical peak impact force (N·BW^{-1}) at each running speed (12, 14, and 16 km·h^{-1}) for the high-ρ midsole (black) and mid-ρ midsole (grey). **** $p < 0.0001$ indicates level of significance*

Average loading rate for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 65.25 ± 18.30 vs. 64.79 ± 16.91; 77.40 ± 23.80 vs. 76.05 ± 22.18; and 89.50 ± 27.88 vs. 88.83 ± 27.12 N·BW^{-1}·s^{-1}, respectively (Figure 5.12). No significant interaction was observed ($F_{(2, 30)} = 0.1293$, $p = 0.879$) or main effect of midsole density ($F_{(1, 15)} = 0.5649$, $p = 0.464$). However, there was a significant main effect of speed, where the average loading rate increased with increases in speed ($F_{(2, 30)} = 38.70$, $p < 0.0001$). Post-hoc multiple comparisons between speeds indicated average loading rate to be significantly greater between 12 vs. 14 km·h^{-1} (-11.70 ± 2.75, $p = 0.0005$); 12 vs. 16 km·h^{-1} (-24.14 ± 2.75, $p < 0.0001$); and 14 vs. 16 km·h^{-1} (-12.44 ± 2.75, $p = 0.0002$).

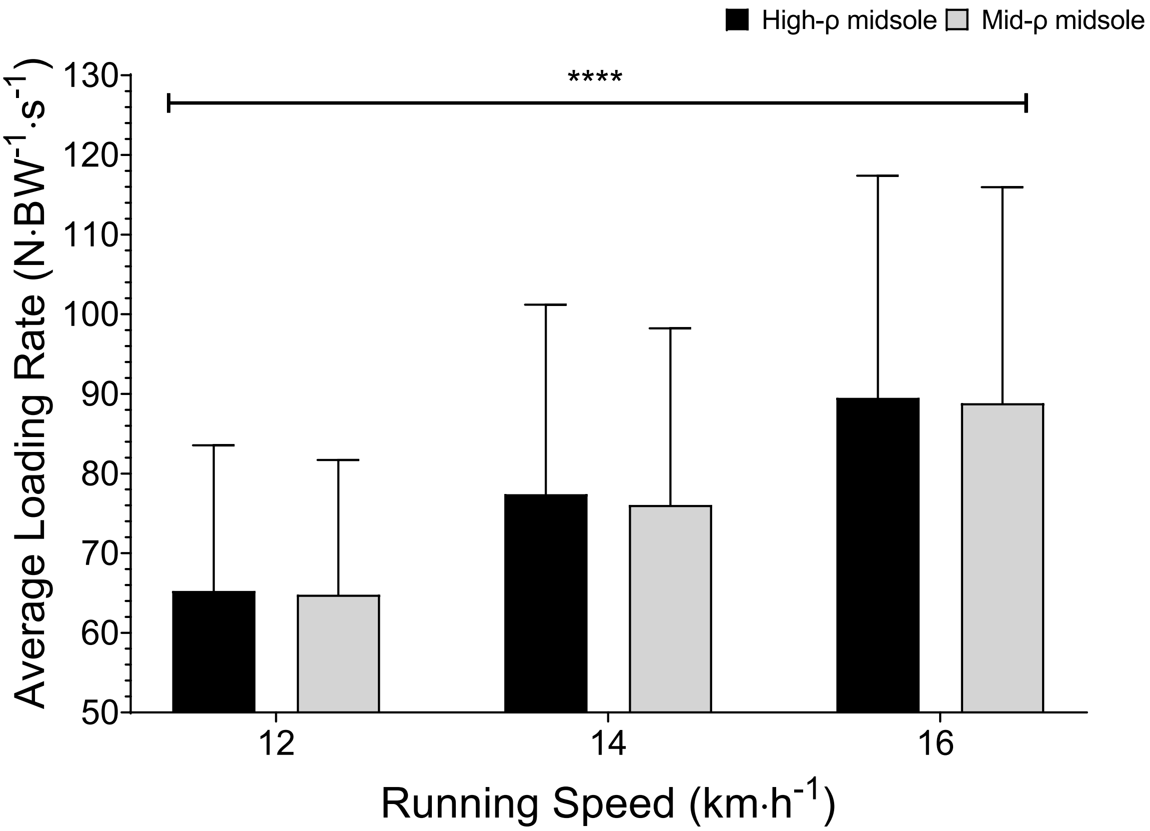

*Figure 5.12. Mean ± SD of average loading rate (N·BW^{-1}·s^{-1}) at each running speed (12, 14, and 16 km·h^{-1}) for the high-ρ midsole (black) and mid-ρ midsole (grey). **** $p < 0.0001$ indicates level of significance*

Peak active force for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 2.74 ± 0.29 vs. 2.76 ± 0.29; 2.92 ± 0.32 vs. 2.91 ± 0.33; and 3.01 ± 0.36 vs. 3.01 ± 0.34 N·BW^{-1}, respectively (Figure 5.13). There was no significant interaction ($F_{(2, 30)} = 0.132$, $p = 0.877$) or main effect of midsole density ($F_{(1, 15)} = 0.2488$, $p = 0.625$). However, there was a significant main effect of speed, with peak active force increasing as speed increased ($F_{(2, 30)} = 78.60$, $p < 0.0001$). Post-hoc multiple comparisons between speeds indicated that peak active force significantly increased between 12 vs. 14 km·h^{-1} (-0.16 ± 0.02, $p < 0.0001$); 12 vs. 16 km·h^{-1} (-0.26 ± 0.02, $p < 0.0001$); and 14 vs. 16 km·h^{-1} (-0.10 ± 0.02, $p = 0.0001$).

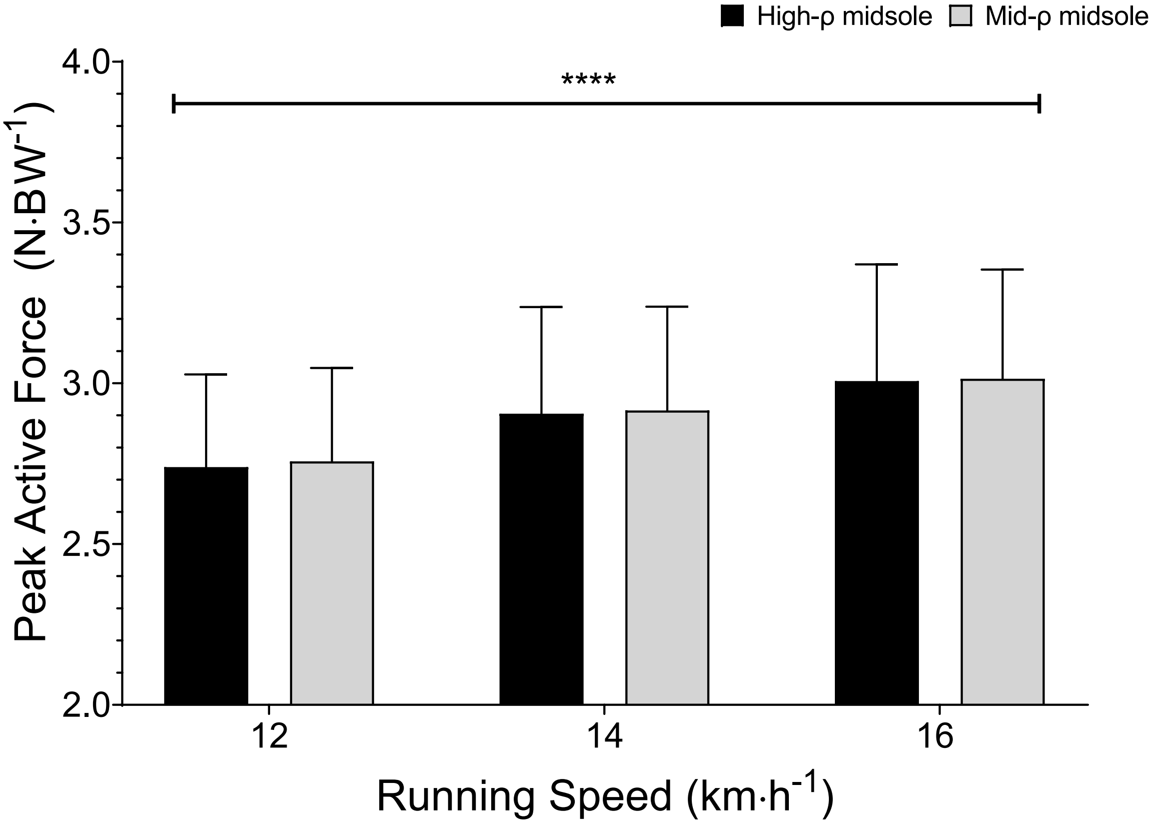

*Figure 5.13. Mean ± SD of peak active force (N·BW^{-1}) at each running speed (12, 14, and 16 km·h^{-1}) for the high-ρ midsole (black) and mid-ρ midsole (grey). **** p < 0.0001 indicates level of significance*

Impulse for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 0.398 ± 0.037 vs. 0.396 ± 0.036; 0.393 ± 0.038 vs. 0.394 ± 0.039; and 0.382 ± 0.038 vs. 0.382 ± 0.038 N·s·BW^{-1}, respectively (Figure 5.14). There was no significant interaction observed ($F_{(2, 30)} = 0.5167$, $p = 0.602$) or main effect of midsole density ($F_{(1, 15)} = 0.001$, $p = 0.981$). There was, however, a significant main effect of speed, where impulse decreased ($F_{(2, 30)} = 19.64$, $p < 0.0001$). Post-hoc multiple comparisons between speeds indicated no significant difference between 12 vs. 14 km·h^{-1} (0.004 ± 0.003, $p = 0.311$). However, significant differences were observed between 12 vs. 16 km·h^{-1} (0.015 ± 0.003, $p < 0.0001$) and 14 vs. 16 km·h^{-1} (0.012 ± 0.003, $p = 0.0003$).

