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Research on musculoskeletal injuries in badminton: Based on a cross-sectional survey and biomechanical analysis

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ABBREVATION

3D: three-dimensional
45C: 45-degree sidestep cutting
ANOVA: analysis of variance
ACL: anterior cruciate ligament
BMI: body mass index
BW: body weight
CVJ: consecutive vertical jumps
D: dominant
EMG: electromyography
FCL: forehand clear stroke (left foot)
FCR: forehand clear stroke (right foot)
FP: frequent pain
GRF: ground reaction forces
HS: high support
KMO: Kaiser-Meyer-Olkin
LS: low support
MVC: maximal voluntary contraction
MTP: metatarsophalangeal
NS: no support
NP: no pain
ND: non-dominant
PU: polyurethane
OP: occasional pain
RMS: root mean square
ROM: range of motion
sEMG: surface electromyography
SD: standard deviation
SPM1d: one-dimensional statistical parametric mapping
TPR: thermoplastic rubber
vGRF: vertical ground reaction force

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ABSTRACT

Badminton is a highly popular sport enjoyed around the globe. Competitors frequently execute a variety of complex movements such as rapid sprints, abrupt stops, multidirectional lunges, and a repertoire of strokes including smashes and clears. These activities subject the lower limbs to significant biomechanical stress, which is a contributing factor to the prevalence of injuries in these regions, particularly affecting the ankle and knee joints.

Acknowledging the pivotal role of footwear in athletic performance and injury prevention, this study bridges the gap between athletes' personal preferences and the biomechanical impact of shoe design. We focus on two critical features: torsional stiffness and arch support, examining their influence on the biomechanical mechanisms that may predispose badminton players to injuries. The intent of this dissertation is to inform the design of badminton footwear that not only enhances player performance but also reduces the risk of lower limb injuries.

The First Research Question of This Thesis: Given the predominant focus on biomechanical studies in the evaluation of badminton footwear features, what are the subjective perspectives and requirements of athletes regarding footwear characteristics, and how might these subjective factors differ between genders? Additionally, considering the asymmetric demands of badminton, are there discrepancies in footwear needs and reported lower limb injuries between an athlete's dominant and non-dominant legs?

The First Objective of This Thesis: To conduct a cross-sectional survey to assess the differences in shoe requirements, reported problems/complaints, and pain locations between male and female badminton players, as well as to compare the footwear feature needs of players' dominant and non-dominant legs. The results from this study will aid in understanding the requirements for badminton footwear and the mechanisms of foot pain, providing insights for recommendations on footwear features.

The Second Research Question of This Thesis: Building on the identification of gender-related differences in badminton footwear needs, this study extends to assess the influence of torsional stiffness—a critical but less examined feature of badminton shoes—on the biomechanics of the lower limbs. How does torsional stiffness impact the performance and injury risk during badminton-specific footwork, particularly concerning the stability and performance of the foot and lower limb joints?

The Second Objective of This Thesis: To empirically assess the effects of varying torsional stiffness levels, with Shore D hardness values of 50, 60, and 70 (denoted as 50D, 60D, and 70D, respectively), in badminton footwear on the biomechanical functioning of the lower limbs during badminton-specific movements. This entails a detailed analysis of ankle, knee, and metatarsophalangeal (MTP) joint kinematics, moments, and ground reaction forces to determine how these variables are influenced by footwear torsional stiffness. The study aims to establish an evidence-based understanding of how stiffness variations can affect players' performance and the incidence of injuries, ultimately guiding the design of badminton shoes that optimize the balance between flexibility and stability for enhanced athletic performance and reduced injury risk.

The Third Research Question of This Thesis: Building upon the previous study that investigated the biomechanical impact of 50D, 60D, and 70D torsional stiffness levels in badminton shoes, how do more finely graduated torsional stiffness levels (55D, 60D, and 65D), along with varying arch support heights, affect the lower limb joint kinematics, kinetics, and contact forces in badminton athletes? Further, is there a compound effect of these finely differentiated levels of torsional stiffness when combined with different arch support heights on the risk and mechanism of injury, as well as on the optimization of performance in badminton?

The Third Research Objective of This Thesis: To determine the combined effects of varying torsional stiffness levels (55D, 60D, and 65D) and arch support heights on lower limb biomechanics using OpenSim musculoskeletal modeling, with a focus on their influence on joint kinematics, kinetics, and contact forces during badminton-specific movements. This objective will explore the potential synergistic or antagonistic interactions between torsional stiffness and arch support height in badminton footwear, assessing their implications for athletic performance optimization and injury prevention in the sport.

