Investigating the Relationship Between Leg Strength and Running Kinematics in Healthy Novice Runners

Chanelle Sciberras

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Faculty of Sport and Health Science
University of Jyväskylä
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Supervisors: Prof Janne Avela and Heidi Jarske

ABSTRACT

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INTRODUCTION. Muscle weakness and biomechanical alterations have been recognized as risk factors for various running-related injuries (RRIs), fuelling a growing interest in understanding the relationship between strength and running biomechanics. While existing research has predominantly focused on the relationship between hip strength and kinematics, other potential associations remain largely unexplored. Moreover, many studies have employed isometric strength testing, which may not accurately reflect muscle function during running. Notably, there is a lack of research on novice runners, despite their heightened susceptibility to RRIs. Consequently, the purpose of this thesis is to investigate the association between lower-limb isokinetic strength and running kinematics in healthy novice runners.

METHODS. 10 male and 10 female novice runners participated in this study. 3D running kinematic data was collected using a marker-based motion capture system (Vicon). Peak isokinetic strength of the hip abductors and adductors, knee flexors and extensors, as well as the ankle plantarflexors, dorsiflexors, invertors and evertors was measured using an isokinetic dynamometer (Biodex System 4 Pro). Spearman correlation coefficients were used to determine the relationship between lower-limb isokinetic strength and stance phase running kinematics.

RESULTS. Isokinetic hip abductor strength was significantly correlated to frontal plane hip kinematics in male novice runners (toe-off angle: $r = -0.620$, $p = 0.004$; minimum angle: $r = -0.624$, $p = 0.003$), but no such correlations were found in females. Overall, the findings do not support the notion that isokinetic hip abduction strength is correlated with knee kinematics in healthy novice runners. Hip adduction strength was associated with several frontal plane ankle kinematics in both male (initial contact angle: $r = -0.650$, $p = 0.002$; toe-off angle: $r = -0.534$, $p = 0.015$; maximum angle: $r = -0.546$, $p = 0.013$; minimum angle: $r = -0.710$, $p =< 0.001$) and female novice runners (toe-off angle: $r = -0.710$, $p = <0.001$; minimum angle: $r = -0.517$, $p = 0.020$; range of motion (ROM): $r = 0.579$; $p = 0.007$). Additionally, knee flexion strength was associated with greater knee adduction in the male runners (initial contact angle: $r = 0.486$, $p = 0.030$; toe-off angle: $r = 0.571$, $p = 0.008$; maximum angle: $r = 0.564$, $p = 0.010$; minimum angle: $r = 0.459$, $p = 0.042$), as well as a larger peak knee flexion angle ($r = 0.617$, $p = 0.004$) and increased sagittal plane ankle ROM ($r = 0.465$, $p = 0.039$) in the female runners. Furthermore, concentric ankle strength exhibited several significant correlations with running kinematics at the hip, knee and ankle in novice runners.

DISCUSSION. Male and female novice runners displayed distinct associations between lower-limb strength and running kinematics. Several significant correlations were identified between lower-limb isokinetic strength and injury-related kinematic parameters. Additionally, the findings suggest that strengthening the muscles of the foot and ankle, which has been shown to reduce RRIs, may also impact joint mechanics higher up the kinematic chain. Further research is needed to validate these results and assess the efficacy of lower-limb strengthening in altering running kinematics and mitigating the risk of RRIs.

Keywords: novice runners, lower-limb strength, isokinetic testing, running kinematics, biomechanics

CONTENTS

ABBREVIATIONS

AFP_ic	Ankle Frontal Plane - angle at initial contact
AFP_max	Ankle Frontal Plane - maximum angle
AFP_min	Ankle Frontal Plane - minimum angle
AFP_rom	Ankle Frontal Plane - range of motion
AFP_tmax	Ankle Frontal Plane - timing of maximum angle
AFP_tmin	Ankle Frontal Plane - timing of minimum angle
AFP_to	Ankle Frontal Plane - angle at toe-off
ASP_ic	Ankle Sagittal Plane - angle at initial contact
ASP_max	Ankle Sagittal Plane - maximum angle
ASP_min	Ankle Sagittal Plane - minimum angle
ASP_rom	Ankle Sagittal Plane - range of motion
ASP_tmax	Ankle Sagittal Plane - timing of maximum angle
ASP_tmin	Ankle Sagittal Plane - timing of minimum angle
ASP_to	Ankle Sagittal Plane - angle at toe-off
ATP_ic	Ankle Transverse Plane - angle at initial contact
ATP_max	Ankle Transverse Plane - maximum angle
ATP_min	Ankle Transverse Plane - minimum angle
ATP_rom	Ankle Transverse Plane - range of motion
ATP_tmax	Ankle Transverse Plane - timing of maximum angle
ATP_tmin	Ankle Transverse Plane - timing of minimum angle
ATP_to	Ankle Transverse Plane - angle at toe-off
GRF	ground reaction force

HFP_ic	Hip Frontal Plane - angle at initial contact
HFP_max	Hip Frontal Plane - maximum angle
HFP_min	Hip Frontal Plane - minimum angle
HFP_rom	Hip Frontal Plane - range of motion
HFP_tmax	Hip Frontal Plane - timing of maximum angle
HFP_tmin	Hip Frontal Plane - timing of minimum angle
HFP_to	Hip Frontal Plane - angle at toe-off
HSP_ic	Hip Sagittal Plane - angle at initial contact
HSP_max	Hip Sagittal Plane - maximum angle
HSP_min	Hip Sagittal Plane - minimum angle
HSP_rom	Hip Sagittal Plane - range of motion
HSP_tmax	Hip Sagittal Plane - timing of maximum angle
HSP_tmin	Hip Sagittal Plane - timing of minimum angle
HSP_to	Hip Sagittal Plane - angle at toe-off
HTP_ic	Hip Transverse Plane - angle at initial contact
HTP_max	Hip Transverse Plane - maximum angle
HTP_min	Hip Transverse Plane - minimum angle
HTP_rom	Hip Transverse Plane - range of motion
HTP_tmax	Hip Transverse Plane - timing of maximum angle
HTP_tmin	Hip Transverse Plane - timing of minimum angle
HTP_to	Hip Transverse Plane - angle at toe-off
KFP_ic	Knee Frontal Plane - angle at initial contact
KFP_max	Knee Frontal Plane - maximum angle
KFP_min	Knee Frontal Plane - minimum angle

KFP_rom	Knee Frontal Plane - range of motion
KFP_tmax	Knee Frontal Plane - timing of maximum angle
KFP_tmin	Knee Frontal Plane - timing of minimum angle
KFP_to	Knee Frontal Plane - angle at toe-off
KSP_ic	Knee Sagittal Plane - angle at initial contact
KSP_max	Knee Sagittal Plane - maximum angle
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KSP_to	Knee Sagittal Plane - angle at toe-off
KTP_ic	Knee Transverse Plane - angle at initial contact
KTP_max	Knee Transverse Plane - maximum angle
KTP_min	Knee Transverse Plane - minimum angle
KTP_rom	Knee Transverse Plane - range of motion
KTP_tmax	Knee Transverse Plane - timing of maximum angle
KTP_tmin	Knee Transverse Plane - timing of minimum angle
KTP_to	Knee Transverse Plane - angle at toe-off
PT/BW	peak torque: body weight
ROM	range of motion
RRI	running-related injury

1. INTRODUCTION

Running is one of the most popular forms of physical activity, probably due to its low cost and accessibility. With an increasing awareness of the benefits associated with physical activity, the popularity of running is always on the rise. Unfortunately, increased participation in running has also led to an increased incidence of running-related injuries (RRIs). (Baltich et al., 2014; Ceyssens et al., 2019)

The reported incidence of RRIs spans a wide range, from 3% to 85%, with injury rates ranging from 2.5 to 33 injuries per 1000 hours of running (Kluitenberg et al., 2015; van Gent et al., 2007; Videbæk et al., 2015). The large variation in the reported incidence can be attributed to differences in studied populations, follow-up periods, and the diverse definitions of RRIs across studies (Ceyssens et al., 2019).

Given the high incidence of injury, it is of utmost importance to understand the etiological factors of RRIs. Identifying the risk factors associated with RRIs is crucial for the development of effective prevention strategies. Running injuries are complex and multifactorial, often involving the interplay of multiple contributing factors. Specific demographic and anthropometric characteristics, biomechanical factors, training variables, and prior injuries have all been previously linked to injury (Ceyssens et al., 2019; Moffit et al., 2020; Winter et al., 2020)

Muscle weakness and aberrant biomechanics have been identified as risk factors for RRIs. For example, greater peak hip adduction during running is a risk factor for patellofemoral pain syndrome in female recreational runners (Noehren et al., 2007) while decreased hip and knee muscle strength was associated with a higher incidence of anterior knee pain (Luedke et al., 2015).

The potential interrelation between strength and biomechanics has been a subject of speculation. Many injury prevention programs have focused on muscle strengthening with the notion that enhancing strength would decrease excessive joint movements and moments linked to injuries. Regrettably, only a limited number of studies have demonstrated a concurrent change in biomechanics with an increase in strength (Snyder et al., 2009; Willy & Davis, 2011). One plausible explanation for this discrepancy is that the selected exercises may not have been task-specific, hindering the transfer of any improvements gained from the intervention to running mechanics (Baltich et al., 2014).

Consequently, the relationship between lower-limb strength and running biomechanics has garnered significant attention throughout the past decade. The majority of studies have investigated the relationship between hip strength and running kinematics at the hip joint, with only a few exploring the connection between hip strength and kinematics at more distal joints. However, the findings across these studies are varied and inconclusive, possibly due to differences in running populations and methodologies utilised across studies. (Baggaley et al., 2015; Brindle et al., Brund et al., 2017; 2020; Foch et al., 2020; Moffit et al., 2020; Rodriguez et al., 2020; Schmitz et al., 2014; Taylor-Haas et al., 2014; Zeitoune et al., 2020)

There is a notable gap in the literature regarding studies investigating the relationship between ankle strength and running kinematics. A recent randomized controlled trial reported that a foot-core strengthening protocol was effective at decreasing RRIs 2.42-fold in recreational runners. Foot strength was significantly correlated with time to injury, meaning that the stronger the foot, the longer it took a runner to get injured. Additionally, statistically significant changes in several foot and ankle kinematic parameters were also reported. Notably, the study only measured mechanics at the foot and ankle, making it impossible to determine whether strengthening the foot and ankle also induced mechanical changes higher up the kinematic chain. (Matias et al., 2022; Taddei et al., 2020)

Despite the existing body of literature, most studies to date have tested muscle strength isometrically and failed to find any significant correlations between lower-limb strength and running kinematics. However, isokinetic measures of strength may be more suitable given the concentric and eccentric muscle actions during running.

The purpose of this study is to investigate the relationship between lower limb isokinetic strength and running kinematics in healthy novice runners. A marker-based optoelectronic system will be used to capture 3D lower-limb kinematics of novice runners. Isokinetic dynamometry will be utilized to measure lower-limb strength at the hip, knee, and ankle joints. This study aims to uncover novel associations between lower-limb strength and running kinematics. Additionally, this is the first study of its kind to focus on novice runners. The outcomes of this study are anticipated to contribute valuable data to the existing body of literature on novice runners and may even guide future running-related research.

2. BIOMECHANICS OF RUNNING

Running is the form of gait utilised to move at quicker speeds. At a speed of around 2.5 m/s, walking becomes very costly, such that one will generally alter his gait from walking to running (Blazevich, 2017). Various factors affect the biomechanics of running. Alterations in running kinematics and kinetics are seen with changes in running speed. It has also been reported that sex, running experience, running surfaces, footwear and the use of orthotics may influence running biomechanics. (Houglum, 2010; Zatsiorsky, 2000)

This chapter aims to describe the kinematics and kinetics of running. It will also highlight the differences in running biomechanics among varying populations of runners.

2.1 The Running Gait Cycle

The gait cycle is the standard unit of measurement in gait analysis. It begins when the foot first touches the ground (initial contact or footstrike) and ends when the same foot contacts the ground again. One complete gait cycle is called a stride. A step refers to the part of the gait cycle from initial contact (or toe-off) of one foot to the initial contact (or toe-off) of the other foot. (Novacheck, 1998)

Running consists of alternating sequences of support and non-support, referred to as stance and swing phase respectively. The phases of the running gait cycle are depicted in Figure 1. Stance phase starts at initial contact and ends at toe-off, just as the foot leaves the ground. In contrast, the swing phase begins at toe-off and ends at initial contact. The stance phase is divided into an absorption and a propulsion phase. Force absorption takes place within the first half of the stance phase, while the second half of stance is responsible for propulsion. (Dugan & Bhat, 2005; Enoka, 2008)

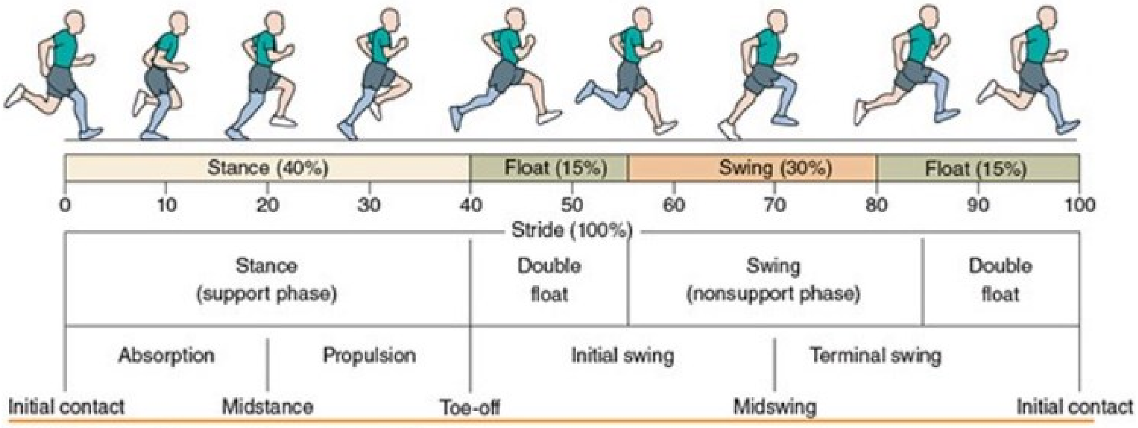


FIGURE 1. Phases of the running gait cycle. From Therapeutic Exercise for Musculoskeletal Injuries (4th ed., p.331), by P.A. Houglum, 2016, Human Kinetics. Copyright 2016 by Peggy A. Houglum.

Running differs from walking in many ways. It is characterized by an increased velocity, the presence of a flight phase, and the absence of a double support phase. The flight phase, also referred to as the airborne or the double float phase, refers to a period throughout the running cycle during which both feet are off the ground. During a running gait cycle, there are two instances during which neither leg is on the ground: at the very beginning and at the end of the swing phase. Consequently, the stance phase of running is shorter when compared to walking. As shown in Figure 2, as running speed increases, less time is spent in stance while swing time and double float phase are longer. Furthermore, cycle time shortens with an increase in speed. (Dugan & Bhat, 2005; Houglum, 2010; Novacheck, 1998 & Zatsiorsky, 2000)

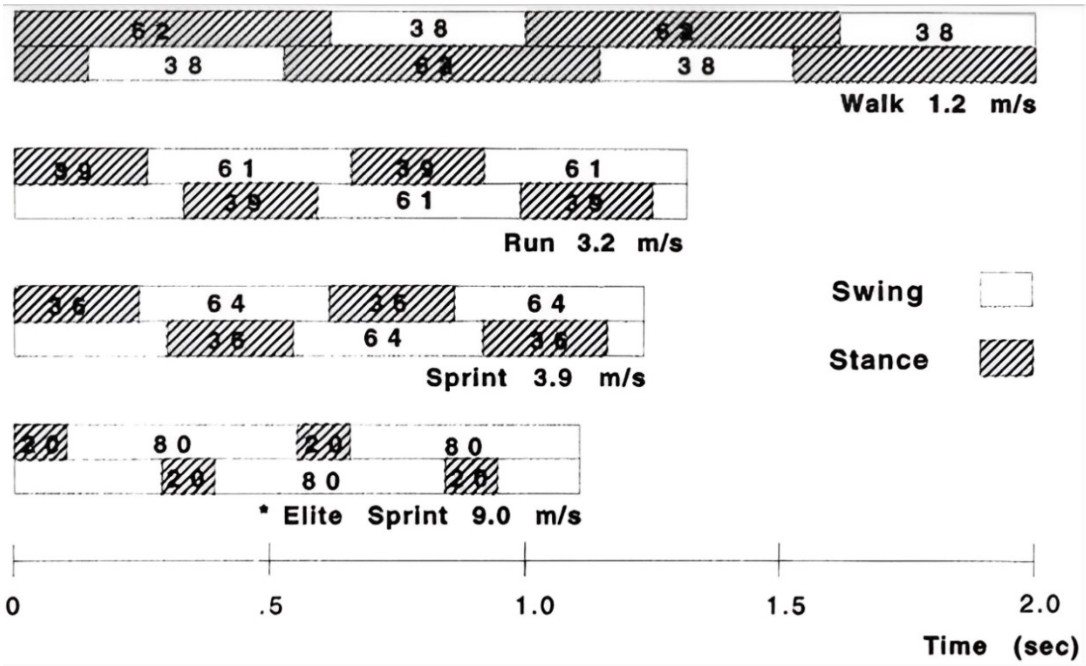


FIGURE 2. Variation in gait cycle parameters with speed of movement. From "The Biomechanics of Running" by T.F. Novacheck, 1998, Gait & posture, 7(1), 77–95. Copyright 1998 by Elsevier Science.

2.2 Joint Kinematics During Running

Kinematics refers to the description of bodies in motion without concern to the forces causing the movement (Novacheck, 1998). This section describes joint kinematics during running and highlights important differences between walking, running, and sprinting. Motion in all three planes will be considered.

2.2.1 Sagittal Plane Kinematics

As speed increases, the pelvis and trunk tilt forward. This lowers the body's centre of mass and maximizes the horizontal force produced during the propulsion phase. The pelvic tilt pattern of movement is similar between walking and running. With faster velocities, pelvic motion is only slightly increased in order to conserve and maintain energy. Pelvic kinematics are depicted in Figure 3 below. (Novacheck, 1998)

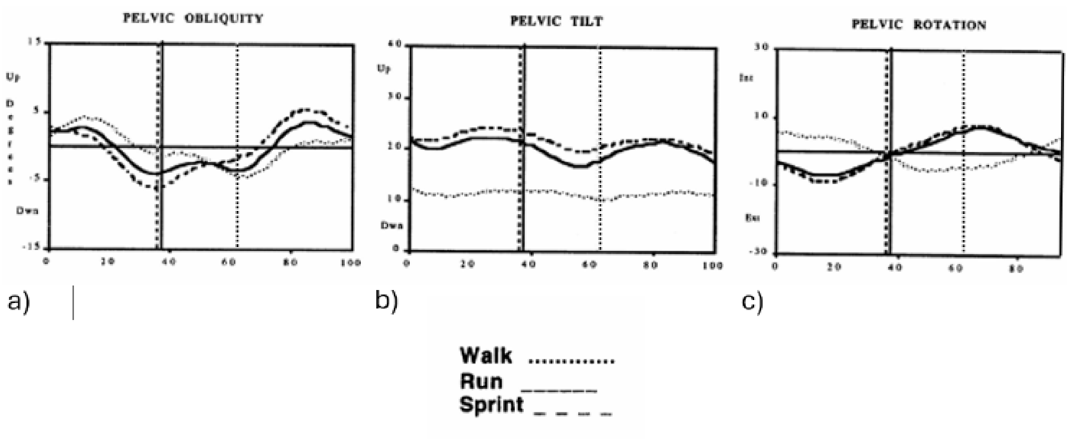


FIGURE 3. Pelvic kinematics in the a) frontal, b) sagittal, and c) transverse planes during walking, running, and sprinting. Adapted from “The Biomechanics of Running” by T.F. Novacheck, 1998, Gait & posture, 7(1), 77–95. Copyright 1998 by Elsevier Science.

The movement of the thigh is similar at different speeds. In sprinting, however, the hip never reaches full extension. Additionally, maximum hip extension during running occurs at toe-off while in walking this occurs slightly earlier (before toe-off). Hip extension occurs during the second half of the swing phase during running. This differs from walking and causes the runner to land with the foot closer to the body’s centre of mass, thus preventing excessive deceleration. As speed increases, maximum hip flexion also increases, which leads to a longer step length. (Novacheck, 1998)

While the pattern of knee motion is similar between walking, running, and sprinting, the extremes of knee range of motion (ROM) are very different. In running, the knee flexes up to approximately 45° during the absorption phase of stance. The knee is then extended up to around 25° during the propulsion phase. In sprinting, there is less knee flexion during the shorter absorption phase, but the knee extends further during the propulsion phase. (Novacheck, 1998)

Swing phase knee kinematics also vary at different speeds. Maximum knee flexion increases with an increase in speed and is around 60°, 90°, and 105°-130° in walking, running, and sprinting respectively. The greater knee flexion serves to reduce the leg moment of inertia, facilitating the movement of the leg onto the next foot strike. (Zatsiorsky, 2000)

Initial contact during walking and running occurs with the heel. As speed increases, the point of initial contact typically changes such that, in sprinting, the midfoot or forefoot is generally the point of initial contact. During walking, there is initial plantarflexion of the foot, as it is lowered to the ground. Conversely, in running and sprinting there is no plantarflexion after initial contact and the foot goes into dorsiflexion as the weight is transferred onto the stance leg. (Dugan & Bhat, 2005)

Maximum dorsiflexion during stance phase is lesser in sprinting than in running since the foot is relatively more plantarflexed at initial contact and the absorption phase is shorter. Maximum ankle plantarflexion is greater in sprinting than in running during the force generation period of stance. Additionally, as speed increases, maximum dorsiflexion and plantarflexion occur earlier within the gait cycle. Furthermore, ankle dorsiflexion during swing phase is reduced in sprinting when compared to running or walking. Since there is an increased amount of hip and knee flexion during sprinting, foot clearance is still achieved. (Novacheck, 1998)

The sagittal plane kinematics of the lower extremity during walking, running, and sprinting can be seen in Figure 4 below (Houglum, 2010).

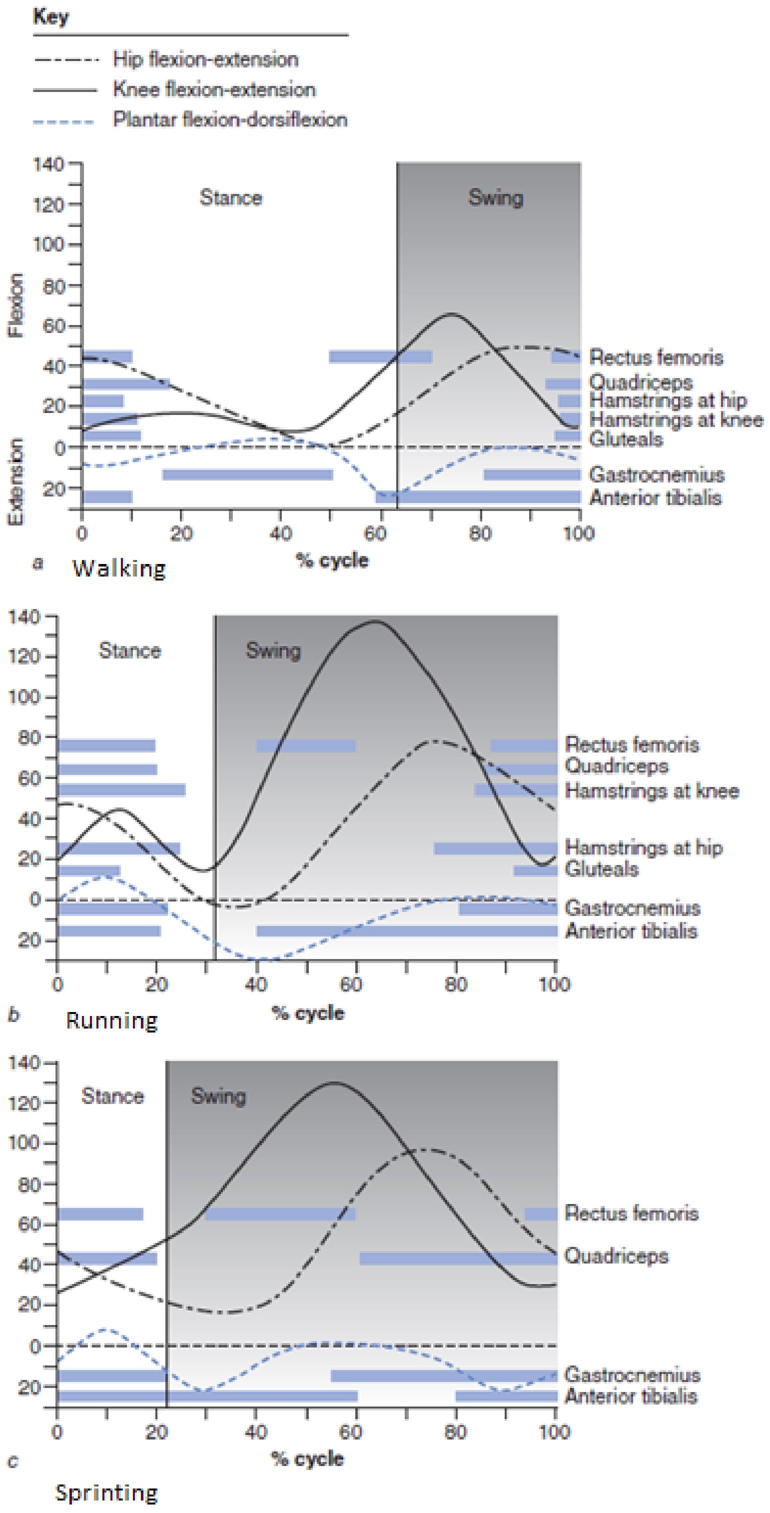


FIGURE 4. Hip, knee, and ankle sagittal plane kinematics and timing of muscle activity during gait when (a) walking, (b) running, and (c) sprinting. From Therapeutic Exercise for Musculoskeletal Injuries (3rd ed., p.373), by P.A. Houglum, 2010, Human Kinetics. Copyright 2010 by Peggy A. Houglum.

2.2.2 Frontal Plane Kinematics

Movement within the frontal plane is more subtle when compared to sagittal motion, but it plays an important role in minimizing upper body movement. Knee and ankle movement in the frontal plane is limited by the collateral ligaments, but significant motion occurs at the hip. As the limb is loaded, at the start of the stance phase, the pelvis remains relatively stationary while the hip goes into adduction. This serves as a shock absorption mechanism. Throughout the rest of the stance phase, the pelvis starts to drop until it reaches its maximum obliquity, at the start of the double float phase. At the beginning of the swing phase, the movement is reversed such that the pelvis elevates to achieve foot clearance. (Novacheck, 1998)

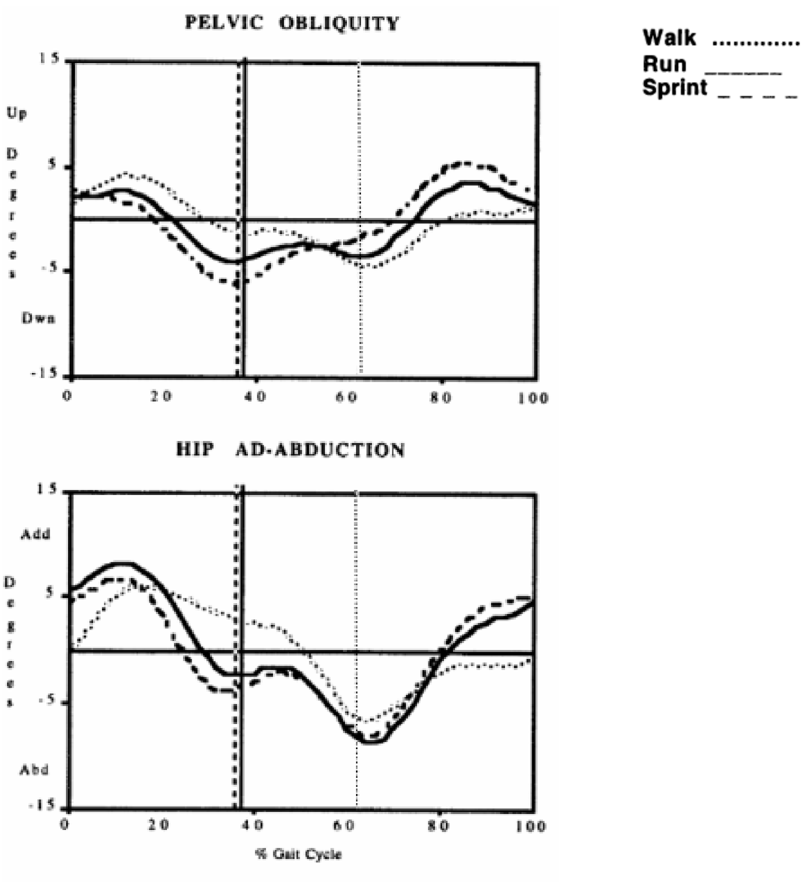


FIGURE 5 - Pelvic and hip frontal plane kinematics during walking, running, and sprinting. Adapted from "The Biomechanics of Running" by T.F. Novacheck, 1998, Gait & posture, 7(1), 77–95. Copyright 1998 by Elsevier Science.

In walking, running, and sprinting, the hip is generally adducted during the initial phase of stance and abducted during swing phase. Hip movement in the frontal plane mirrors pelvic movement (Figure 5). The almost reciprocal movement of the hip and pelvis acts to minimize shoulder and head movement. This acts to dissociate lower extremity movement from the movement of the upper extremity, minimizing trunk and head motion, which in turn, maintains balance and equilibrium. (Novacheck, 1998)

2.2.3 Transverse Plane Kinematics

Once again, movement in the transverse plane is much smaller in magnitude when compared to the sagittal plane. Pelvis function and motion during walking are very different from that during running or sprinting (refer to Figure 3). In walking, the pelvis is maximally rotated forward at initial contact. This allows for longer strides but results in decreased horizontal velocity. In running and sprinting there is maximum internal rotation during midswing to lengthen the stride but by initial contact, the pelvis is externally rotated. This maximizes horizontal propulsion force and minimizes loss of speed. During running and sprinting, the pelvis also acts as a pivot between the counter-rotating shoulders and lower limbs. (Novacheck, 1998)

Pronation of the foot occurs in the absorption phase of stance when the limb is being loaded. Supination occurs in the generation or propulsion phase of stance which provides a stable lever for push-off. Pronation and supination are tri-planar movements, involving multiple joints of the foot and ankle. During weight-bearing, pronation consists of ankle dorsiflexion, subtalar eversion, and forefoot abduction. On the contrary, supination refers to ankle plantarflexion, subtalar inversion, and forefoot adduction. (Dugan & Bhat, 2005; Novacheck, 1998)

2.3 Joint Kinetics During Running

Kinetics refers to the study of forces and moments causing movement of a body. The study of kinetics provides an understanding of the basic mechanisms of human movement. (Robertson et al., 2014) By combining kinematic data and ground reaction force (GRF) data, the inverse dynamics approach may be used to calculate net joint moments and powers (Novacheck, 1998).

2.3.1 Sagittal Plane Kinetics

The sagittal plane joint moments and powers are depicted in Figure 7 below. Throughout the first part of stance, from initial contact to foot flat, the tibialis anterior and gastrocnemius-soleus muscles co-contract to stabilize the foot at impact. During walking and running (rearfoot strikers), the tibialis anterior muscle acts eccentrically at initial contact to control the descent of the forefoot onto the ground. (Houglum, 2010) In sprinting, initial contact is on the forefoot followed by immediate dorsiflexion (Novacheck, 1998). Tibialis anterior contracts concentrically to accelerate the tibia over the fixed foot. This serves to maintain or increase running speed. The gastrocnemius-soleus muscles simultaneously act eccentrically to control the forward progression of the tibia over the foot. (Dugan & Bhat, 2005)

Joint motion, eccentric muscle contraction, and articular cartilage compression are important factors for impact absorption. Ankle dorsiflexion, as well as hip and knee flexion also contribute to dissipating the force of impact at footstrike. Total energy absorption increases with an increase in speed. The vertical GRF may reach up to 2.2 times bodyweight after footstrike during running compared to 1.1 times body weight during walking (Figure 6). (Dugan & Bhat, 2005)

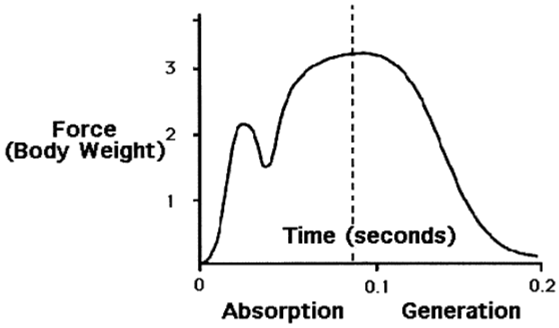


FIGURE 6. A typical vertical ground reaction force schematic of a rearfoot striker. From "The Biomechanics of Running" by T.F. Novacheck, 1998, Gait & posture, 7(1), 77–95.