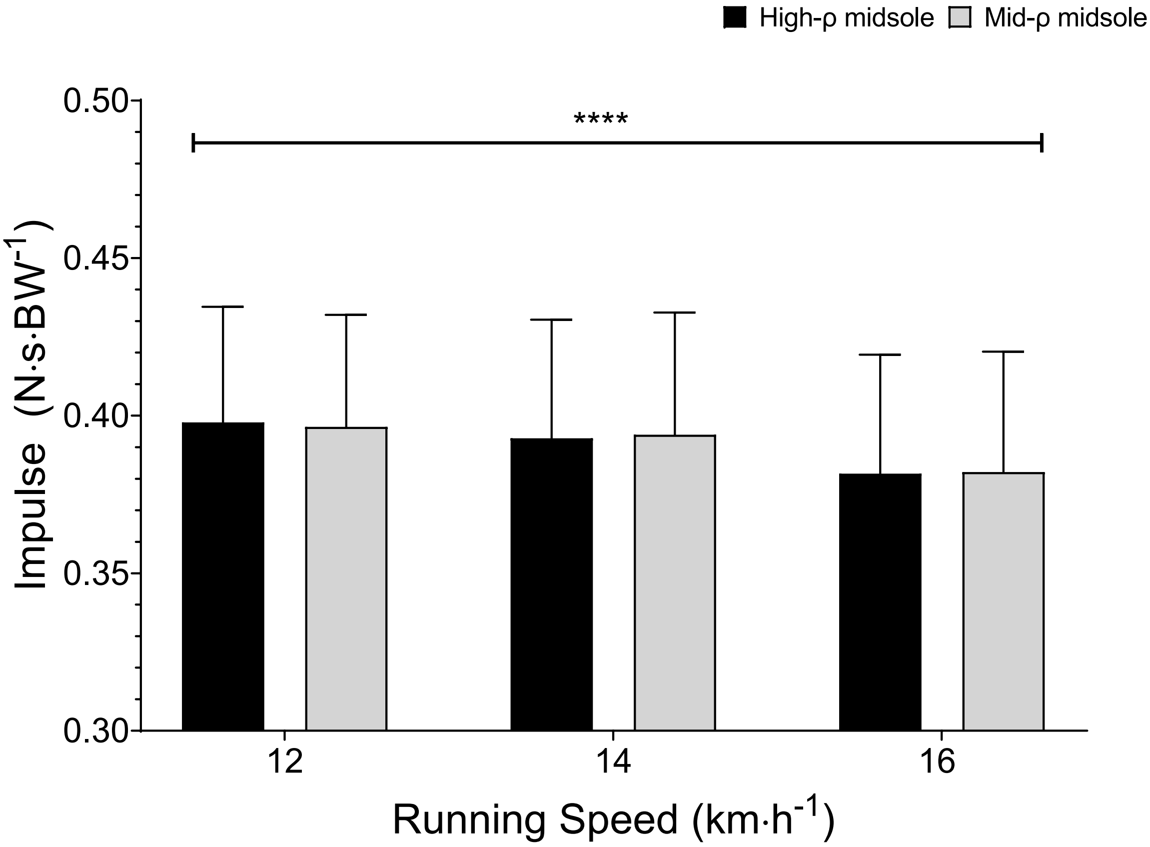

*Figure 5.14. Mean ± SD of impulse (N·s·BW^{-1}) at each running speed (12, 14, and 16 km·h^{-1}) for the high-ρ midsole (black) and mid-ρ midsole (grey). **** $p < 0.0001$ indicates level of significance*

5.2.3.1 Kinetic Variables CV %

The CV % of kinetic variables, expressed as mean ± SD, are illustrated in Table 5.2.

Vertical peak impact force CV % displayed no speed*midsole density interaction ($F_{(2, 30)}$ = 0.607, p= 0.552) or main effect of speed ($F_{(2, 30)}$ = 0.221, p = 0.803). However, there was a significant main effect for variation in midsole density ($F_{(1, 15)}$ = 7.564, p = 0.015). Post-hoc testing highlighted no significant differences between the midsole density conditions. Further a significant speed*midsole density interaction for average loading rate CV % ($F_{(2, 30)}$ = 3.496, p = 0.043) and a significant main effect of midsole density ($F_{(1, 15)}$ = 8.458, p = 0.011) was observed, but no main effect of speed ($F_{(2, 30)}$ = 0.524, p = 0.597). Post-hoc multiple comparisons presented no difference between the high-ρ and mid-ρ midsoles.

There was no significant interaction for peak active force CV % ($F_{(2, 30)}$ = 1.569, p = 0.225), along with no main effect of midsole density ($F_{(1, 15)}$ = 0.139, p =0.714) or speed ($F_{(2, 30)}$ = 1.203, p = 0.314). Impulse CV % also presented no interaction ($F_{(2, 30)}$ = 1.154, p = 0.329), along with no main effect of midsole density ($F_{(1, 15)}$ = 2.381, p = 0.144) or speed ($F_{(2, 30)}$ = 0.034, p = 0.966).

Table 5.2. Mean ± SD of the CV % for kinetic variables, expressed as a percentage

Midsole Density	**High-ρ**	**Mid-ρ**	**High-ρ**	**Mid-ρ**	**High-ρ**	**Mid-ρ**
Speed ($km \cdot h^{-1}$)	*12*	*12*	*14*	*14*	*16*	*16*
Vertical Peak Impact Force	8.76 ± 1.76	7.99 ± 1.55	8.76 ± 2.71	8.58 ± 2.67	8.78 ± 3.05	8.55 ± 2.38
Average Loading Rate	15.34 ± 3.11	13.92 ± 2.16	14.58 ± 3.76	15.12 ± 4.48	15.63 ± 3.63	14.73 ± 3.55
Peak Active Force	2.63 ± 0.65	2.42 ± 0.39	2.46 ± 0.43	2.56 ± 0.48	2.65 ± 0.53	2.67 ± 0.52
Impulse	2.11 ± 0.95	1.81 ± 0.31	2.01 ± 0.35	1.85 ± 0.32	1.92 ± 0.24	1.95 ± 0.34

5.2.4 Joint Kinematics

Stance phase knee flexion for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 28.87 ± 8.74 vs. 29.89 ± 10.20; 31.55 ± 11.29 vs. 31.39 ± 10.72; 29.69 ± 11.7 vs. 30.81 ± 12.72°, respectively. There was no significant speed*midsole density interaction (F $_{(2, 30)}$ = 0.238, p = 0.790), main effect of midsole density (F $_{(1, 15)}$ = 0.569, p = 0.462) or speed (F $_{(2, 30)}$ = 1.250, p = 0.301). Stance phase knee extension for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was -22.61 ± 4.36 vs. -23.14 ± 5.80; -23.41 ± 5.40 vs. -24.45 ± 5.83; -22.95 ± 5.86 vs. -23.86 ± 6.54°, respectively. Presenting no significant interaction (F $_{(2, 30)}$ = 0.144, p = 0.866), along with no main effect of midsole density (F $_{(1, 15)}$ = 3.346, p = 0.087) or speed (F $_{(2, 30)}$ = 1.021, p = 0.373).

Swing phase knee flexion for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 64.38 ± 15.46 vs. 64.90 ± 15.45; 65.58 ± 12.52 vs. 66.70 ± 15.57; 71.54 ± 12.40 vs. 70.93 ± 10.10°, respectively. There was no significant speed*midsole density interaction (F $_{(2, 30)}$ = 0.080, p = 0.923) or main effect of midsole density (F $_{(1, 15)}$ = 0.033, p = 0.859). There was, however, a significant main effect of speed, where swing phase knee flexion increased (F $_{(2, 30)}$ = 3.758, p = 0.035). Post-hoc comparisons between speeds indicated that swing phase knee flexion significantly increased between 12 vs. 16 km·h^{-1} (-6.59 ± 2.52, p = 0.036); but not between 12 vs. 14 km·h^{-1} (-1.50 ± 2.52, p = 0.823); or 14 vs. 16 km·h^{-1} (-5.09 ± 2.52, p = 0.125). Swing phase knee extension for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was -70. 62 ± 16.49 vs. -71.68 ± 17.15; -73.73 ± 15.31 vs. -73.65 ± 18.61; -78.26 ± 15.38 vs. -77.88 ± 12.85°, respectively. Likewise, there was no significant interaction (F $_{(2, 30)}$ = 0.113, p = 0.894) or main effect of midsole density (F $_{(1, 15)}$ = 0.019, p = 0.892). However, a significant main effect of speed was found, where swing phase knee extension increased (F $_{(2, 30)}$ = 8.363, p = 0.0013). Post-hoc comparisons between speeds indicated that swing phase knee extension significantly increased between 12 vs. 16 km·h^{-1} (6.92 ± 1.71, p = 0.001); and 14 vs. 16 km·h^{-1} (4.38 ± 1.71, p = 0.041); but not between 12 vs. 14 km·h^{-1} (2.54 ± 1.71, p = 0.313).

Stance phase dorsiflexion for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 27.33 ± 5.96 vs. 28.39 ± 9.15; 29.83 ± 7.04 vs. 29.63 ± 10.66; 27.09 ± 9.48 vs. 28.73 ± 11.93°, respectively. There was no significant speed*midsole density interaction ($F_{(2, 30)} = 0.183$, $p = 0.834$), along with no main effects of midsole density ($F_{(1, 15)} = 0.545$, $p = 0.472$) or speed ($F_{(2, 30)} = 1.326$, $p = 0.281$). Stance phase plantarflexion for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was -53.91 ± 9.80 vs. -53.88 ± 11.15; -63.86 ± 16.36 vs. -63.79 ± 17.97; -70.94 ± 18.35 vs. -72.76 ± 21.07°, respectively. There was no significant interaction ($F_{(2, 30)} = 0.607$, $p = 0.552$) or main effect of midsole density ($F_{(1, 15)} = 0.120$, $p = 0.734$). However, there was a significant main effect of speed, with stance phase plantarflexion increasing as speed increased ($F_{(2, 30)} = 30.81$, $p < 0.0001$). Post-hoc comparisons between speeds indicated significance between 12 vs. 14 km·h^{-1} (9.93 ± 2.29, $p = 0.0004$); 12 vs. 16 km·h^{-1} (17.95 ± 2.29, $p < 0.0001$); and 14 vs. 16 km·h^{-1} (8.02 ± 2.91, $p = 0.0041$).