This dissertation investigates the interplay between footwear characteristics and musculoskeletal injuries in badminton, integrating subjective athlete preferences with objective biomechanical evaluations. The first segment of the study conducts a cross-sectional survey to discern gender-specific footwear demands and foot injury patterns among badminton players, highlighting the necessity for distinct shoe designs for female athletes. The second segment examines the influence of varying levels of torsional stiffness in badminton shoes on lower limb biomechanics, revealing that an intermediate stiffness level optimally balances flexibility and stability. The final segment employs OpenSim musculoskeletal modeling to explore the combined effects of torsional stiffness and arch support on lower limb biomechanics, suggesting that tailored footwear can enhance performance and mitigate injury risks.

The cumulative findings underscore the significance of gender-specific requirements and biomechanical factors in the design of badminton footwear. The insights derived from this research advocate for the development of innovative shoe designs that cater to the nuanced needs of badminton players, aiming to elevate performance while reducing the incidence of injuries. Future research directions may include longitudinal studies across varying athletic levels and foot morphologies to further understand the biomechanical adaptations to footwear modifications and their implications for sports performance and injury rates.

1. INTRODUCTION

1.1 Overview of badminton

1.1.1 Badminton movements characteristics

Badminton, characterized by its high-speed and dynamic nature, demands exceptional agility, speed, and endurance from its players. The sport revolves around rapid, multidirectional movements, essential for responding to the shuttlecock's unpredictable trajectory and the opponent's strategic plays. Players must possess the ability to change direction swiftly, often within milliseconds, to keep pace with the game's fast rhythm (Phomsoupha and Laffaye, 2015).

Speed in badminton is twofold: footwork speed and racket speed. Players need quick reflexes and rapid movements to strike the shuttlecock accurately and powerfully. This speed is complemented by a high level of endurance. Despite the short duration of rallies, the game's repetitive nature demands sustained physical exertion. Players engage in specialized training routines to enhance their endurance, focusing on both aerobic and anaerobic capacities to meet the game's demands (Faude et al., 2007).

Strength, especially in the lower limbs, is crucial for executing explosive movements such as jumps, lunges, and quick directional changes. Badminton players undergo comprehensive training that includes plyometric exercises and strength training to improve their ability to perform these explosive movements efficiently and maintain stability during intense gameplay (Manrique and Gonzalez-Badillo, 2003).

Technical skills in badminton encompass a variety of stroke types and footwork patterns. Advanced players demonstrate high skill levels in executing smashes, net shots, drops, and defensive strokes, requiring precise timing, coordination, and strategic thinking. Developing these technical skills is a primary focus in training, as they are crucial for effective shot-making and efficient court movement (Abian-Vicen et al., 2013).

Cognitive and visual skills are significant in badminton. Players must have excellent visual acuity and cognitive abilities to anticipate the shuttlecock's flight path, read the opponent's game, and make quick decisions. Training often includes drills to enhance reaction time, visual tracking, and decision-making skills, vital for maintaining a competitive edge (Sattler et al., 2015).

Badminton's intermittent nature, with short, intense bursts of activity followed by brief rest periods, places unique metabolic demands on players. Both aerobic and anaerobic energy systems are extensively utilized during play. This aspect influences training, nutrition, and recovery strategies, tailored to optimize energy production, utilization, and recovery during and after matches (Ming, Keong and Ghosh, 2008)

Understanding the biomechanics of badminton movements is crucial for performance enhancement and injury prevention. The sport involves repetitive, high-intensity actions that can lead to musculoskeletal injuries, particularly in the lower limbs. Proper technique, combined with targeted strength and flexibility training, is key to mitigating injury risks. Emphasizing recovery and rest is also vital, as these elements are integral to maintaining physical health and preventing overuse injuries (Fahlström et al., 2006).

In addition to physical and technical aspects, psychological factors play a significant role in badminton. Mental toughness, focus, and the ability to handle pressure are essential for success. Players often work with sports psychologists to develop mental strategies to enhance performance under competitive stress. This mental training includes visualization, concentration exercises, and techniques to manage anxiety and maintain composure during critical moments in a match (Jones, Hanton and Connaughton, 2002).

The equipment used in badminton, particularly the racket and shuttlecock, also influences movement characteristics. The racket's weight, balance, and string tension can affect stroke power and control, while the shuttlecock's design and material impact its flight and speed. Players choose their equipment based on their playing style and physical capabilities, often experimenting with different configurations to find the optimal setup for their game (Cooke, 2002).