The knee moment pattern is similar in running and sprinting. The hamstrings become dominant during the second half of swing, in preparation for initial contact. The knee flexor moment serves to control rapid knee extension. Soon after initial contact, the quadriceps take over, producing a knee extensor moment. The peak knee extensor moment is greater during running than sprinting since during running there is a greater degree of knee flexion as the limb is loaded. In running, eccentric quadriceps activity following initial contact plays an important role in shock absorption. Conversely, in sprinting, most of the shock absorption at impact is taken up by the ankle plantar flexors. (Novacheck, 1998)

During the second half of stance, the quadriceps work concentrically and generate power to contribute to the forward thrust of the body, as the foot pushes off the ground (Novacheck, 1998). At this point of stance, the vertical GRF reaches its maximum. During running, vertical GRF may reach up to 2.8 times body weight during the generation phase of stance, as can be seen in Figure 6. (Dugan & Bhat, 2005)

During swing, the function of the muscles around the knee is mainly to absorb power and control the movement of the swinging limb. In early swing phase, rectus femoris acts eccentrically to prevent excessive knee flexion. Later in the swing phase, as the knee is rapidly extending, eccentric contraction of the hamstrings serves to control the momentum of the tibia and prevents hyperextension of the knee. (Novacheck, 1998)

Both the hip flexors and extensors are involved in power generation during running and sprinting. The hip extensors are dominant just before and just after initial contact. Peak hip flexion occurs during the second half of swing in both running and sprinting. Just after peak hip flexion, there is concentric contraction of the hip extensors in preparation for landing. Throughout the first half of stance, the hip extensors keep on generating power and the hip continues to rapidly extend. The hip flexors become dominant during the second half of stance up until the first half of swing. The role of the hip flexors during the second half of stance is to decelerate the backward rotating thigh in preparation for swing. (Novacheck, 1998)

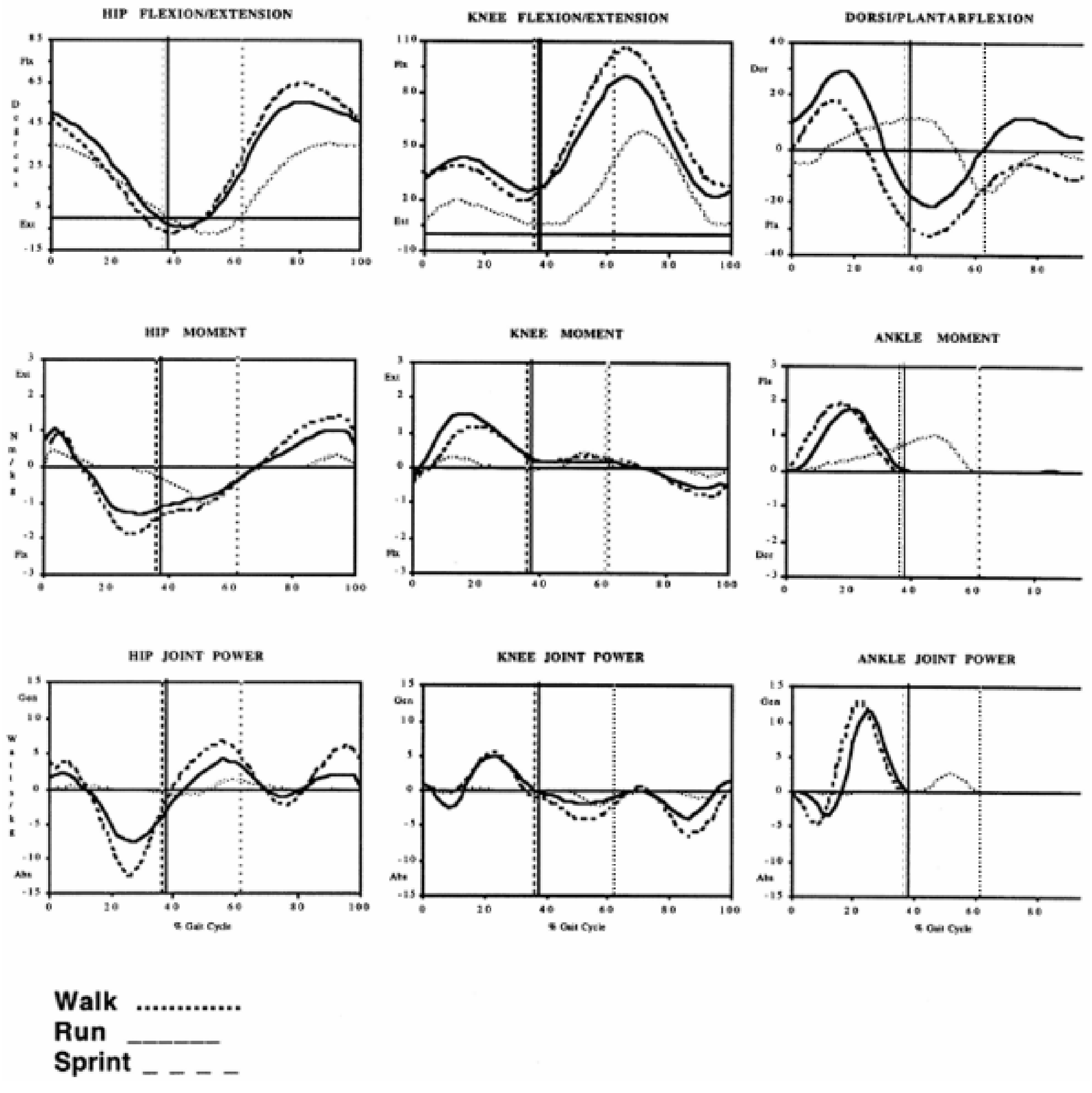


FIGURE 7. Sagittal plane joint motion, moments, and powers during walking, running, and sprinting. From “The Biomechanics of Running” by T.F. Novacheck, 1998, Gait & posture, 7(1), 77–95. Copyright 1998 by Elsevier Science.

2.3.2 Frontal Plane Kinetics

The power generated and absorbed in the frontal plane is much less than in the sagittal plane. The muscles and ligaments contributing to frontal plane moments function primarily as stabilizers. (Novacheck, 1998)

During stance, there is a continuous hip abductor moment which is produced primarily by the gluteus medius muscle. Throughout the absorption phase of stance, the GRF falls medial to the hip, creating an external hip adduction moment. At this point, the gluteus medius contracts eccentrically to control hip adduction. Conversely, gluteus medius works concentrically during the propulsion phase of stance to generate power. (Novacheck, 1998)

In summary, the main sources of power generation are from 1) the hip extensors during the second half of swing and the first half of stance; 2) the hip flexors after toe-off; and 3) the knee extensors, hip abductors, and ankle plantar flexors during the generation phase of stance. As speed increases, more power is generated and the relative contribution from the different muscle groups changes, as can be seen in Figure 8 below. (Novacheck, 1998)

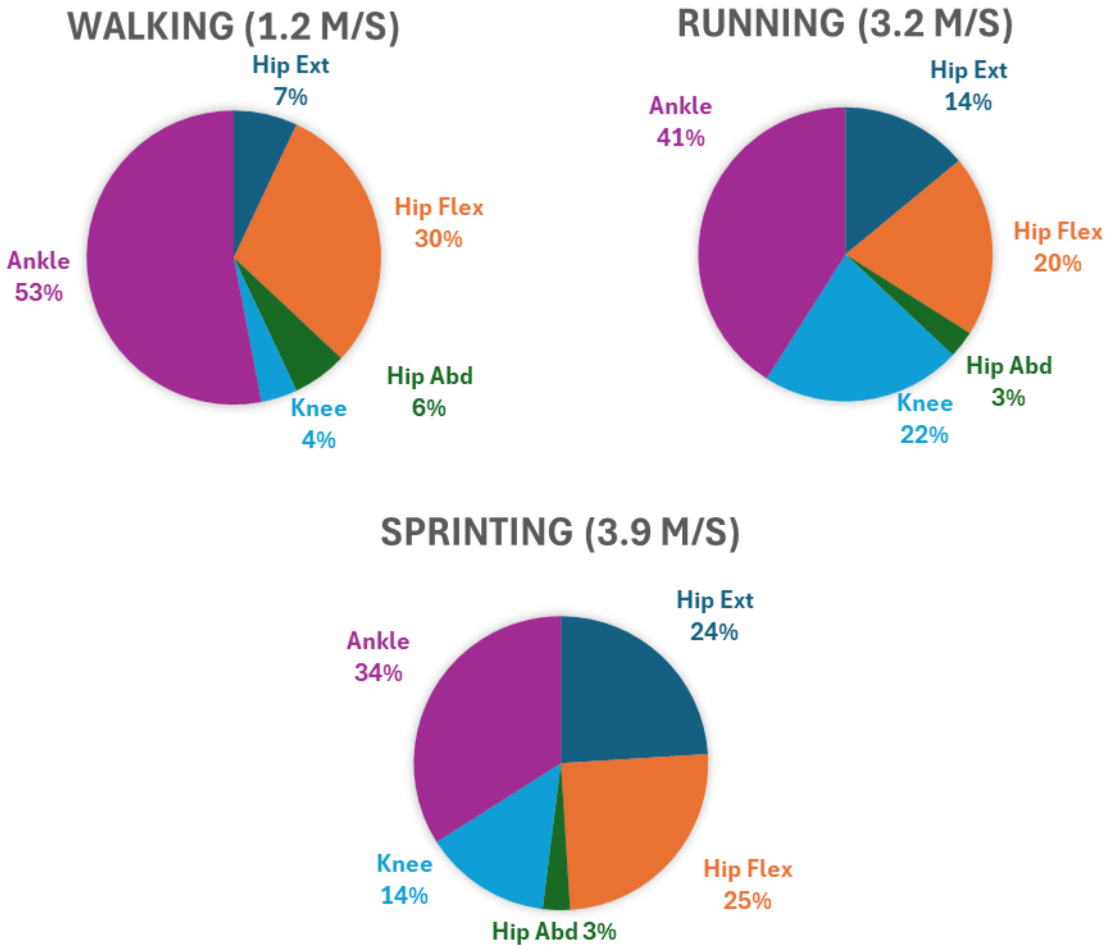


FIGURE 8. Sources of power generation during walking, running, and sprinting. Adapted from "The Biomechanics of Running" by T.F. Novacheck, 1998, Gait & posture, 7(1), 77–95. Copyright 1998 by Elsevier Science.

2.4 Novice vs Experienced Runners

Novice runners are at a greater risk of injury when compared to more experienced runners. In their meta-analysis, Videbæk et al. (2015) report that novice runners sustained 17.8 (95 % CI 16.7–19.1) RRIs per 1000 hours of running, while recreational runners sustained only 7.7 (95 % CI 6.9–8.7) RRIs. Running mechanics may be one factor contributing to this discrepancy. Differences in running mechanics between novice and more experienced runners have been previously reported (Harrison et al., 2021, Maas et al., 2018; Quan et al., 2021).

In their study on male runners, Quan et al. (2021) investigated whether sagittal plane kinematics and kinetics during stance phase differed between novice and experienced runners. The authors reported that novice runners had larger kinematic and kinetic parameters of the hip and ankle. More specifically, the maximum and minimum ankle angles, ankle ROM, plantarflexion torque, and maximum angular velocity of the ankle joint were greater in novice runners. Additionally, maximum and minimum knee angles were smaller in novice runners, but knee ROM was increased. With regards to the hip, novice runners exhibited a larger hip flexion angle, while experienced runners had an increased maximum extension torque and power. It was also reported that novice runners had a larger vertical instantaneous loading rate. (Quan et al., 2021)

Two studies were carried out exclusively on female runners (Harrison et al., 2021; Schmitz et al., 2014). Schmitz et al. (2014) did not find any significant differences between novice and experienced runners in impact peak, loading rate, non-sagittal hip kinematics, or hip strength (external rotation and abduction). In contrast, Harrison et al. (2021) found that novice female runners had decreased ankle eversion and hip adduction, but greater knee internal rotation and abduction (Figure 9) during the stance phase compared to experienced runners.

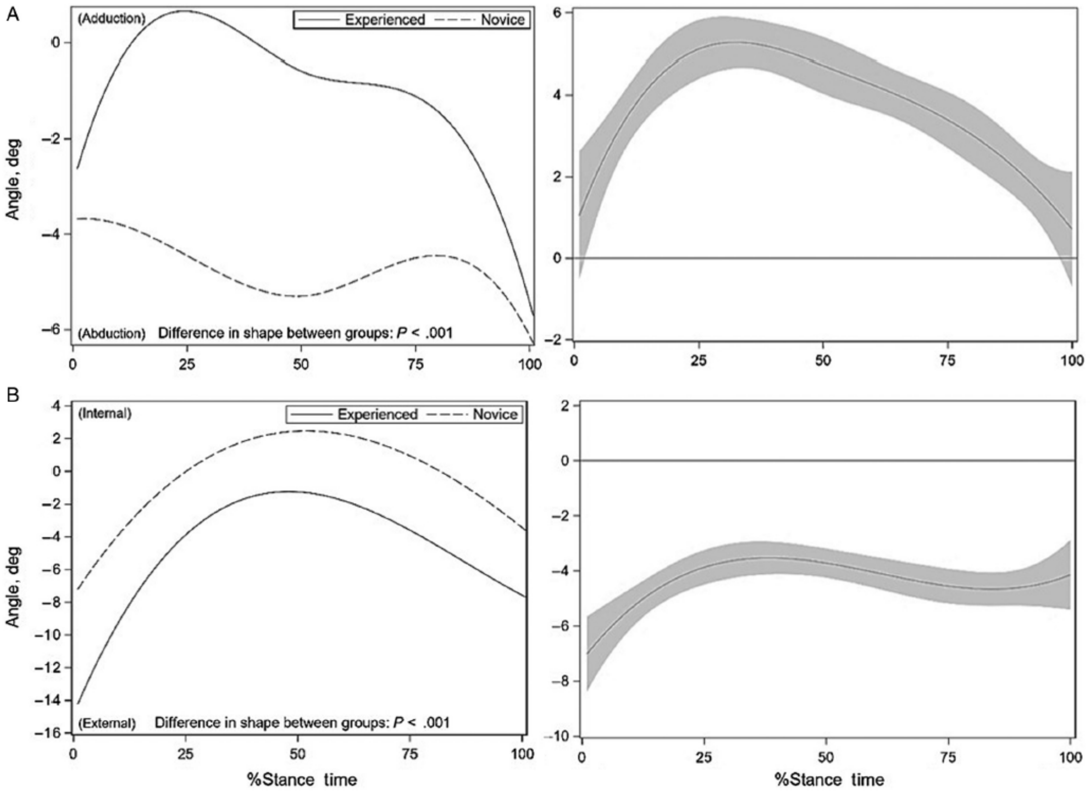


FIGURE 9. Knee joint motion during stance (left column) and mean difference between groups with 95% confidence interval (right column). (A) Frontal plane; (B) Transverse plane. From “Comparison of Frontal and Transverse Plane Kinematics Related to Knee Injury in Novice versus Experienced Female Runners,” by K. Harrison et al, 2021, Journal of Applied Biomechanics, 37(3), p. 254-262. Copyright 2021 by Human Kinetics.

Differences between the novice and more experienced runners following fatigue have also been found. Maas et al. (2018) reported that novice runners displayed greater kinematic changes than competitive runners when fatigued. Following an exhaustive run, peak forward trunk lean increased only in the novice group. Additionally, hip abduction during mid-swing increased in the novice group but decreased in the competitive runners.

In summary, running biomechanics may differ between novice and more experienced runners and could be one reason for the greater injury risk experienced by novice runners. Additionally, running experience should always be kept into consideration when comparing results from different studies, since what is relevant for one population of runners might not be applicable for another.

2.5 Sex-Specific Differences

Differences in injury rate and location exist between male and female runners (Bazuelo-Ruiz et al., 2018). It has been previously reported that women are at a lower risk than men for sustaining RRIs (van der Worp et al., 2015). Risk factors for RRIs are also sex-specific. According to the systematic review by van der Worp et al. (2015), age, previous sports activity, running on a concrete surface, participating in a marathon, weekly running distance between 48 and 63 kilometres, and wearing running shoes for 4 to 6 months were associated with a greater risk of injury in women than in men. Additionally, a history of previous injuries, having a running experience of 2 years or less, restarting running, weekly running distance between 20 to 29 miles, and having a running distance of more than 40 miles per week were associated with a greater risk of RRI in men than in women. (van der Worp et al., 2015).

One possible explanation for these sex-specific differences in the injury risk profile could be due to the dissimilar running patterns between men and women (Bazuelo-Ruiz et al., 2018). A number of studies have previously observed differences in running kinematic and kinetic parameters between male and female runners. More specifically, female runners displayed greater hip adduction, hip internal rotation, and knee abduction angles and lesser knee internal rotation excursion than males (Gehring et al., 2014; Sakaguchi et al., 2014; Wilson et al., 2012). Sakaguchi et al. (2014) also report greater peak rearfoot eversion in male runners while Hannigan et al. (2018) observed a significantly greater hip extension, hip internal rotation, trunk flexion, and trunk external rotation excursion (difference between the angle at initial contact and the peak angle during stance) in females compared to males.

Bazuelo-Ruiz et al. (2018) investigated the effect of both fatigue and gender on the kinematic and GRF parameters in recreational runners. Female runners had higher dorsiflexion and knee flexion angles in both pre-fatigue and fatigue conditions when compared to males. Additionally, a higher loading rate but a lower active peak force was observed in females when compared to males in both conditions. Following fatigue, the only kinematic changes observed were in the ankle. Females demonstrated decreased dorsiflexion at foot strike while males had decreased plantar flexion at toe-off. With respect to the GRF, fatigue led to a decreased loading rate and impact peak force in females, and higher peak propulsive forces in males. (Bazuelo-Ruiz et al., 2018)

3. THE RELATIONSHIP BETWEEN LOWER-LIMB STRENGTH AND KINEMATICS IN HEALTHY RUNNERS

Injured runners commonly display a combination of muscle weakness and altered mechanics. For example, runners with anterior knee pain displayed less pronation during the first 10% of stance and had weaker knee extensors when compared to healthy controls (Duffey et al., 2000). Researchers have hypothesized that lower extremity strength deficiencies may alter running kinematics, which in turn may predispose runners to injury. Consequently, there is a growing body of literature investigating the relationship between lower extremity strength and running kinematics in healthy runners (Baggaley et al., 2015; Brindle et al., Brund et al., 2017; 2020; Foch et al., 2020; Hannigan et al., 2018; Moffit et al., 2020; Rodriguez et al., 2020; Schmitz et al., 2014; Taylor-Haas et al., 2014; Venable et al., 2022; Zeitoune et al., 2020). This chapter will go through the findings from these studies and will highlight current gaps in the literature. For methodological details of the studies mentioned in this section, please refer to Appendix 1.

The relationship between hip strength and hip kinematics during the stance phase of running has recently received particular attention. Tables 1 and 2 below provide a summary of findings from various studies examining the relationship between hip strength and hip adduction and internal rotation kinematics, respectively.

The relationship between hip abduction strength and hip adduction kinematics during running is the most frequently studied. Given that a large peak hip adduction angle is a risk factor for multiple overuse injuries in women, it is not surprising that female runners have been the primary subjects of investigation (Noehren et al., 2007; Noehren et al., 2013).

While one study reported a significant correlation between isometric hip abduction strength and hip adduction excursion (Hannigan et al., 2018), other studies found no relationship between isometric hip abduction strength and hip adduction kinematics in female runners (Baggaley et al., 2015; Brindle et al., 2020; Foch et al., 2020; Schmitz et al., 2014; Venable et al., 2022; Zeitoune et al., 2020). In male runners, one study found isokinetic hip abductor strength to be inversely correlated with frontal plane hip ROM (Taylor-Haas et al., 2014). Conversely, Brund et al. (2017) and Hannigan et al. (2018)

did not find eccentric or isometric hip abductor strength to be correlated with hip adduction kinematics in their male runners. Additionally, hip abduction strength was not correlated with hip internal rotation kinematics in any of the available studies (Hannigan et al., 2018; Rodriguez et al., 2020; Taylor-Haas et al., 2014; Venable et al., 2022; Zeitoune et al., 2020).

TABLE 1. Studies investigating the correlation between hip strength and hip adduction kinematics during the stance phase of running.

	Hip abduction strength	**Hip external rotation strength**	
Baggaley et al., 2015	No		**Hip adduction kinematics**
Brindle et al., 2020	No		
Brund et al., 2017	No		
Foch et al., 2020	No		
Hannigan et al., 2018	Yes – females No – males	No	
Rodriguez et al., 2020	No	Yes	
Schmitz et al., 2014	No		
Taylor-Haas et al., 2014	Yes		
Venable et al., 2022	No		
Zeitoune et al., 2020	No		

Note. Yes = significant correlation found between variables. No = no significant correlation found. Empty boxes signify that a particular association was not investigated in that study.

Regarding the relationship between hip external rotation strength and hip adduction kinematics, one study found a fair correlation in a mixed-sex cohort (Rodriguez et al., 2020), while another study found no association in male or female runners (Hannigan et al., 2018). Additionally, hip external rotation strength did not correlate with hip internal rotation kinematics in male or female runners (Hannigan et al., 2018; Rodriguez et al., 2020; Schmitz et al., 2014; Zeitoune et al., 2020).

Isokinetic hip extension strength exhibited an inverse correlation with transverse plane hip ROM in adolescent cross-country male runners (Taylor-Haas et al., 2014). In contrast, isometric hip extensor strength showed no correlation with hip internal rotation excursion in female runners (Zeitoune et al., 2020) or with peak hip internal rotation in a mixed-sex sample of collegiate distance runners (Moffit et al., 2020).

TABLE 2. Studies investigating the correlation between hip strength and hip internal rotation kinematics during the stance phase of running.

	Hip abduction strength	**Hip external rotation strength**	**Hip extension strength**	
Moffit et al., 2020			No	**Hip internal rotation kinematics**
Hannigan et al., 2018	No	No		
Rodriguez et al., 2020	No	No		
Schmitz et al., 2014		No		
Taylor-Haas et al., 2014	No		Yes	
Venable et al., 2022	No			
Zeitoune et al., 2020	No	No	No	

Note. Yes = significant correlation found between variables. No = no significant correlation found. Empty boxes signify that a particular association was not investigated in that study.

The relationship between hip strength and knee running kinematics has also been studied, albeit to a lesser extent (Table 3). Heinert et al. (2008) reported that female athletes with weaker hip abductors demonstrated significantly greater knee abduction during all phases of the stance phase of running when compared to their stronger counterparts. Similarly, Venable et al. (2022) found hip abductor muscle strength to be associated with the knee adduction angle in their sample of female collegiate cross-country runners. Interestingly, Venable et al., (2022) also observed statistically significant correlations between left-sided hip abduction strength and the right knee adduction at initial contact as well as the right peak knee adduction angle, suggesting that hip abductor strength may be related to knee kinematics of the contralateral leg. In contrast, male runners did not exhibit any correlations between hip abduction strength and frontal plane knee kinematics (Brund et al., 2017; Taylor-Haas et al., 2014).

TABLE 3. Studies investigating the correlation between hip strength and knee kinematics during the stance phase of running.

	Hip abduction strength	**Hip extension strength**	
Brund et al., 2017	No - (non-sagittal planes)		**Knee Kinematics**
Heinert et al., 2008	Yes - (frontal plane)		
Moffit et al., 2020		No (all planes)	
Taylor-Haas et al., 2014	No (all planes)	No (all planes)	
Venable et al., 2022	Yes – (frontal plane) No – (sagittal plane)		

Note. Yes = significant correlation found between variables. No = no significant correlation found. Empty boxes signify that a particular association was not investigated in that study.

Hip abductor strength was not correlated with sagittal plane knee kinematics in male or female runners (Taylor-Haas et al., 2014; Venable et al., 2022). Additionally, in male runners, hip abductor strength did not exhibit a correlation with transverse plane knee kinematics (Brund et al., 2017; Taylor-Haas et al., 2014). Nevertheless, there are no available reports regarding this relationship in female runners.

Some studies have also investigated the relationship between hip extensor strength and knee kinematics. Hip extensor strength was not correlated with knee ROM in any plane in male cross-country runners (Taylor-Haas et al., 2014). Similarly, it did not correlate with the peak knee flexion, abduction or internal rotation angle in a mixed-sex sample of distance runners (Moffit et al., 2020). Interestingly, Moffit et al. (2020) observed an association between a more global assessment of lower-limb strength and favourable knee kinematics: increased strength in the 1-RM back squat was correlated with a greater peak knee flexion angle and a smaller peak knee internal rotation angle. Table 3 provides a summary of the findings from the studies examining the relationship between hip strength and knee kinematics mentioned in this section.

Research exploring additional relationships between leg strength and running kinematics beyond those discussed above is limited. For instance, only one study examining the correlation between hip abduction strength and ankle kinematics could be found (Venable et al., 2022). In this study, isokinetic hip abduction strength showed a moderate correlation with supination at initial contact and peak pronation in female cross-country runners (Venable et al., 2022). Similarly, the study by Moffit et al. (2020) is the only study to date to investigate the relationship between knee strength and running kinematics. The authors report that isometric knee extensor strength did not exhibit an association with hip or knee kinematics in any plane in collegiate distance runners (Moffit et al., 2020).

The current body of literature exploring the connection between lower-limb strength and running kinematics in healthy individuals raises several important considerations. Firstly, differences in the studied populations and methodologies utilised across studies should be kept in consideration when comparing results (Ceyssens et al, 2019; Vannatta et al., 2020). Key factors such as age, weight, sex and running experience may influence running biomechanics as well as a runner’s predisposition to injury (Bazuelo Ruiz et al., 2018; Gehring et al., 2014; Hannigan et al., 2018; Harrison et al., 2021; Maas et al., 2018; Quan et al., 2021; Sakaguchi et al., 2014; van der Worp et al., 2015; Wilson et al., 2012). Consequently, findings from one specific group of runners may not necessarily apply to all other runners. Notably, there is a lack of research on this topic focusing on novice runners, despite them being the most susceptible to injury (Videbæk et al., 2015).

Secondly, the majority of studies tested strength isometrically. The suitability of isometric dynamometry for measuring strength in runners has been previously questioned (Brindle et al., 2020; Rodriguez et al., 2020; Taylor-Haas et al., 2014). A major limitation of isometric dynamometry is that it tests muscle strength at fixed joint positions (Taylor-Haas et al., 2014). Because of its static nature, this method may allow subjects to generate greater muscle torque at a given position when compared to isokinetic dynamometry (Prentice, 2006). During the stance phase of running, the hip muscles are primarily working concentrically and eccentrically throughout an arc of movement. Isokinetic dynamometry tests the muscle throughout a ROM in a single degree of freedom and assesses both concentric and eccentric muscle function. (Taylor-Haas et al., 2014)

Since running is a dynamic movement, isokinetic testing may therefore provide a more valid strength measure when compared to isometric dynamometry. Rodriguez et al. (2020) did not find any significant correlations between isometric hip strength measures and peak gluteal muscle forces during the stance phase of running, further confirming the notion that isometric testing is unable to portray the muscular demands imposed during running. The high cost and prolonged set-up time associated with isokinetic dynamometry are probably the major reasons why this method hasn’t been utilised as frequently as isometric dynamometry within clinical and research settings. (Rodriguez et al., 2020; Taylor-Haas et al., 2014)

Lastly, there is a lack of research investigating the relationship between ankle strength and ankle, knee and hip biomechanics in runners. The majority of running injury prevention programs have traditionally adopted a "top-down approach", whereby strengthening the hip musculature is expected to mitigate excessive movements and moments at the hip, knee, and/or ankle (Baltich et al., 2014). However, outcomes from such interventions vary; for instance, a 6-week program targeting hip abductors and external rotators yielded no alterations in hip or knee mechanics (Willy and Davis, 2011), while another reported decreased eversion ROM, increased hip adduction ROM, and reduced rearfoot inversion and knee abduction moments (Snyder et al., 2009). Moreover, a 12-week resistance training program, encompassing hip abductor, quadriceps, and core strengthening, was not effective at reducing injuries among first-time marathon runners (Toresdahl et al., 2020).

A “ground-up approach” has been recently suggested for the prevention of RRIs. It is hypothesized that strengthening the extrinsic and intrinsic muscles of the foot could induce favourable changes at the ankle, knee and/or hip joints. A year-long running injury prevention programme, focusing on strengthening the foot-ankle muscles, effectively reduced RRIs and altered injury-related foot-ankle kinematics (Matias et al., 2022; Taddei et al., 2020). These findings suggest a potential association between ankle strength and foot-ankle kinematics. It is possible that the intervention also altered kinematics further up the kinematic chain, potentially contributing to the reduction in RRIs. However, this study did not measure biomechanics at the hip and knee, preventing definitive evidence to support this claim. Presently, there are no studies exploring the relationship between ankle strength and running kinematics. The findings from the study by Taddei et al. (2020) provide grounds to speculate that important associations may exist between ankle strength and running biomechanics, highlighting the need for future research in this area.

In summary, the association between lower-limb strength and running biomechanics remains unclear. Additional research is warranted to address the current gaps in the literature. Future studies should focus on novice runners and incorporate strength measurements that are more specific to running.

4. RUNNING-RELATED INJURIES

This chapter goes into detail about the role of muscle weakness and running kinematics in RRIs. The first section of this chapter will present the findings from previous studies done on injured runners. The second and third sections will identify specific kinematic parameters and strength deficiencies which have been recognized as risk factors for various RRIs. It is important to note that only findings from prospective studies have been considered.

4.1 Strength and biomechanics of injured runners

Injured runners often present with decreased muscle strength and altered running biomechanics (Fields et al., 2010). Inter-limb strength differences have been observed in injured runners. Niemuth et al. (2005) reported that injured runners had weaker hip abductors and hip flexors but stronger hip adductors of the injured lower extremity when compared to the uninjured leg, while uninjured runners showed no significant differences in hip muscle strength between their right and left lower extremities.

Weakness of the hip abductors was found to be related to iliotibial band syndrome. Long-distance runners diagnosed with iliotibial band syndrome exhibited reduced hip abductor strength in the affected leg compared to their unaffected leg and in comparison to other uninjured runners. Furthermore, a 6-week rehabilitation programme, consisting of ultrasound therapy, iliotibial band stretches and strengthening of the hip abductors was successful at improving pain as well as hip abduction torque. (Fredericson et al., 2000; Mucha et al., 2017)

Altered biomechanics in injured runners have also been reported. According to a systematic review by Aderem & Louw (2015), increased peak knee internal rotation and increased trunk ipsilateral flexion during the stance phase of running were reported in female runners with iliotibial band syndrome. Additionally, longer duration of eversion and increased rearfoot eversion at heel-off were reported in runners with Achilles' tendinopathy or medial tibial stress syndrome (MTSS) (Becker et al., 2017).

Weakness of the hip musculature, specifically the hip abductors and external rotators, as well as atrophy of the vastus medialis obliquus have been previously observed in individuals with patellofemoral pain syndrome (Petersen et al., 2014). Additionally, Barton et al. (2009) reported that patients with patellofemoral pain syndrome presented with delayed timing of peak rearfoot eversion, increased rearfoot eversion at heel-strike, and reduced eversion ROM during gait. Furthermore, Dierks et al. (2008) found that recreational runners with patellofemoral pain syndrome presented with decreased hip abductor strength and increased peak hip adduction during running when compared to uninjured runners.

4.2 Biomechanical risk factors of RRIs

Altered biomechanics are evident not only in injured runners but have also been recognized as risk factors for the development of RRIs (Fields et al., 2010). However, literature concerning the role of running biomechanics in the development of RRIs is limited and inconsistent.

Recent systematic reviews highlight the lack of prospective evidence linking biomechanical variables to the risk of RRIs. Retrospective studies compare injured runners to healthy matched controls. However, a limitation of retrospective designs is the inability to determine whether the observed differences between subjects were already present before the injury. Furthermore, alterations in running biomechanics may stem from compensatory movement strategies due to pain and/or injury. Thus, without prospective research, it is not possible to establish whether differences in running biomechanics between injured and uninjured runners are a cause or an effect of injury. (Ceyssens et al, 2019; Vannatta et al., 2020)

The following section will present various kinematic parameters that have been *prospectively* linked with the aetiology of RRIs.

Greater **peak hip adduction** in female recreational runners was identified as a risk factor for patellofemoral pain syndrome and iliotibial band syndrome (Noehren et al., 2007; Noehren et al., 2013) but was not related to RRI risk in collegiate cross-country runners (Dudley et al., 2017). Less **hip adduction at toe-off** was associated with general RRIs in recreational runners (Dillon et al., 2023). Additionally, peak hip adduction and **hip adduction at initial contact** did not differ between injured and uninjured female collegiate cross-country runners (Venable et al., 2022). **Hip internal rotation** was not a risk factor for RRIs in collegiate cross-country runners (Dudley et al., 2017; Venable et al., 2022) or for the development of patellofemoral pain syndrome in female recreational runners (Noehren et al., 2013).

In a cohort comprising both male and female recreational runners, no significant association was observed between **peak knee flexion** and general RRIs (Messier et al., 2018). Similarly, Venable et al. (2022) did not find peak knee flexion or **knee flexion at initial contact** to be related to RRIs in female collegiate cross-country runners. However, peak knee flexion may play a role in the development of Achilles tendon injuries. The findings by Hein et al. (2014) and Stiffler-Joachim et al. (2023) suggest that reduced peak knee flexion may predispose runners to Achilles tendinopathy. In contrast, Skypala et al. (2023) report that runners with a larger peak knee flexion angle, as well as a more flexed knee at initial contact, demonstrated an increased propensity for Achilles tendon injuries. More specifically, each 1-degree rise in knee flexion at initial contact and midstance was associated with a 15% higher risk of sustaining an Achilles tendon injury (Skypala et al., 2023). Thus, the association between knee flexion and Achilles tendon injury remains unclear.

In a recent prospective study, several frontal plane knee kinematic parameters (minimum knee abduction, knee abduction at initial contact, peak knee abduction and knee abduction at toe-off) were found to be associated with RRIs in recreational runners (Dillon et al., 2023). Runners demonstrating overall less **knee abduction** (knee valgus) during stance went on to develop an RRI (Dillon et al., 2023). On the other hand, **peak knee adduction** and **knee adduction at initial contact** were not associated with injury in female collegiate cross-country runners (Venable et al. 2022).

Greater **peak knee internal rotation** and **femoral external rotation** (relative to the global coordinate system) in female recreational runners are also important contributing factors to the development of iliotibial band syndrome (Noehren et al., 2007). Similarly, Dillon et al. (2023) found greater **knee internal-external rotation excursion** to be associated with general RRIs in a cohort of mixed-sex recreational runners.

Decreased **peak eversion** in female recreational runners is an important factor in the development of iliotibial band syndrome and patellofemoral pain syndrome (Noehren et al., 2007; Noehren et al., 2013) while greater peak eversion is a risk factor for Achilles tendinopathy in male and female recreational runners (Hein et al., 2014). In contrast, peak eversion is not a risk factor for general RRIs in recreational and collegiate cross-country runners (Dudley et al., 2017; Kuhman et al, 2016; Venable et al., 2022).

Based on the findings by Messier et al. (2018), **eversion velocity** and **eversion ROM** are not considered risk factors for the development of general RRIs in recreational runners. However, the role of these parameters in the development of RRIs in collegiate cross-country runners remains inconclusive. (Vannatta et al., 2020). Additionally, **eversion duration** was not found to be a risk factor for general RRIs in collegiate cross-country runners (Kuhman et al. 2016). Furthermore, late **timing of peak eversion** was associated with an increased incidence of an RRI in recreational runners (Jungmalm et al., 2020).