Stance phase hip extension for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 45.47 ± 4.86 vs. 45.56 ± 5.04; 50.84 ± 5.24 vs. 50.97 ± 5.79; 54.45 ± 5.67 vs. 54.29 ± 5.11°, respectively. There was no significant speed*midsole density interaction ($F_{(2, 30)} = 0.089$, $p = 0.915$) or a main effect of midsole density ($F_{(1, 15)} = 0.002$, $p = 0.961$). There was, however, a significant main effect of speed, where stance phase hip extension increased ($F_{(2, 30)} = 100.7$, $p < 0.0001$). Post-hoc comparisons between speeds indicated significance between 12 vs. 14 km·h^{-1} (-5.39 ± 0.63, $p < 0.0001$); 12 vs. 16 km·h^{-1} (-8.85 ± 0.63, $p < 0.0001$); and 14 vs. 16 km·h^{-1} (-3.47 ± 0.63, $p < 0.0001$). Swing phase hip flexion for the high-ρ and mid-ρ midsoles across the speeds 12, 14, and 16 km·h^{-1} was 49.81 ± 3.87 vs. 50.57 ± 3.98; 56.23 ± 5.07 vs. 56.38 ± 4.56; 61.17 ± 4.98 vs. 60.98 ± 3.79°, respectively. There was also no significant interaction ($F_{(2, 30)} = 0.765$, $p = 0.474$) or main effect of midsole density ($F_{(1, 15)} = 0.204$, $p = 0.658$). However, there was a significant main effect of speed, with swing phase hip flexion increasing as speed increased ($F_{(2, 30)} = 197.3$, $p < 0.0001$). Post-hoc comparisons between speeds indicated significance between 12 vs. 14 km·h^{-1} (-6.11 ± 0.55, $p < 0.0001$); 12 vs. 16 km·h^{-1} (-10.88 ± 0.55, $p < 0.0001$); and 14 vs. 16 km·h^{-1} (-4.78 ± 0.55, $p < 0.0001$).

5.2.4.1 Joint Kinematics CV %

The CV % of kinetic variables, expressed as mean ± SD, are presented in Table 5.3.

Stance phase knee flexion CV % did not present a significant speed*midsole density interaction ($F_{(2, 30)} = 0.283$, $p = 0.755$). There was no main effect of midsole density ($F_{(1, 15)} = 2.823$, $p = 0.114$), but there was a significant main effect of speed ($F_{(2, 30)} = 4.490$, $p = 0.0197$). Post-hoc multiple comparisons between speeds indicated significance between 12 vs. 16 $km \cdot h^{-1}$ (-2.47 ± 0.94, $p = 0.035$); and 14 vs. 16 $km \cdot h^{-1}$ (-2.40 ± 0.94, $p = 0.041$). Stance phase knee extension CV % did show a significant speed*midsole density interaction ($F_{(2, 30)} = 3.533$, $p = 0.0419$). There was no main effect of midsole density ($F_{(1, 15)} = 0.014$, $p = 0.906$), but there was a significant main effect of speed ($F_{(2, 30)} = 11.78$, $p = 0.0002$). Post-hoc multiple comparisons between speeds indicated significance between 12 vs. 16 $km \cdot h^{-1}$ (1.53 ± 0.33, $p = 0.0002$); and 14 vs. 16 $km \cdot h^{-1}$ (1.20 ± 0.33, $p = 0.003$).

Swing phase knee flexion CV % did not show a significant interaction ($F_{(2, 30)} = 2.022$, $p = 0.1500$) or main effect of midsole density ($F_{(1, 15)} = 0.148$, $p = 0.706$). There was a significant main effect of speed ($F_{(2, 30)} = 6.659$, $p = 0.0040$), however, post-hoc multiple comparisons between speeds only indicated significance between 12 vs. 16 $km \cdot h^{-1}$ (-1.11 ± 0.31, $p = 0.003$). Further, there was no significant interaction ($F_{(2, 30)} = 2.730$, $p = 0.081$) for swing phase knee extension CV %, or main effect of midsole density ($F_{(1, 15)} = 0.609$, $p = 0.447$). There was, however, a significant main effect of speed ($F_{(2, 30)} = 12.03$, $p = 0.0001$). Post-hoc multiple comparisons between speeds revealed a significant difference between 12 vs. 16 $km \cdot h^{-1}$ (1.23 ± 0.25, $p < 0.0001$); and 14 vs. 16 $km \cdot h^{-1}$ (-0.76 ± 0.25, $p = 0.015$).

Stance phase dorsiflexion CV % presented no significant speed*midsole density interaction ($F_{(2, 30)} = 0.238$, $p = 0.790$), with no main effects of midsole density ($F_{(1, 15)} = 3.376$, $p =0.086$). However, there was a significant main effect of speed ($F_{(2, 30)} = 5.867$, $p = 0.0071$). Key post-hoc multiple comparisons between speeds presented significance between 12 vs. 16 $km \cdot h^{-1}$ (-5.01 ± 1.66, $p = 0.014$); and 14 vs. 16 $km \cdot h^{-1}$ (-4.84 ± 1.66, $p = 0.018$). Stance phase plantarflexion CV % also showed no significant interaction ($F_{(2, 30)} = 0.912$, $p = 0.412$) or main effect of midsole density ($F_{(1, 15)} = 1.566$, $p = 0.230$). There was, however, a significant main effect of speed ($F_{(2, 30)} = 16.93$, $p < 0.0001$). Post-hoc multiple comparisons between speeds also indicated significance between 12 vs. 16 km·h^{-1} (5.13 ± 0.89, $p < 0.0001$); and 14 vs. 16 km·h^{-1} (2.97 ± 0.89, $p = 0.006$).

There was no significant speed*midsole density interaction ($F_{(2, 30)} = 0.072$, $p = 0.931$) for stance phase hip extension CV %, no main effect of midsole density ($F_{(1, 15)} = 0.2894$, $p = 0.599$) or speed ($F_{(2, 30)} = 2.175$, $p = 0.131$). Swing phase hip flexion CV % also showed no significant interaction ($F_{(2, 30)} = 0.421$, $p = 0.660$) or main effect of midsole density ($F_{(1, 15)} = 0.001$, $p = 0.979$). However, there was a significant main effect of speed ($F_{(2, 30)} = 7.534$, $p = 0.0022$). Post-hoc multiple comparisons revealed significance only between 12 vs. 14 km·h^{-1} (0.24 ± 0.09, $p = 0.028$); and 12 vs. 16 km·h^{-1} (0.33 ± 0.09, $p = 0.002$).

Table 5.3. Mean ± SD of the CV % for kinematic joint variables, expressed as a percentage

Midsole Density	**High-ρ**	**Mid-ρ**	**High-ρ**	**Mid-ρ**	**High-ρ**	**Mid-ρ**
Speed (km·h^{-1})	*12*	*12*	*14*	*14*	*16*	*16*
Stance Phase Knee Flexion	7.6 ± 1.9	7.8 ± 2.8	7.3 ± 1.5	8.2 ± 2.3	9.8 ± 6.4	10.5 ± 4.9
Stance Phase Knee Extension	-6.0 ± 1.7	-5.9 ± 1.6	-6.6 ± 1.7	-6.1 ± 1.5	-7.3 ± 2.3	-7.8 ± 2.6
Swing Phase Knee Flexion	4.4 ± 1.4	4.4 ± 1.2	5.1 ± 2.1	4.5 ± 1.7	5.3 ± 2.0	5.7 ± 1.9
Swing Phase Knee Extension	-4.4 ± 1.2	-4.5 ± 1.2	-5.0 ± 1.3	-4.8 ± 1.5	-5.3 ± 1.3	-6.0 ± 1.7
Stance Phase Dorsiflexion	7.5 ± 2.1	9.2 ± 5.5	7.6 ± 2.8	9.3 ± 4.6	11.8 ± 6.8	14.8 ± 11.8
Stance Phase Plantarflexion	-4.9 ± 2.0	-5.0 ± 2.5	-7.8 ± 3.8	-6.4 ± 2.7	-10.2 ± 4.6	-10.0 ± 4.8
Stance Phase Hip Extension	3.3 ± 0.7	3.3 ± 0.6	3.2 ± 0.7	3.1 ± 0.7	3.3 ± 0.6	3.3 ± 0.6
Swing Phase Hip Flexion	3.2 ± 0.9	3.3 ± 0.5	3.0 ± 0.6	2.9 ± 0.3	2.9 ± 0.5	2.9 ± 0.6

Chapter Six – Discussion

This study was undertaken with the aim of investigating *in vitro* properties of ATPU foam, varying in density and manufactured into geometrically identical running shoe midsoles, to assess the effects on *in vivo* parameters of running gait. These parameters included spatiotemporal, kinetic, and joint kinematic measures across different running speeds. In particular, the study focused on how midsole cushioning properties influenced vertical peak impact force and average loading rate during real-world overground running.

It was hypothesised that *in vitro* testing would show that a midsole composed of a lower-density ATPU foam would have greater energy absorption and energy recovery. Furthermore, it was hypothesised that during *in vivo* experimental trials, parameters of running gait related to ground reaction forces, specifically vertical peak impact force and average loading rate, would be reduced in the lower-density midsole. It was also expected that increases in running speed would influence spatiotemporal, kinetic, and joint kinematic parameters of gait.

The main findings show that: (a) during *in vitro* testing the mid-ρ midsole absorbed and recovered significantly more energy than the high-ρ midsole; (b) increases in running speed during *in vivo* trials significantly increased vertical peak impact force, average loading rate, peak active force, stride frequency, swing phase knee flexion and extension, stance phase plantarflexion, stance phase hip extension, and, swing phase hip flexion, while decreasing stride duration, ground contact time, and impulse; (c) *in vivo* trials also demonstrated that the mid-ρ midsole, exhibiting greater cushioning capabilities during *in vitro* testing, had no significant main effect on vertical peak impact force, average loading rate, or any other parameter of running gait, along with no significant interactions.