Finally, the playing surface in badminton can affect movement patterns and injury risk. Most professional badminton is played on indoor courts with synthetic or wooden flooring, which offer a certain level of grip and cushioning. Players must adapt their footwork and movement strategies to the court surface to optimize performance and reduce the risk of slips and falls (Fernandez-Fernandez, Kinner and Ferrauti, 2010). In summary, badminton movements are a complex interplay of physical, technical, cognitive, psychological, and equipment-related factors.

1.1.2 Biomechanics in badminton

1.1.2.1 Research areas in badminton biomechanics

Badminton, recognized as an official Olympic sport since 1992, demands high levels of physical and technical skill from its players. In the field of badminton biomechanics, the analysis of player movements plays a pivotal role. This area of research not only focuses on the performance of athletes during matches but also involves the optimization of sports techniques and the prevention of sports injuries. The analysis of badminton players primarily concentrates on aspects such as stroke action, footwork, and body balance, all of which collectively determine an athlete's performance on the court.

The efficiency and technical precision of stroke action are crucial components of badminton biomechanics research. Studies indicate that badminton players need to execute rapid and accurate movements to counter their opponents' plays during matches. For instance, research by Cabello Manrique and González-Badillo (Manrique and Gonzalez-Badillo, 2003) highlighted that the maximum heart rate of badminton players during matches can reach up to 190.5 beats per minute, with an average heart rate of 173.5 beats per minute, underscoring the high intensity and physical demands of the sport. Additionally, the study revealed that the average rally duration was 6.4 seconds with rest intervals of 12.9 seconds, reflecting the high-intensity and intermittent nature of badminton.

Injury prevention is another significant aspect of biomechanical research in badminton. Detailed analysis of players' movements can identify factors that may lead to injuries, enabling the development of preventive measures. For example, biomechanical analysis of critical areas such as the shoulders and knees can help design more effective training and match strategies to reduce the risk of injuries(Liu et al., 2022).

Equipment optimization is key to enhancing athletes' performance (Moritz, Haake and Odenwald, 2006). The design of badminton rackets and footwear directly impacts players' performance (Bouché, 2017). Biomechanical methods can be used to optimize equipment design, making it more suitable for the specific movement patterns and demands of the sport. For instance, optimizing the weight, elasticity of rackets, and the supportiveness of shoes can improve stroke efficiency and on-court agility(Stefanyshyn and Wannop, 2015).

1.1.2.2 Biomechanical research methods in badminton

The biomechanical study of badminton is integral to enhancing athletic performance, reducing injury risks, and refining training practices. This is achieved through various advanced biomechanical methodologies, including kinematic and kinetic analyses, wireless electromyography (EMG), and sophisticated computer simulations. These techniques provide a comprehensive understanding of athlete movements and interactions with equipment.

Building upon these methodologies, human motion analysis stands out as a pivotal technique in high-level sports performance assessment. A study conducted in 2017 explored the dynamics of a right-forward lunge in a badminton scenario, aiming to distinguish the movement patterns between professional and amateur badminton players (Mei et al., 2017), this research was instrumental in highlighting the nuances that separate elite performance. In a related study within the same year, researchers delved into the biomechanics of sports footwear, focusing on the variations in bending and torsional angles between different parts of the shoe (Park et al., 2017), this investigation, particularly concerning the ankle's Range of Motion (ROM), was crucial in understanding how the stiffness in the forefoot region of sports shoes affects the biomechanics of the foot and ankle.

Delving deeper into the kinematic analysis techniques, there are two primary methods for analyzing human movement in sports. The first is a video-based approach, where cameras record athletes during training or competition, providing extrinsic visual feedback (Pueo, 2016). This feedback is available immediately after the task completion or following the manual digitization of body landmarks using dedicated software. The second method involves automatic motion tracking systems, also known as motion capture, which track and record human motion in real-time, eliminating the need for delayed digitizing (Lopez Elvira et al., 2017). These systems employ various capturing techniques, ranging from multiple video cameras using infrared light to single-camera systems with additional sensors for depth information retrieval in a scene (Liebermann et al., 2002). Motion capture is extensively used for quantitative analysis in various sports disciplines and activities, including technique and competition evaluation (Molías, Ranilla and Cervera, 2017). From a biomechanical perspective, motion capture is a primary data source, aiding researchers in understanding the mechanics of human movement.