Based on the findings by Hein et al. (2014) and Stiffler-Joachim et al. (2023), decreased **peak ankle dorsiflexion** was found to be a risk factor for Achilles tendinopathy in recreational and collegiate cross-country runners, respectively. On the other hand, peak ankle dorsiflexion was not associated with increased risk of general RRIs in collegiate cross-country runners (Kuhman et al., 2016).

4.3 The role of lower-limb weakness as a risk factor for RRIs

Muscle weakness is frequently attributed to the altered kinematics observed in injured runners. Additionally, strength training is included in most rehabilitation and injury prevention programmes. Yet, literature concerning lower extremity strength and its contribution to RRIs is limited and inconclusive. Due to a lack of prospective evidence, it is unclear whether muscle weakness contributes to injury or develops as a result of injury. The following section will present findings from previous *prospective* studies investigating the role of muscle weakness in the aetiology of RRIs.

Some prospective evidence suggests a correlation between lower-limb weakness and an increased incidence of RRIs. In a study involving high school cross-country runners, hip abductor, knee flexor, and knee extensor weakness were linked to an increased incidence of anterior knee pain (Luedke et al., 2015). Similarly, a 52-week prospective study involving over 200 subjects revealed that recreational runners with weak hip abductors in relation to adductors experienced a 17.3% higher injury rate (Jungmalm et al., 2020). Hip abductor weakness was also found to be related to MTSS in collegiate cross-country runners (Becker et al., 2018). Furthermore, weakness of the quadriceps and hamstrings as well as increased strength of the hip external rotators were identified as risk factors for patellofemoral pain syndrome (Boling et al., 2009) while weak knee flexors and plantarflexors were associated with Achilles tendon injuries (Hein et al., 2014; Mahieu et al., 2006).

Contrary to the findings mentioned, Messier et al. (2018) concluded that isokinetic concentric strength of the lower extremity is not predictive of general RRIs in recreational runners. Similarly, concentric hip abductor strength was not related to general RRIs in female collegiate cross-country runners (Venable et al., 2022). Additionally, studies by Dillon et al. (2021), Dillon et al. (2023), and Torp et al. (2018) found no statistically significant differences in isometric lower-limb strength between injured runners and those who remained injury-free.

Thus, while some evidence points to a connection between altered kinematics, muscle weakness, and RRIs, further prospective research is necessary to validate these observations. Recent systematic reviews advocate for large sample sizes and improved methodologies in future studies (Ceyssens et al., 2019; Vannatta et al., 2020).

5. PURPOSE OF THE STUDY

Lower-limb weakness and altered biomechanics have been identified as significant risk factors for RRIs (Dillon et al., 2023; Ceyssens et al., 2019; Luedke et al., 2015). Muscle weakness is believed to contribute to excessive joint kinematics commonly associated with running injuries. Consequently, a growing body of literature has emerged, aiming to explore the relationship between lower-limb strength and running biomechanics in healthy runners.

The prevailing literature has predominantly concentrated on investigating the relationship between hip strength and running kinematics, particularly at the hip and knee joints, yielding conflicting results. Notably, differences in the populations studied and the methodologies utilised create challenges in comparing results across studies, highlighting the necessity for additional research.

A noticeable gap in the literature exists concerning studies exploring the relationship between ankle strength and running kinematics. Promising outcomes from an 8-week foot-core exercise program, which reduced RRIs and altered foot-ankle kinematics in recreational runners, hint at a potential association between ankle strength and running kinematics (Matias et al., 2022; Taddei et al., 2020). However, this area remains largely unexplored, presenting an opportunity for further investigation.

The majority of existing studies utilised isometric dynamometry to quantify muscle strength. However, isometric dynamometry tests strength at fixed positions, raising concerns about its capacity to accurately represent muscle function during running. The reliance on isometric strength measures in prior studies may have potentially obscured meaningful associations between lower-limb strength and running kinematics. (Brindle et al., 2020; Rodriguez et al., 2020; Taylor-Haas et al., 2014)

Despite novice runners being particularly susceptible to injuries, there is a notable lack of research focusing on this group of runners. Given the distinct biomechanics of novice runners compared to their more experienced counterparts, findings from studies involving seasoned runners may not be directly applicable (Harrison et al., 2021; Maas et al., 2018; Quan et al., 2021). This underscores the need for investigations focusing on novice runners to address this research gap.

In light of the aforementioned issues, the relationship between strength and running biomechanics remains unclear. This study aims to investigate the association between lower limb isokinetic strength and 3D running kinematics in healthy novice runners. This study will include strength measures of various muscle groups of the lower-limb, along with several stance phase running kinematics of the hip, knee and ankle joints, allowing for an in-depth analysis of their relationship. While the study does not aim to make statistical comparisons between male and female runners, data from both male and female novice runners will be analysed and presented separately. This approach is taken due to previously reported sex-specific differences in running biomechanics.

Based on the existing literature, several hypotheses have been formulated:

- Isokinetic hip abduction strength is expected to correlate with frontal plane hip kinematics but not with knee kinematics in male runners.
- Isokinetic hip abduction strength will not be correlated with hip kinematics but is expected to be correlated with frontal plane knee kinematics in female runners.
- Ankle strength is expected to be associated with hip, knee, and ankle joint kinematics.

6. METHODS

6.1 Subjects

Ten male (age: 35.2 ±9.7 years, mass: 73.6 ±5.4 kg, height 182.4 ±5.3 cm, BMI 22.2 ±1.9 kg/m^2) and ten female (age: 38.7 ±6.5 years, mass: 63.6 ±5.8 kg, height 166.9 ±5.4 cm, BMI 22.8 ±1.4 kg/m^2) healthy novice runners participated in this study. Subjects were recruited from Finland's Pirkanmaa area via notifications in social media, newspapers, web pages and e-mail mailing lists. Inclusion criteria were the following: a) less than two years of weekly running exposure, b) between 18 to 55 years, c) BMI between 18.5 and 25.9 kg/m^2 and d) being a rearfoot striker. Subjects were excluded from the study if they suffered any injuries within the three months preceding the onset of the study that would affect their running ability.

This study was part of a larger international research project conducted by the Tampere Research Centre of Sports Medicine, the UKK Institute and the University of Calgary. The research project lasted for two years and recruited over 150 novice recreational runners per year. Ten male and ten female subjects who met the inclusion criteria of this study were then randomly selected from the total number of participants recruited during the first year of the project and included in this study.

All subjects participated voluntarily and were informed about their right to withdraw from the study at any point without the need to give a reason for their withdrawal. Written informed consent was obtained from all subjects prior to the commencement of the study. All procedures were conducted in accordance with the ethical principles outlined in the Declaration of Helsinki and ethical approval was obtained from the Ethics Committee of the Pirkanmaa Hospital District in August 2020.

6.2 Experimental Protocol

The study followed a cross-sectional design whereby all measurements and tests for one subject were carried out in a single session. Measurements were conducted at the UKK Institute in Tampere, and each testing session lasted around 2.5 hours per subject.

The first step of the experimental protocol was taking the subjects’ anthropometric measurements. These included the subjects' height, weight, leg length, knee, ankle, elbow and wrist width, and the heel-to-toe drop of the subjects’ footwear using an external calliper. Next, the subjects were asked to warm up by walking for five minutes and running for five minutes at a self-selected pace. Following the warm-up, the subjects were prepped and performed the overground running gait analysis. Lastly, the isokinetic strength measurements were carried out.

6.2.1 Running gait analysis

Three-dimensional running kinematics and kinetics were measured using a marker-based motion capture system (Vicon). Marker data were collected at 240Hz using eight cameras (Vicon T-series) positioned around two synchronized force plates (AMTI BP6001200-2K) embedded in the surface of the runway. Ground reaction forces were simultaneously collected at a sampling rate of 2400Hz. The setup for the running trials can be seen in Figure 10.

55 retroreflective markers were placed on the subjects according to the conventional gait model 2.5 (CGM 2.5), as seen in Figure 11. CGM 2.5 was used to calculate kinematics and kinetics using Vicon Nexus 2.10.3. The CGM is a widely used biomechanical model that has been subjected to considerable validation work over the years (PyCGM2, n.d.). Subjects wore their own footwear. Bony landmarks on the foot were palpated through the subjects’ footwear and the foot markers were attached directly to the shoes. The cameras were calibrated according to the manufacturer’s instructions before the running trials were recorded.

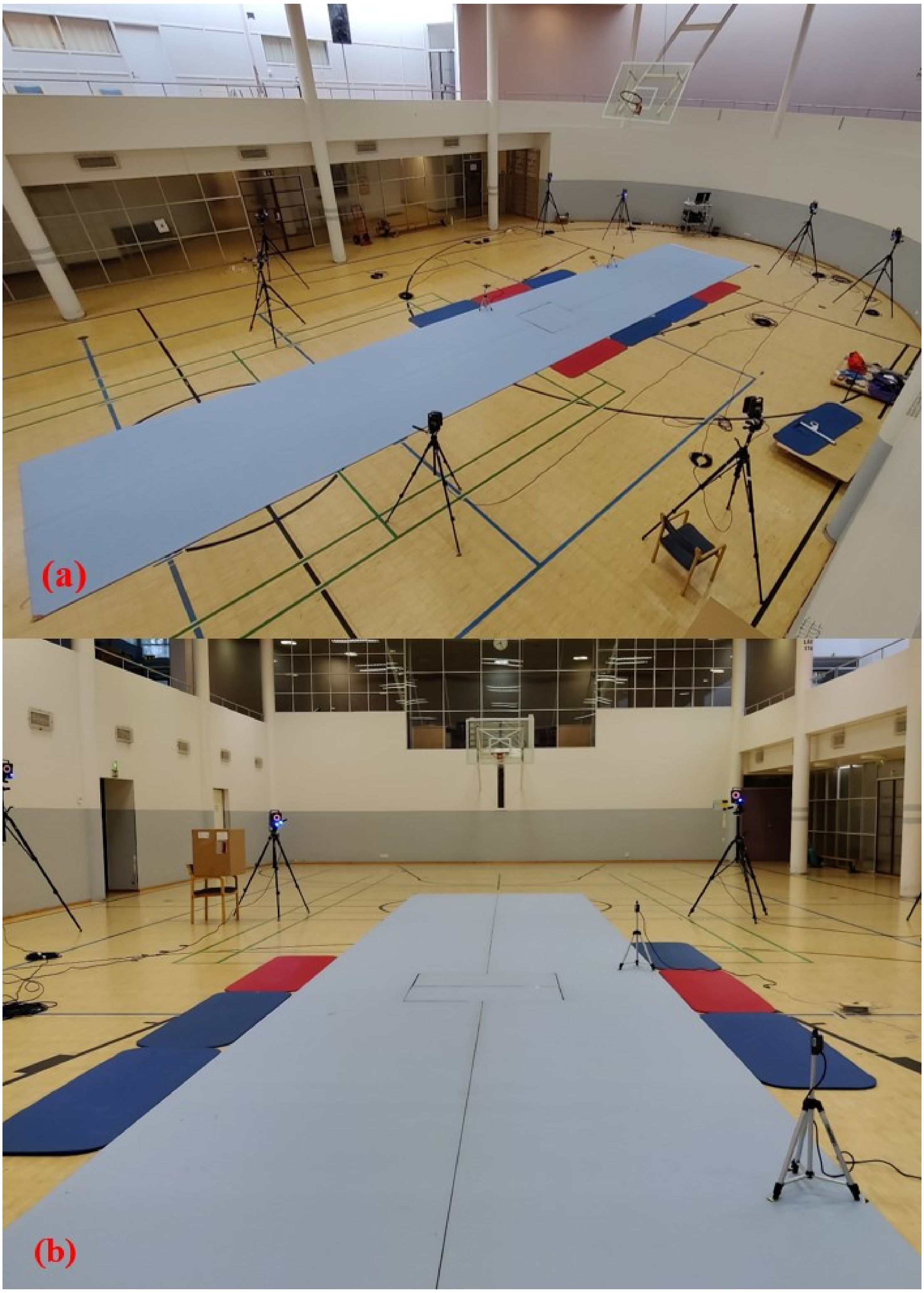


FIGURE 10. Set-up of the running trials. a) Eight cameras (Vicon T-series) were positioned around two synchronized force plates (AMTI BP6001200-2K) embedded in the surface of the runway. b) Two photocells (Newtest Powertimer) were placed 5 metres apart and centred on the force plates within the motion capture space.

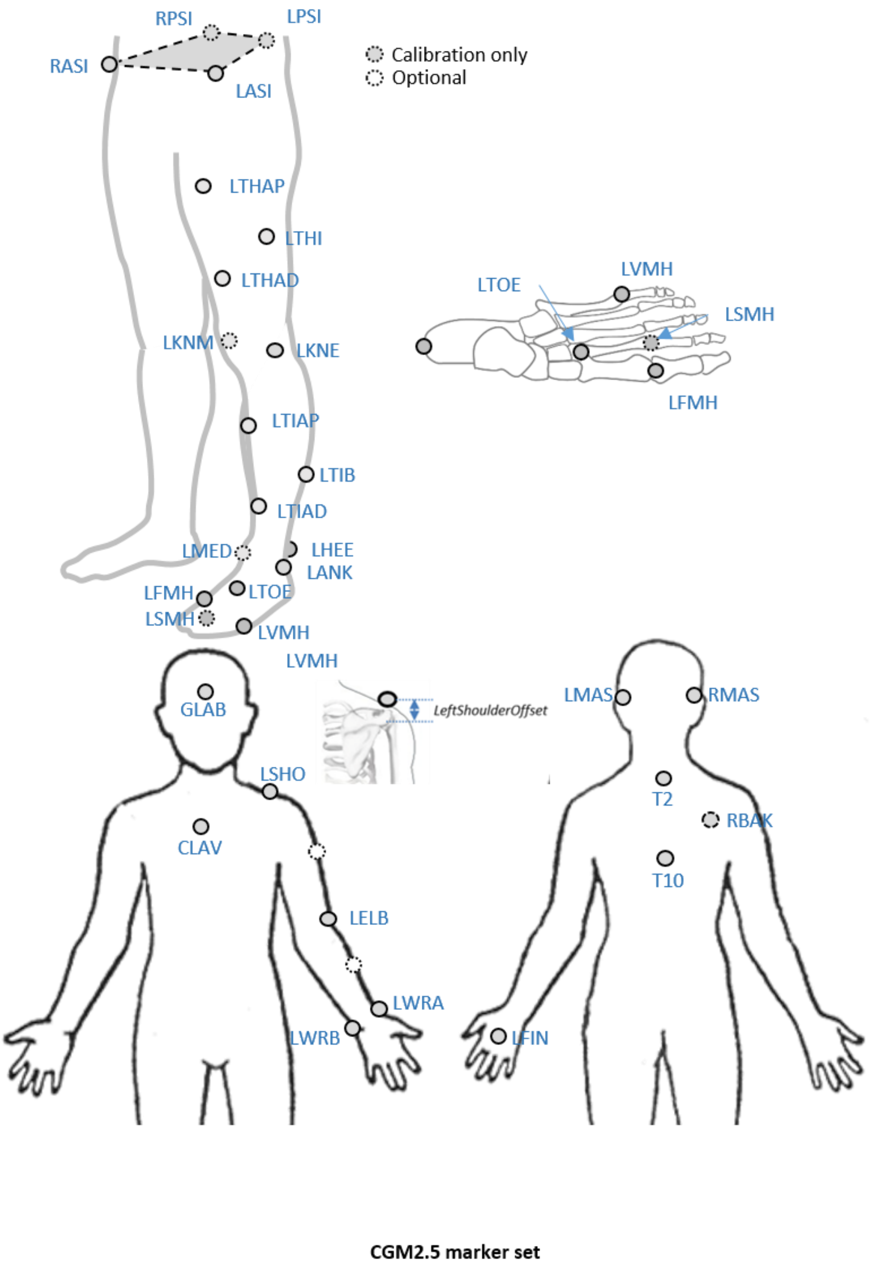


FIGURE 11. CGM2.5 marker set. From CGM 2.5 by PyCGM2, n.d. (https://pycgm2.netlify.app/cgm/cgm2.5/)

The subjects were asked to stand still on the force platforms with their shoulders abducted and their elbows flexed to 90˚. A static trial was captured which was used to determine the joint centres and to scale the model to the subjects’ mass and segment lengths. Once the static trial was captured, the static markers (medial knee, medial malleolus, and second metatarsal head) were removed.

Next, the subjects were instructed to run along a 27-metre runway at a speed of 3.5 m/s (Figure 10a). Running speed was measured using two photocells (Newtest Powertimer) placed 5 metres apart that were centred on the force plates within the motion capture space (Figure 10b). Running trials were conducted until 5 successful trials per leg were obtained. A trial was considered successful if the subject's running speed was within ± 5% of 3.5 m/s, if all markers were attached to the subject during the trial, and if the entire foot landed on one of the force plates without a visible change in running mechanics. The subjects were not made aware of the force plates to avoid having them manipulate their running pattern in an attempt to land on the force plate. Subjects were allowed to rest as needed to avoid fatigue. Once the running trials were complete, all the markers were removed, and the participants proceeded with the isokinetic strength tests.

6.2.2 Isokinetic strength measurements

Following the running trials, lower-limb isokinetic strength was measured using an isokinetic dynamometer (Biodex System 4 Pro) and System Advantage 4 Software (version 4.63). Tests were carried out in the following order for all participants: (1) ankle plantar/dorsiflexion, (2) ankle inversion/eversion, (3) knee extension/flexion and (4) hip abduction/adduction.

Isokinetic strength was tested concentrically and in a continuous movement for both movement directions. The range of motion was subject-specific and was determined by asking the subjects to perform the movement at their full ROM. All tests were done unilaterally and repeated on both lower limbs, randomizing the starting limb.

The subjects were allowed to familiarise themselves with the movement by practising it using light effort. Once they felt comfortable with the movement the subjects performed a warm-up set consisting of three continuous sub-maximal repetitions at 50%, 70% and 90% of their maximum strength. Following a one-minute rest, the subjects performed three maximal repetitions. Verbal encouragement was given throughout. Three repetitions were chosen because previous research suggests that three repetitions are enough for subjects new to isokinetic testing to achieve their best result (Hietamo et al., 2020; Baltich et al., 2014; Hietamo et al., 2021). Once the maximal sets were done, the same testing protocol was immediately repeated on the contralateral limb.

Ankle Isokinetic Testing Position. Test positions were standardized and based on the Biodex Multi-Joint System Pro setup guidelines. In both ankle tests, the subjects were seated with the back of the seat slightly tilted backwards. The tested lower limb was elevated and supported on the back of the thigh, just above the knee. The shin was placed horizontally and straight forward, and the foot was secured to the footplate. The subjects were stabilised by two shoulder straps crossing at the chest and a third strap over the waist. During the ankle plantar/dorsiflexion tests, the lateral malleolus was aligned with the axis of rotation. During the ankle inversion/eversion tests, the footplate was plantarflexed at 15 degrees and the axis of rotation was set to pass through the body of the talus. The testing positions for ankle plantar/dorsiflexion and ankle inversion/eversion tests can be seen in Figures 12 and 13 respectively. The testing velocity for both ankle tests was set at 30°/s given previously reported good to excellent reliability of ankle peak torques at this velocity (Kaminski & Dover, 2001; Webber & Porter, 2010; Holmbäck et al., 1999).

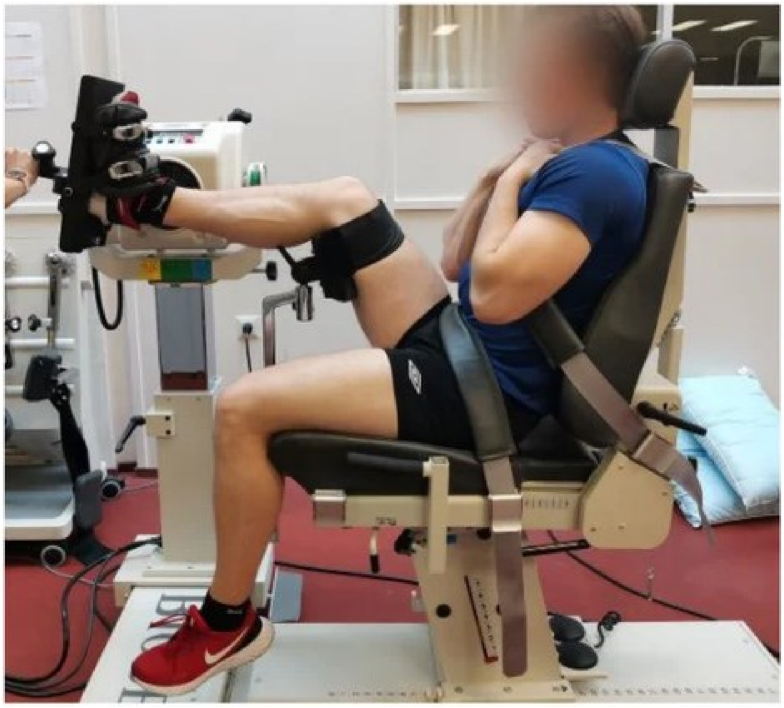


FIGURE 12. Testing position of ankle plantar and dorsiflexion. From "Test–retest reliability of isokinetic ankle, knee and hip strength in physically active adults using biodex system 4 pro," by J. Tuominen et al., 2023, *Methods and Protocols, 6* (2), 26 (https://doi.org/10.3390/mps6020026). Copyright 2023 by Tuominen et al.

FIGURE 13. Testing position of ankle inversion/eversion strength measurement. From “Test−retest reliability of isokinetic ankle, knee and hip strength in physically active adults using biodex system 4 pro,” by J. Tuominen et al., 2023, *Methods and Protocols, 6* (2), 26 (https://doi.org/10.3390/mps6020026). Copyright 2023 by Tuominen et al.

Knee Isokinetic Testing Position. For the knee extension/flexion strength test the subjects were comfortably seated with the tested lower limb extended straight out in front of them. The femur was fully supported by the seat and the leg was attached to the dynamometer via a strap just above the ankle. The subjects were stabilised by two shoulder straps crossing at the chest, a waist strap, and a thigh strap, as seen in Figure14 below. The axis of rotation of the dynamometer was aligned with the lateral femoral condyle. Knee isokinetic strength was measured at a velocity of 60˚/s in accordance with previous studies (Hartmann et al., 2009; Adsuar et al., 2011; Carvalho et al., 2011; Collado-Mateo et al., 2019; Collado-Mateo et al., 2020; Fagher et al., 2016; Lienhard et al., 2013; Tsiros et al., 2011; Hietamo et al., 2021).

FIGURE 14. Testing position of knee extension and flexion. From “Test–retest reliability of isokinetic ankle, knee and hip strength in physically active adults using biodex system 4 pro,” by J. Tuominen et al., 2023, *Methods and Protocols, 6* (2), 26 (https://doi.org/10.3390/mps6020026). Copyright 2023 by Tuominen et al.

Hip Isokinetic Testing Position. Concentric isokinetic hip abduction and adduction strength was measured with the subjects in side-lying, facing away from the dynamometer. The greater trochanter was used to align the axis of rotation of the dynamometer with that of the tested hip joint. The subjects were stabilised by a strap over the waist and a second strap on the contralateral limb, placed just below the knee. The tested lower limb was attached to the dynamometer just above the knee. A testing velocity of 30°/sec was considered suitable for measuring torques with a small range of motion (Baltich et al., 2014). The setup for the hip isokinetic strength testing can be seen in Figure 15 below.

FIGURE 15. Testing position of hip abduction and adduction. From “Test–retest reliability of isokinetic ankle, knee and hip strength in physically active adults using biodex system 4 pro,” by J. Tuominen et al., 2023, *Methods and Protocols, 6* (2), 26 (https://doi.org/10.3390/mps6020026). Copyright 2023 by Tuominen et al.

6.3 Data Analysis

6.3.1 Running gait analysis

Data analysis was restricted to the stance phase. Discrete kinematic variables were based on 5 successful trials for each leg and were calculated for the hip, knee, and ankle in all three planes of motion. An average of the 5 trials was calculated for each leg and used for statistical correlations. The following discrete kinematic variables were calculated for the hip, knee, and ankle in all three planes of movement and abbreviated as follows:

1) **Initial contact angles (˚):**
    a. HSP_ic - Hip Sagittal Plane - angle at initial contact
    b. HFP_ic - Hip Frontal Plane - angle at initial contact
    c. HTP_ic - Hip Transverse Plane - angle at initial contact

   d. KSP_ic - Knee Sagittal Plane - angle at initial contact
   e. KFP_ic - Knee Frontal Plane - angle at initial contact
   f. KTP_ic - Knee Transverse Plane - angle at initial contact
   g. ASP_ic - Ankle Sagittal Plane - angle at initial contact
   h. AFP_ic - Ankle Frontal Plane - angle at initial contact
   i. ATP_ic - Ankle Transverse Plane - angle at initial contact

2) **Toe-off angles (˚):**
   a. HSP_to - Hip Sagittal Plane - angle at toe-off
   b. HFP_to - Hip Frontal Plane - angle at toe-off
   c. HTP_to - Hip Transverse Plane - angle at toe-off
   d. KSP_to- Knee Sagittal Plane - angle at toe-off
   e. KFP_to - Knee Frontal Plane - angle at toe-off
   f. KTP_to - Knee Transverse Plane - angle at toe-off
   g. ASP_to- Ankle Sagittal Plane - angle at toe-off
   h. AFP_to - Ankle Frontal Plane - angle at toe-off
   i. ATP_to - Ankle Transverse Plane - angle at toe-off

3) **Maximum angles (˚):**
   a. HSP_max - Hip Sagittal Plane – maximum angle
   b. HFP_max - Hip Frontal Plane - maximum angle
   c. HTP_max - Hip Transverse Plane - maximum angle
   d. KSP_max - Knee Sagittal Plane - maximum angle
   e. KFP_max - Knee Frontal Plane - maximum angle
   f. KTP_max - Knee Transverse Plane - maximum angle
   g. ASP_max - Ankle Sagittal Plane - maximum angle
   h. AFP_max - Ankle Frontal Plane - maximum angle
   i. ATP_max - Ankle Transverse Plane - maximum angle

4) **Timing of maximum angles (%):**
   a. HSP_tmax - Hip Sagittal Plane – timing of maximum angle
   b. HFP_tmax - Hip Frontal Plane - timing of maximum angle
   c. HTP_tmax - Hip Transverse Plane - timing of maximum angle
   d. KSP_tmax - Knee Sagittal Plane - timing of maximum angle
   e. KFP_tmax - Knee Frontal Plane - timing of maximum angle
   f. KTP_tmax - Knee Transverse Plane - timing of maximum angle
   g. ASP_tmax - Ankle Sagittal Plane - timing of maximum angle

  h. AFP_tmax - Ankle Frontal Plane - timing of maximum angle
  i. ATP_tmax - Ankle Transverse Plane - timing of maximum angle

5) **Minimum angles (˚):**
  a. HSP_min - Hip Sagittal Plane – minimum angle
  b. HFP_min - Hip Frontal Plane - minimum angle
  c. HTP_min - Hip Transverse Plane - minimum angle
  d. KSP_max - Knee Sagittal Plane - minimum angle
  e. KFP_min - Knee Frontal Plane - minimum angle
  f. KTP_min - Knee Transverse Plane - minimum angle
  g. ASP_min - Ankle Sagittal Plane - minimum angle
  h. AFP_min - Ankle Frontal Plane - minimum angle
  i. ATP_min - Ankle Transverse Plane - minimum angle
  j.

6) **Timing of minimum angles (%):**
  a. HSP_tmin - Hip Sagittal Plane – timing of minimum angle
  b. HFP_tmin - Hip Frontal Plane - timing of minimum angle
  c. HTP_tmin - Hip Transverse Plane - timing of minimum angle
  d. KSP_tmin - Knee Sagittal Plane - timing of minimum angle
  e. KFP_tmin - Knee Frontal Plane - timing of minimum angle
  f. KTP_tmin - Knee Transverse Plane - timing of minimum angle
  g. ASP_tmin - Ankle Sagittal Plane - timing of minimum angle
  h. AFP_tmin - Ankle Frontal Plane - timing of minimum angle
  i. ATP_tmin - Ankle Transverse Plane - timing of minimum angle

7) **Range of Motion (˚):**
  a. HSP_rom - Hip Sagittal Plane – range of motion
  b. HFP_rom - Hip Frontal Plane - range of motion
  c. HTP_rom - Hip Transverse Plane - range of motion
  d. KSP_rom - Knee Sagittal Plane - range of motion
  e. KFP_rom - Knee Frontal Plane - range of motion
  f. KTP_rom - Knee Transverse Plane - range of motion
  g. ASP_rom - Ankle Sagittal Plane - range of motion
  h. AFP_rom - Ankle Frontal Plane - range of motion
  i. ATP_rom - Ankle Transverse Plane - range of motion

The maximum and minimum angles were defined as the greatest and smallest angles achieved throughout the stance phase. The timing of the maximum and minimum angles is represented as a percentage of the stance phase and was calculated as follows:

$$timing\ of\ maximum\ angle\ (\%) = \frac{timing\ of\ maximum\ angle\ (s)}{timing\ of\ toe\ off\ (s)}\ x\ 100$$

$$timing\ of\ minimum\ angle\ (\%) = \frac{timinig\ of\ minimum\ angle\ (s)}{timing\ of\ toe\ off\ (s)}\ x\ 100$$

Range of motion was calculated by subtracting the minimum angle from the maximum angle as follows:

$$\mathrm{ROM}(^{\circ}) = \text{maximum angle}(^{\circ}) - \text{minimum angle}(^{\circ})$$

For the hip and knee joints, positive values indicate greater degrees of flexion, adduction and internal rotation while negative values indicate greater degrees of extension, abduction and external rotation. For the ankle, positive values indicate greater degrees of dorsiflexion, inversion and adduction while negative values indicate greater values of extension, eversion and abduction.

Gap filling was done in Vicon Nexus 2.10.3. Marker trajectory data and analog data from the force platforms were filtered using a low-pass, fourth-order, zero-lag Butterworth filter. Trajectory data was cut off at a frequency of 12 Hz while analog data was filtered at 50 Hz. Foot strike and toe-off events were identified when the vertical ground reaction force reached a threshold of 15 N. CGM 2.5 was used to calculate kinematics and kinetics and 3D data was presented in joint coordinate system. The model output data was exported from Vicon Nexus 2.10.3 as a CSV file and further data analysis were done in Microsoft Excel and MATLAB R2022a (The MathWorks Inc., Natick, Massachusetts, USA).

6.3.2 Isokinetic strength measurements

The force signal was filtered and windowed using the default specifications of the Biodex software. Peak torque: body weight (PT/BW) was chosen as the outcome parameter. PT/BW is a ratio expressed as a percentage, representing the maximum torque production relative to the subject's body weight. Maximum torque production was considered to be the highest torque produced during the three maximal repetitions.

6.4 Statistical Analysis

Statistical analysis was carried out in IBM SPSS Statistics 28.0. Means and standard deviations for all strength and kinematic parameters were calculated separately for males and females. In view of the small sample size, Spearman correlation coefficients were used to determine the correlation between lower limb isokinetic strength and stance phase running kinematics. Mean kinematic values from each subject’s right and left legs were used to compute statistical correlations and were treated as being independent. Given that male and female runners exhibit different running biomechanics and injury risk profiles, separate statistical analysis was carried out for male and female subjects. Statistical correlations were calculated between all isokinetic strength parameters (hip abduction and adduction, knee flexion and extension, and ankle dorsiflexion, plantarflexion, inversion and eversion PT/BW) and all discrete kinematic parameters of the hip, knee and ankle in all three planes of movement. Correlations were determined to be statistically significant at $p < 0.05$. The strength of the Spearman correlation coefficients was interpreted as little or no relationship ($0 < r \leq 0.25$), fair ($0.25 < r \leq 0.50$), moderate to good ($0.50 < r \leq 0.75$), and good to excellent ($r > 0.75$) (Portney and Watkins, 2000).

7. RESULTS

7.1 Descriptive statistics

The descriptive statistics of all isokinetic strength variables for male and female subjects are listed in Table 4 below.

TABLE 4. Descriptive statistics of the isokinetic concentric strength measurements of the male and female subjects (mean ± standard deviation).

Muscle Strength	**Females**	**Males**
Hip Abduction	175.8 ± 32.4	186.1 ± 32.5
Hip Adduction	176.3 ± 35.3	188.4 ± 50.6
Knee Extension	210.8 ± 24.2	238.3 ± 26.1
Knee Flexion	108.7 ± 8.8	121.7 ± 23.0
Ankle Plantarflexion	125.2 ± 34.6	130.7 ± 27.8
Ankle Dorsiflexion	37.5 ± 5.3	47.1 ± 8.7
Ankle Inversion	46.6 ± 8.3	40.7 ± 7.9
Ankle Eversion	28.8 ± 4.6	29.5 ± 6.0

The descriptive statistics of the subjects' hip, knee, and ankle stance phase running kinematics can be found in Tables 5, 6 and 7, respectively.

TABLE 5. Descriptive statistics of the hip kinematic variables of the male and female subjects (mean ± standard deviation).

Hip Kinematics		**Females**	**Males**
Sagittal Plane Flexion (+) / Extension (-)	Initial contact (˚)	44.3 ± 6.0	37.8 ± 4.1
	Toe-off (˚)	-6.5 ± 5.5	-4.8 ± 4.1
	Maximum angle (˚)	44.3 ± 5.9	38.8 ± 3.8
	Timing of maximum angle (%)	1.3 ± 3.2	11.7 ± 11.3
	Minimum angle (˚)	-6.5 ± 5.5	-4.8 ± 4.1
	Timing of minimum angle (%)	99.9 ± 0.4	100.0 ± 0.1
	Range of motion (˚)	50.8 ± 4.1	43.6 ± 3.4
Frontal Plane Adduction (+) / Abduction (-)	Initial contact (˚)	7.5 ± 3.7	3.6 ± 2.1
	Toe-off (˚)	-5.3 ± 2.4	-4.4 ± 1.7
	Maximum angle (˚)	16.8 ± 4.7	12.9 ± 2.2
	Timing of maximum angle (%)	35.6 ± 3.6	34.2 ± 3.3
	Minimum angle (˚)	-5.6 ± 2.3	-4.6 ± 1.6
	Timing of minimum angle (%)	97.6 ± 3.0	97.9 ± 2.6
	Range of motion (˚)	22.4 ± 5.2	17.6 ± 2.4
Transverse Plane Internal Rotation (+) / External Rotation (-)	Initial contact (˚)	5.1 ± 4.8	2.8 ± 5.4
	Toe-off (˚)	1.7 ± 7.1	3.6 ± 6.2
	Maximum angle (˚)	6.8 ± 5.8	8.2 ± 5.1
	Timing of maximum angle (%)	34.8 ± 39.0	67.9 ± 30.2
	Minimum angle (˚)	-8.6 ± 5.9	-5.6 ± 4.5
	Timing of minimum angle (%)	41.9 ± 13.0	39.7 ± 8.8
	Range of motion (˚)	15.4 ± 3.0	13.8 ± 5.8

TABLE 6. Descriptive statistics of the knee kinematic variables of the male and female subjects (mean ± standard deviation).