6.1 *In Vitro*

In vitro testing is advantageous because it allows for the midsole's capability to be assessed without the influence of factors that need to be controlled with *in vivo* experimental protocols (Wang et al., 2010). Therefore, *in vitro* testing was conducted on the right mid-ρ and high-ρ midsoles prior to the *in vivo* trials. The manufacturer specifications reported a 21.43% difference between the mid-ρ and high-ρ midsoles (0.14 ± 0.02 vs. 0.17 ± 0.02 $g{\cdot}cm^{-3}$, respectively). *In vitro* results in the present study demonstrated that the mid-ρ midsole significantly absorbed and recovered more energy than the high-ρ midsole. Such findings could be attributed to the significantly greater maximum deformation occurring in the mid-ρ midsole, which allows more energy to be absorbed as it is loaded with force. This supports the hypothesis that *in vitro* results would show that a lower-density ATPU foam midsole has greater energy absorption and energy recovery. Such results adhere to previous *in vitro* research where it has been demonstrated that midsoles effectively absorb impact energy (Shorten & Mientjes, 2011). Studies that provide mechanical test results typically show that more cushioned midsoles will maximise the energy absorbed (Aimar et al., 2024), with higher values representing better cushioning properties of the material (Clarke et al., 1983; Komi et al., 1987; Shorten & Mientjes, 2011). The primary aim of the midsole is to facilitate energy absorption (cushioning) during the initial impact of each step during running (Sun et al., 2020; Zhang et al., 2022), while recovering the maximum amount of energy (Aimar et al., 2024; Shorten, 1993). In the latter case, and when energy recovered was presented as a percentage of energy absorbed, there was a significant difference between high-ρ and mid-ρ midsoles, with the mid-ρ midsole recovering a greater percentage of energy. The amount of energy recovered is dependent on the cellular structure of the midsole material as it absorbs energy and deforms (Silva et al., 2009). A midsole with greater elastic properties will recover more energy, as the material releases its stored energy upon unloading (Aimar et al., 2024; Shorten, 1993). Previous studies have shown that shoes classified as more cushioned through mechanical testing tend to recover a greater amount energy (Frederick et al., 1986; Hoogkamer et al., 2018; Isherwood et al., 2021; Isherwood et al., 2024; Wang et al., 2012), likely due to the increased compression of the cellular structure upon impact (Verdejo & Mills, 2004). However, contrary to the claims made by running shoe companies outside the laboratory, where energy recovery is promoted as a business tool (Shorten, 2024), the scientific literature reveals that only a limited percentage of recovered energy contributes to an improved running economy (Fuller et al., 2015; Hoogkamer et al., 2018; Shorten, 1993). Consequently, it remains uncertain whether a higher percentage of energy recovery consistently leads to enhanced running performance; instead, it is possible that an optimal percentage may vary among individuals due to factors such as running speed, foot strike pattern, body mass, or joint range of motion, and could be determined with further testing (Boedicker et al., 2010).

It has been suggested that lower density foams have the ability to absorb and recover more energy (Burns & Joubert, 2024), while materials with a higher density tend to deform less reducing the energy absorbed (Paton et al., 2007). The results from this study support this, as the mid-ρ midsole absorbed and recovered more energy than the high-ρ midsole. Wang et al. (2012), mechanically tested midsoles made of EVA and two PU foams (PU-1 and PU-2) with reported densities of 0.2, 0.28, and 0.38 $g \cdot cm^{-3}$, before and after 500 km of running. Significant differences in peak force were observed among the three midsoles across the various running distances. The EVA (918.2 – 968.0 N) and PU-1 (909.6 – 972.9 N) midsoles exhibited lower peak forces than the PU-2 (983.0 – 1105.6 N) midsole, suggesting that EVA and PU-1 had greater cushioning properties than PU-2. The EVA midsole also recovered significantly more energy (50.8 – 51.7%) than PU-1 (40.1 – 44.0%) and PU-2 (39.6 – 42.3%) at all running distances. Although EVA and PU-1 had similar densities and comparable cushioning properties (as indicated by peak force), they differed in their energy recovery capabilities. In contrast, the two PU materials, which had different densities, demonstrated differing cushioning properties but similar levels of energy recovery (Wang et al., 2012). In the present study, a modified industry standard test was employed, utilising a different midsole material (ATPU) with lower densities in comparison to those used by Wang et al. (2012). However, the findings from both studies indicate that the density of the midsole significantly influences its mechanical properties. This supports the idea that adjusting the density of the midsole's foam can enhance cushioning (Shimazaki et al., 2016), allowing the material to absorb and recover more energy (Burns & Joubert, 2024).

In vitro test results suggest a reduction in the magnitude of ground reaction forces experienced during the running gait cycle (Shorten & Mientjes, 2011). Manufacturers, athletic footwear companies, and researchers focus on modifying the material properties of the midsole to improve impact absorption (Hamill et al., 2011; Milani et al., 1997), specifically by delaying the time to the vertical peak impact force, thereby reducing loading rate (De Wit et al., 2000). Such modifications are important because both vertical peak impact force and loading rate have been associated with the repetitive overloading of the musculoskeletal system, which can lead to running-related injuries (Ceyssens et al., 2019).

However, *in vitro* findings do not frequently translate to what is observed during *in vivo* experimental trials (Aerts & De Clercq, 1993; Clarke et al., 1983; Hennig et al., 1993; Nigg et al., 1987; Shorten & Mientjes, 2011). Within the peer-reviewed literature there are non-conclusive findings regarding the influence of midsole cushioning on the reductions of impact (Nigg et al., 1987), associated loading (Kulmala et al., 2018), and running performance related metrics (Hoogkamer et al., 2018). This uncertainty underscores the importance of recognising that once the shoe is placed on the runners foot it becomes a dynamic and functional element (Bates et al., 1978). Therefore, it is critical to evaluate the midsole not only in controlled *in vitro* settings, but also under real-world *in vivo* conditions, as demonstrated in the present study.

6.2 *In Vivo*

6.2.1 Running Speed

Running speed is important to acknowledge because it directly influences parameters of gait (Weyand et al., 2010), whereby changes in speed affect force production, joint movements, and overall running performance (Farris & Sawicki, 2012). Prescribed running speeds for the *in vivo* experimental trials were 12, 14, and 16 km·h^{-1}. The results indicated that the pacing strategy was effective for both 12 and 14 km·h^{-1}, as there were no discrepancies between the prescribed speed and the actual speed achieved in each midsole density condition, and no further differences when comparing conditions at each speed. However, there was a difference between the prescribed speed and actual speed at 16 km·h^{-1}, with the actual speed falling short of the prescribed speed (high-ρ = 15.81; mid-ρ = 15.78 km·h^{-1}).

Nevertheless, the speeds recorded were not significantly different between the midsole density conditions.

Additionally, it has been noted that standardising overground running speed during multiple trials on a force plate can be challenging, with studies often permitting speed variations of ± 5 to 10% (Almonroeder & Benson, 2017; Riazati et al., 2019; Riley et al., 2008; Sinclair et al., 2013). In the present study, the CV % of speeds recorded at 1 Hz across each trial were consistently below these previously mentioned thresholds. Specifically, the mean ± SD CV % for both high-ρ and mid-ρ midsoles across at speeds of 12, 14, and 16 km·h^{-1} were all under 2.5%. Therefore, it can be concluded that speed was effectively maintained throughout all *in vivo* experimental trials.

6.2.2 Spatiotemporal Variables

The *in vivo* experimental trials were completed at three different speeds on a 360 m stretch of road surfaced with tarmacadam, enabling parameters of gait to be collected during real-world overground road running. The use of pressure-sensitive insoles enabled the evaluation of multiple and successive impact cycles (Verdejo & Mills, 2004), resulting in participants taking between 96 and 127 right steps on average, with the number of steps significantly decreasing as running speed increased. Traditionally, the most widely used approach for data collection of overground running requires participants to run over a force plate while simultaneously being filmed (Riazati et al., 2019). However, this only allows for the measurement of a single stride (Bazett-Jones et al., 2013; Brown et al., 2014; Brown et al., 2016), whereby a large majority of biomechanical studies draw scientific conclusions based on ten or fewer steps (Oliveira & Pirscoveanu, 2021). Consequently, it has been suggested that the number of ground contacts collected during an experiment may influence the results (Bates et al., 1983). Collecting at least 25 steps from each participant is recommended to increase the likelihood of achieving data stability and validity across different running biomechanical variables (Oliveira & Pirscoveanu, 2021). Furthermore, 20 consecutive steps are required to be 95% confident of stable joint angles regardless of the plane of motion, running speed, or time of capture (Riazati et al., 2019). In contrast, Belli et al. (1995) recommended that 32 – 64 consecutive steps are needed to obtain an acceptable measure of variability for gait parameters. Others have suggested that research practices should use trials lasting a minimum of four minutes (Burns & Joubert, 2024), with data averaged over the last one to two minutes (Saunders et al., 2004). It is also important to account for acceleration and deceleration speed zones to ensure steps used for analysis are performed at a constant speed (Melvin et al., 2014). Therefore, the multiple and successive steps analysed in this study exceeded previous recommendations and were collected at controlled speeds with minimal variation.

As expected, and consistent with prior research, increasing running speed had a significant main effect on the spatiotemporal parameters of gait. Specifically, increasing speed from 12 to 16 km·h^{-1} resulted in an increase in stride frequency and swing time, due to decreased stride durations and ground contact times (Cavanagh, 1987; Mero & Komi, 1986; Morin et al., 2007). Such adaptations to the gait cycle enable a rapid leg turnover through angular acceleration of the lower limb joints, while reducing time spent in the stance phase of gait (Cavagna et al., 1988; Cavagna et al., 1991; Hunter et al., 2004; Kaneko, 1990; Salo et al., 2011; Weyand et al., 2000). This is essential when running speed increases (Pink et al., 1994), resulting in shorter ground contact times and a greater application of propulsive forces (Derrick et al., 1998; Frederick & Hagy, 1986; Mercer et al., 2005; Mercer et al., 2002; Weyand et al., 2010; Weyand et al., 2000). Applying more force in the opposition to gravity enables runners to reach faster speeds (Weyand et al., 2000) by increasing the vertical velocity at toe-off, thereby increasing both swing time and the distance travelled between steps (Weyand et al., 2000). As such, swing time increases as a result of diminished stance time (Dugan & Bhat, 2005; Mann & Hagy, 1980; Pink et al., 1994), requiring the leg to move quicker to achieve the necessary ground clearance and forward momentum at faster running speeds (Dugan & Bhat, 2005). In the present study, a significant main effect of speed on swing time was observed; however, post-hoc testing revealed significance only between 12 and 14 km·h^{-1}. It has been suggested that swing time can converge among runners as speed increases (Weyand et al., 2000). Therefore, to achieve higher speeds, runners apply more force to the ground, specifically within a speed range of 2 -7 m·s^{-1}, thereby generating greater ground reaction forces, enabling a longer stride (Hamner & Delp, 2013; Mercer et al., 2005; Schache et al., 2014). This allows runners to achieve the swing times necessary to reposition their legs during the swing phase of the gait cycle (Weyand et al., 2000).