Kinetic analysis in badminton is pivotal for understanding the forces and moments involved in the sport, crucial for enhancing performance and preventing injuries. Ground reaction forces are key, measured using force platforms to understand the load on lower limbs and movement efficiency (Phomsoupha and Laffaye, 2015). Racket dynamics, including forces and torques during swings and impacts, are analyzed using high-speed cameras and sensors, providing insights into racket speed and impact forces (Manrique and Gonzalez-Badillo, 2003). Joint forces and moments, particularly at the knee, ankle, and shoulder, are calculated using motion capture and force platform data, essential for injury prevention strategies

(Kuntze, Mansfield and Sellers, 2010). Additionally, kinetic analysis aids in understanding energy expenditure, important for conditioning ((Nelson and Gregor, 1976), and impact analysis informs equipment design and technique development to minimize injury risks (Lam et al., 2018).

Considering the physical demands of badminton, the sport necessitates coordinated muscle use. Various muscles including wrist flexors and extensors, and biceps and triceps, are involved. This sport's intensity often leads to a considerable number of injuries (Song et al., 2020). In sports biomechanics, understanding muscle activity is crucial for optimizing performance and minimizing injury risks. EMG analysis, particularly surface electromyography (sEMG), plays a pivotal role in this context. sEMG facilitates the study of neuromuscular patterns orchestrated by the central nervous system during dynamic activities, offering insights into muscle activity that are essential in evaluating and improving sports performance (Marta et al., 2014; Dinis et al., 2021; Sire et al., 2021). Electromyographic measurements are integral to developing testing protocols and enhancing sports equipment. They enable the evaluation of muscle electrical activity, which is fundamental in assessing movement performance across various activities. This evaluation aids in guiding efficient muscle usage, enhancing activity, and reducing injury risks (Türker and Sze, 2013). Moreover, the study of neuromuscular patterns through EMG offers valuable information in sports for guiding performance, injury prevention, managing muscle conditioning, skill improvement, and motor control. Utilizing EMG to analyze changes in muscle activity, especially with variations in speed or under conditions of muscle fatigue, provides a comprehensive understanding of muscular dynamics. This information is vital for optimizing performance and decreasing the likelihood of sports injuries (Nummela, Rusko and Mero, 1994; Paul and Wood, 2002; D’AMEN et al., 2011).

Beyond physical analysis, computational modeling and simulation, such as OpenSim and FEA software, provide additional theoretical frameworks. These tools are crucial for simulating movements and offer in-depth insights into biomechanics.

OpenSim is instrumental in creating complex musculoskeletal models, while FEA specializes in simulating the biomechanical responses of bones, joints, and tissues (Rajagopal et al., 2016; Zhang & Fan, 2018).

In conclusion, while these modern biomechanical research methods offer in-depth insights, they require substantial resources. However, these would cost enormous financial and human resources. In contrast, retrospective studies in hospital and clinics tend to underestimate the incidences and types of injuries (Garrick, 1987), since injured amateur players often do not seek medical help, especially in the case of minor injuries (e.g., blisters, ankle sprain). Moreover, retrospective studies can employ personal interviews and structured questionnaires (Feit and Berenter, 1993), which can allow researchers to gather a vast amount of data using reasonable human and financial resources (Figure 1).