Knee Kinematics		**Females**	**Males**
Sagittal Plane Flexion (+) / Extension (-)	Initial contact (˚)	12.1 ± 4.8	10.6 ± 4.9
	Toe-off (˚)	9.0 ± 4.8	13.2 ± 4.7
	Maximum angle (˚)	47.6 ± 2.1	46.0 ± 2.9
	Timing of maximum angle (%)	40.0 ± 1.9	40.0 ± 1.7
	Minimum angle (˚)	7.6 ± 3.6	9.9 ± 4.8
	Timing of minimum angle (%)	63.4 ± 42.5	36.5 ± 32.9
	Range of motion (˚)	40.0 ± 3.2	36.1 ± 3.0
Frontal Plane Adduction (+) / Abduction (-)	Initial contact (˚)	0.9 ± 2.2	1.2 ± 2.6
	Toe-off (˚)	0.5 ± 2.0	0.5 ± 2.4
	Maximum angle (˚)	1.7 ± 2.0	2.0 ± 2.9
	Timing of maximum angle (%)	47.5 ± 39.8	45.0 ± 27.1
	Minimum angle (˚)	-6.0 ± 2.8	-3.3 ± 4.3
	Timing of minimum angle (%)	45.0 ± 8.6	53.0 ± 16.0
	Range of motion (˚)	7.8 ± 2.3	5.4 ± 2.3
Transverse Plane Internal Rotation (+) / External Rotation (-)	Initial contact (˚)	-13.8 ± 10.3	-17.0 ± 8.2
	Toe-off (˚)	-22.3 ± 12.5	-22.4 ± 5.9
	Maximum angle (˚)	3.3 ± 11.9	-2.4 ± 6.9
	Timing of maximum angle (%)	55.7 ± 7.1	47.7 ± 8.5
	Minimum angle (˚)	-22.4 ± 12.5	-23.2 ± 5.7
	Timing of minimum angle (%)	97.3 ± 8.8	82.4 ± 27.6
	Range of motion (˚)	25.7 ± 4.3	20.8 ± 3.8

TABLE 7. Descriptive statistics of the ankle kinematic variables of the male and female subjects (mean ± standard deviation).

Ankle Kinematics		**Females**	**Males**
Sagittal Plane Dorsiflexion (+) / Plantarflexion (-)	Initial contact (˚)	12.0 ± 2.9	12.4 ± 3.4
	Toe-off (˚)	-21.2 ± 3.7	-19.1 ± 5.1
	Maximum angle (˚)	27.7 ± 2.3	27.3 ± 2.4
	Timing of maximum angle (%)	55.9 ± 2.5	55.0 ± 2.0
	Minimum angle (˚)	-21.2 ± 3.7	-19.1 ± 5.1
	Timing of minimum angle (%)	99.9 ± 0.3	100.0 ± 0.0
	Range of motion (˚)	48.8 ± 4.2	46.5 ± 4.2
Frontal Plane Inversion (+) / Eversion (-)	Initial contact (˚)	-0.4 ± 0.8	-0.3 ± 0.6
	Toe-off (˚)	-1.2 ± 0.9	-0.9 ± 1.1
	Maximum angle (˚)	-0.1 ± 0.7	0.1 ± 0.7
	Timing of maximum angle (%)	40.9 ± 20.7	50.9 ± 26.7
	Minimum angle (˚)	-1.3 ± 0.9	-1.0 ± 1.0
	Timing of minimum angle (%)	79.9 ± 30.6	77.9 ± 28.5
	Range of motion (˚)	1.2 ± 0.6	1.1 ± 1.1
Transverse Plane Adduction (+) / Abduction (-)	Initial contact (˚)	5.9 ± 8.5	4.3 ± 4.3
	Toe-off (˚)	14.0 ± 7.7	12.0 ± 6.1
	Maximum angle (˚)	14.4 ± 7.6	12.5 ± 5.9
	Timing of maximum angle (%)	79.9 ± 30.6	87.2 ± 23.1
	Minimum angle (˚)	1.6 ± 7.3	0.6 ± 6.3
	Timing of minimum angle (%)	40.9 ± 20.7	42.6 ± 15.3
	Range of motion (˚)	12.8 ± 3.2	12.0 ± 2.9

7.2 Hip abduction strength and running kinematics

Please refer to Appendix 2 and 3 for a bar chart displaying all Spearman correlation coefficients computed between hip abduction PT/BW and running kinematics in male and female novice runners, respectively.

Several meaningful relationships were found between hip abduction strength and hip kinematics in the male subjects (Figure 16), but no significant correlations were observed in the females. In the sagittal plane, hip abduction strength was positively correlated with the hip angle at initial contact and the maximum hip angle. The strength of the relationships ranged from moderate to good. In the frontal plane, hip abduction strength was moderately and negatively correlated with the hip angle at toe-off, as well as the minimum hip angle.

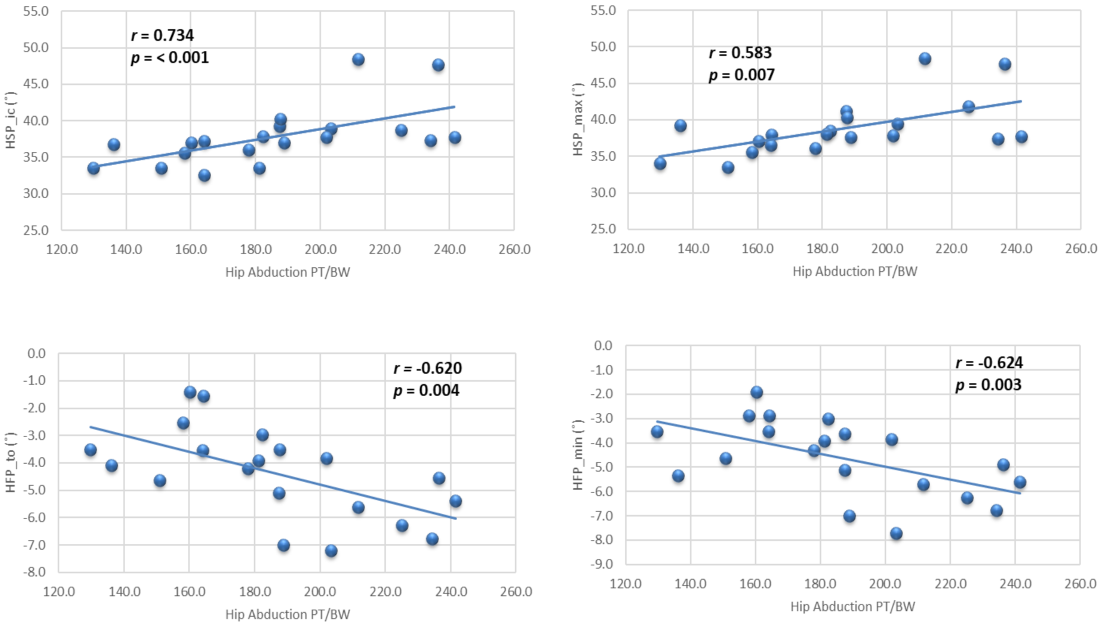


FIGURE 16. Scatterplots depicting significant correlations between peak hip abductor strength and hip kinematics in the male subjects.

Several significant associations were found between hip abduction strength and ankle kinematics in both male (Figure 17) and female (Figure 18) novice runners. In the male subjects, hip abduction peak torque was negatively correlated with the maximum frontal plane ankle angle, as well as the ankle ROM in the transverse plane. The strength of these relationships was fair and moderate, respectively. In the female subjects, hip abduction strength was fairly associated with the sagittal plane ankle angle at initial contact and moderately related to ankle ROM in the frontal plane.

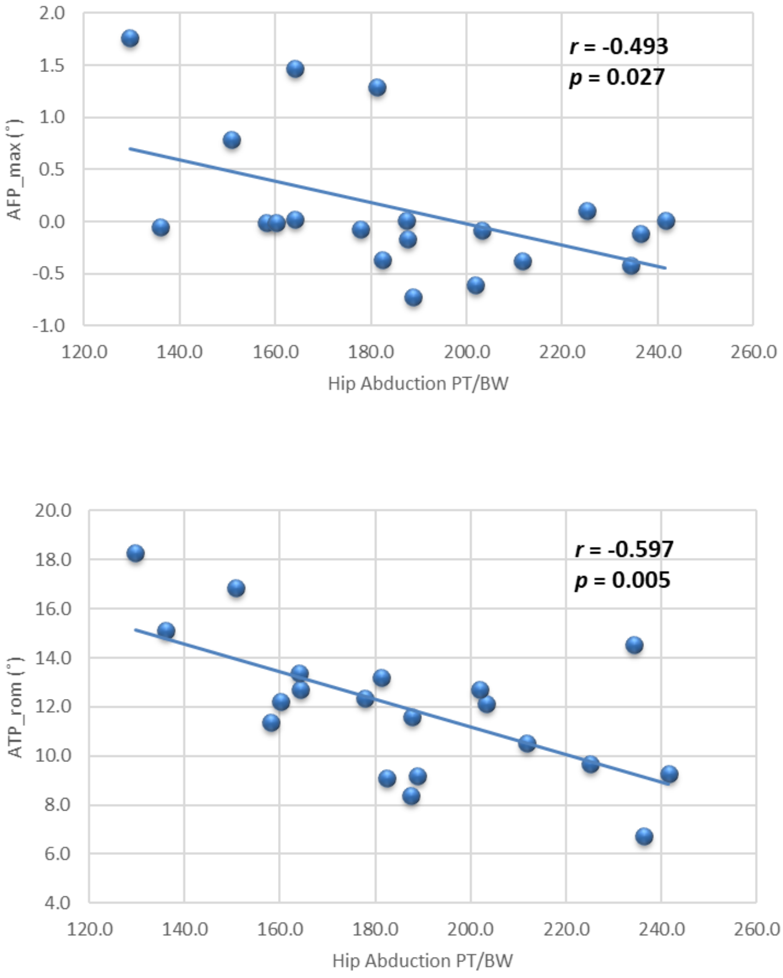
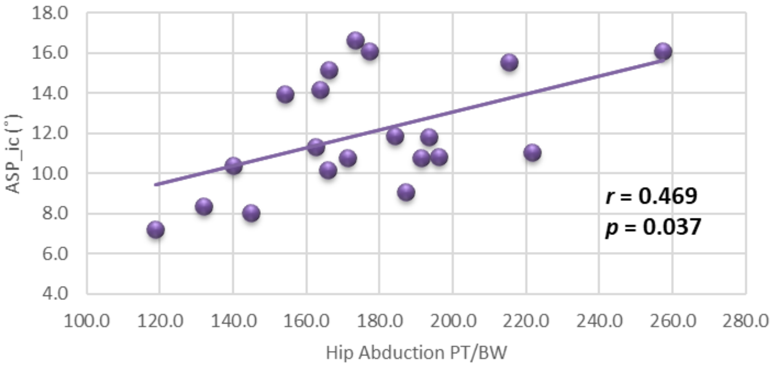


FIGURE 17. Scatterplots depicting the significant correlations found between hip abduction strength and ankle kinematics in the male subjects.



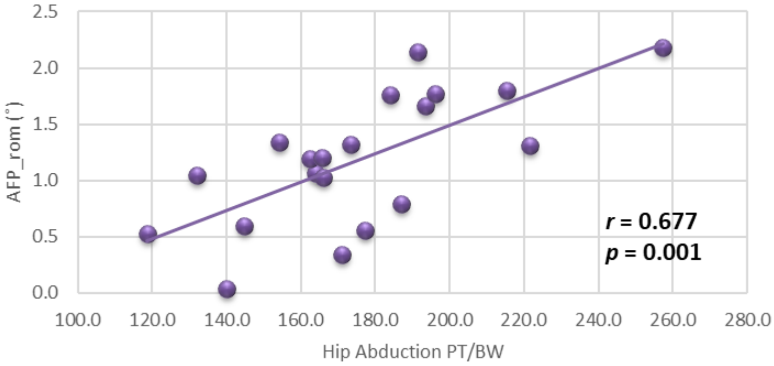


FIGURE 18. Scatterplots depicting the significant correlations found between hip abduction strength and ankle kinematics in the female subjects.

7.3 Hip adduction strength and running kinematics

Please refer to Appendix 4 and 5 for a bar chart displaying all Spearman correlation coefficients computed between hip adduction PT/BW and running kinematics in male and female novice runners, respectively.

Regarding hip kinematics, the only statistically significant finding was a moderate and negative association between hip adduction strength and the timing of the peak hip flexion angle in the male subjects.

Several significant associations were found between hip adduction strength and ankle kinematics in both males and females. Female novice runners demonstrated significant correlations between peak concentric hip adduction torque and non-sagittal ankle kinematics. In the transverse plane, hip adduction strength was fairly and positively correlated with the ankle angle at toe-off and the minimum angle (Figure 19). In the frontal plane (Figure 20), a strong negative correlation was observed between hip adduction torque and the ankle angle at toe-off, as well as the minimum ankle angle. Additionally, a moderate positive relationship was found between adduction strength and ankle ROM in the frontal plane.

In the male runners, significant correlations were observed between hip adduction strength and frontal plane ankle kinematics (Figure 21). Specifically, hip adduction strength was negatively and moderately correlated with the ankle angle at initial contact, the ankle angle at toe-off, the maximum ankle angle, and the minimum ankle angle.

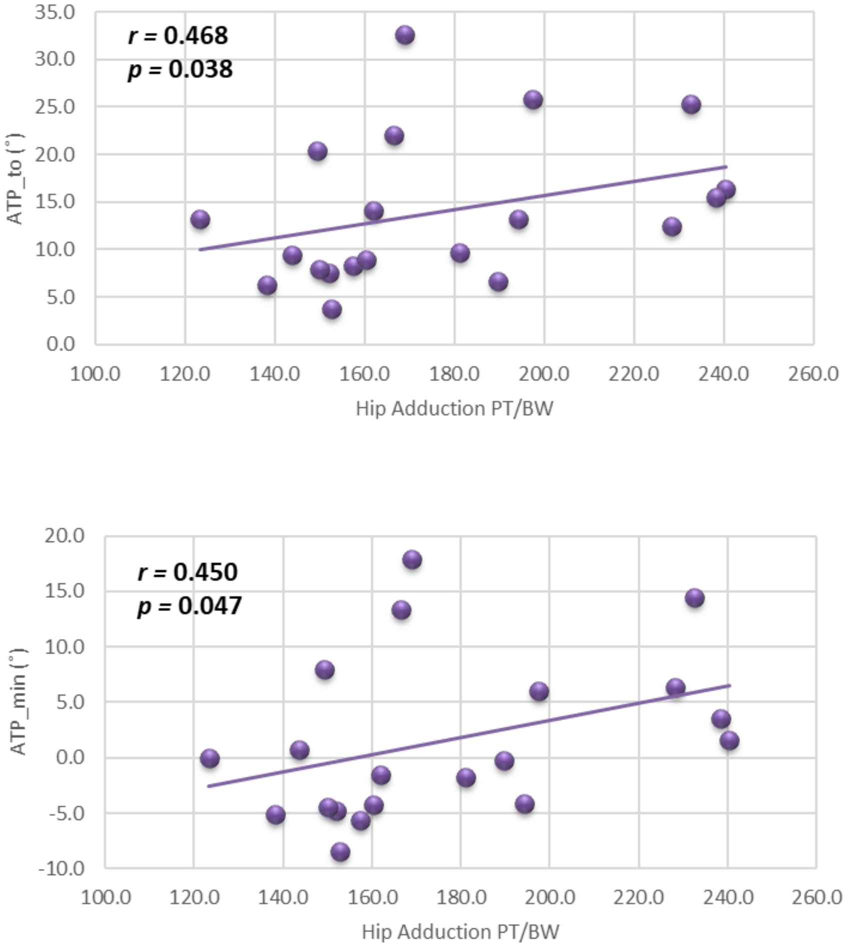
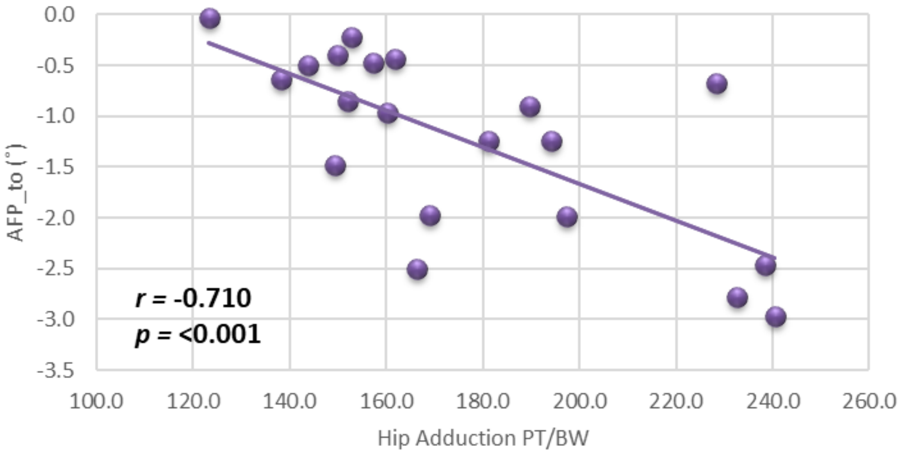
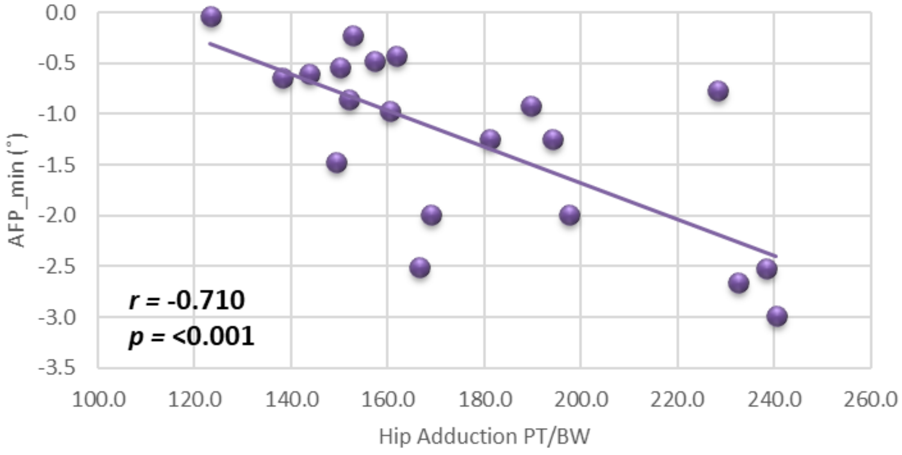


FIGURE 19. Scatterplots depicting the significant correlations found between hip adduction strength and transverse plane ankle kinematics in the female subjects.





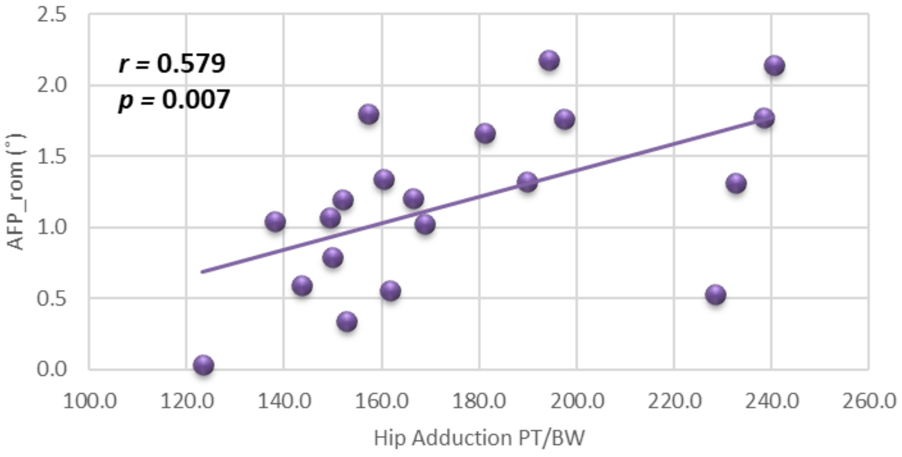


FIGURE 20. Scatterplots depicting the significant correlations found between hip adduction strength and frontal plane ankle kinematics in the female subjects.

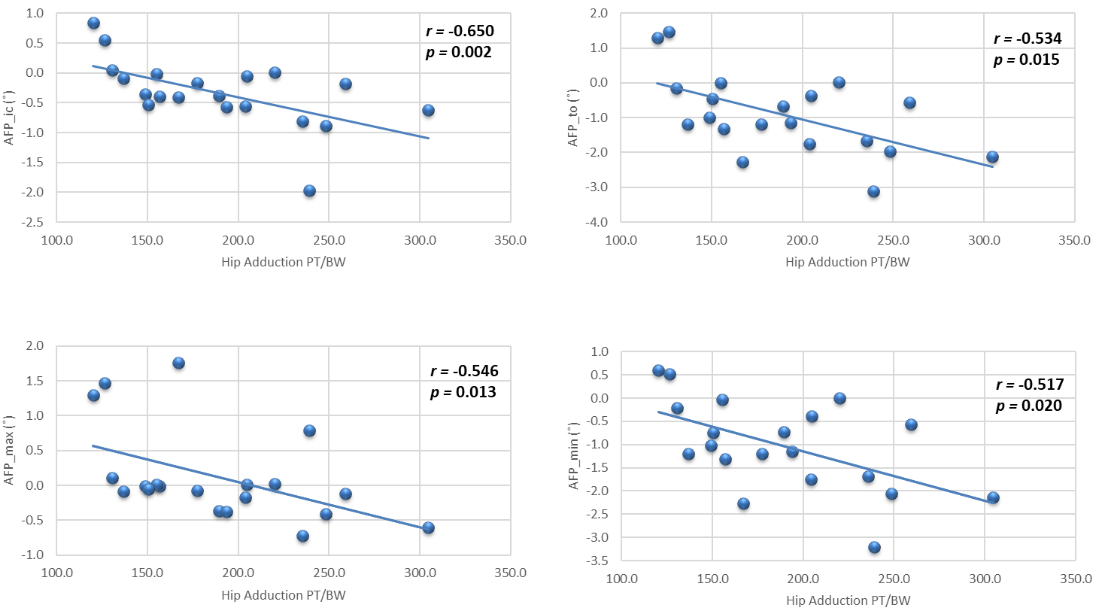


FIGURE 21. Scatterplots depicting the significant correlations found between hip adduction strength and frontal plane ankle kinematics in the male subjects.

7.4 Knee extension strength and running kinematics

Please refer to Appendix 6 and 7 for a bar chart displaying all Spearman correlation coefficients computed between knee extension PT/BW and running kinematics in male and female novice runners, respectively.

Several statistically significant associations were found between knee extension strength and hip kinematics in the male subjects (Figure 22), but no significant correlations were observed in the females. In the sagittal plane, there were negative and fair correlations between knee extensor strength and the hip angle at toe-off, as well as the minimum hip angle. In the frontal plane, there was a positive and fair correlation with the maximum hip angle, and a positive and moderate correlation with the timing of the maximum hip angle.

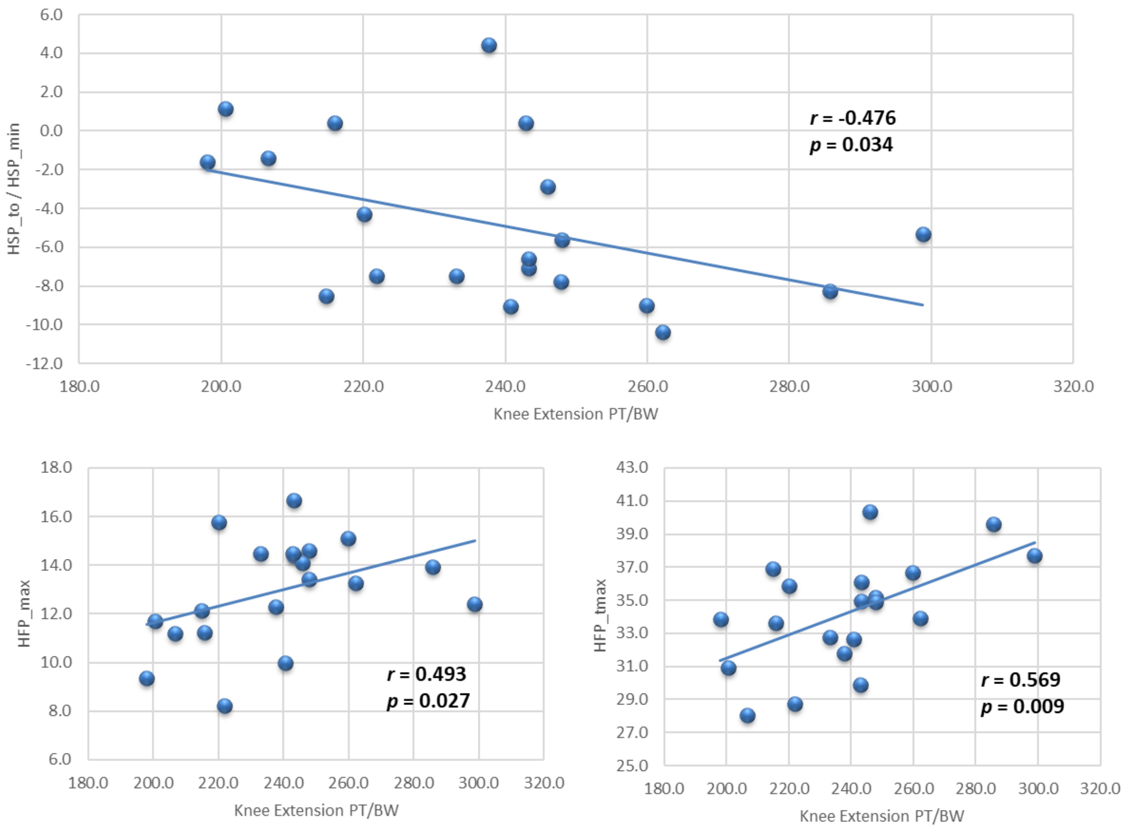


FIGURE 22. Scatterplots depicting the significant correlations found between knee extension strength and hip kinematics in the male subjects. HSP_to and HSP_min share the same plot since these two variables coincide.

No significant correlations were found between peak knee extension torque and knee kinematics in either the male or female subjects.

In the female runners, significant correlations were found between knee extensor strength and ankle kinematics in all three planes of movement. In the sagittal plane, there was a moderate, positive correlation between knee extensor strength and the ankle angle at initial contact (Figure 23). In the frontal plane, knee extensor strength was moderately and positively correlated with the timing of the minimum ankle angle and with ankle ROM. In the transverse plane, there was a moderate, positive correlation between the timing of the maximum ankle angle and knee extensor strength.

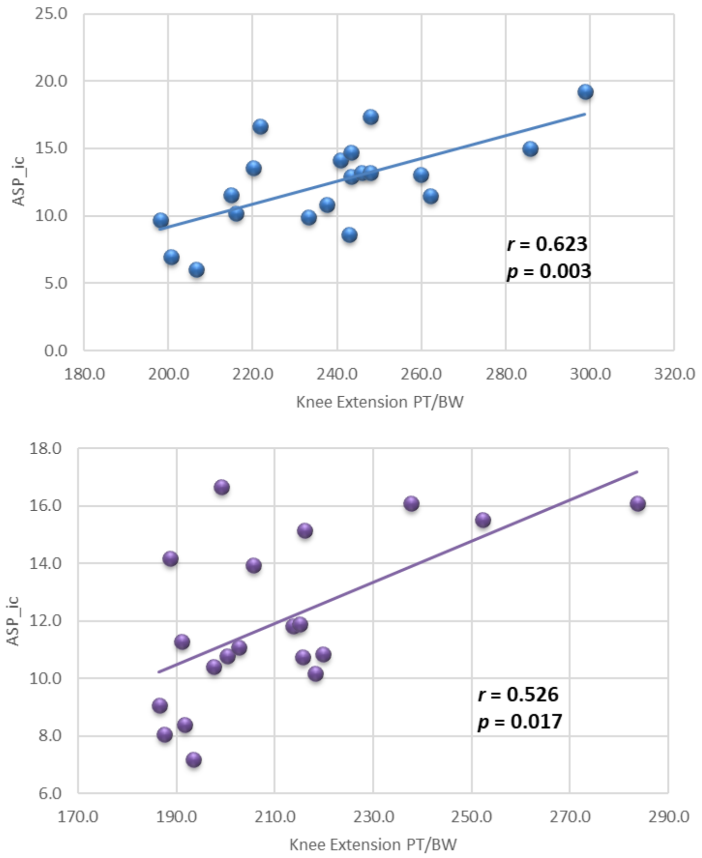


FIGURE 23. Scatterplots depicting a significant correlation between knee extension strength and the ankle sagittal plane angle at initial contact (ASP_ic) in the male (blue) and female (purple) subjects.

The male runners also exhibited significant correlations in all planes of movement. Similar to the females, knee extensor strength was moderately and positively correlated with the sagittal plane ankle angle at initial contact (Figure 23). In the frontal plane, knee extensor strength was fairly and negatively correlated with the timing of the maximum ankle angle, and fairly and positively correlated with the timing of the minimum ankle angle. In the transverse plane, knee extensor strength was fairly and positively correlated with the timing of the maximum ankle angle, and moderately and negatively correlated with the timing of the minimum ankle angle.

7.5 Knee flexion strength and running kinematics

Please refer to Appendix 8 and 9 for a bar chart displaying all Spearman correlation coefficients computed between knee flexion PT/BW and running kinematics in male and female novice runners, respectively.

The male subjects demonstrated several positive correlations between knee flexion strength and knee kinematics in the frontal plane (Figure 24). Specifically, there was a fair relationship between knee flexor strength and the knee angle at initial contact, as well as the minimum knee angle. Additionally, moderate correlations were found between knee flexor strength and the knee angle at toe-off, as well as the maximum knee angle. On the other hand, the only significant result in the female runners was a moderate and positive correlation between knee flexion strength and the maximum knee sagittal plane angle (Figure 25).

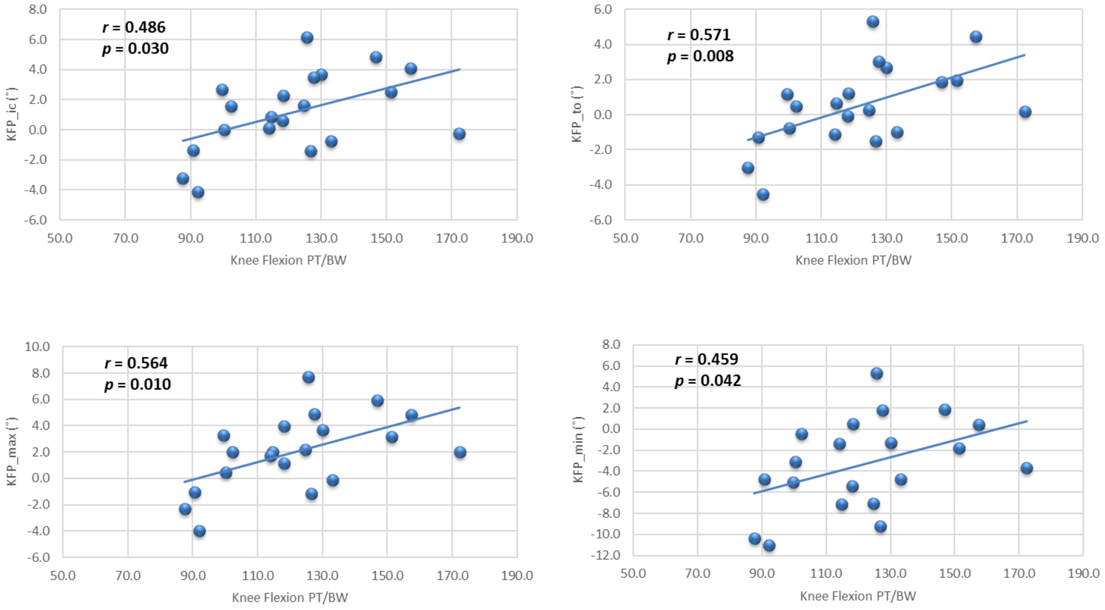


FIGURE 24. Scatterplots depicting the significant correlations found between knee flexion strength and knee kinematics in the male subjects.

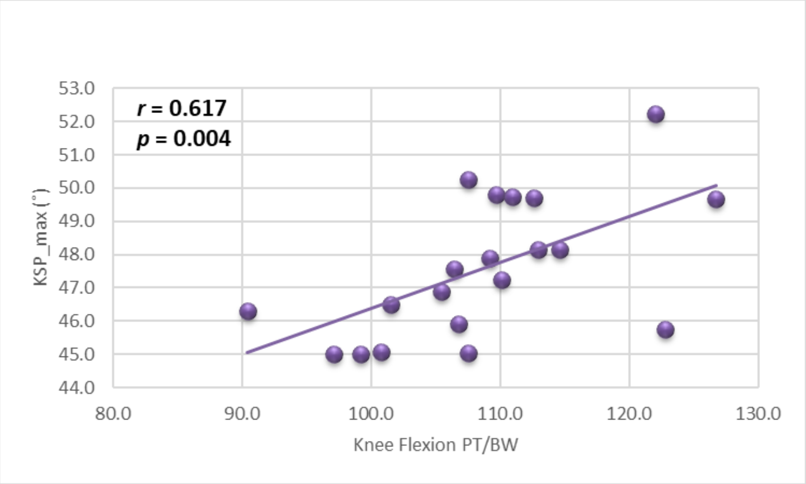


FIGURE 25. Scatterplot depicting a significant correlation between knee flexion strength and the maximum knee angle in the sagittal plane (KSP_max) in the female subjects.