The high-ρ and mid-ρ midsoles did not present a significant main effect of midsole density or a significant interaction on the number of steps taken by participants. Consequently, the spatiotemporal parameters of running gait also presented no significant main effects of midsole density or significant interactions. This supports previous studies that reported no changes in stride duration (Macdermid et al., 2025; Meardon et al., 2018), or stance time (Meardon et al., 2018) as a result of midsole cushioning; when participants were required to run on a treadmill with pressure-sensitive insoles (Macdermid et al., 2025) or over a force plate (Meardon et al., 2018). It was assumed that participants' techniques were unaltered between the different midsole conditions, however, these findings could be constrained by the narrow range of speeds examined (2.78 – 3.89 $m \cdot s^{-1}$). The present study does not corroborate earlier findings suggesting that midsoles with enhanced energy recovery properties directly influence stride frequency or ground contact times (Flores et al., 2019; Hoogkamer et al., 2018). There was a significant difference in energy recovered between the high-ρ and mid-ρ midsoles ($p < 0.0001$); however, this did not significantly influence the spatiotemporal parameters of running gait. This suggests that the midsole with greater energy recovery did not require additional time to recover during the propulsive phase. The method used to assess energy recovery was consistent with Hoogkamer et al. (2018) and Flores et al. (2019), which involved calculating the area under the unloading curve of the force-displacement hysteresis curve. However, the rate at which force was applied in the present study was considerably lower, which may have influenced the absolute values obtained. Additionally, no effect of midsole cushioning was observed on swing time, aligning with previous treadmill-based studies (Macdermid et al., 2025; Malisoux et al., 2021). Collectively, these findings suggest that participants maintained consistent running mechanics regardless of the midsole density condition, supporting the preferred movement path paradigm (Nigg et al., 2017)

6.2.3 Kinetic Variables

Understanding strategies to attenuate impact-related metrics is critical, especially as runners increase their speed (Arampatzis et al., 1999). As hypothesised, increases in running speed significantly increased vertical peak impact force and average loading rate, with post-hoc testing indicating significance between all speeds for both gait parameters. Previous research has consistently shown that ground reaction forces during the absorption phase of gait increase in magnitude as running speed increases (Brughelli et al., 2011; Nilsson & Thorstensson, 1987). This increase occurs due to no change in body mass or segment dimensions, but rather the result of greater lower limb segment acceleration upon ground contact (Dixon et al., 2000; Schache et al., 2014). Although the present study examined a narrower range of running speeds, the findings are consistent with earlier work by Nigg et al. (1987), who demonstrated a linear increase in vertical peak impact force across 1 $m{\cdot}s^{-1}$ speed increments between 3 and 6 $m{\cdot}s^{-1}$, with forces rising from 1.33 to 2.17 kN. Similar findings have shown a strong correlation between vertical peak impact force and running speed, with a correlation coefficient of $r = 0.81$ ($p < 0.05$) for speeds ranging from 3.2 ± 0.3 to 6.4 ± 0.5 $m{\cdot}s^{-1}$ (Mercer et al., 2002). As running speed increases, there is a concomitant rise in vertical peak impact force and average loading rate, indicative of rapid force application. This increase in force is also associated with significantly shorter ground contact times at elevated speeds (Nummela et al., 2007).

The kinetic gait parameter associated with propulsion, peak active force, exhibited a significant increase with escalating running speeds, with post-hoc analyses confirming significant differences across all speed conditions. As running speed increases, greater force production is requisite during the propulsive phase; however, this occurs with a reduced ground contact time, as evidenced in both this study and previous research (Derrick et al., 1998; Frederick & Hagy, 1986; Mercer et al., 2005; Mercer et al., 2002; Weyand et al., 2010; Weyand et al., 2000). Force production is the product of mass and acceleration, and despite these demands, swing time did not show significant differences between 12 vs. 16 or 14 vs. 16 $km{\cdot}h^{-1}$. This would indicate that increases in speed are more closely related to how effectively and rapidly force can be applied during ground contact, rather than the time that the swing leg spends in the air (Weyand et al., 2000). Furthermore, vertical impulse demonstrated a significant main effect of speed, with post-hoc comparisons revealing significant differences between 12 vs. 16 and 14 vs. 16 km·h^{-1}. These findings align with previous research reporting reductions in vertical impulse at faster running speeds (Dorn et al., 2012; Macdermid et al., 2025; Nummela et al., 2007; Weyand et al., 2010; Weyand et al., 2000), despite concurrent increases in overall ground reaction forces. As running speed increases, the shape of the ground reaction force trace typically changes. It is characterised by a shorter ground contact time and corresponding rise in amplitude and steepness, which corresponds to a greater loading rate. Decreases in vertical impulse at faster speeds have been attributed to reduction in ground contact time that outweighs the increase in effective force applied to the ground (Weyand et al., 2000).

The primary aim of the midsole is to facilitate energy absorption (Sun et al., 2020; Zhang et al., 2022), while recovering the maximum amount of energy (Aimar et al., 2024; Shorten, 1993), thereby acting as a fundamental element in managing the amplitude of ground reaction forces that are experienced throughout the running gait cycle (Aerts & De Clercq, 1993; Nigg et al., 1995). It was hypothesised that parameters of running gait related to ground reaction force within the absorption phase, vertical peak impact force and average loading rate, would be reduced in the midsole with a lower density. These particular parameters of gait have been demonstrated to play a role in the development of running-related injuries (Davis et al., 2016), with decreases in these variables linked to a reduced incidence (Law et al., 2019). Currently, there is no standardised classification for midsole cushioning; however, it is plausible that vertical peak impact force and associated loading rate would decrease in a midsole deemed to have greater cushioning capability (Shorten & Mientjes, 2011). However, no significant main effects of midsole density or significant interactions between speed and midsole density, were observed for vertical peak impact force or average loading rate. As neither of these variables experienced greater attenuation in the mid-ρ midsole, the hypothesis that vertical peak impact force and average loading rate would be reduced cannot be accepted.

The findings related to vertical peak impact force in the present study are consistent with prior research demonstrating that increased cushioning does not significantly reduce vertical peak impact forces when compared to less cushioned shoes (Clarke et al., 1983; De

Wit et al., 1995; Isherwood et al., 2024; Nigg et al., 1987; Shorten & Mientjes, 2011). These equivocal outcomes have been described as the ‘impact peak anomaly’ which suggests that the vertical impact peak force comprises two distinct components: a high-frequency ‘true’ impact load and a lower-frequency load (Shorten & Mientjes, 2011). This phenomenon has been attributed, in part, to limitations of using force plates to capture ground reaction forces reflecting whole-body acceleration, rather than forces acting specifically on the lower extremities (Shorten & Mientjes, 2011). As a result, the true impact-related component may be obscured due to the inclusion of both high-frequency and low-frequency loads, contributing to potential inaccuracies in quantifying the impact event itself (Shorten & Mientjes, 2011). In contract, studies using pressure-sensitive insoles, placed directly inside the shoe, have demonstrated that vertical peak impact force can be attenuated with increased midsole cushioning (Bergstra et al., 2015; Macdermid et al., 2025; Ogston, 2019). Pressure-sensitive insoles measure loads acting on the surface of the foot, rather than forces acting on the bottom of the shoe, as is the case with force plates (Dixon, 2008). This approach enables a more direct assessment of the midsole’s absorption capabilities across consecutive impact cycles (Verdejo & Mills, 2004), particularly in environments that support natural overground running mechanics. It also highlights the critical role of measurement methodology when evaluating parameters of running gait and midsole function. The present study found no significant differences in ground reaction forces between midsole densities during overground running trials across different speeds. In contrast, studies reporting significant effects using pressure-sensitive insoles often conducted data collection in constrained environments, such as on treadmills (Macdermid et al., 2025; Ogston, 2019), or overground along a short 22 m runway (Bergstra et al., 2015), and typically examined narrower speed ranges (2.78 to 3.89 $m \cdot s^{-1}$). These differences in experimental setup may partly explain the discrepancies between findings.

Furthermore, loading rate has been proposed to decrease with increased midsole cushioning, as greater cushioning disperses the impact force over a longer period of time (Reinschmidt & Nigg, 2000). However, in the present study, the average loading rate was not significantly attenuated, supporting previous research that reported no significant differences in vertical average (Malisoux et al., 2021; Play et al., 2024), instantaneous (Malisoux et al., 2021) or maximal loading rate (Nigg et al., 1987) across different cushioning conditions. In contrast, maximal loading rate has been demonstrated to significantly reduce with increased cushioning. For example, Isherwood et al. (2021) reported that a difference of 0.66 *g* in mechanical peak impact acceleration between shoe conditions significantly reduced maximal loading rates when data were collected across eight right foot strikes on a 145 m concrete loop. Subjective perceptions of comfort may also play a role, as runners have previously indicated that impacts feel softer in more cushioned shoes (Milani et al., 1997; Sterzing et al., 2013). Consequently, when data is collected from a small number of non-consecutive steps, participants may unconsciously alter their running technique based on perceived comfort. The present study mitigated this risk by averaging ground reaction force data across 96 to 127 right steps per trial, reducing the likelihood of conscious or unconscious adaptations, especially under the added distraction of a pacing cyclist. Supporting this, Macdermid et al. (2025) demonstrated that the average loading rate was lower in a cushioned shoe compared to a minimalist shoe when tested on a treadmill at speeds of 2.78 and 3.89 $m \cdot s^{-1}$ using pressure-sensitive insoles. However, this effect may have been influenced by the geometric differences between shoe conditions and the substantial energy absorption difference, where the cushioned shoe absorbed 690% more energy than the non-cushioned counterpart (Macdermid et al., 2025). Conversely, Huang (2019) found that midsoles with the lowest density (0.035 $g \cdot cm^{-3}$) produced the greatest maximum loading rate. This was attributed to the earlier occurrence of the first vertical peak force, resulting in a more rapid application of force over time (Huang, 2019).