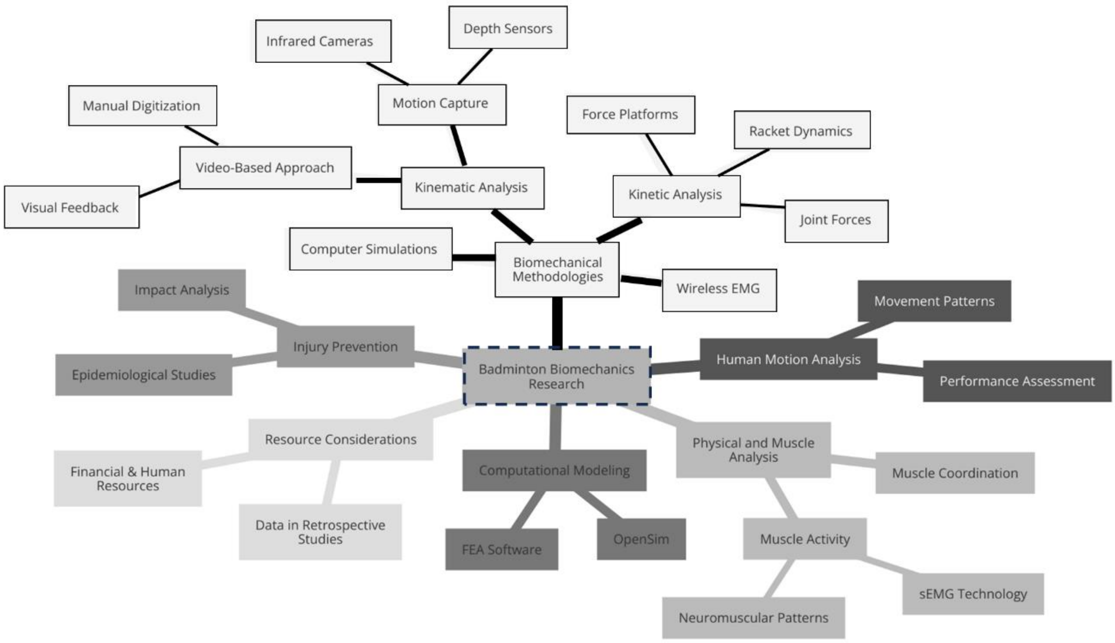


Figure 1. Comprehensive Overview of Badminton Biomechanics Research.

1.2 Musculoskeletal injuries in badminton

1.2.1 Lower Limb Injuries

Badminton is a globally popular sport requiring players to execute movements like lunge steps, turns, sprints, jumps, and landings (Kuntze et al., 2010). Even though it's a non-contact physical sport, the rapid movements may lead to injuries, especially in the lower extremities (Pardiwala et al., 2020). Common injuries mainly include strains, sprains, and ligament injuries (Jørgensen and Winge, 1987; Shariff, George and Ramlan, 2009; Mei et al., 2017). Remarkably, lower limb injuries account for 58% of the total injury cases in badminton, with over 50% of these injuries occurring in the ankle and knee joints (Figure 2) (Phomsoupha and Laffaye, 2020).

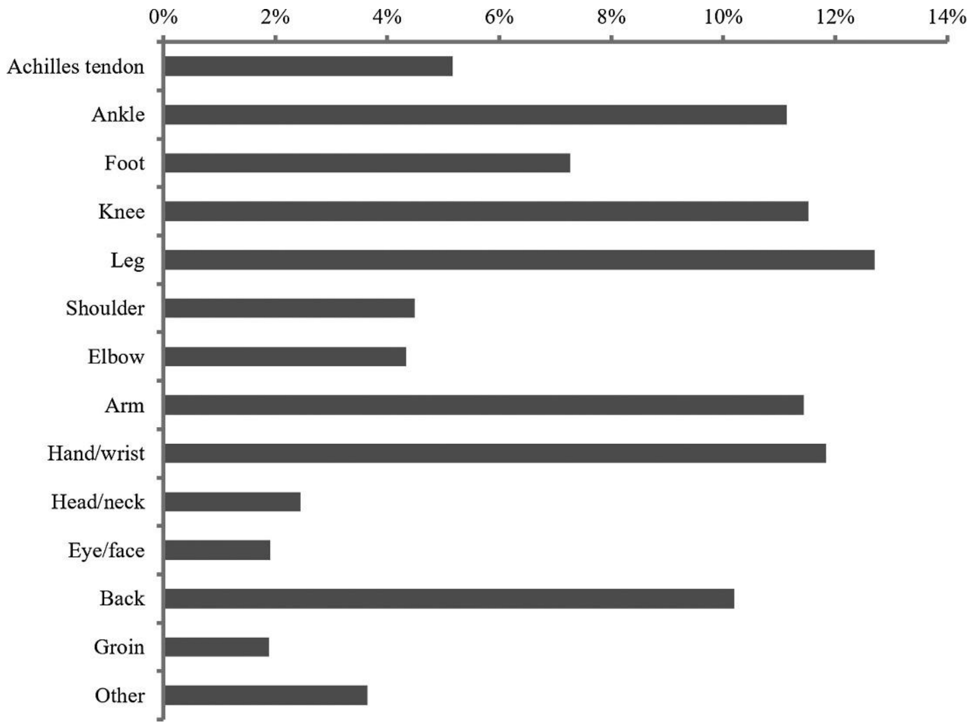


Figure 2. Body sites distribution of badminton injuries. (Phomsoupha and Laffaye, 2020).