Regarding ankle kinematics, the female subjects demonstrated a fair and positive correlation between knee flexor strength and ankle ROM in the sagittal plane (Figure 26). In the male runners, a moderate and negative correlation was observed between knee flexor strength and the maximum ankle angle in the frontal plane.

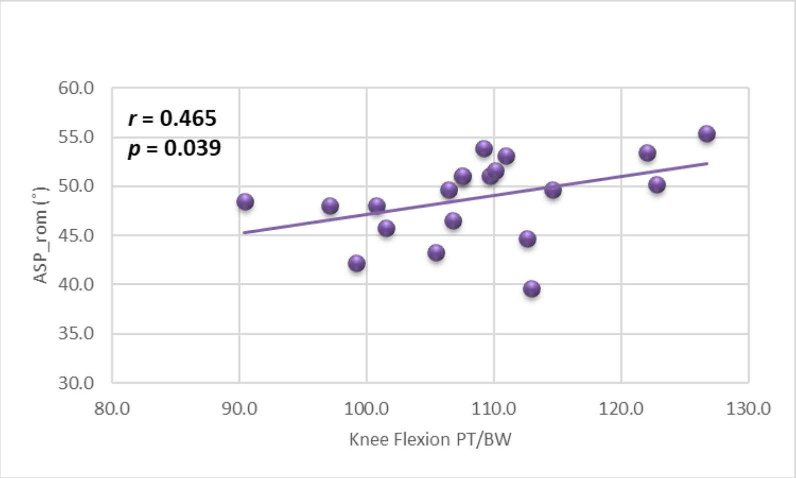


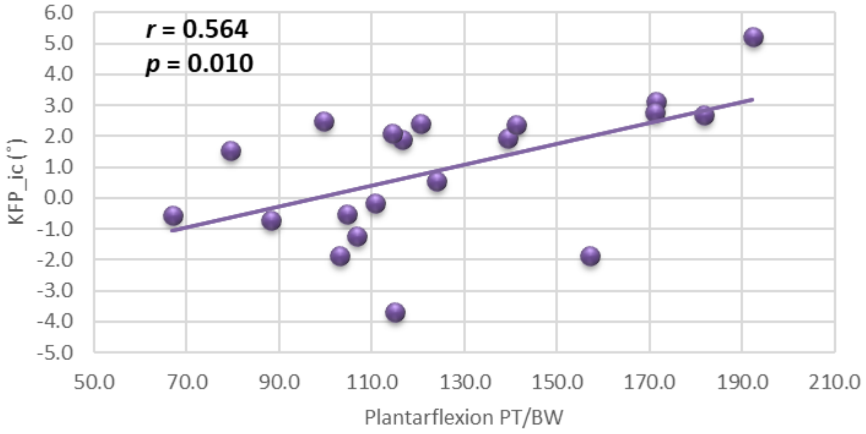
FIGURE 26. Scatterplot depicting a significant correlation between knee flexion strength and ankle range of motion in the sagittal plane (ASP_rom) in the female subjects.

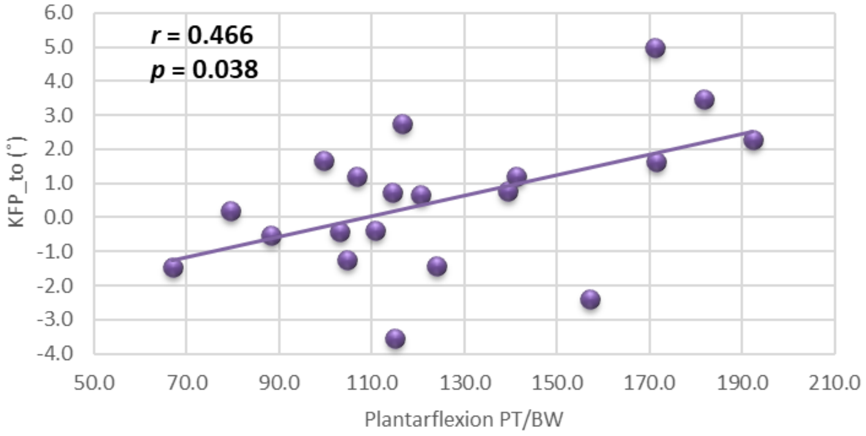
7.6 Ankle plantarflexion strength and running kinematics

Please refer to Appendix 10 and 11 for a bar chart displaying all Spearman correlation coefficients computed between ankle plantarflexion PT/BW and running kinematics in male and female novice runners, respectively.

No statistically significant correlations between plantarflexion strength and hip kinematics were observed in the female runners. Conversely, in the male subjects, significant correlations were observed in the sagittal and transverse planes. In the sagittal plane, there was a moderate and negative relationship between plantarflexion strength and the hip angle at toe-off, which also corresponds to the minimum hip angle. In the transverse plane, plantarflexion strength was moderately and negatively correlated with the hip angle at toe-off, and fairly and negatively correlated with the maximum hip angle.

Several statistically significant correlations were found between plantarflexion strength and knee kinematics in the female subjects, but none were observed in the males. In the sagittal plane, plantarflexion peak torque was positively and moderately correlated with knee ROM. In the frontal plane, plantarflexion strength showed positive correlations with the knee angle at initial contact, the knee angle at toe-off, and the maximum knee angle (Figure 27). The strength of these correlations ranged from fair to moderate. In the transverse plane, plantarflexion strength was positively and moderately correlated with knee ROM (Figure 28).





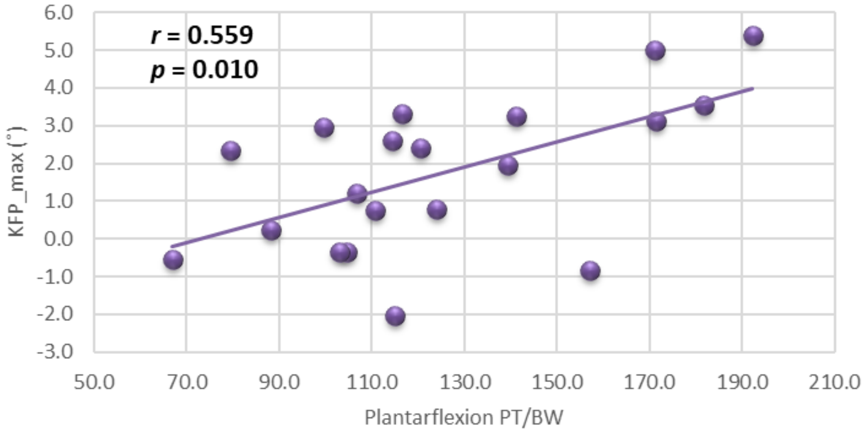


FIGURE 27. Scatterplots depicting the significant correlations found between plantarflexion strength and frontal plane knee kinematics in the female subjects.

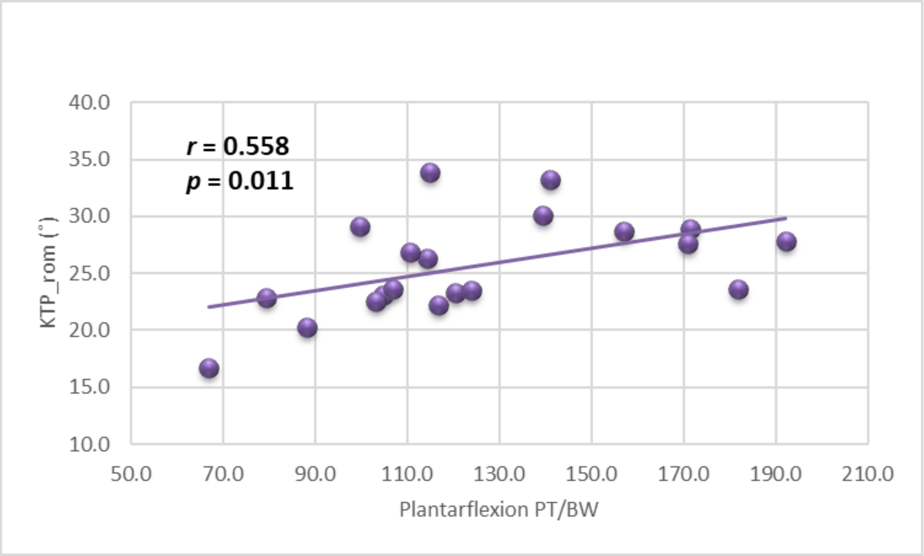
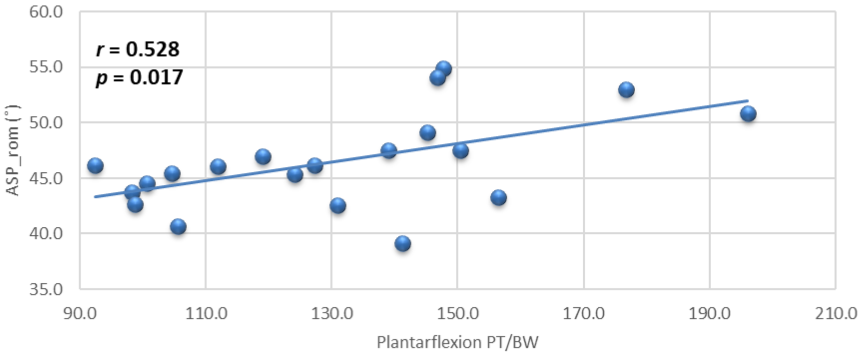


FIGURE 28. Scatterplot depicting a significant correlation between plantarflexion strength and knee range of motion in the transverse plane (KTP_rom) in the female subjects.

Both male and female novice runners exhibited several statistically significant correlations between peak concentric plantarflexion torque and ankle kinematics. In the female runners, significant correlations were observed in the sagittal plane. There was a negative and moderate correlation between plantarflexion strength and both the ankle angle at toe-off and the minimum ankle angle. Additionally, plantarflexion strength was positively and fairly related to the timing of the maximum ankle angle and the ankle ROM (Figure 29).



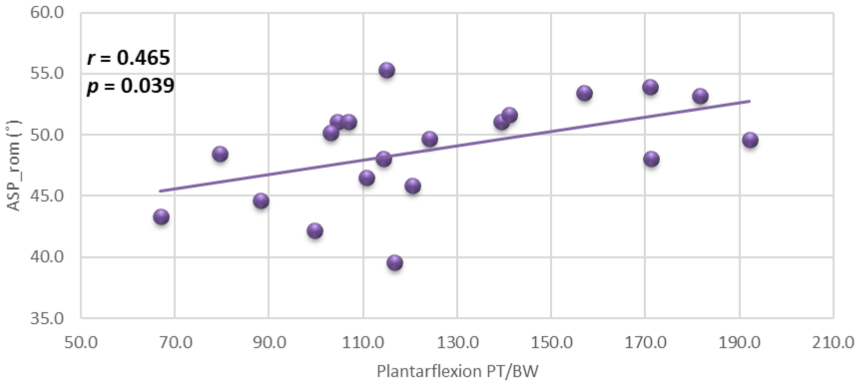


FIGURE 29. Scatterplots depicting a significant correlation between plantarflexion strength and ankle range of motion in the sagittal plane (ASP_rom) in the male (blue) and female (violet) subjects.

In the male subjects, significant correlations were observed between plantarflexion strength and ankle kinematics in the sagittal and transverse planes. In the sagittal plane, plantarflexion peak torque was strongly correlated with the ankle angle at initial contact (Figure 30) and moderately associated with ankle ROM (Figure 29). In the transverse plane (Figure 31), positive and moderate correlations were found between plantarflexion strength and the ankle angle at toe-off, the maximum ankle angle, and the minimum ankle angle. Furthermore, there was a negative and fair correlation between plantarflexion strength and the timing of the minimum ankle angle.

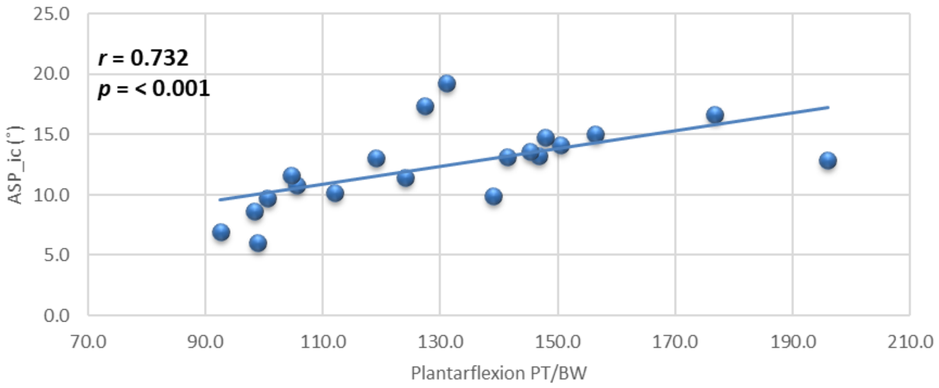


FIGURE 30. Scatterplot depicting a strong, positive correlation between plantarflexion strength and the ankle sagittal plane initial contact angle (ASP_ic) in the male subjects.

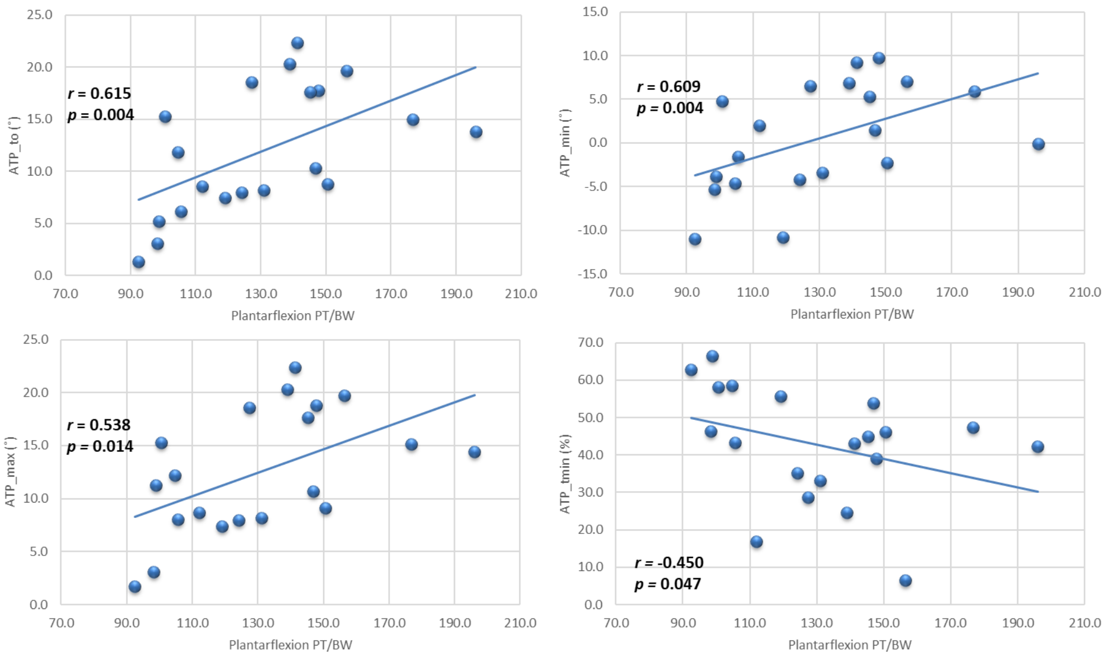


FIGURE 31. Scatterplots depicting the significant correlations found between plantarflexion strength and transverse plane ankle kinematics in the male subjects.

7.7 Ankle dorsiflexion strength and running kinematics

Please refer to Appendix 12 and 13 for a bar chart displaying all Spearman correlation coefficients computed between ankle dorsiflexion PT/BW and running kinematics in male and female novice runners, respectively.

Statistically significant correlations were found between dorsiflexion strength and transverse plane hip kinematics in both male and female subjects. In the female runners, dorsiflexion strength was positively and moderately correlated with the hip angle at toe-off and with the timing of the maximum hip angle. Similarly, in the male runners, a positive and moderate relationship was found between dorsiflexion strength and the timing of the maximum hip angle. Additionally, dorsiflexion strength exhibited a fair and positive correlation with hip ROM in the male runners.

Several statistically significant associations were found between dorsiflexion peak torque and knee kinematics. In the female runners, dorsiflexion strength was inversely correlated with several knee joint kinematics in the transverse plane (Figure 32). More specifically, dorsiflexion strength was correlated with the knee angle at initial contact, the knee angle at toe-off, the maximum knee angle, and the minimum knee angle. The strength of these correlations ranged from fair to moderate. In the male runners, the only significant result was a moderate and negative correlation between dorsiflexion strength and the timing of the maximum knee angle in the sagittal plane.

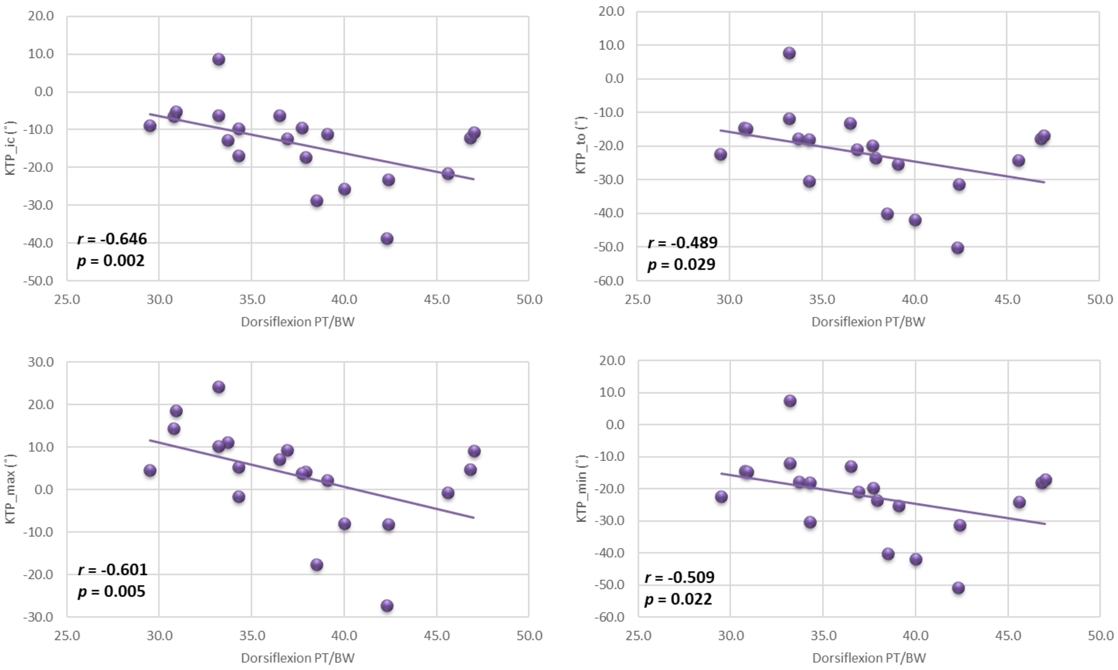


FIGURE 32. Scatterplots depicting the significant correlations found between dorsiflexion strength and knee kinematics in the female subjects.

The female runners exhibited multiple significant correlations between peak concentric dorsiflexion torque and ankle kinematics in both the sagittal and transverse planes. In the sagittal plane, there was a moderate positive correlation between dorsiflexion strength and the maximum ankle angle (Figure 33), as well as a moderate negative correlation with the timing of the maximum ankle angle (r = -0.542, p = 0.014).

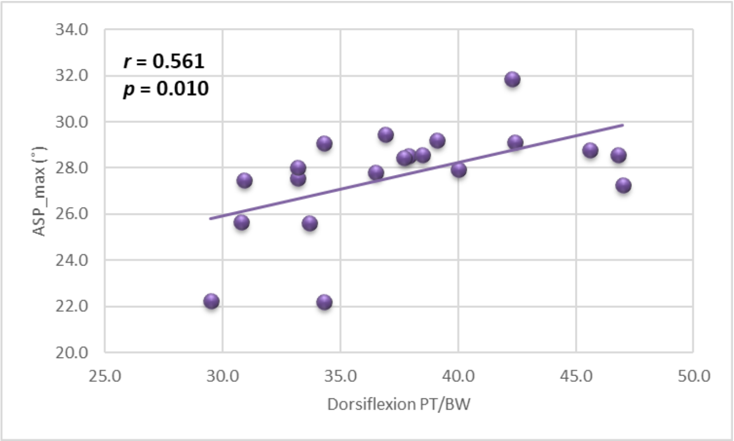


FIGURE 33. Scatterplot depicting a moderate, positive correlation between dorsiflexion strength and the ankle sagittal plane maximum angle (ASP_max) in the female subjects.

In the transverse plane, the females displayed fair positive correlations between dorsiflexion strength and the ankle angle at initial contact, the ankle angle at toe-off, and the maximum ankle angle (Figure 34).

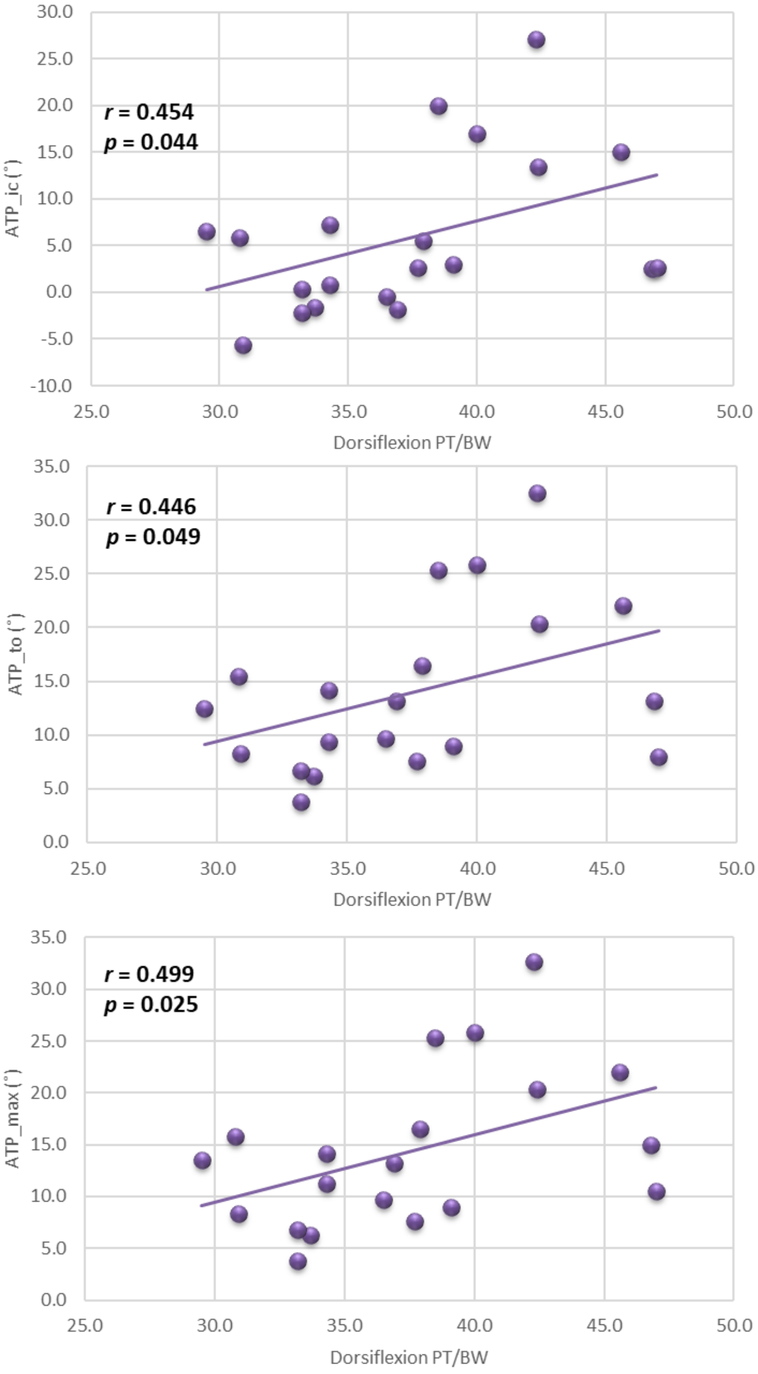


FIGURE 34. Scatterplots depicting the significant correlations found between dorsiflexion strength and transverse plane ankle kinematics in the female subjects.

7.8 Ankle inversion strength and running kinematics

Please refer to Appendix 14 and 15 for a bar chart displaying all Spearman correlation coefficients computed between ankle inversion PT/BW and running kinematics in male and female novice runners, respectively.

Figures 35 and 36 depict the significant associations between inversion strength and hip kinematics in the female and male subjects, respectively. In the sagittal plane, statistically significant fair and positive correlations were observed in the female novice runners. Specifically, inversion strength was correlated to the hip angle at initial contact, as well as the maximum hip angle.

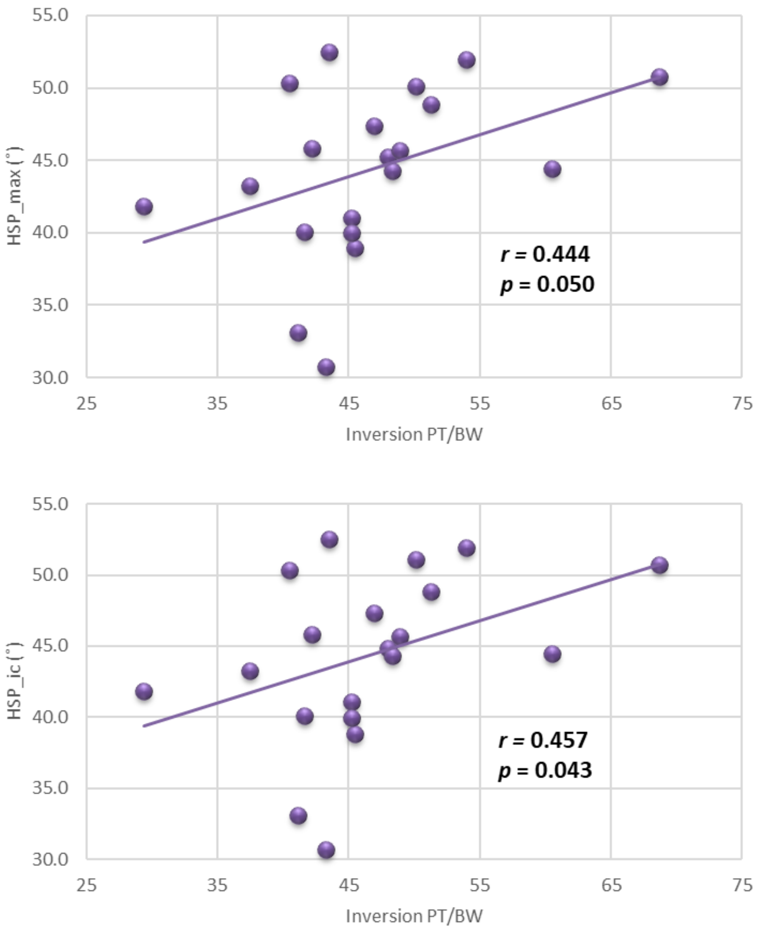


FIGURE 35. Scatterplots depicting the significant correlations found between inversion strength and hip kinematics in the female subjects.

The male runners also showed a fair correlation between inversion strength and the maximum hip angle in the sagittal plane. However, in contrast to the females, these two variables were negatively correlated. Male subjects also exhibited statistically significant correlations between inversion strength and non-sagittal running kinematics. In the frontal plane, inversion peak torque was moderately and positively correlated with the hip angle at initial contact. In the transverse plane, inversion strength was fairly and positively correlated with the minimum hip angle.

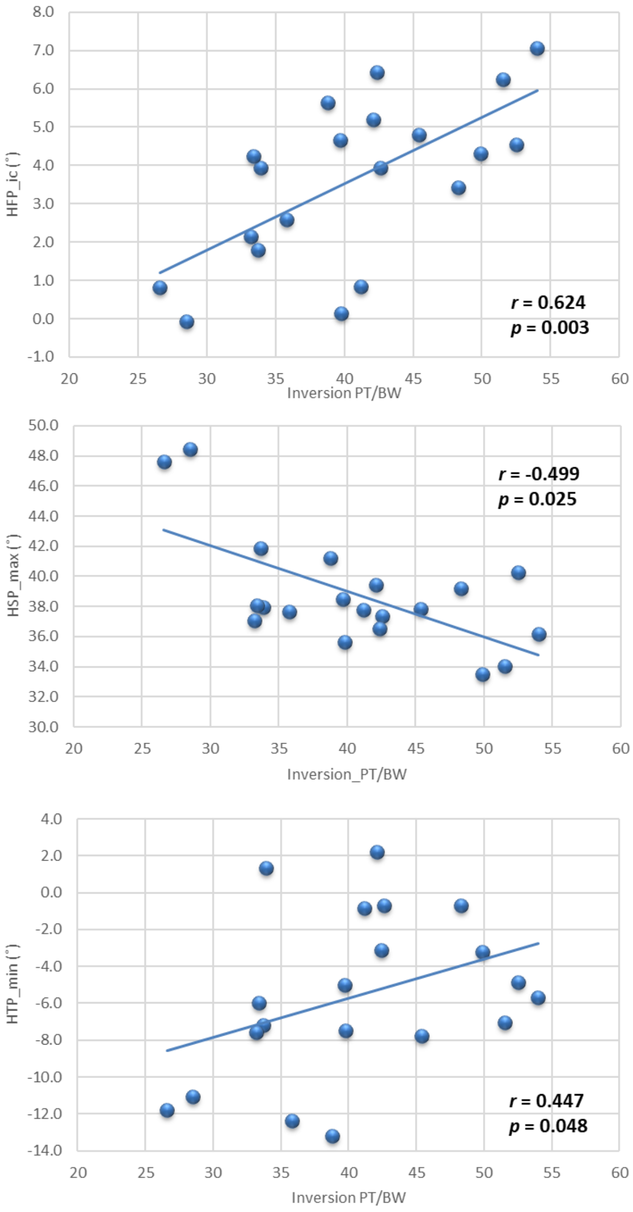


FIGURE 36. Scatterplots depicting the significant correlations found between inversion strength and hip kinematics in the male subjects.

Only the female subjects exhibited statistically significant associations between peak concentric inversion strength and knee joint kinematics (Figure 37). Ankle inversion strength was positively and fairly correlated with the timing of the maximum knee angle in both the sagittal and the transverse plane.

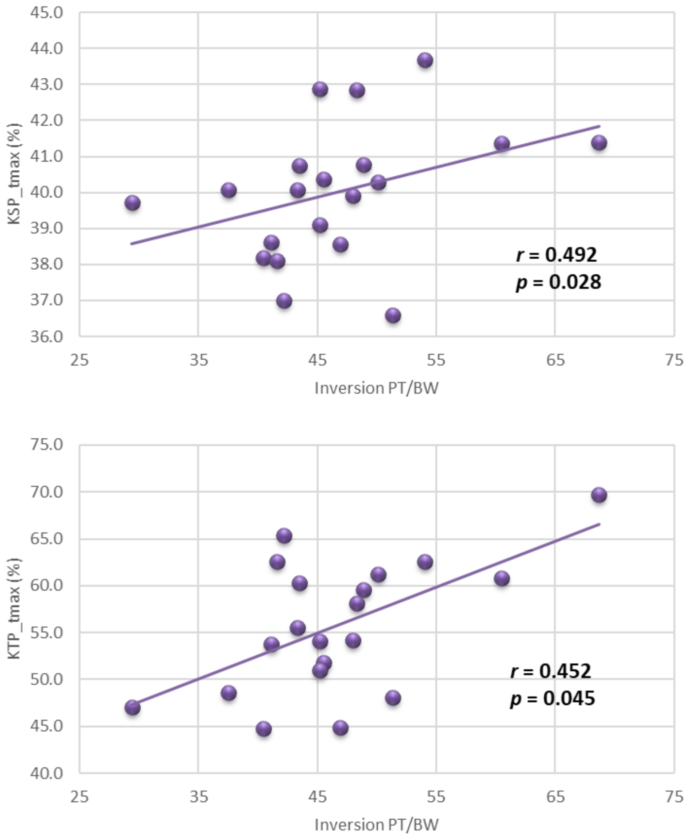


FIGURE 37. Scatterplots depicting the significant correlations found between inversion strength and knee kinematics in the female subjects.

The scatter plots of the significant correlations found between inversion PT/BW and ankle kinematics in the female subjects can be found in Figure 38. In the sagittal plane, the female runners showed a moderate positive correlation between inversion strength and the timing of the maximum ankle angle.

In the frontal plane, statistically significant correlations were observed in both males and females. Among the females, there was a fair negative correlation between inversion strength and the ankle angle at toe-off, as well as a good positive correlation between inversion strength and ankle ROM. In the males, inversion strength was negatively correlated with the ankle angle at toe-off and the minimum ankle angle, and positively correlated with the ankle ROM (Figure 39). The strength of these correlations ranged from fair to moderate. In the transverse plane, the males exhibited a positive moderate correlation between inversion PT/BW and the ankle ROM.