The kinetic parameter of gait related to propulsion, peak active force, did not present a significant main effect of midsole density, or a significant interaction between speed and midsole density. While energy recovery during *in vitro* testing was significantly greater in the mid-ρ compared to the high-ρ midsole, this difference was not sufficient enough to significantly influence the propulsive phase. Previous research has indicated that the magnitude of peak active force increases with a more cushioned shoe (Clarke et al., 1983; Hoogkamer et al., 2018). This could potentially be attributed to the energy recovery occurring at the wrong time, or at the incorrect frequency (Nigg et al., 2000), requiring the runner to work harder by applying more force to the ground, in order to compensate for the energy being dissipated inefficiently, compromising the ultimate influence of improving performance (Stefanyshyn & Nigg, 2000). Conversely, others have observed no main effect of midsole cushioning on peak active force (Isherwood et al., 2021; Macdermid et al., 2025; Malisoux et al., 2021; Shorten & Mientjes, 2011), with findings attributed to the vertical oscillation of the centre of mass being unaffected, reflected through no change in vertical impulse (Clarke et al., 1983; Flores et al., 2019; Macdermid et al., 2025; Malisoux et al., 2021). Such findings were observed in the present study, where impulse presented no significant main effect of midsole density, or significant interaction. While running speed had a significant main effect on the spatiotemporal and kinetic variables of gait, there was no interaction with midsole density. This suggests that a greater level of material difference may be required to cause a noticeable interaction with the tested running speeds. It could also be speculated that participants adapted their movement patterns to compensate for the small variation in midsole cushioning (Hardin et al., 2004). This may occur through changes in the perceived load on the foot, shifting the focus from internal to external sensations (Nigg et al., 1987), modulating sensory feedback, and altering neuromuscular control mechanisms (Alfuth & Rosenbaum, 2012).

The cyclic motion of the running gait cycle means that identical spatiotemporal, kinetic, and kinematic movements are unlikely due to intrinsic and extrinsic factors (Bartlett et al., 2007; Preatoni et al., 2013). Feedback and feedforward control mechanisms influence parameters of gait, enabling both reactive and anticipatory adjustments to a runner's movements, influencing muscle activation and overall movement patterns (Khajooei et al., 2024). These adjustments commonly occurs prior to the foot making initial contact with the ground (Nigg, 2001), allowing the runner to pre-emptively adapt to extrinsic factors such as the running surface (Moore, 2016). As such, the variability of impact-related metrics experienced during overground running, where speed and terrain undergo continual changes, may potentially be amplified compared to more controlled conditions imposed by a treadmill (Hanley & Mohan, 2014). However, all 16 participants who completed the *in vivo* experimental trials ran at controlled speeds, with no significant differences between the high-ρ and mid-ρ midsoles at 12, 14, or 16 km·h^{-1} on the same tarmacadam surface. The CV % for vertical peak impact force presented more variation compared to other kinetic variables, but there was no main effect of speed, nor was there a speed and midsole density interaction. However, there was a significant main effect of midsole density, where greater variation was highlighted in the high-ρ midsole, but post-hoc testing did not identify significance between the midsoles. Further, the CV % for average loading rate was considerably higher than any other kinetic variable, presenting a significant speed and midsole density interaction and a main effect of midsole density. Greater variation was highlighted in the high-ρ midsole at speeds of 12 and 16 km·h^{-1}, however, there was no main effect of speed, and post-hoc testing presented no difference between the mid-ρ or high-ρ midsoles. Within the gait cycle, vertical peak impact force occurs early during initial contact and is associated with a time period that is too fast for reactive neuromuscular control (Nigg et al., 1981). Instead, it has been proposed that feedforward control influences joint positioning prior to foot strike (Nigg, 2001), as well as the deformation of passive structures during impact (Challis & Pain, 2008). Therefore, variability occurs due to natural fluctuations in how a runner adjusts their movement patterns before the foot makes initial contact with the ground, as a result of feedforward control, and is commonly observed across different shoe cushioning conditions (Addison & Lieberman, 2015; Chambon et al., 2014; Hardin et al., 2004; Squadrone & Gallozzi, 2009). These variations are not random errors, but rather a reflection of the body's adaptable strategies to maintain and optimise running performance (Hafer et al., 2019). An additional explanation for the variability observed between steps may be that differences in foot placement of the running surface result in varying impact forces (Thomas & Derrick, 2003). Unfortunately, it was not possible to identify which specific steps involved atypical foot-ground contact with the tarmacadam surface. Nevertheless, the absence of significant differences in the CV % for spatiotemporal parameters of gait is a favourable finding. This consistency enhances confidence in the interpretation of kinetic data, as excessive variability in step mechanics has previously been shown to obscure and confound kinetic outcomes (Derrick et al., 1998; Thomas & Derrick, 2003).

Subtle variations in running gait may be beneficial by dispersing impact forces through musculoskeletal structures and increasing tissue adaptation (Nordin & Dufek, 2019). Variability can also reflect the capacity of the neuromuscular system to adjust and control parameters of running gait (Harbourne & Stergiou, 2009). Therefore, the greater CV % in the high-ρ midsole for vertical peak impact force at all running speeds and average loading rate at 12 and 16 km·h^{-1} could be attributed to the reduction in midsole cushioning. This reduction likely causes greater variability in force distribution across successive steps (Cavanagh & Lafortune, 1980), leading to increased force transmission (Dugan & Bhat, 2005).

However, other researchers propose that greater variability or changes in running gait mechanics could indicate underlying issues (Iqbal & Chow, 2025; Nordin & Dufek, 2019). For instance, a lower CV % suggests consistency and predictability in how the body manages impact forces during each stride (Godin et al., 2024). Thereby, the mid-ρ midsole, which exhibited less variation, may indicate better efficiency in absorbing impact forces, contributing to an increased stability over repeated impact cycles (Kyröläinen et al., 1995).

6.2.4 Joint Kinematics

Joint kinematic data were collected simultaneously to elucidate changes in spatiotemporal and/or kinetic parameters, given that only one study has related kinetic findings and shoe cushioning to alterations in kinematic variables (Baltich et al., 2015). Running speed had a significant main effect on all joint kinematic variables, except for stance phase knee flexion and extension, and stance phase dorsiflexion. Faster running speeds are achieved with increases in hip, knee and ankle joint flexion-extension ranges of motion (Nilsson et al., 1985). The demands placed on the musculoskeletal system at higher speeds increase, causing joint kinematics to be adapted in response to the ground reaction forces experienced throughout the running gait cycle (McNair & Marshall, 1994). This is reflective of real-world running, where speed is susceptible to variation as the body segments accelerate and decelerate with each foot fall (Lee & Farley, 1998), even when running at a controlled speed (Abbiss & Laursen, 2008). Furthermore, running speed had a significant main effect on the CV % for the following joint kinematics: stance phase knee flexion and extension, swing phase knee flexion and extension, stance phase dorsiflexion, stance phase plantarflexion, and stance phase hip flexion. However, the variation observed within each individual variable was very similar. Stance phase knee extension CV % presented a significant speed and midsole density interaction, but no main effect of midsole density.

From an angular perspective, no significant main effects of midsole density or significant interactions were observed for any joint kinematic variable. This leads to the plausible assumption that participants' techniques remained relatively unchanged between the high-ρ and mid-ρ midsoles, supporting the preferred movement path paradigm (Nigg, 2001; Nigg, 2010; Nigg et al., 2017), where it is suggested that the magnitude of joint motion may fluctuate, but the trajectory is stable (Agresta et al., 2022). However, this paradigm is still in the early stages of research and currently there are no standardised or common clinical tests to assess variability of or deviation from an individuals preferred movement path (Agresta et al., 2022). As such, the type of biomechanical variability, and its expected response needs to be clarified when assessing a runner's response to footwear.

The joint kinematic findings in this study disagree with previous research, where vertical peak impact force increased as the midsole cushioning increased, leading to greater ankle and knee joint stiffness (Baltich et al., 2015). To maintain effective movement control with a more cushioned midsole, greater joint stiffness may be necessary. This increased stiffness could result in a greater decelerated mass upon impact, potentially explaining the increased vertical impact peak observed in the soft midsole (Baltich et al., 2015). It has also been demonstrated that changes in midsole hardness and peak impact acceleration can affect lower limb kinematics (Milani et al., 1997; Nigg et al., 2012). However, the footwear conditions used in those studies often involved greater variations in midsole properties, which may have contributed to the observed kinematic differences. In the present study, the absence of change in joint kinematics between the midsoles does not adequately account for the lack of significant differences observed in the spatiotemporal or kinetic variables.

Stance phase knee flexion is an important variable as this is where the energy is being absorbed by the musculoskeletal system, allowing the runner to dissipate impact more readily (Souza, 2016). Previous research has shown that midsole cushioning enables individuals to run with straighter legs (less knee flexion), thereby reducing muscular effort (Kerdok et al., 2002; McMahon et al., 1987). The findings in the present study suggest that the cushioning differences between the tested midsoles were insufficient to alter habitual gait mechanics. This is supported by findings from Aminaka et al. (2018) who also observed no joint kinematic differences at the knee or ankle joints at initial contact or active peak ($p > 0.05$), in a highly cushioned and control shoe. Similarly, Isherwood et al. (2021) reported no changes in lower limb kinematics when participants ran on a concrete loop with mechanically distinct midsoles. These findings collectively suggest that a threshold level of material contrast may be necessary to provoke detectable changes in joint kinematics, which help explain differences in spatiotemporal and/or kinetic outcomes. Additionally, methodological differences, such as continuous versus discontinuous data collection, may influence the sensitively of kinematic assessments. Continuous data collection may yield more stable and representative joint angle measures, potentially masking subtle differences between experimental shoe conditions (Isherwood et al., 2021).

Therefore, the ATPU foam materials that were different in density, produced significant differences during *in vitro* testing, where that the mid-ρ midsole absorbed and recovered more energy. However, *in vivo* trials during real-world overground running showed that these differences were not substantial enough to significantly influence parameters of running gait. These findings indicate the need for further research in this area.

6.3 Limitations

This study initially aimed to investigate three different midsole densities. However, as previously noted in the disclaimer, the low-ρ midsole could not be manufactured within the timeframe required to complete the thesis. As a result, data collection and analysis were limited to the high-ρ and mid-ρ midsoles. Although significant differences were observed in the two midsoles during *in vitro* testing, these differences did not translate into statistically significant effects during the *in vivo* experimental trials. This outcome suggests that a more pronounced contrast in material properties may be necessary to elicit measurable changes in parameters of running gait. It is plausible that inclusion of the unmanufactured low-ρ midsole could have yielded significant *in vivo* effects, particularly with regard to the ground reaction force metrics. According to manufacturer specifications, the density difference between the mid-ρ and low-ρ midsoles was a 42.9%, and between the high-ρ and low-ρ, 52.9%. The density of the shoes provided by the manufacturer was assumed to be correct; however, at the time of *in vitro* testing the shoes were not weighed. Knowing the weight of each shoe would have confirmed that the density was the same for each midsole following the foaming process. Furthermore, due to the change in study design, the research may have been underpowered. The original priori power calculation was based on the inclusion of distinctly different footwear conditions; however, the final analysis included only two midsoles with relatively modest density differences. While *in vitro* results confirmed material-level differences, the *in vivo* findings demonstrated that the midsoles functioned similarly, as no significant differences in running gait parameters were observed.

A modified industry standard mechanical test method was used to assess the capability of the midsoles, offering a general characterisation of the mechanical energy absorbed and recovered, in a direction relevant to the spring-mass dynamics of runners (McMahon & Cheng, 1990). However, considerable variability exists in the mechanical testing of running shoe midsole material properties. It has been suggested that test results are influenced by the impacting mass, along with the vertical velocity, and the area of contact at impact with the shoe (Nigg, 1990), failing to capture the wide range of forces and patterns of application that are experienced during real-world running (Mohammadi & Nourani, 2025; Nigg & Liu, 1999). Such factors should be taken into consideration, as they are vital to the stress placed on the midsole materials. Simulating running would require three-dimensional forces, along with the ability to manipulate the loading phase to impart pressure to various regions of the midsole (Hoogkamer et al., 2018). In the current study, mechanical testing was conducted at a slower rate than would typically occur during actual running, with loading applied only to the heel region. As such, ongoing modifications to standardised mechanical test protocols are necessary to better replicate loading rates and patterns associated with ground reaction forces during running.

Experimental trials were performed outdoors on a 360 m stretch of road surfaced with tarmacadam, reflective of real-world overground running. While this setting enhances ecological validity, it may have contributed to the variability observed in vertical peak impact force and average loading rate. Nonetheless, natural variability in running gait is well documented, particularly with respect to changes in foot strike patterns between steps (Thomas & Derrick, 2003), which are modulated by feedforward mechanisms that influence joint positioning prior to initial contact (Nigg, 2001). All participants ran on the same tarmacadam surface, with no differences observed between midsole densities at speeds of 12, 14, and 16 km·h^{-1}. Further, the length of road was sheltered from prevailing wind by a 15 m high evergreen hedge and environmental conditions were closely controlled, with no trials completed in the presence of headwinds, tailwinds, rain or if the tarmacadam surface was wet, as these conditions have previously been shown to affect the cushioning capabilities of the midsole (Cook et al., 1985). Completing experimental trials using this approach provides a more comprehensive investigation of the parameters of running gait, compared to discontinuous, single-step ground reaction force measurements, typically obtained with a force plate. However, results may be limited by the use of LoadSol® Pro-t insoles, determining total spatiotemporal and kinetic variables. The use of LoadSol® Pro-act would allow for anterior, central, and posterior parameters of gait to be obtained, providing valuable insights for identifying different loading patterns through the use of spatial analysis.

6.4 Future Research

Repeating this experimental protocol with all three midsole densities and incorporating LoadSol® Pro-act insoles would enable spatial analysis to be conducted, by distinguishing the specific foot regions through which force is transmitted. This approach would allow for a more nuanced understanding of foot-loading patterns during overground running. Furthermore, analyses incorporating both spatial and frequency domain components have demonstrated that the *in vivo* effects of running shoe cushioning on heel impact forces may correspond more closely with *in vitro* findings than previously assumed (Pańtak, 2020; Shorten & Mientjes, 2011). Such an approach would facilitate a more comprehensive examination of the biomechanical mechanisms underlying impact attenuation and enhance the ecological validity of midsole evaluations in real-world overground running conditions.

Future research should aim to determine the threshold of midsole density change required to elicit significant differences in both mechanical (*in vitro*) and biomechanical (*in vivo*) outcomes. Such investigations should explore whether alterations in midsole density can meaningfully influence parameters of gait linked to injury risk, while simultaneously enhancing running performance. To better replicate the forces experienced during real-world running, mechanical testing should incorporate a range of loads and loading rates applied to different regions of the shoe, that reflect typical ground reaction forces. These findings would not only benefit the end-user by promoting safer and more efficient footwear but also provide valuable insights for the research and development sector. Understanding the interaction between material properties and biomechanical responses can guide the innovation of running shoe midsoles, enabling manufacturers to innovate purpose-built cushioning systems that optimise running performance.

Chapter Seven – Conclusion

The purpose of this study was to investigate *in vitro* properties of ATPU foam, with varying densities integrated into geometrically identical running shoes, to assess the effects on *in vivo* parameters of running gait. These parameters included spatiotemporal, kinetic, and joint kinematic measures across different running speeds. Specifically, the study focused on how midsole cushioning properties influenced vertical peak impact force and average loading rate during real-world overground running.

The main findings of the study were that during *in vitro* testing the mid-ρ midsole absorbed and recovered significantly more energy than the high-ρ midsole. *In vivo* trials during real-world overground running, demonstrated that increases in running speed significantly influenced spatiotemporal, kinetic, and joint kinematic parameters of running gait. However, no significant main effects of midsole density or significant interactions were observed for vertical peak impact force, average loading rate, or any other parameter of running gait.

Hence, it can be concluded that although the ATPU foam materials differed in density and produced significant differences during *in vitro* testing when manufactured into midsoles, these differences were not substantial enough to elicit significant changes during the *in vivo* overground running trials. This suggests that a greater level of material difference may be required to produce observable changes in parameters of running gait. It is also that plausible runners adapt their movement patterns in response to variations of midsole cushioning by modulating perceived loading, shifting focus from internal to external sensory cues, and adjusting neuromuscular control mechanisms accordingly.

The practical implications of this study indicate that individuals may not experience changes in running performance solely due to subtle differences in midsole foam properties. Ultimately, a well-designed midsole should support natural movement patterns by facilitating energy absorption and recovery, thereby assisting with the attenuation of the ground reaction forces experienced throughout the running gait cycle. Future research should continue to investigate *in vitro* and *in vivo* interactions across a broader range of midsole densities, particularly in environments that replicate the demands of real-world overground running.

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Appendices

Appendix One: Information Sheet

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

School of Sport, Exercise & Nutrition
College of Health
Massey University
Tennent Drive
Palmerston North 4442

The Interaction Between Footwear Midsole Properties and Parameters of Running Gait Under Different Loads

Participant Information Form

Thank you for considering participation in this study, where the interaction between footwear midsole properties and parameters of running gait under different load is being investigated.

Why are we doing this?

Running is an increasingly popular exercise worldwide for both females and males, offering huge health benefits, where shoe technology has become a multi-billion-dollar business. Over time, the shoe industry has evolved and responded to needs by developing specialised shoes to include cushioning, motion control, and stability to cater for individual needs. The shoes midsole plays a critical role in managing impact force. The midsole is the part of the shoe under the foot, and it can be made of the variety of different materials using polymer compounds. This part of the shoe is important because it helps absorb shock when the foot touches the ground. The midsole also gives some of the energy back to the runner to assist with propulsion.

However, there is very little research concerning how changes to the polymer compound of the midsole affects a shoe's mechanical properties and how this relates to running biomechanics. Therefore, this study aims to assess different polymer compound midsole properties and the influence that these have on mechanical testing and running biomechanics.

Who's the research team?

Researcher: Stephanie Walker – Masters Student (School of Sport, Exercise and Nutrition, Massey University), [redacted]; [redacted]

Supervisor: Dr. Paul Macdermid (School of Sport, Exercise and Nutrition, Massey University) (06) 9516824; P.W.macdermid@massey.ac.nz

Supervisor: Associate Professor Darryl Cochrane (School of Sport, Exercise and Nutrition, Massey University), (06) 9517532; D.Cochrane@massey.ac.nz

Who can participate?

You will be one of sixteen trained runners to participate in running biomechanical testing for this study. You will undergo health screening for any medical conditions that may prevent you from taking part in this study. You need to be injury-free to participate in this study and have not sustained any lower limb injuries in the last two months that have prevented you from participating in usual running training.

You will required to fit the pair of test shoes and run at speeds of 10, 12, 14, and 16 km/hr, equivalent to 6, 5, 4:17, and 3:45 min/km, respectively. Each of the these running speeds will be completed in 360 m intervals.

What's involved?