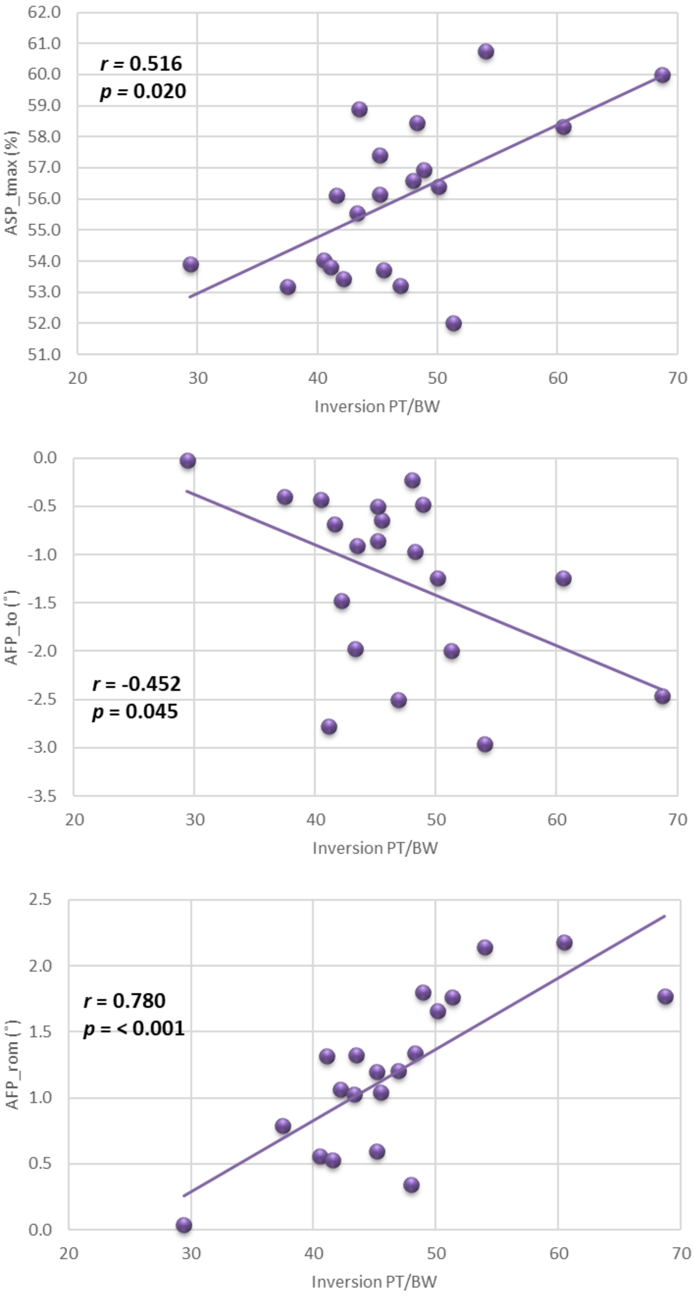


FIGURE 38. Scatterplots depicting the significant correlations found between inversion strength and ankle kinematics in the female subjects.

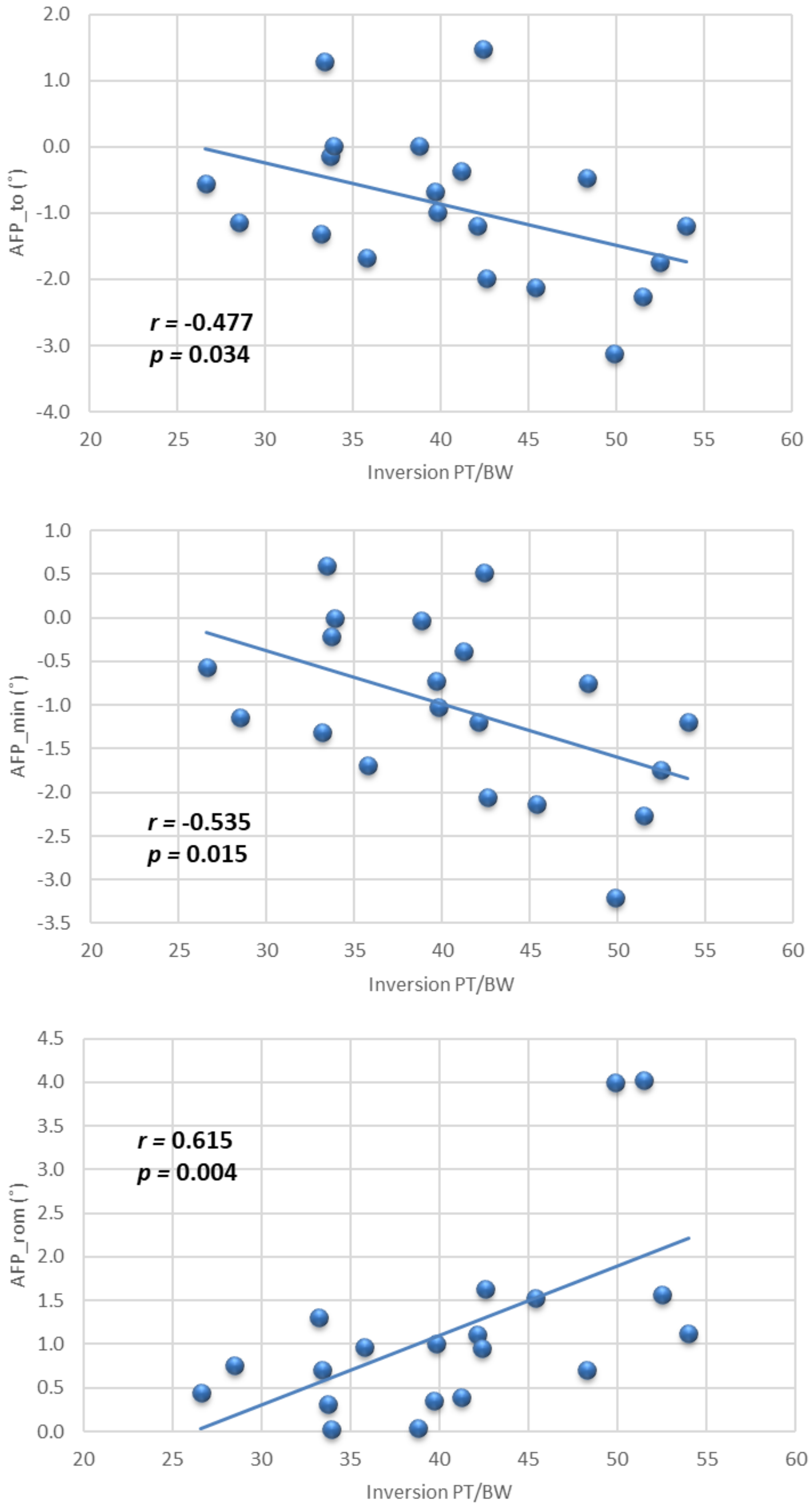


FIGURE 39. Scatterplots depicting the significant correlations found between inversion strength and frontal plane ankle kinematics in the male subjects.

7.9 Ankle eversion strength and running kinematics

Please refer to Appendix 16 and 17 for a bar chart displaying all Spearman correlation coefficients computed between ankle eversion PT/BW and running kinematics in male and female novice runners, respectively.

Eversion strength was not significantly correlated with any of the hip kinematic variables in either of the subject groups.

The female runners displayed several positive associations between eversion strength and knee joint kinematics in the sagittal plane, as depicted in Figure 40. More specifically, there were moderate and positive correlations between eversion strength and the knee angle at toe-off, as well as the maximum knee angle. Additionally, there was a positive and fair relationship between eversion strength and the minimum knee angle in the sagittal plane. In the male runners, significant results were observed in the frontal plane (Figure 41). These include positive and fair correlations between eversion strength and both the maximum and minimum knee angles.

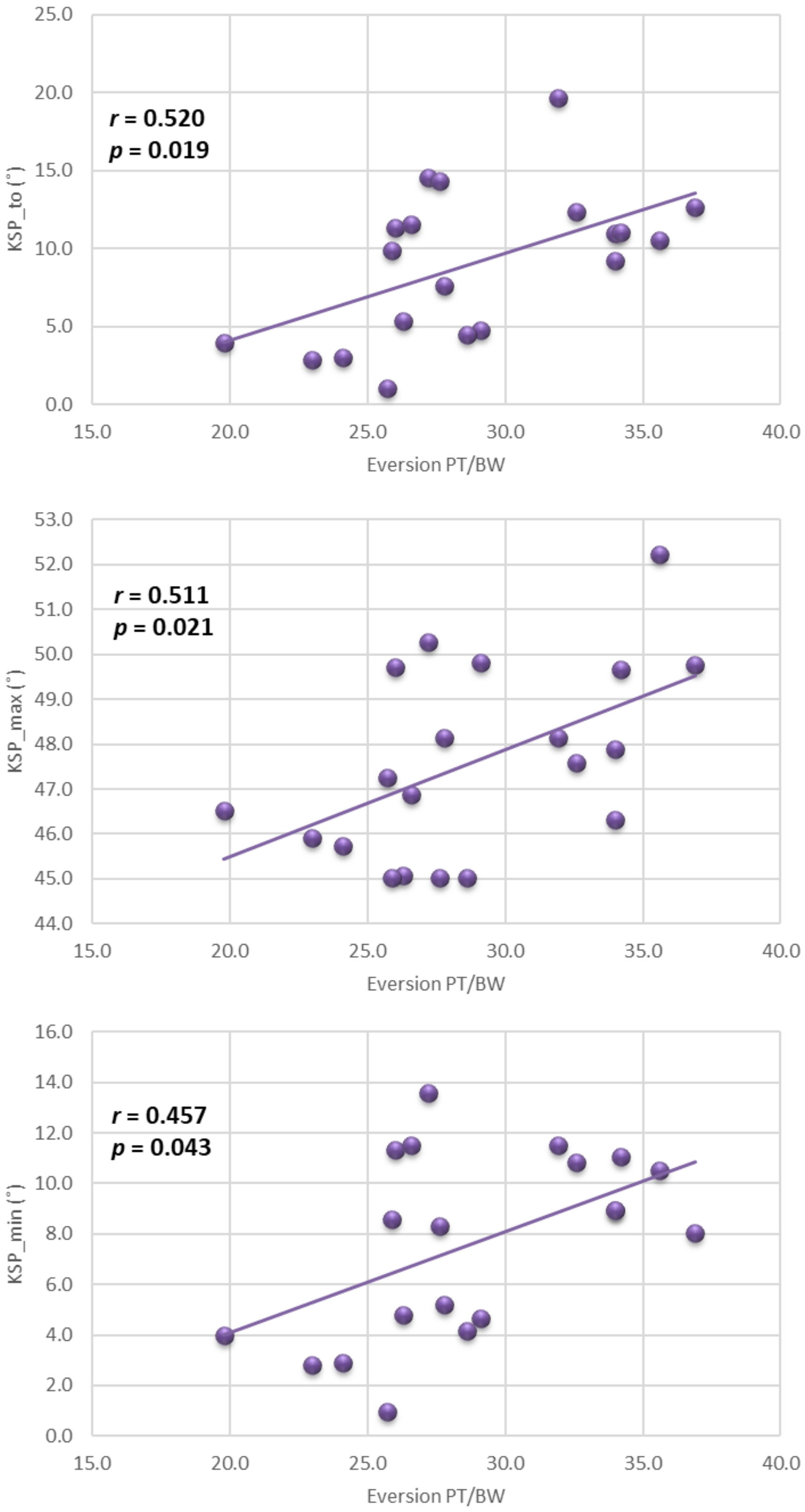


FIGURE 40. Scatterplots depicting the significant correlations found between eversion strength and knee kinematics in the female subjects.

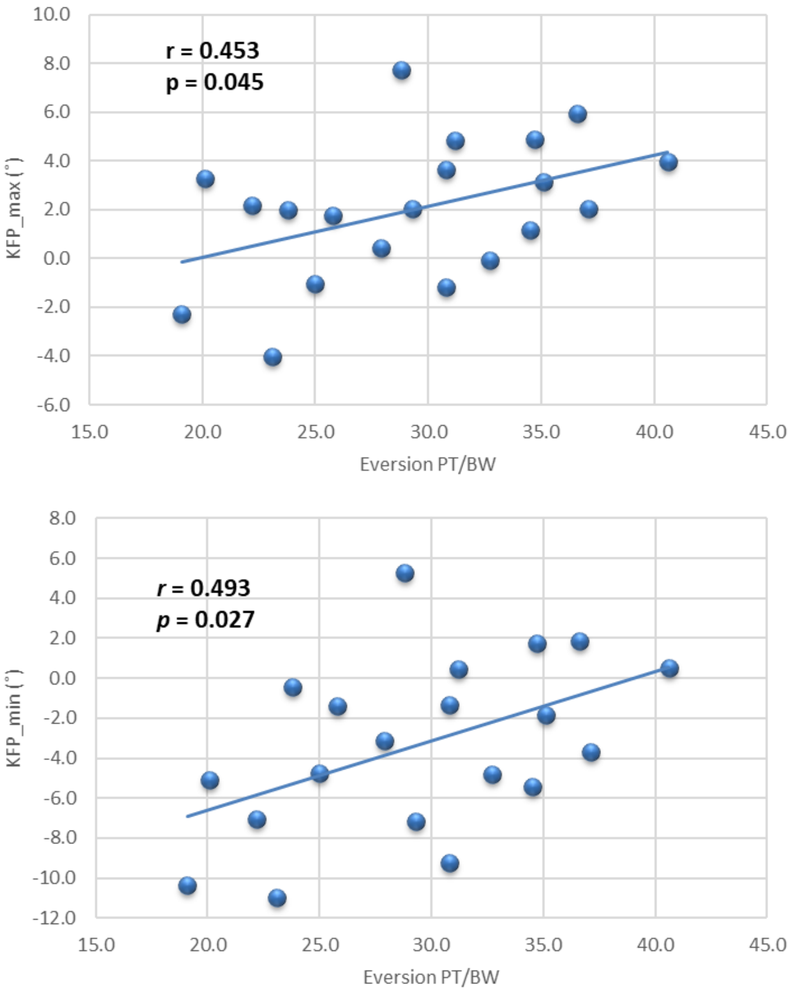


FIGURE 41. Scatterplots depicting the significant correlations found between eversion strength and knee kinematics in the male subjects.

Statistically meaningful correlations were found between eversion strength and ankle kinematics in the female runners (Figure 42). In the sagittal plane, there was a moderate positive correlation between eversion PT/BW and the maximum ankle angle, as well as the ankle ROM. In the frontal plane, a fair positive correlation was observed between the timing of the maximum ankle angle and eversion strength. In the transverse plane, eversion strength was fairly and positively correlated with the timing of the minimum ankle angle and moderately and positively correlated with ankle ROM. In contrast, no statistically significant correlations were found between ankle eversion strength and ankle kinematics in the male participants.

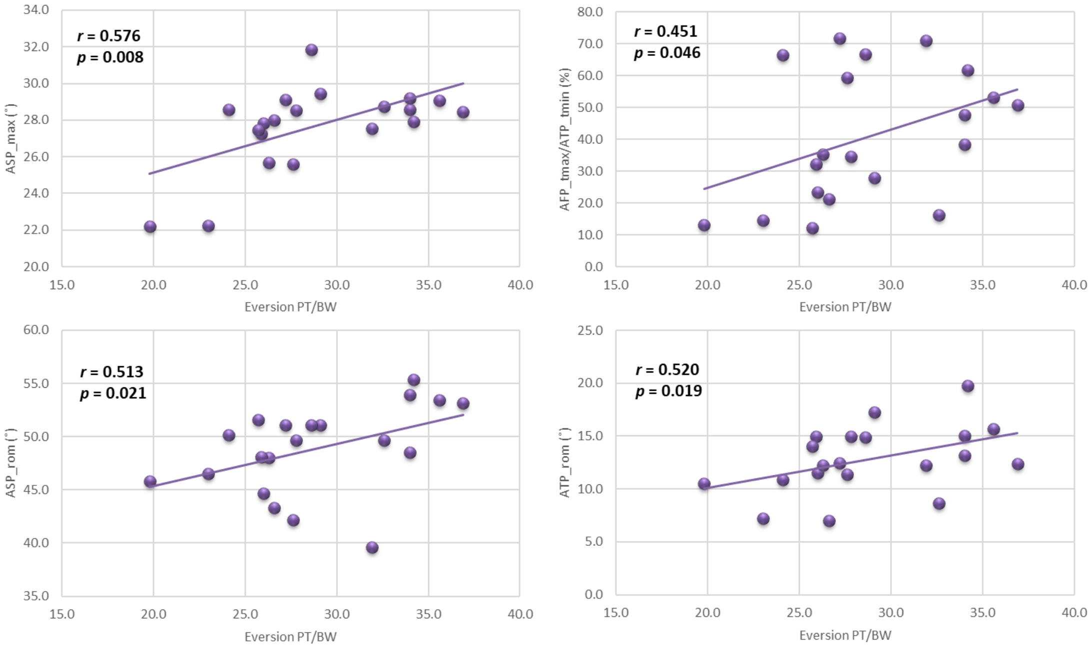


FIGURE 42. Scatterplots depicting the significant correlations found between eversion strength and ankle kinematics in the female subjects. AFP_tmax and ATP_tmin share the same plot since these two variables coincide.

8. DISCUSSION

The purpose of this study was to investigate the relationship between lower limb isokinetic strength and running kinematics in healthy novice runners. Based on the current literature, it was hypothesized that isokinetic hip abduction strength would be correlated with frontal plane hip kinematics but not with knee kinematics in the male runners. In female runners, it was hypothesized that isokinetic hip abduction strength would not be correlated with hip kinematics but would exhibit a correlation with frontal plane knee kinematics. Furthermore, ankle strength was expected to be related to several hip, knee and ankle joint kinematics. The findings are largely consistent with the initial hypotheses, except for the absence of significant correlations between hip abduction strength and knee kinematics in the female runners.

8.1 Hip abduction strength and running kinematics

In the female runners, peak hip abduction concentric torque was significantly correlated with sagittal and frontal plane ankle kinematics but was not related to hip or knee joint running kinematics. On the other hand, male runners demonstrated several significant correlations between hip abduction torque and running kinematics.

8.1.1 Hip abduction strength and hip kinematics

As hypothesised, no correlations were found between isokinetic hip abduction strength and hip kinematics in the female runners. This is in accordance with the prevailing trend in prior research involving healthy female runners (Baggaley et al., 2015; Brindle et al., 2020; Foch et al., 2020; Schmitz et al., 2014; Venable et al., 2022; Zeitoune et al., 2020). In contrast, Hannigan et al. (2018), found a significant correlation between hip abduction strength and hip adduction excursion in their female runners. Excursion angles were not measured in this study and thus it is not possible to compare results between these two studies. Nevertheless, it's worth noting that only 16% of the variance in hip kinematics could be described by hip abductor muscle strength, indicating that factors other than muscle strength are likely involved (Hannigan et al., 2018).

Most of the available studies examining the relationship between hip abductor strength and running kinematics assessed strength isometrically. The study by Venable et al. (2022) was the only one to assess hip abductor strength in female runners using isokinetic and concentric measurements, much like this study. Therefore, the results from this study confirm the findings of Venable et al. (2022) and add to the literature by demonstrating that a lack of correlation between isokinetic hip abductor strength and hip kinematics holds true not only for experienced runners but also for novice runners.

Greater peak hip adduction is a risk factor for iliotibial band syndrome and patellofemoral pain syndrome in female runners (Noehren et al., 2007; Noehren et al., 2013). Hip abductor weakness has long been a suspected culprit but hip abductor strengthening programs were not successful at reducing hip adduction during running (Snyder et al., 2009; Willy & Davis, 2011) or at reducing the incidence of overuse injuries (Toresdahl et al., 2020). The findings from this study point toward other potential contributors to these injury-related hip kinematics beyond deficiencies in hip abduction strength.

As hypothesised, hip abductor strength exhibited a moderate correlation with frontal plane hip kinematics in male novice runners. Specifically, stronger hip abductors were moderately associated with greater hip abduction at toe-off and a larger peak hip abduction angle. Although there is currently no comparative data available, the findings align with the functional role of the hip abductors in generating power during the latter part of the stance phase (Novacheck, 1998).

In contrast to the study by Taylor-Haas et al. (2014), no correlation between hip ROM in the frontal plane and isokinetic hip abductor strength was found in the male runners. This discrepancy could pertain to variations in the participants' age and running experience across the studies.

In line with Taylor-Haas et al. (2014), no statistically significant correlations were found between hip abductor strength and sagittal plane hip ROM in male runners. However, a strong positive correlation was observed between hip abductor strength and the hip flexion angle at initial contact, as well as a moderate positive correlation with the peak hip flexion angle. These associations have not been previously studied and merit further exploration.

No significant associations were identified between hip abductor strength and hip adduction kinematics or transverse plane hip kinematics in male novice runners, consistent with prior research findings (Brund et al., 2017; Hannigan et al., 2018; Taylor-Haas et al., 2014). These results provide a valuable addition to the existing literature, as this relationship has not been previously explored among novice runners.

8.1.2 Hip abduction strength and knee kinematics

It has been previously proposed that hip abductor weakness may allow for excessive femoral adduction during stance, which in turn may result in a more abducted knee, commonly referred to as knee valgus or dynamic valgus. Dynamic valgus is believed to increase lateral forces acting on the patella and it is commonly reported in patients suffering from patellofemoral pain syndrome. (Dierks et al., 2008; Petersen et al., 2014)

Contrary to both existing literature and the initial hypothesis, no significant correlations were observed between isokinetic hip abduction torque and knee kinematics in the female runners. In a separate prospective observational study involving collegiate cross-country female runners, a moderate positive relationship was found between isokinetic hip abduction strength and both the knee adduction angle at initial contact and the peak knee adduction angle (Venable et al., 2022). Furthermore, Heinert et al. (2008) found that recreational female athletes with weak hip abductors exhibited around 4° greater knee abduction during stance compared to their stronger counterparts. These disparities may be attributed to variations in participants' running backgrounds, age, and methodological approaches across the studies.

In line with this study’s hypothesis, hip abduction strength showed no overall association with knee kinematics in the male runners. Similarly, Taylor-Haas et al. (2014) did not identify any statistically significant associations between peak isokinetic hip abductor torque and knee ROM in any plane. Additionally, Brund et al. (2017) reported no correlations between eccentric hip abduction strength and non-sagittal knee kinematics in male recreational runners.

Overall, the findings from this study do not support the notion that isokinetic hip abductor strength is correlated with knee kinematics in healthy novice runners. In view of the lack of literature available, particularly concerning novice runners, further investigation is required to better understand the relationship between hip abductor muscle strength and knee kinematics.

8.1.3 Hip abduction strength and ankle kinematics

In the female runners, superior hip abductor strength was associated with increased dorsiflexion at initial contact and greater ankle ROM in the frontal plane. Similar to the findings from this study, Venable et al. (2022) found statistically significant correlations between hip abductor strength and frontal plane ankle kinematics in their cohort of female cross-country runners. Specifically, moderate correlations were reported between hip abductor strength variables and supination at initial contact, as well as peak pronation during stance (Venable et al., 2022).

In the male subjects, peak hip abduction torque was associated with a smaller peak inversion angle as well as decreased ankle ROM in the transverse plane. Frontal and transverse plane ankle kinematics are believed to be contributing factors in common RRIs such as patellofemoral pain syndrome (Barton et al., 2009; Duffey et al., 2000; Kindel et al., 2019). Studies examining the association between hip abduction strength and ankle kinematics in male runners are currently lacking. The results from this study imply that non-sagittal ankle kinematics may be related to isokinetic hip abductor strength in male novice runners. Additional research is warranted to confirm these findings and to better understand the link between hip abduction strength and more distal joint kinematics.

8.2 Hip adduction strength and running kinematics

To the author’s knowledge, there are no previous studies investigating the correlation between hip adductor strength and running kinematics.

The finding that hip adduction strength is associated with an earlier timing of peak hip flexion in male subjects aligns with the functional role of the hip adductors. In addition to hip adduction, the hip adductors contribute to pelvic stabilization and to sagittal plane hip movement. They assist the primary hip flexors and extensors to flex the hip when it is maximally extended and to extend the hip when it is in maximum flexion. During running, the involvement of the hip adductors generates more force to swing the leg faster. This is particularly relevant during flexion as it enables the runner to drive forward from the hip instead of the foot, reducing the risk of overstriding. (Neumann, 2010)

Several moderate to strong correlations were found between hip adduction strength and frontal plane ankle kinematic parameters in both male and female novice runners. In the female runners, stronger hip adductors were associated with overall greater ankle eversion and adduction during stance, as well as increased ankle ROM in the frontal plane. Similarly, males with stronger hip adductors exhibited greater ankle eversion throughout stance.

Various frontal plane ankle kinematics have been previously studied in relation to RRIs in different populations of runners. There is moderate evidence that reduced peak eversion is considered a risk factor for patellofemoral pain syndrome and iliotibial band syndrome in female recreational runners (Vannatta et al., 2020). Conversely, increased eversion has also been linked to injury. There is very limited evidence that greater eversion is a contributing factor in the development of Achilles tendinopathy in male and female recreational runners (Vannatta et al., 2020). Furthermore, greater peak eversion was related to higher injury risk in male and female cross-country runners (Becker et al., 2018 & Kuhman et al., 2016).

The results show that hip adduction strength is closely correlated with frontal plane ankle kinematics in healthy novice runners. Further research is required to examine whether similar associations exist in other populations of runners and whether interventions targeting the hip adductors are effective at reducing RRIs. Furthermore, due to a lack of studies on novice runners, the influence of altered running kinematics on the injury risk profile of this specific group is yet unknown.

8.3 Knee extension strength and running kinematics

Knee extension strength was associated with several hip kinematics in the male subjects, but not in the female runners. Additionally, no statistically significant correlations were found between knee extension strength and knee kinematics in either group of runners. To date, only one prior study has investigated the relationship between knee extensor strength and hip and knee kinematics. Moffit et al. (2020) failed to find any significant associations between knee extensor strength and peak hip extension, adduction, or internal rotation. Interestingly, their results align with the patterns observed in the female novice runners but contradict the findings in the male subjects. Similarly, Moffit et al. (2020) also did not observe any correlation between knee extensor strength and peak knee flexion, abduction, or internal rotation.

Several differences between the two studies should be noted. Moffit et al. (2020) measured knee extensor strength isometrically, whereas this study measured strength concentrically. The previous study involved a mixed-sex cohort of collegiate distance runners, unlike this study which focused on novice runners. Additionally, the statistical analysis in the previous study was conducted on the entire sample, and no sex-specific reports were available. These methodological differences are important to consider when comparing the two studies. Consequently, further research targeting novice runners is required to confirm the findings from this study regarding the relationship between knee extension strength and hip and knee kinematics.

Regarding ankle kinematics, knee extensor strength was associated with several parameters in all three planes of movement for both groups of runners. Notably, male and female runners with stronger knee extensors exhibited delayed peak eversion. This finding may be clinically meaningful since delayed peak eversion has been prospectively linked to an increased incidence of RRIs in recreational runners (Jungmalm et al., 2020). Future research should explore the generalizability of these findings to other populations of runners and assess the efficacy of interventions targeting the knee extensors in modifying eversion timing and reducing the risk of RRIs. To the best of the author's knowledge, no previous studies have investigated the relationship between knee extensor strength and ankle kinematics in uninjured runners. Given this gap in the literature, direct comparisons with existing findings are not feasible, emphasizing the distinct contribution of this study and highlighting the importance of further research in this area.

8.4 Knee flexion strength and running kinematics

This is the first study to investigate the relationship between isokinetic knee flexor strength and running kinematics. In the female subjects, greater knee flexor strength was associated with a more pronounced peak knee flexion angle and with increased ankle ROM in the sagittal plane. This finding could be clinically relevant since reduced knee flexion during stance may be indicative of compromised shock absorption capabilities, which could predispose runners to injury (Souza, 2016). Indeed, prospective studies have reported that runners who developed Achilles tendon injuries already exhibited diminished knee flexor strength, along with reduced peak knee flexion and dorsiflexion in an uninjured state (Hein et al., 2014; Stiffler-Joachim et al., 2023).

Among the male participants, knee flexor strength correlated with several frontal plane knee kinematic parameters indicating overall greater knee adduction during stance. Extreme varus and valgus knee positions during weight-bearing activities are thought to increase the load on the medial and lateral aspects of the knee, potentially leading to injuries. While there is still a lack of prospective evidence, a few studies have associated frontal plane knee kinematics with lower limb injuries. In one study, military recruits with a larger frontal plane projection angle during running, single-leg squat, and single-leg standing at baseline went on to developed patellofemoral pain syndrome (Alrayani et al., 2023). Another study found that recreational runners with less knee valgus and greater valgus-varus excursion were at a higher risk for general RRIs (Dillon et al., 2023). Additionally, team sport athletes displaying a larger frontal plane projection angle during the single-leg squat were 2.7 times more likely to sustain a lower extremity injury and 2.4 times more likely to develop an ankle injury (Räisänen et al., 2018).

Thus, these findings bear clinical significance as knee flexor strength was found to be associated with several injury-related running kinematics. Subsequent research is needed to identify whether similar associations between knee flexor strength and running kinematics are also present in other running populations. Moreover, future studies should investigate whether interventions targeting the knee flexors can effectively modify these injury-related running kinematics and, consequently, reduce the risk of injury.

8.5 Ankle strength and running kinematics

This is the first study to investigate the relationship between ankle strength and running kinematics in healthy novice runners. Therefore, a comparison with previous studies is not feasible due to the current lack of available data.

8.5.1 Ankle plantarflexion strength and running kinematics

Several statistically significant correlations were observed between plantarflexion strength and hip, knee, and ankle running kinematics. Notably, female novice runners with stronger plantarflexors exhibited overall greater knee adduction throughout stance as well as increased knee ROM in the transverse plane. In a recent prospective study, several frontal and transverse plane knee kinematic parameters were found to be associated with general RRIs in recreational runners (Dillon et al., 2023).Therefore, the finding that plantarflexion strength is correlated to non-sagittal knee kinematics could be relevant in clinical and research settings.

Plantarflexion strength was also associated with several sagittal plane ankle kinematics in both male and female novice runners. Notably, a strong positive correlation between plantarflexion strength and the ankle angle at initial contact was observed among the male subjects, indicating that runners with stronger plantarflexors exhibited greater ankle dorsiflexion at initial contact. Additionally, plantarflexion strength was associated with several transverse plane ankle kinematics in the male runners, indicating overall greater ankle adduction during stance.

8.5.2 Ankle dorsiflexion strength and running kinematics

Ankle dorsiflexion strength correlated with multiple running kinematic parameters. Specifically, female novice runners with greater dorsiflexor strength demonstrated a tendency toward a more externally rotated knee position (tibia) and increased ankle adduction throughout stance.

Greater peak knee internal rotation was found to be prospectively linked to the development of iliotibial band syndrome in female recreational runners (Noehren et al., 2007). Additionally, prospective research has established a connection between a smaller peak dorsiflexion angle and Achilles tendon injuries in runners (Hein et al., 2014; Stiffler-Joachim et al., 2023). This study reveals that female novice runners with stronger dorsiflexors exhibit reduced peak knee internal rotation angles and increased peak dorsiflexion angles. These findings suggest that increased dorsiflexion strength may be associated with a reduction in kinematic parameters linked to injuries. However, further research is needed to investigate whether these findings could be extended to other populations of runners and to examine whether strengthening the dorsiflexors would effectively mitigate the incidence of iliotibial band syndrome and/or Achilles tendon injuries.

8.5.3 Ankle inversion strength and running kinematics

The results concerning the relationship between inversion strength and running kinematics suggest that the invertors may have an impact not only on the ankle but also on joints further up the kinematic chain. In this study, inversion strength was associated with several hip and knee joint kinematics occurring during the absorption phase of stance, suggesting a potential contribution to shock attenuation. For instance, female novice runners with stronger invertors landed with a more flexed hip upon initial contact and had a greater peak hip flexion angle.

Additionally, invertor strength correlated with greater eversion as well as increased ankle ROM in the frontal plane in both male and female novice runners. These results were unexpected considering the invertors' role in controlling pronation. One potential explanation could be the notable variability in the non-sagittal ankle kinematic data

(Table 7). Thus, results related to non-sagittal ankle kinematics should be interpreted with caution. Another factor to consider is that strength was measured concentrically. In accordance with the principle of specificity, concentric strength measures may not adequately reflect the eccentric action of the invertors during the loading phase.

8.5.4 Ankle eversion strength and running kinematics

Concentric eversion strength was correlated with several ankle kinematic parameters in the female subjects but not in the males. With regards to knee kinematics, eversion strength was associated with overall greater knee flexion in the females and with greater knee adduction in the males. As previously mentioned, frontal plane knee kinematics have been associated with RRIs, although prospective evidence is still greatly limited and somewhat conflicting. Eversion strength was not correlated to hip kinematics in either group of novice runners.

As hypothesised, concentric ankle strength was found to be associated with several injury-related running kinematics. These findings support the idea that strengthening the muscles of the foot and ankle could alter joint mechanics higher up the kinematic chain. While the underlying mechanisms are not yet fully understood, it has been previously reported that a "ground-up approach" was effective at reducing the incidence of RRIs (Taddei et al., 2020).

8.6 Strengths and limitations

This study holds several key strengths. It is the first study to assess the relationship between leg strength and running kinematics in novice runners. It stands alone in its comprehensive analysis, encompassing multiple kinematic variables and isokinetic leg strength measurements. Furthermore, this study presents data on unique kinematic parameters in both female and male novice runners. This data not only provides a valuable reference for future comparative studies but also contributes to understanding sex-specific running patterns. However, it is crucial to acknowledge the use of shoe-mounted markers, a method that introduces a potential source of variability. Previous research has highlighted differences in frontal and transverse plane ankle kinematics between shoe- and skin-mounted markers (Sinclair et al., 2013), necessitating caution in interpreting these results.

Additionally, the separate analysis of data for males and females aligns with recommendations from previous studies (Vannatta et al., 2020). This approach is crucial, given the dissimilar running patterns and distinct injury-risk profiles observed between sexes (Bazuelo-Ruiz et al., 2018).

This study is not without limitations. The primary constraint lies in the small sample size, coupled with high variability, especially within the non-sagittal kinematic parameters (Tables 5, 6, 7). Due to the limited sample size, the non-parametric Spearman Correlation test was used, which is a less powerful statistical test when compared to its parametric equivalent. Collectively, these factors reduce the statistical power of the study and may also increase the likelihood of type 1 errors. Furthermore, most statistically significant correlations observed exhibit fair to moderate strength, suggesting that variables beyond leg strength may influence the measured joint kinematics. Therefore, caution should be exercised when interpreting the study's findings.

The omission of foot posture assessment and the lack of footwear standardization represent additional limitations. Previous studies report altered foot kinematics during walking and running between subjects with normal-arched feet and those with flat feet or high-arched feet (Djun & Chay, 2021; Ho & Tan, 2022; Levinger et al., 2010). Thus, it is possible that some of the subjects had altered foot posture which may have influenced the results. The choice of footwear, unstandardized in this study, introduces a potential confounding factor, as different footwear types may influence running kinematics (Becker & Borgia, 2020; Willy & Davis, 2014). While efforts were made to account for footwear differences using sole thickness measurements, potential variations in running mechanics associated with diverse footwear were not entirely eliminated.

8.7 Future directions

In this study, peak isokinetic concentric strength was used as a measure of lower-limb strength. Since running is a submaximal activity, maximal strength may not accurately represent the strength demands during running. Future studies should consider other characteristics of muscle function such as neuromuscular control, muscle activation patterns and muscular endurance.

Current literature suggests that runners may demonstrate altered kinematics and reduced muscle strength when in an exerted state, which may increase their risk of injury (Borgia et al., 2022; Dierks et al., 2010; Riazati et al., 2020). Studies investigating the relationship between lower-limb strength and running kinematics, including the current study, have typically tested the subjects in a rested and non-fatigued state. Testing runners at exertion levels comparable to those experienced during training could potentially reveal important and more meaningful correlations that might otherwise go unnoticed. For instance, hip abduction strength did not show a correlation with the hip adduction angle at the start of a prolonged run in runners with patellofemoral pain syndrome. However, by the end of the run, these two variables exhibited a strong correlation (Dierks et al., 2008). Thus, future research should keep this into consideration.

Such considerations could enhance the applicability of research findings to real-world running scenarios and contribute to a better understanding of the relationship between lower-limb strength and running kinematics.

9. CONCLUSION

Muscle weakness and altered kinematics have been identified as risk factors for various RRIs, resulting in increased interest in exploring the connection between strength and running kinematics. While most studies have primarily examined muscle strength isometrically, yielding inconclusive results, the predominant concentric and eccentric muscle actions in running suggest that isokinetic testing may offer a more valid and task-specific measure of strength. Moreover, there is a notable gap in research investigating the relationship between ankle strength and running kinematics.

The purpose of this thesis was to investigate the association between lower-limb isokinetic strength and running kinematics in healthy novice runners. Male and female novice runners exhibited different associations between lower-limb strength and running kinematics. As predicted, the male runners exhibited a correlation between hip abductor strength and frontal plane hip kinematics but not knee kinematics. In line with the initial hypothesis, no correlations were found between isokinetic hip abduction strength and hip kinematics in the female runners. Contrary to the hypothesis, there were no significant correlations between isokinetic hip abduction torque and knee kinematics in the female runners. Nonetheless, as anticipated, several statistically significant correlations were identified between isokinetic ankle strength and running kinematics in both male and female novice runners.

This is the first study to include such a comprehensive analysis of the relationship between lower-limb strength and running kinematics. Several statistically significant correlations were observed between lower-limb isokinetic strength and injury-related kinematic parameters. While these findings are promising, further research is imperative to confirm the results from this study and assess the efficacy of lower-limb strengthening in altering running kinematics and mitigating the risk of RRIs.

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APPENDIX 1

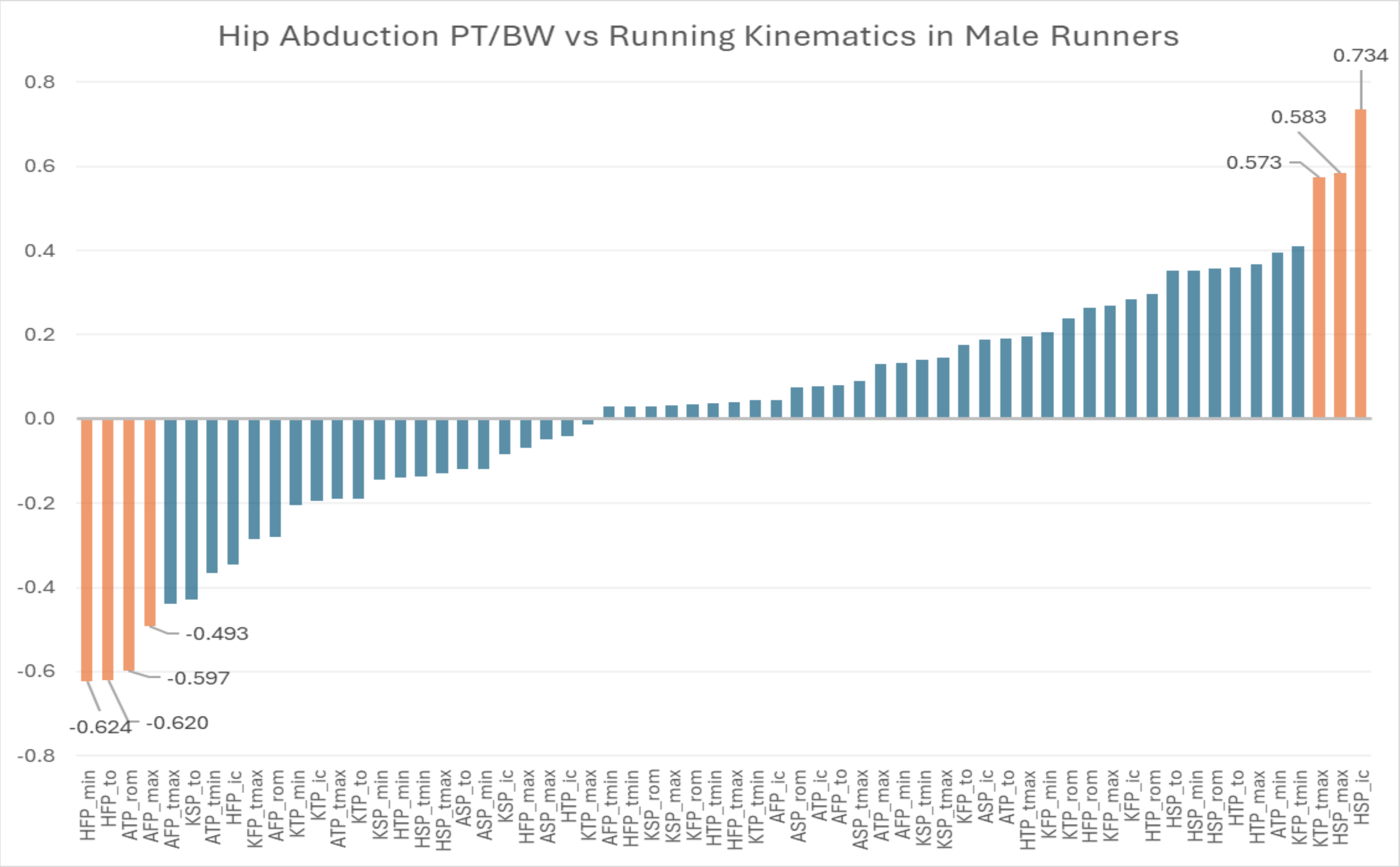
Methodological details of the studies investigating the relationship between lower extremity strength and running kinematics.

HDD – handheld dynamometry, n/a – not available

Study	Population	Running Background	Muscle Strength Test	Kinematic Analysis
Baggaley et al., 2015	Females 18 - 40 years	≥ 30 min, 3x/week	Isometric	Speed – standardized Surface - treadmill Shoes - standardized Foot markers – n/a
Brindle et al., 2020	Females 18 - 45 years	≥ 16km/week, 1 year/more	Eccentric - HHD	Speed – standardized Surface - overground Shoes - standardized Foot markers - skin
Brund et al., 2017	Males 18 – 60 years	≥ 2x/week, min 2 years	Eccentric – isokinetic dynamometer	Speed – standardized Surface - treadmill Shoes – n/a Foot markers – shoes
Foch et al., 2020	Females 18 - 45 years	≥ 10km/week	Isometric – isokinetic dynamometer	Speed – self-selected Surface - treadmill Shoes – standardized Foot markers – skin
Hannigan et al., 2018	Mixed (seperate analysis) 18 - 60 years	≥20 miles/week	Isometric – Biodex dynamometer	Speed – self-selected Surface - overground Shoes – not standardized Foot markers - n/a
Heinert et al., 2008	Females recreational athletes	Athletic/aerobic activity ≥ 3x/week	Isometric – HHD	Speed – standardized Surface - treadmill Shoes – standardized Foot markers – shoes

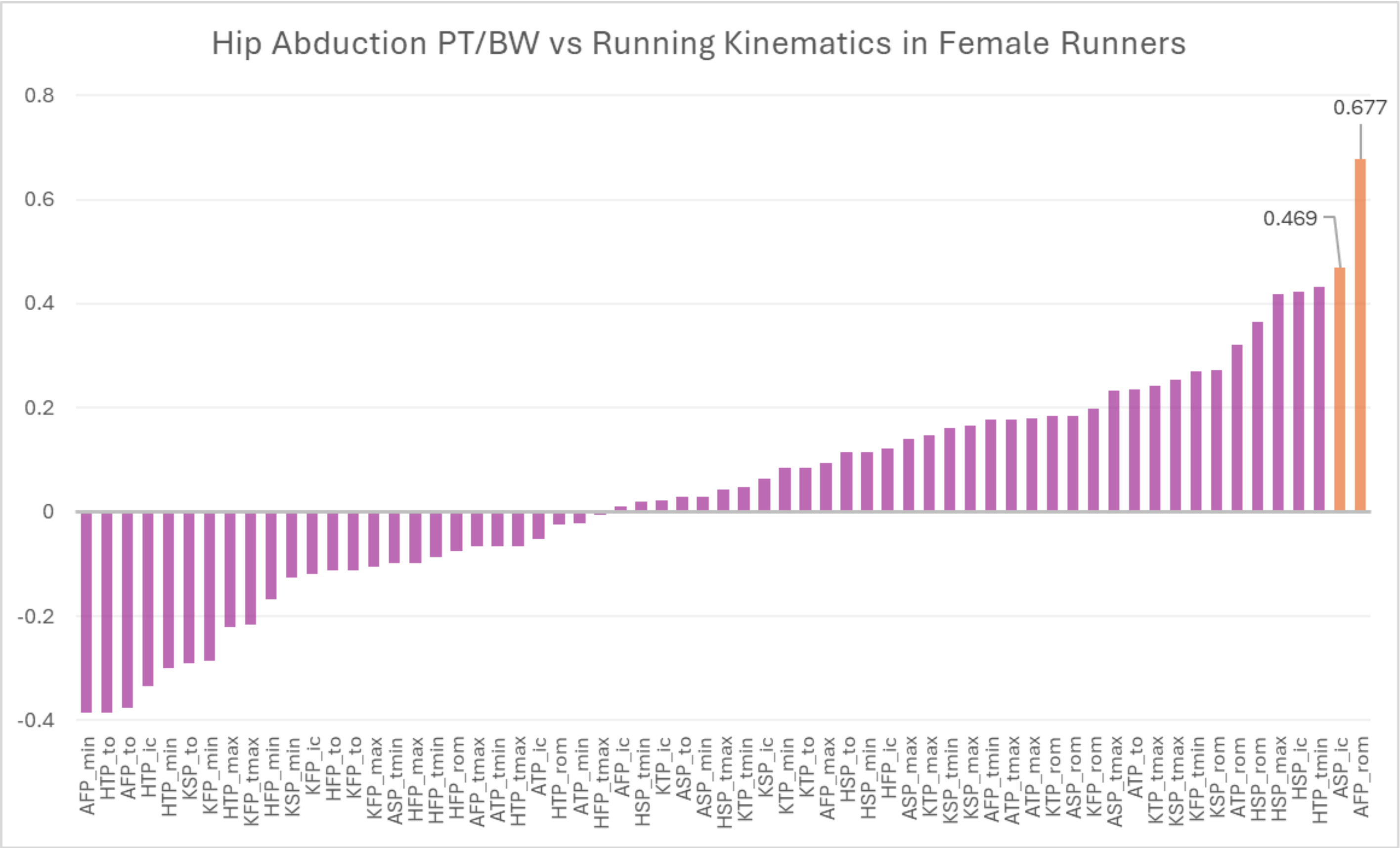
Moffit et al., 2020	Collegiate distance runners Mixed sex Mean age – 20.02 years	Mean distance – 84.56 km/week	1-RM Back Squat Isometric – isokinetic dynamometer	Speed – self-selected Surface - overground Shoes – standardized Foot markers – n/a
Rodriguez et al., 2020	Collegiate cross-country runners Mixed sex 18-20 years	Members of the men's or women's university cross-country team	Isometric – HHD	Speed – self-selected Surface - overground Shoes – not standardized Foot markers – n/a
Schmitz et al., 2014	Females	Experienced group: ≥12 miles/week, past year Novice group: No running at least past 5 years	Isometric – HHD	Speed – standardized Surface - treadmill Shoes – standardized Foot markers – shoes
Taylor-Haas et al., 2014	High school or collegiate male cross-country runners Mean age: 18.3 +/- 1.9 years	≥ 20km/week	Concentric – isokinetic dynamometer	Speed – self-selected Surface - treadmill Shoes – standardized Foot markers – shoes
Venable et al., 2022	Collegiate female cross-country runners 18 – 28 years	≥ 25 miles/week	Concentric – isokinetic dynamometer	Speed – self-selected Surface - treadmill Shoes – n/a Foot markers – n/a
Zeitoune et al., 2020	Female recreational runners 20 – 40 years BMI< 26kg/m^2	≥ 1 year treadmill running	Isometric – HHD	Speed – standardized Surface - treadmill Shoes – not standardized Foot markers – shoes

APPENDIX 2



A diagram showing the Spearman Correlation Coefficients computed between hip abduction PT/BW and all the kinematics variables measured from the male runners during the stance phase of running. Variables displaying statistically significant correlations with hip abduction PT/BW are marked in orange.

APPENDIX 3



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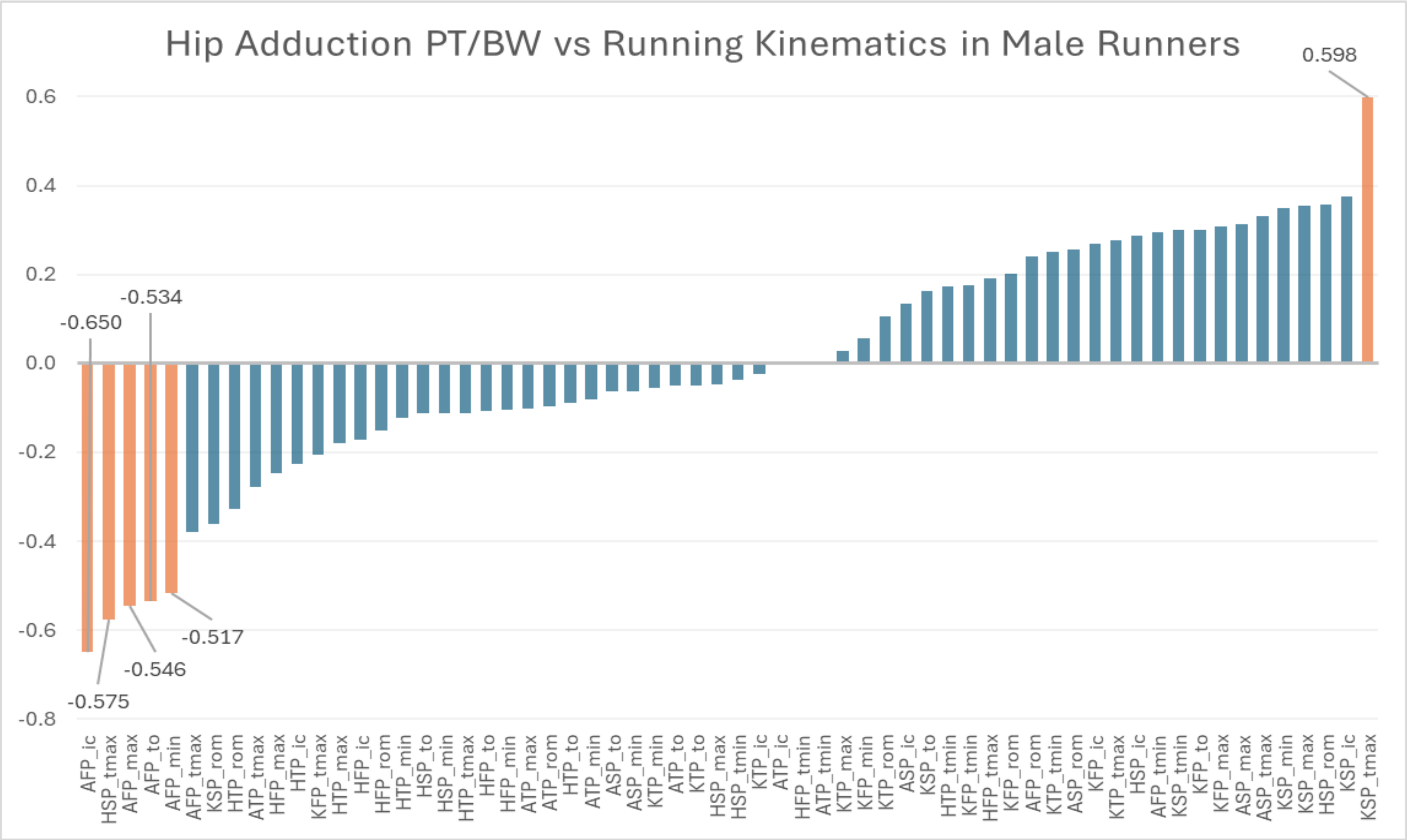
APPENDIX 4



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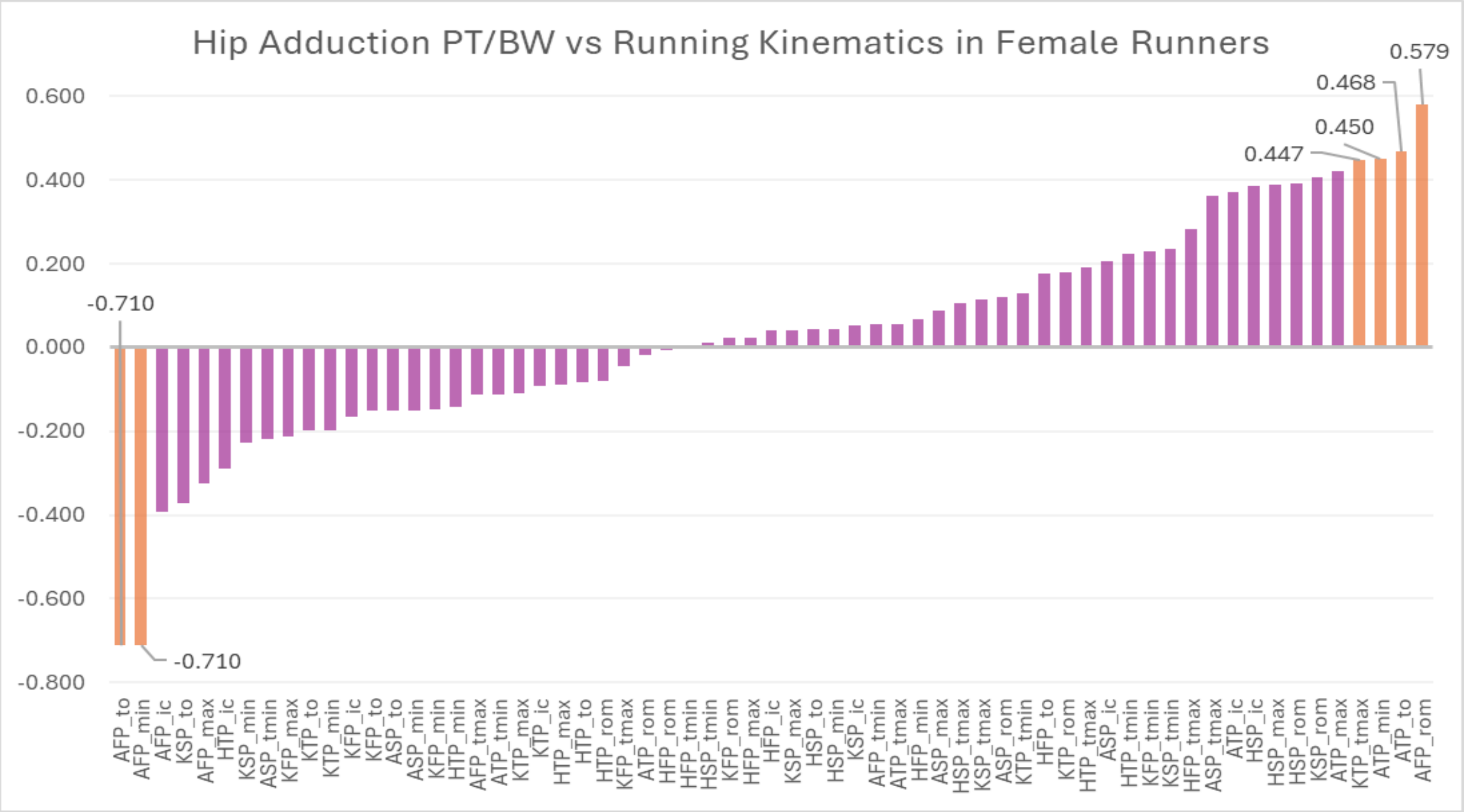
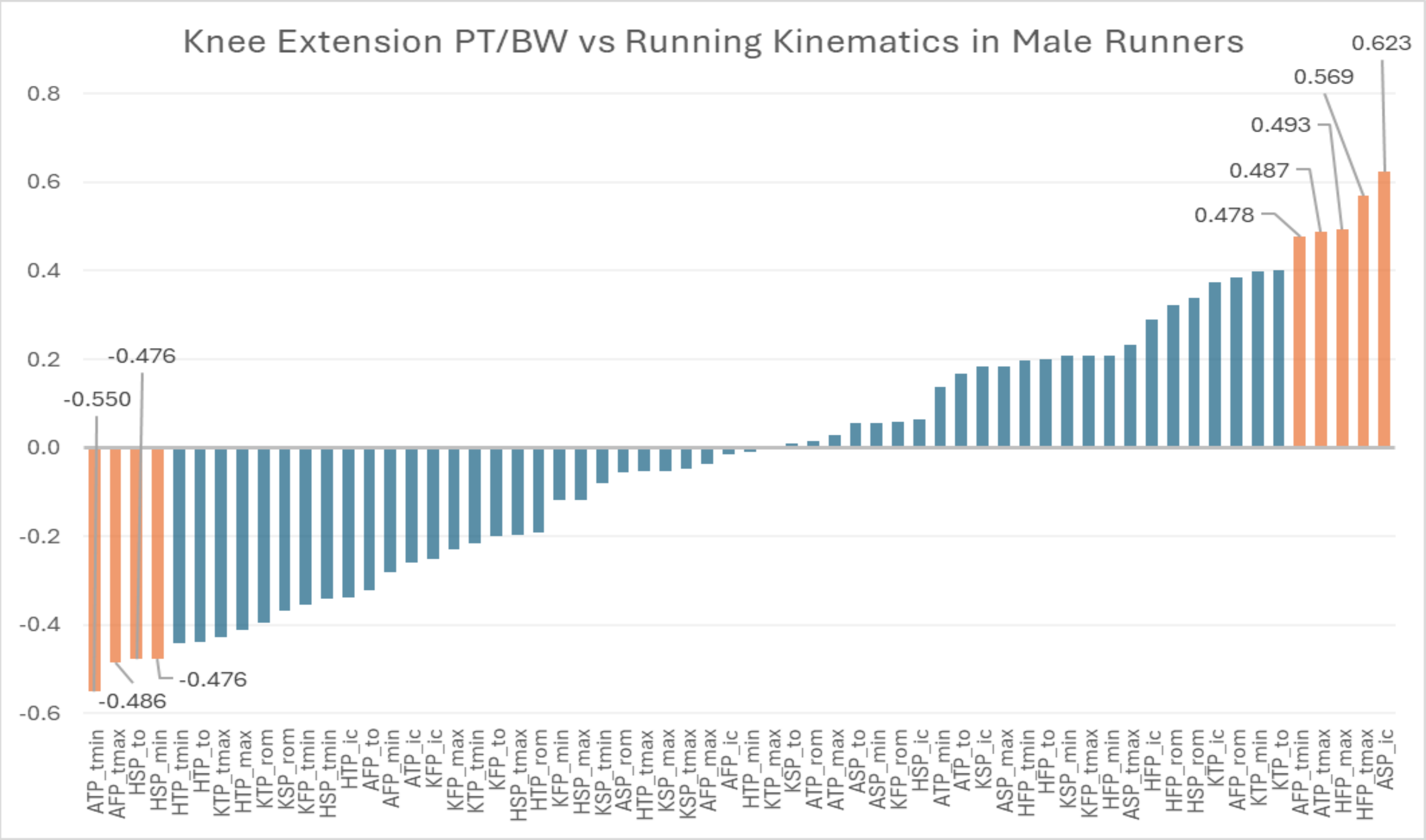
APPENDIX 5



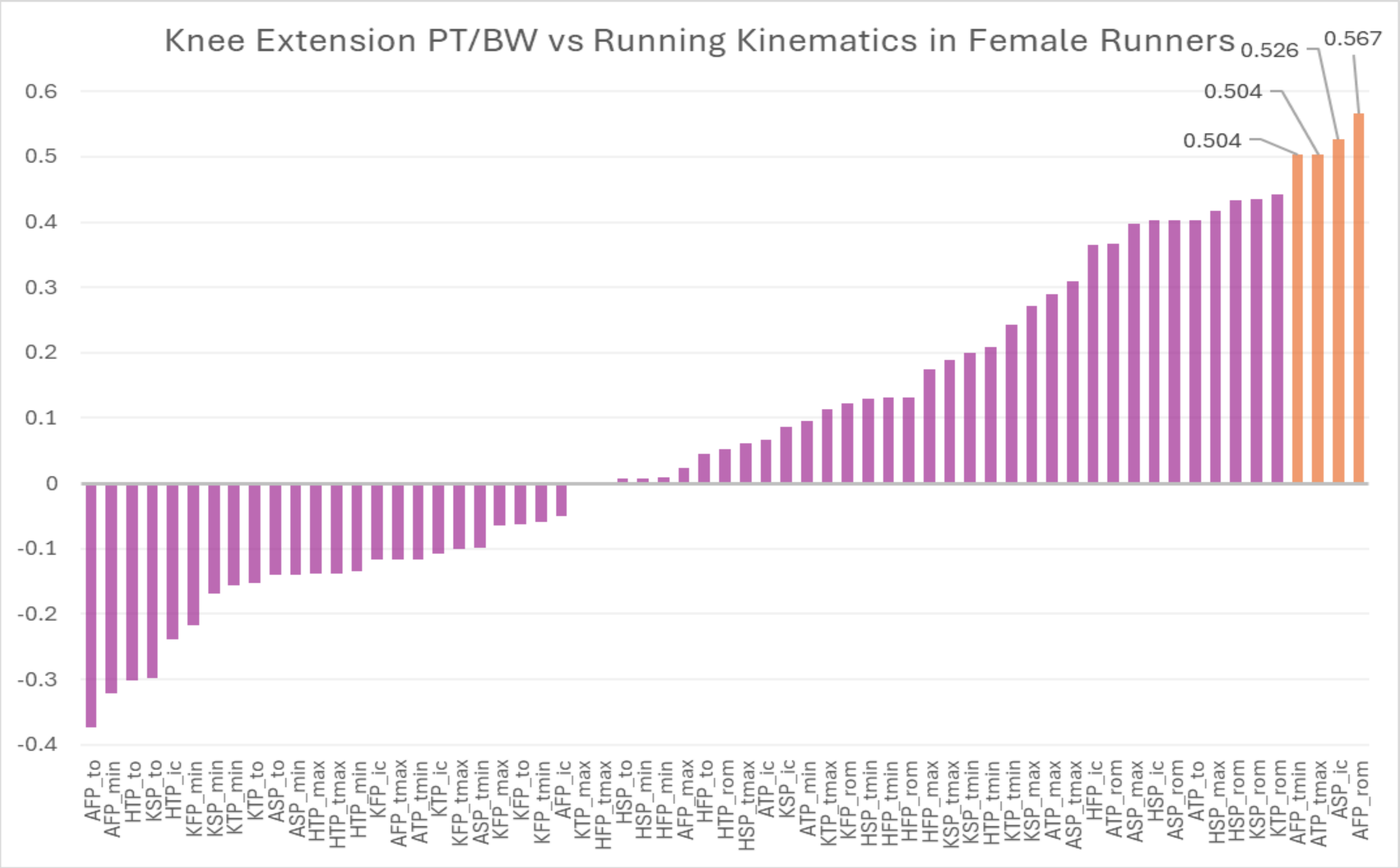
A diagram showing the Spearman Correlation Coefficients computed between hip adduction PT/BW and all the kinematics variables measured from the female runners during the stance phase of running. Variables displaying statistically significant correlations with hip adduction PT/BW are marked in orange.

APPENDIX 6



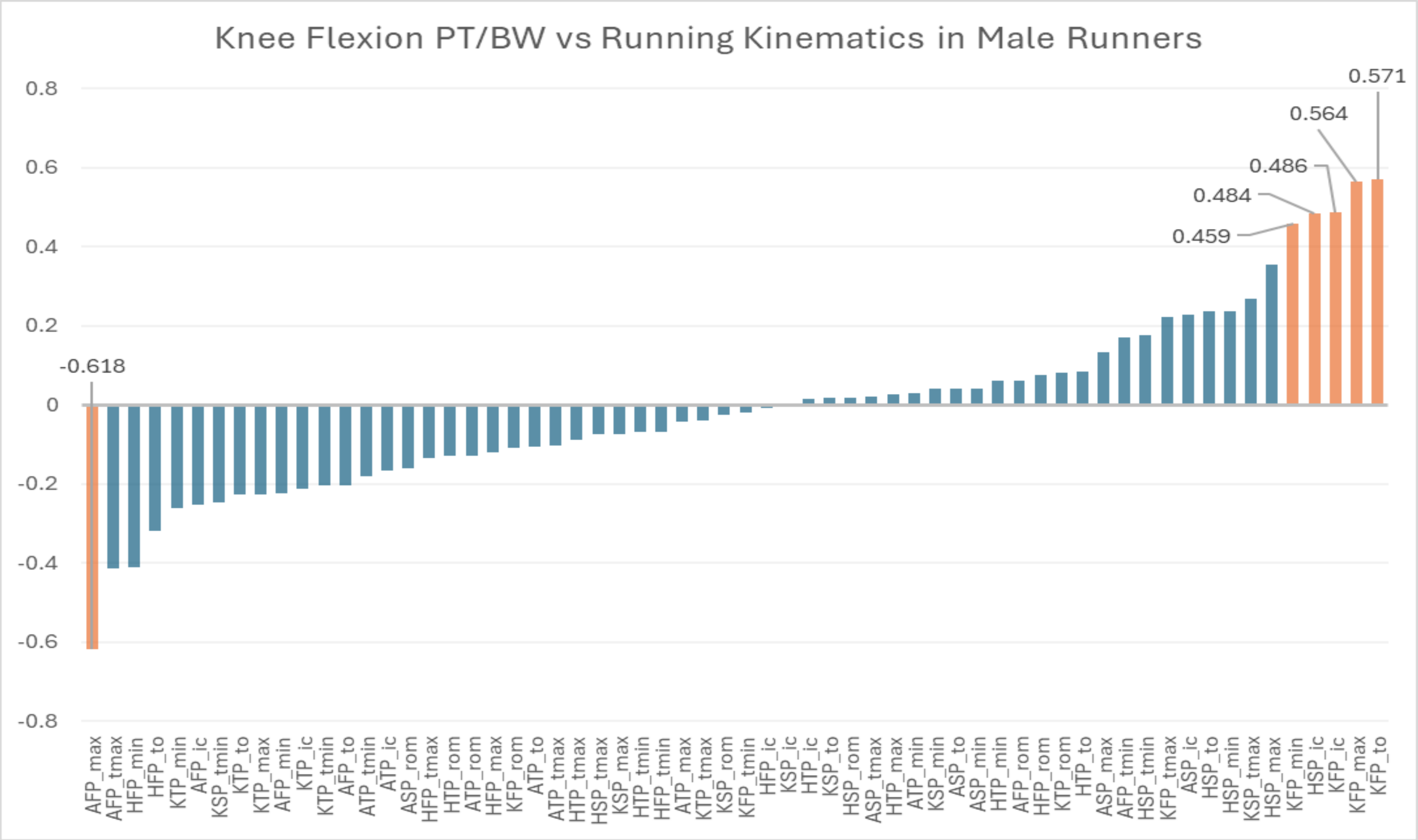
A diagram showing the Spearman Correlation Coefficients computed between knee extension PT/BW and all the kinematics variables measured from the male runners during the stance phase of running. Variables displaying statistically significant correlations with knee extension PT/BW are marked in orange.

APPENDIX 7



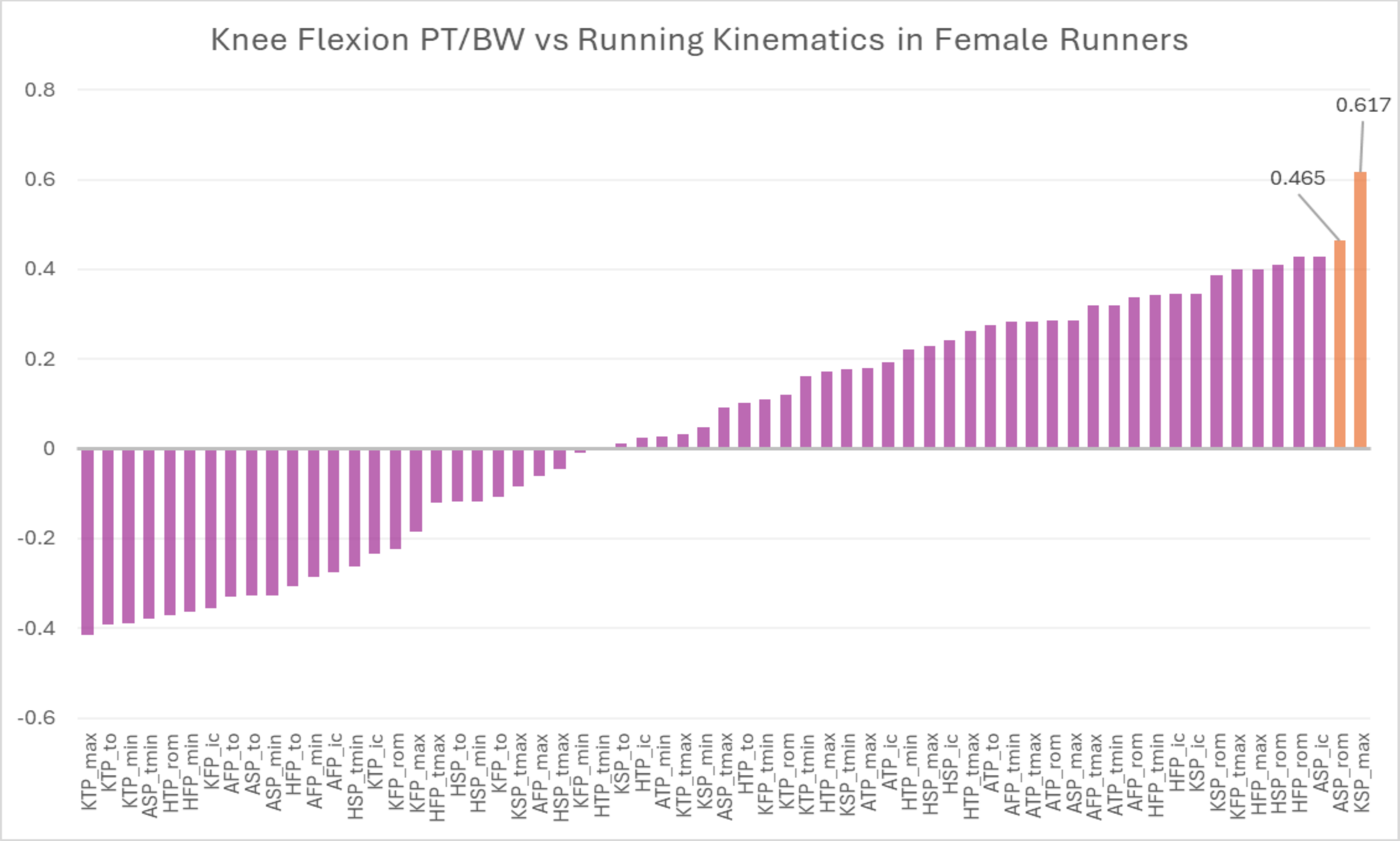
A diagram showing the Spearman Correlation Coefficients computed between knee extension PT/BW and all the kinematics variables measured from the female runners during the stance phase of running. Variables displaying statistically significant correlations with knee extension PT/BW are marked in orange.