Running biomechanical testing:

On arrival at the Dairy Farm Road, Massey University, Palmerston North, you will complete anthropometric measurements, including height, weight, and age. Force sensor insoles will then be placed into a pair of testing shoes and calibrated based on your body weight. You will then complete a 720 m familiarisation warm-up at 10 km/hr, on tarmacadam. A pacer bike will assist you in ensuring the correct running pace. You will then complete an incremental running speed protocol, consisting of 360 m stages at speeds of 12, 14, and 16 km/hr, returning to the starting point at 10 km/hr after each interval. The pacer bike will continue to assist you in ensuring the correct running pace. You will have a 5-minute rest to change shoes and recalibrate insoles before completing the trial again in the other pair of shoes. All tests will be performed in a counter-balanced order of shoe conditions.

How long will it take?

You will need to schedule approximately 1 hour of time for the entire study.

Benefits of participating?

You will receive a digital summary of your results at the completion of this study. The overall findings will inform us of how changes to the polymer compound of the midsole affects a shoe's mechanical properties and how this relates to running biomechanics.

The results from this study could help you to carefully chose your future athletic shoes in order to provide you with optimum protection, thus prolonging the duration of your physical exercise, which is beneficial in maintaining a healthy lifestyle. The results will also assist with the advancement of technical athletic footwear.

How's your data handled and stored?

Your information is kept private and secure according to Massey University procedures and policy of data collection and storage, that will entail data being stored on a secured network that is encrypted with a password. Other physical data sheets will be stored in a locked cabinet in Stephanie Walker's office. After 18 months, all data will be destroyed. If you choose to withdraw from this study, including after an injury, your data will be destroyed and deleted appropriately.

What are your rights as a participant?

Participation is voluntary. You have the right to choose not to answer questions, ask your own questions, and receive a summary of the findings. Additionally, you have the right to withdraw during the study and up to two weeks after data collection and your data will not be processed.

Compensation for Injury

If physical injury results from your participation in this study, you should visit a treatment provider to make a claim to ACC as soon as possible. ACC cover and entitlements are not automatic, and your claim will be assessed by ACC in accordance with the Accident Compensation Act 2001. If your claim is accepted, ACC must inform you of your entitlements and help you access those entitlements. Entitlements may include, but are not limited to, treatment costs, travel costs for rehabilitation, loss of earnings, and/or lump sums for permanent impairment. Compensation for mental trauma may also be included, but only if this is incurred because of physical injury.

If your ACC claim is not accepted, you should immediately contact the researcher. The researcher will initiate processes to ensure you receive compensation equivalent to that to which you would have been entitled had ACC accepted your claim.

Ethical Approval

This project has been reviewed and approved by the Massey University Human Ethics Ohu Matatika 1, Application OM1 24/44. If you have any concerns about the conduct of this research, please contact the Chairperson, Massey University Human Ethics Ohu Matatika 1, email humanethics1@massey.ac.nz.

Appendix Two: Health Screening Questionnaire

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

School of Sport, Exercise & Nutrition
College of Health
Massey University
Tennent Drive
Palmerston North 4442

The Interaction Between Footwear Midsole Properties and Parameters of Running Gait Under Different Loads

Health Screening Questionnaire

Name: ____

Address: ____

Phone: ________________________________

Age: ________________

Emergency contact

Name: ____

Phone: ________________________________

Please read the following questions carefully. If you have any difficulty, please advise the medical practitioner, nurse or exercise specialist who is conducting the exercise test.

Please answer all of the following questions by ticking only <u>one</u> box for each question:

The questions are based upon the Physical Activity Readiness Questionnaire (PAR-Q), originally devised by the British Columbia Dept of Health (Canada), as revised by [1]Thomas *et al.* (1992) and [2]Cardinal *et al.* (1996), and with added requirements of the Massey University Human Ethics Committee. The information provided by you on this form will be treated with the strictest confidentiality.

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Qu 1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

Yes ☐ No ☐

Qu 2. Do you feel a pain in your chest when you do physical activity?

Yes ☐ No ☐

Qu 3. In the past month have you had chest pain when you were not doing physical activity?

Yes ☐ No ☐

Qu 4. Do you lose your balance because of dizziness or do you ever lose consciousness?

Yes ☐ No ☐

Qu 5. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?

Yes ☐ No ☐

Qu 6. Do you take any other medication?

Yes ☐ No ☐

If yes, please state what the medication is for: ____

Qu 7. Have you had an injury that has prevented you from participating in physical activity within the last two months?

Yes ☐ No ☐

Qu 8. Have you been hospitalised recently?

Yes ☐ No ☐

Qu 9. Do you have a bone or joint problem (for example back, knee or hip) that could be made worse by a change in your physical activity?

Yes ☐ No ☐

Qu 10. Do you know of any other reason why you should not do physical activity?

Yes ☐ No ☐

Qu 11. Have any immediate family had heart problems prior to the age of 60?

Yes ☐ No ☐

Qu 12. What is average weekly running kilometres from the past two months? ______________________

I have read, understood and completed this questionnaire.

Signature ***(Participant):*** ____ Date: ___________________

References

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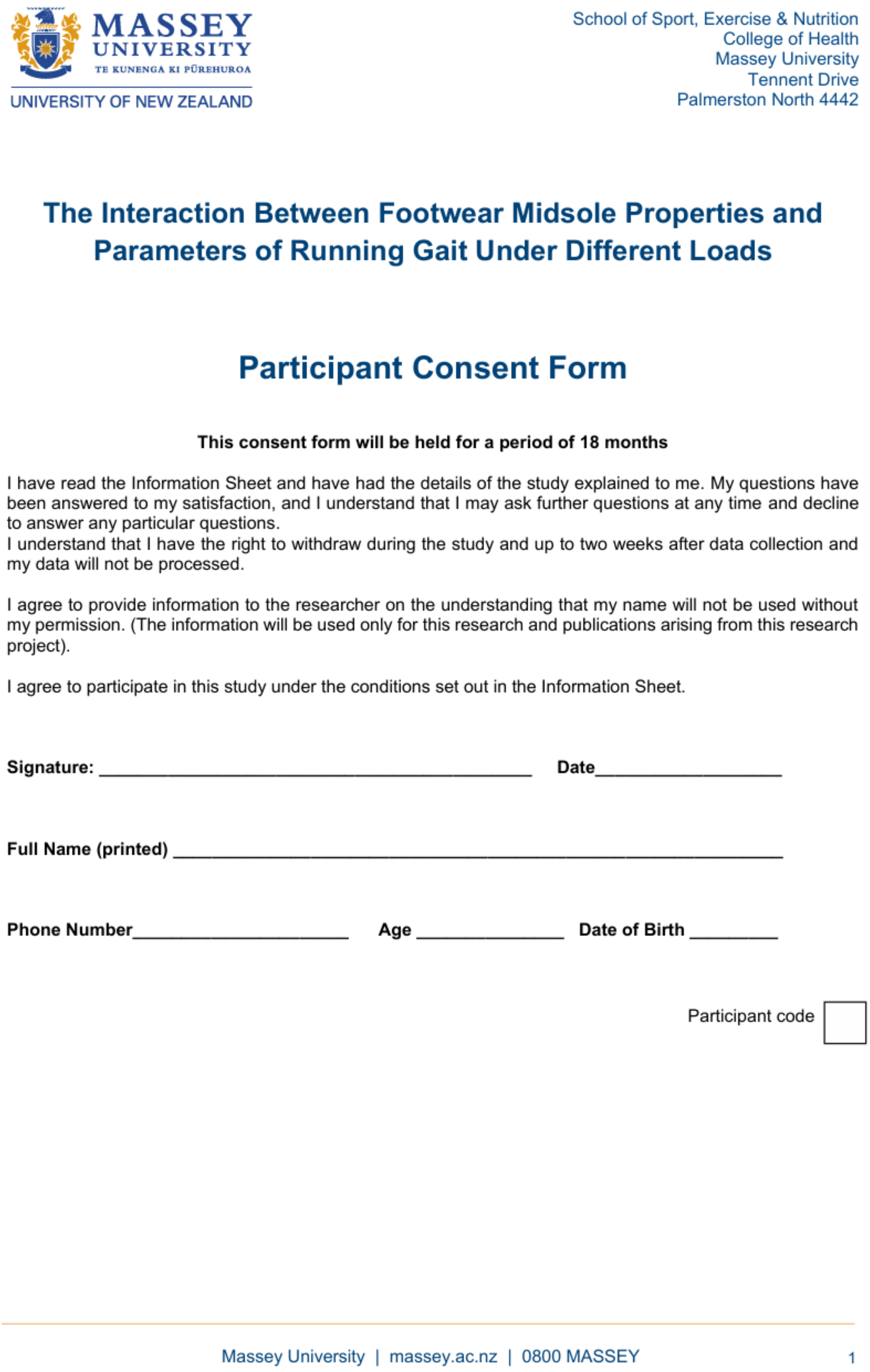
Appendix Three: Informed Consent



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Palmerston North 4442

The Interaction Between Footwear Midsole Properties and Parameters of Running Gait Under Different Loads

Participant Consent Form

This consent form will be held for a period of 18 months

I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time and decline to answer any particular questions.
I understand that I have the right to withdraw during the study and up to two weeks after data collection and my data will not be processed.

I agree to provide information to the researcher on the understanding that my name will not be used without my permission. (The information will be used only for this research and publications arising from this research project).

I agree to participate in this study under the conditions set out in the Information Sheet.

Signature: ________________________________ **Date**__________________

Full Name (printed) ____

Phone Number____________________ **Age** ______________ **Date of Birth** ________

Participant code ☐

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Appendix Four: Massey University Human Ethics Committee, Ohu Matatika 1, Application 24/44

MASSEY
UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

19/09/2024

Dear: Stephanie Walker

Re: Ethics Application - OM1 24/44 - The interaction between footwear midsole properties and parameters of running gait under different loads.

Thank you for the above application that was considered by the Massey University Human Ethics Committee:

Ohu Matatika 1 at their meeting held on **Tuesday, 13 August 2024**

On behalf of the Committee I am pleased to advise you that the ethics of your application are approved.

Approval is for three years. If this project has not been completed within three years from the date of this letter, reapproval must be requested.

If the nature, content, location, procedures or personnel of your approved application change, please advise the Secretary of the Committee.

Yours sincerely

Tracy Riley

Professor Tracy Riley,

Acting Chair, Research Ethics Chair's Committee

Research Ethics Office, Research and Enterprise

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