APPENDIX 8



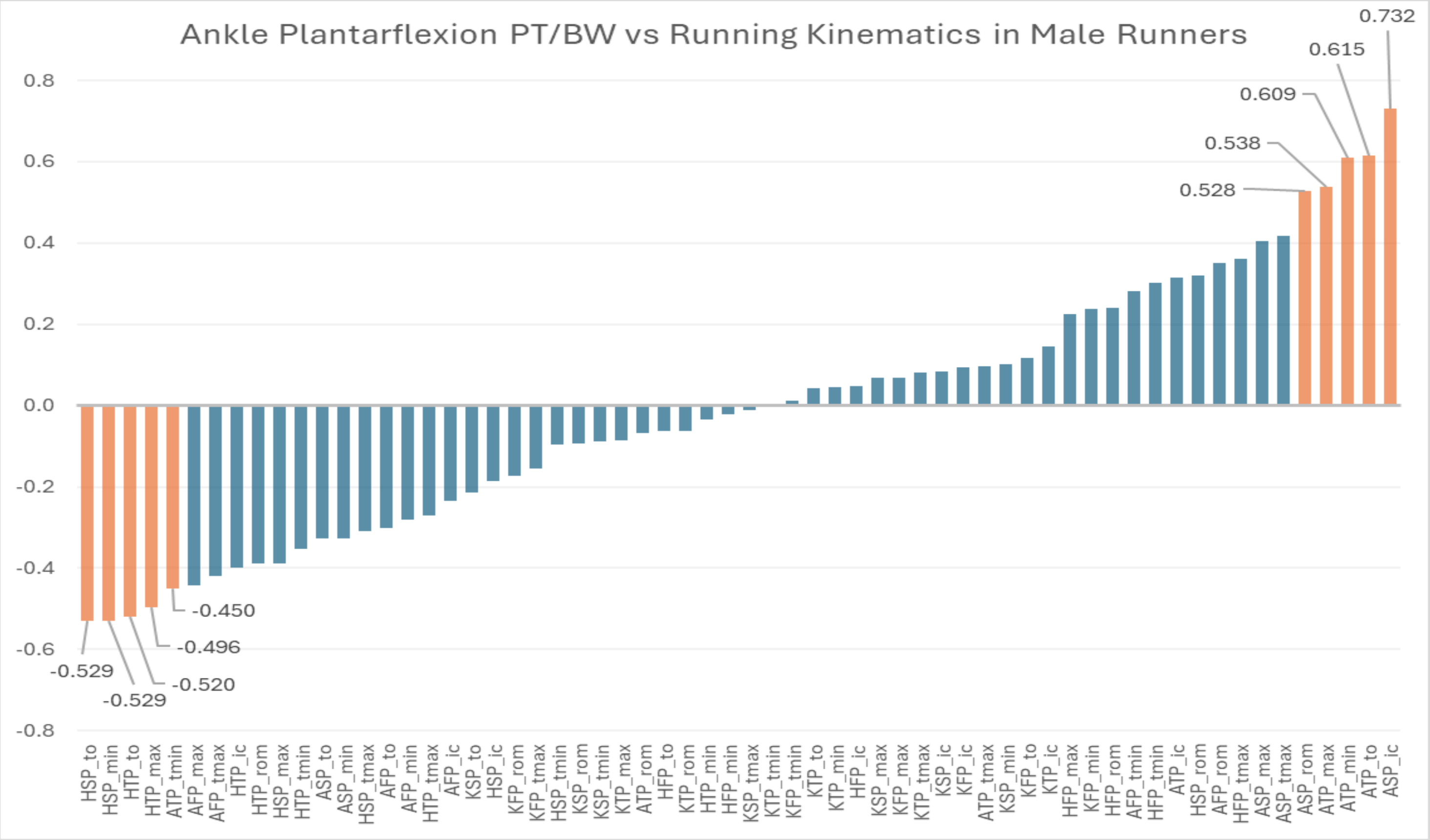
A diagram showing the Spearman Correlation Coefficients computed between knee flexion PT/BW and all the kinematics variables measured from the male runners during the stance phase of running. Variables displaying statistically significant correlations with knee flexion PT/BW are marked in orange.

APPENDIX 9



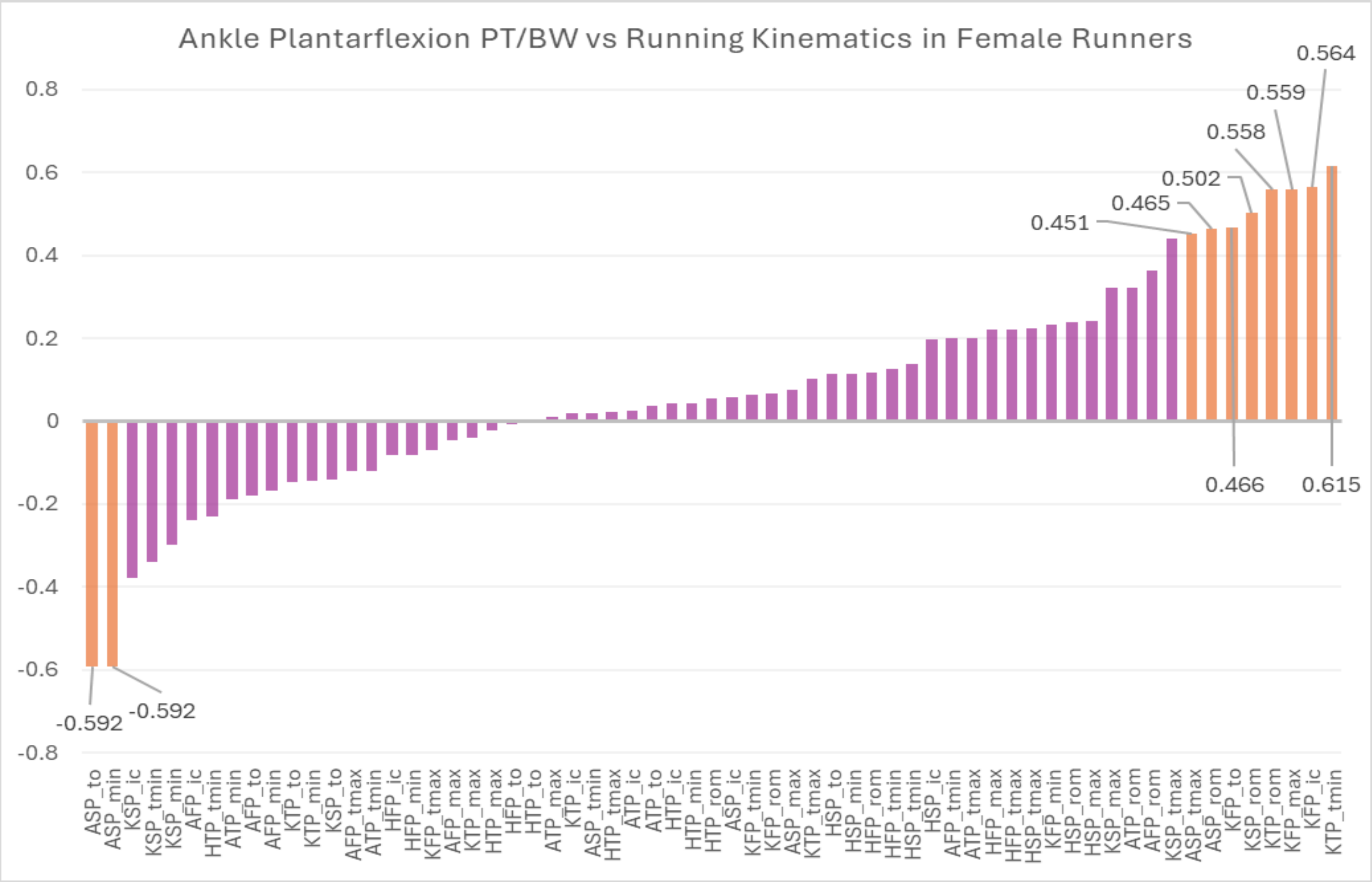
A diagram showing the Spearman Correlation Coefficients computed between knee flexion PT/BW and all the kinematics variables measured from the female runners during the stance phase of running. Variables displaying statistically significant correlations with knee flexion PT/BW are marked in orange.

APPENDIX 10



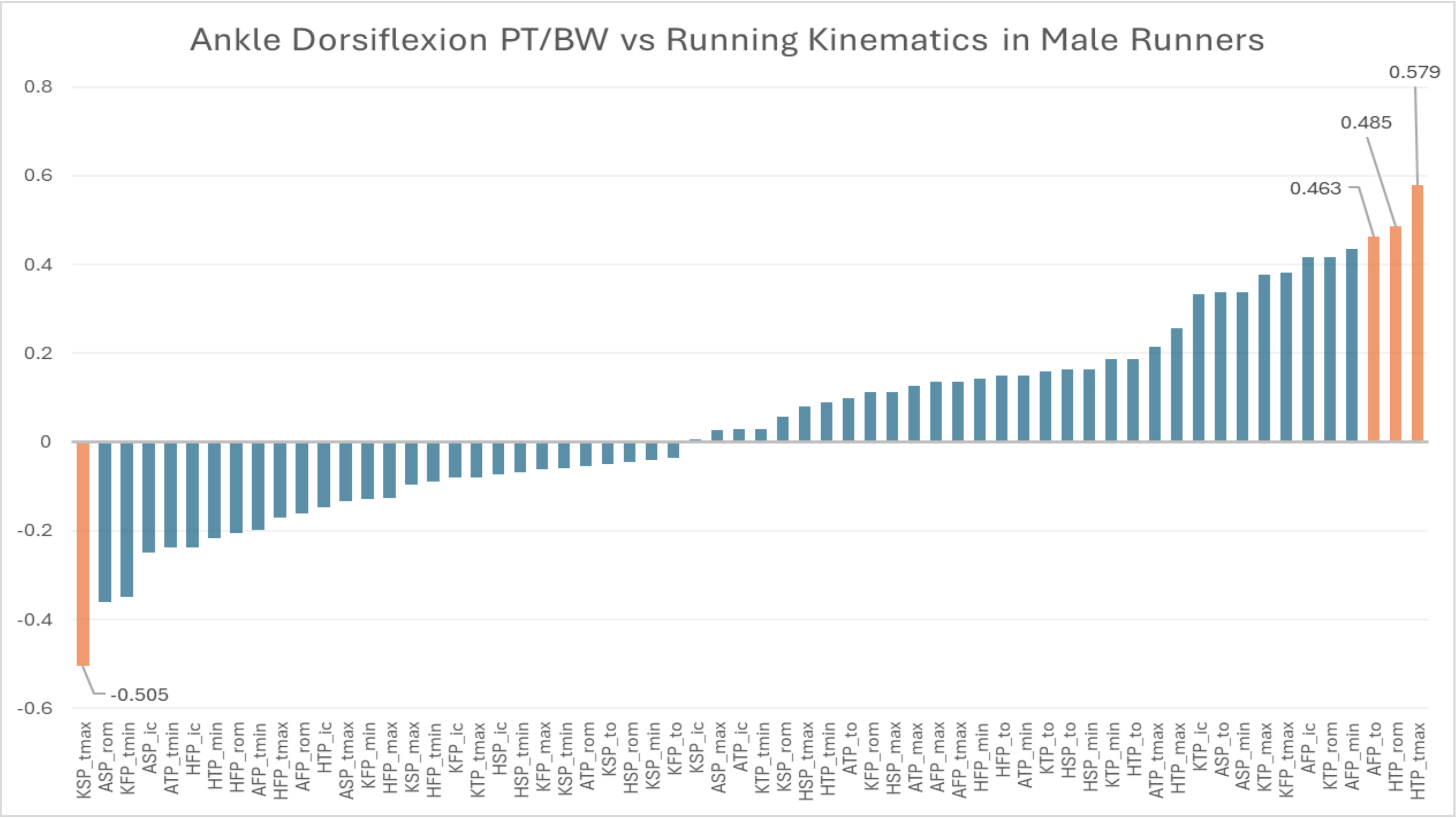
A diagram showing the Spearman Correlation Coefficients computed between plantarflexion PT/BW and all the kinematics variables measured from the male runners during the stance phase of running. Variables displaying statistically significant correlations with plantarflexion PT/BW are marked in orange.

APPENDIX 11



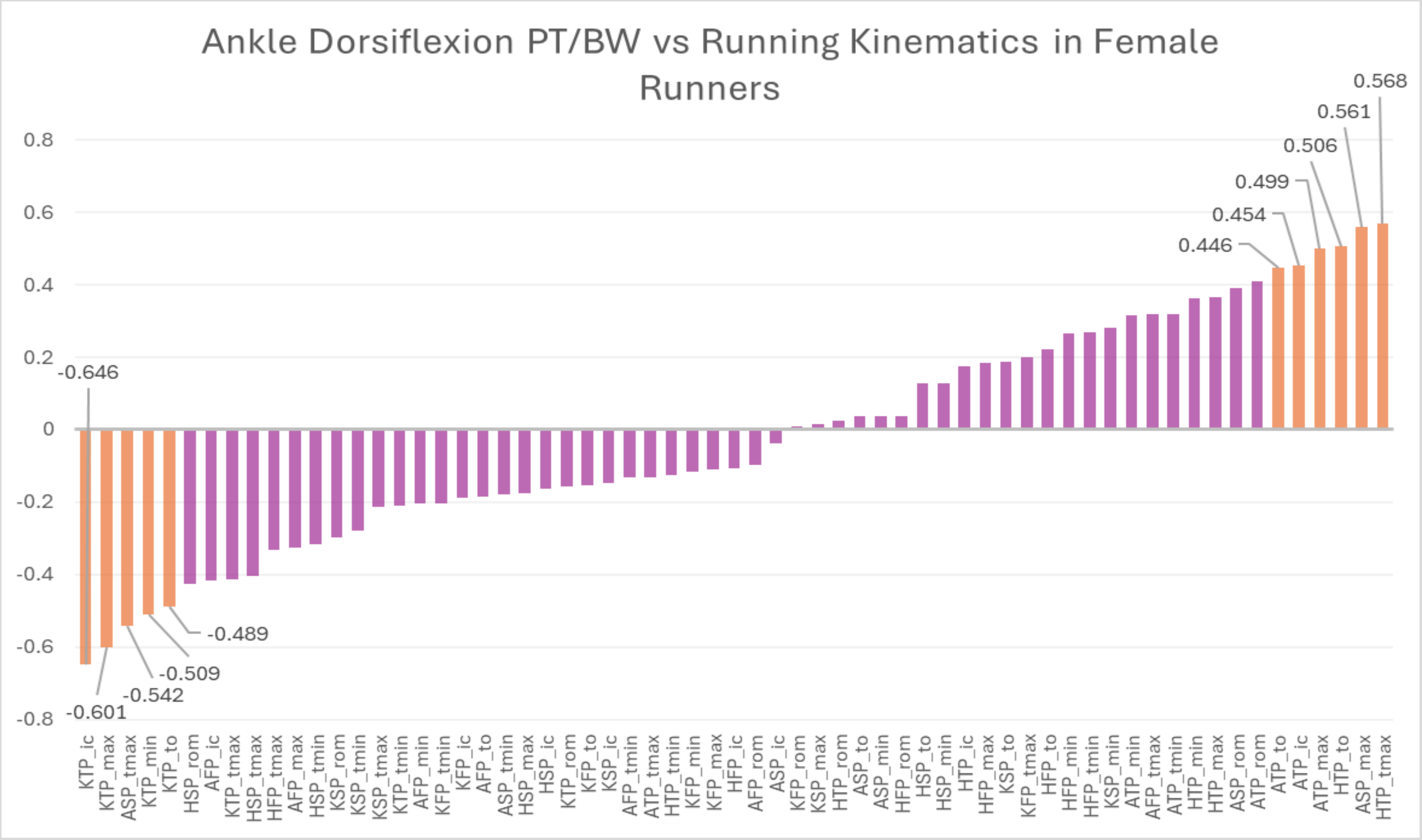
A diagram showing the Spearman Correlation Coefficients computed between plantarflexion PT/BW and all the kinematics variables measured from the female runners during the stance phase of running. Variables displaying statistically significant correlations with plantarflexion PT/BW are marked in orange.

APPENDIX 12



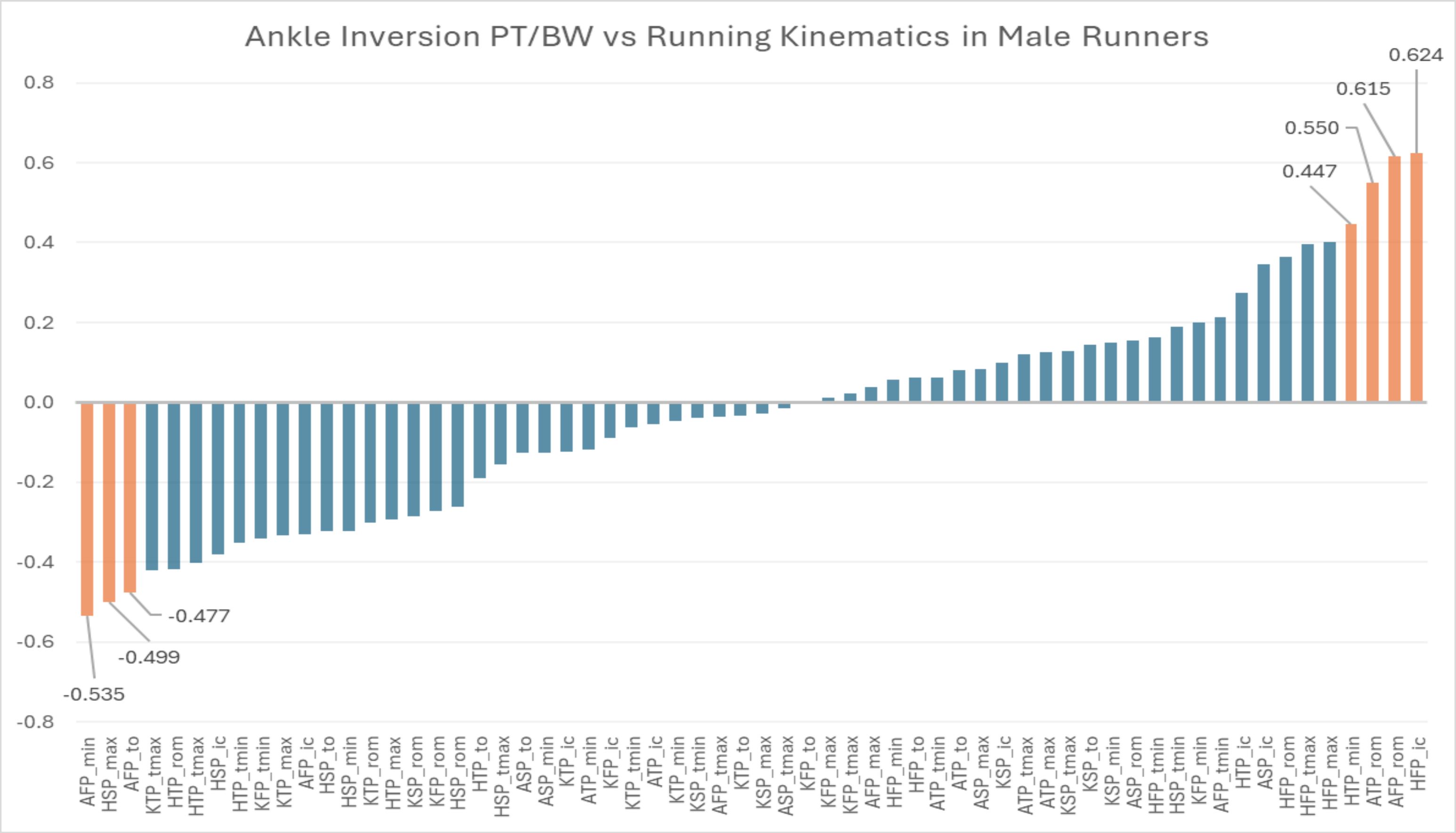
A diagram showing the Spearman Correlation Coefficients computed between dorsiflexion PT/BW and all the kinematics variables measured from the male runners during the stance phase of running. Variables displaying statistically significant correlations with dorsiflexion PT/BW are marked in orange.

APPENDIX 13



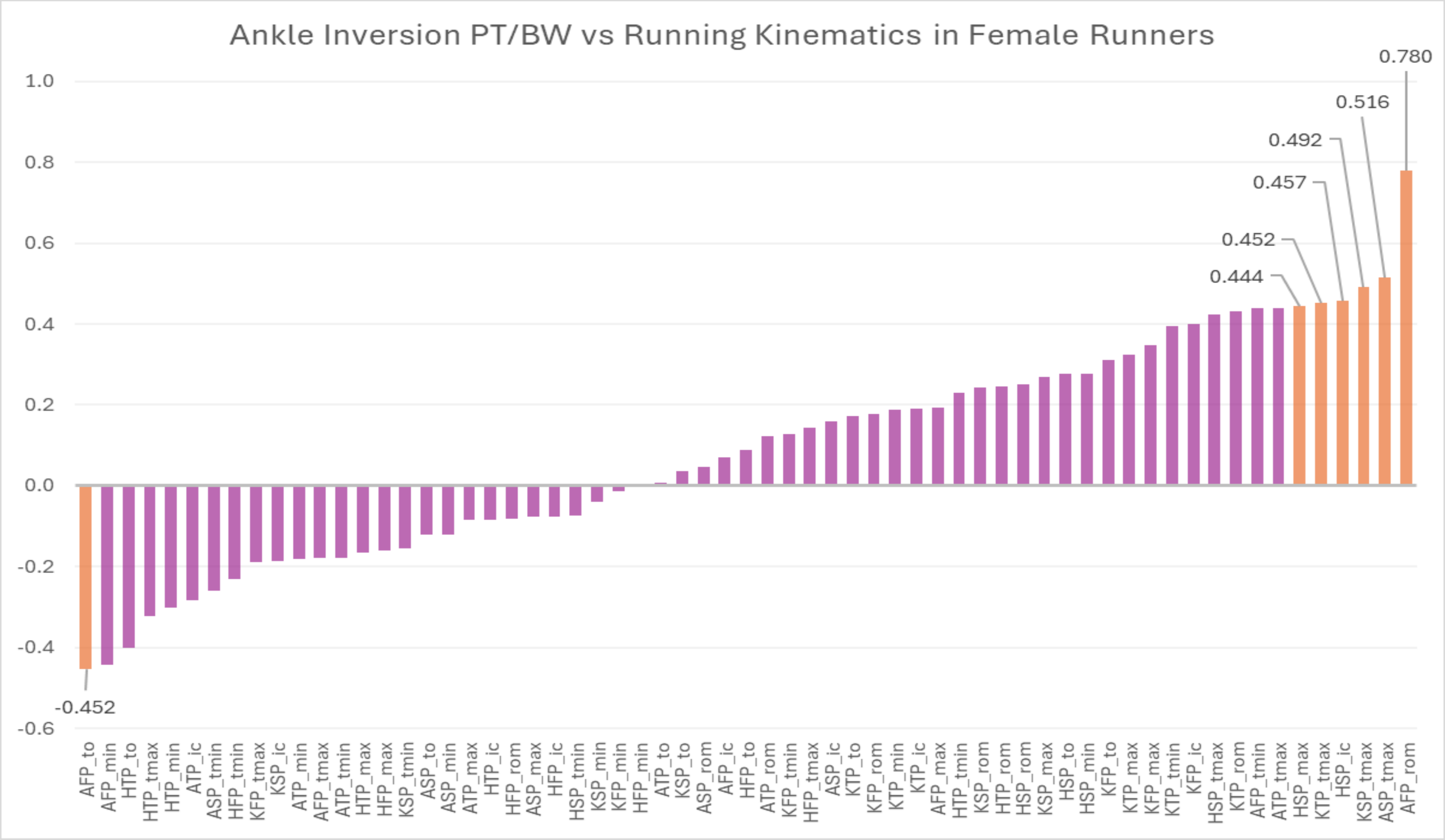
A diagram showing the Spearman Correlation Coefficients computed between dorsiflexion PT/BW and all the kinematics variables measured from the female runners during the stance phase of running. Variables displaying statistically significant correlations with dorsiflexion PT/BW are marked in orange.

APPENDIX 14



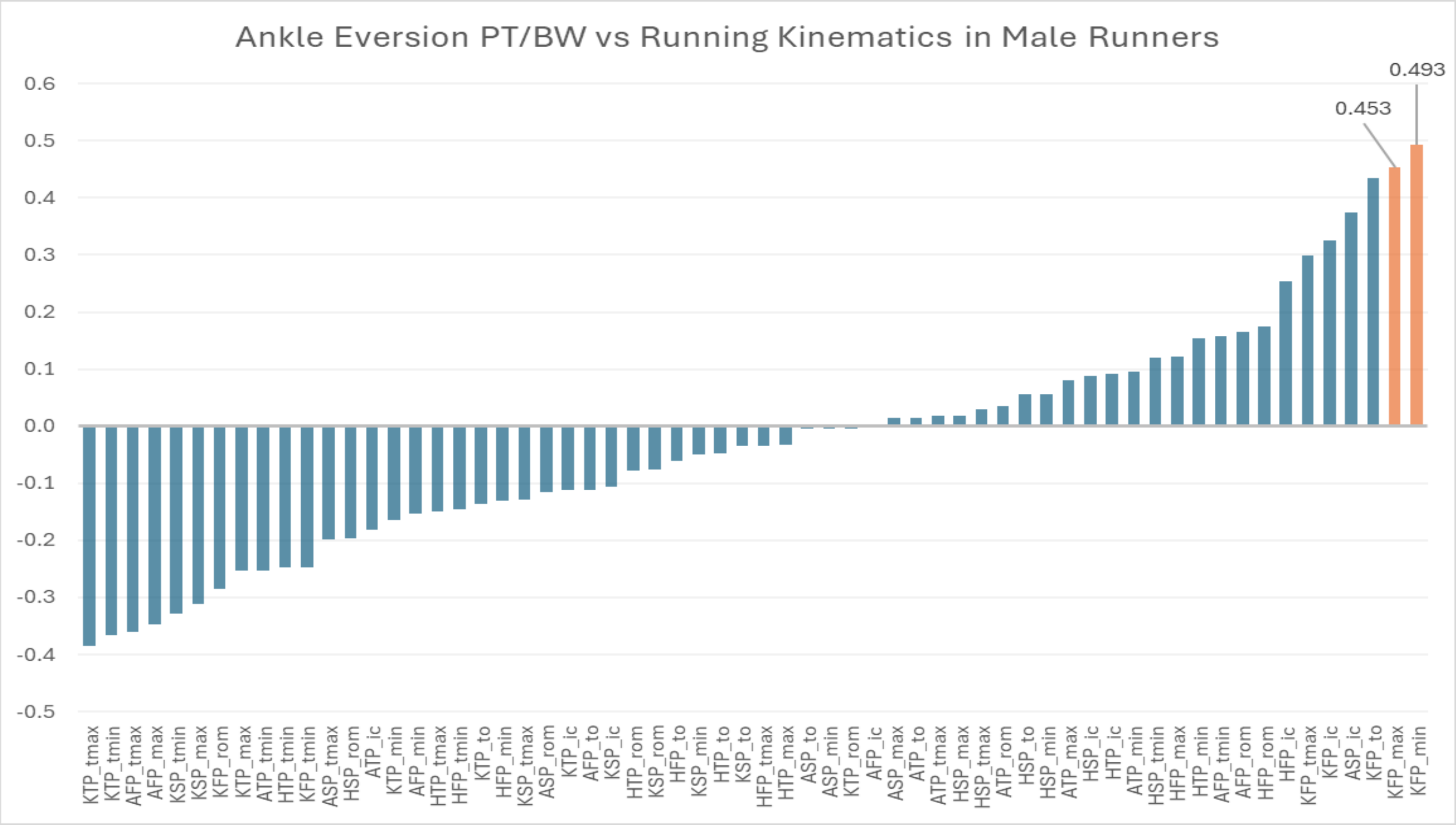
A diagram showing the Spearman Correlation Coefficients computed between inversion PT/BW and all the kinematics variables measured from the male runners during the stance phase of running. Variables displaying statistically significant correlations with inversion PT/BW are marked in orange.

APPENDIX 15



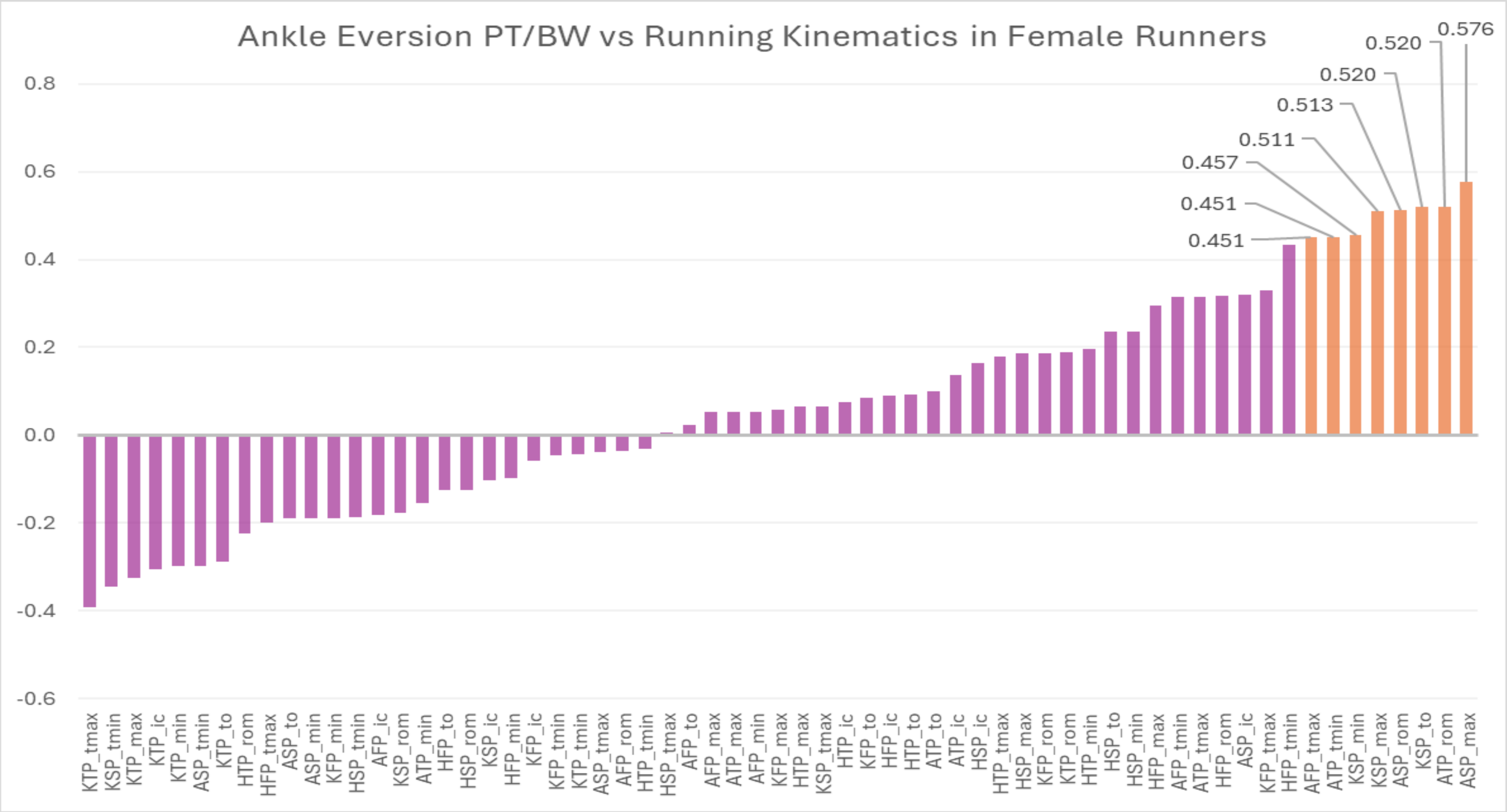
A diagram showing the Spearman Correlation Coefficients computed between inversion PT/BW and all the kinematics variables measured from the female runners during the stance phase of running. Variables displaying statistically significant correlations with inversion PT/BW are marked in orange.

APPENDIX 16



A diagram showing the Spearman Correlation Coefficients computed between eversion PT/BW and all the kinematics variables measured from the male runners during the stance phase of running. Variables displaying statistically significant correlations with eversion PT/BW are marked in orange.

APPENDIX 17



A diagram showing the Spearman Correlation Coefficients computed between eversion PT/BW and all the kinematics variables measured from the female runners during the stance phase of running. Variables displaying statistically significant correlations with eversion PT/BW are marked in orange.