An earlier Danish study observed that the mean injury incidence among both recreational and elite badminton players was 0.85 injuries per year or 2.9 injuries per 1,000 hours (Jørgensen and Winge, 1987). Of particular concern are injuries to the Achilles tendon, a critical component for movement, highly vulnerable due to the sport's intense activities like rapid directional changes, jumps, and sprints (Kaalund et al., 1989; Möller, Astron and Westlin, 1996; Fahlström, Lorentzon and Alfredson, 2002a; b; Singh, 2017). Achilles tendon injuries typically arise from repetitive stress on the tendon during activities such as lunges and quick directional shifts (Boesen et al., 2011). These movements exert significant strain on the tendon, potentially leading to conditions ranging from tendinitis to tendon ruptures (Fahlström, Björnstig and

Lorentzon, 1998a), as shown in Figure 3. Research shows that sports involving jumping and rapid acceleration, fundamental elements of badminton, have a higher incidence of Achilles tendon ruptures (Lian, Engebretsen and Bahr, 2005; Hübscher et al., 2010). Such injuries are prevalent among both professional and recreational players, often due to inadequate conditioning or improper technique(Boesen et al., 2011).

Figure 3. Achilles tendon injuries, A: Normal Achilles tendon; B: Achilles tendonitis; C: Achilles tendon rupture.

Following the discussion on Achilles tendon, it's noteworthy that anterior cruciate ligament (ACL) injuries, making up to 70% of non-contact sports injuries (Kimura et al., 2012) , also represent a major concern in badminton. Furthermore, 37% of these injuries require surgical treatment (Tsuda, Kimura and Ishibashi, 2015). In badminton, where movements often involve frequent jumping, landing, and quick returns to the starting position, such injuries are common. Two key mechanisms for ACL injuries in badminton are identified: injuries on the knee opposite the racket hand during single-leg landings, primarily on the backhand side (Kimura et al., 2012). and injuries on the racket-hand side knee due to plant-and-cut movements, especially on the forehand side of the court (Kimura et al., 2012). These movements result in greater knee extensor activation, increasing the tension on the ACL and the risk of injury (Kimura et al., 2012).

Moreover, ACL injuries are prevalent in sports like basketball, soccer, and volleyball, which involve repetitive jumping, landing, and position changes. Female athletes are particularly at risk, with an incidence of ACL injuries three to six times higher than in males. This disparity is attributed to factors such as hormonal influences, menstrual cycles, and anatomical, genetic, and neuromuscular differences (Shelbourne, Davis and Klootwyk, 1998; Hewett et al., 2005a; Prodromos et al., 2007; Renstrom et al., 2008; Posthumus et al., 2009, 2010; Waldén et al., 2011). Research by Hewett et al. (Hewett et al., 2005a) and Numata et al. (Numata et al., 2018) observed larger knee valgus angles in female athletes with ACL injuries. Further, video analyses by Olsen et al. (Olsen et al., 2004) and Koga (Koga et al., 2010) have confirmed that increased knee valgus angles during landing are closely associated with ACL injuries in females.

Lunging is a crucial movement in sports such as badminton, squash, and fencing, enabling athletes to quickly stop, stabilize, and prepare for the next action (Cronin, McNAIR and MARSHALL, 2003). In badminton, lunges constitute over 15% of all movements and are integral to positioning and shuttlecock striking (Kuntze et al., 2010; Brahms, 2014; Huang et al., 2014). However, these movements also increase injury risks, particularly at the knee and ankle joints, with incidence rates ranging from 63% to 92% (Herbaut, Delannoy and Foissac, 2018).

The impact load during lunging can reach up to 2.5 times body weight, demanding high muscle activity for lower extremity stabilization (Phomsoupha and Laffaye, 2015). This stress can result in muscle fatigue, leading to discomfort, pain, and further injuries (Boesen et al., 2006; Hu et al., 2015). The strain is particularly evident in the Achilles and patella tendons during intensive lunges, where loads can be six to 12 times, and five times body weight, respectively (Lee and Loh, 2019).

It is interesting to note that professional athletes tend to have a lower incidence of these injuries, likely due to their advanced training, superior techniques, and overall better physical conditioning, which help in managing peak horizontal GRF and loading rates more effectively (Lam, Ding and Qu, 2017a; Herbaut et al., 2018). They adjust their movement mechanics to dissipate stresses and accommodate impact, unlike their amateur counterparts (Huang et al., 2014; Lam et al., 2017a). The forehand and backhand forward lunges, which see greater foot impact loading and higher frequency in gameplay, present additional challenges, especially the backhand forward lunge that demands more core stability and knee dynamic stability (Hu et al., 2015; Lee and Loh, 2019; Valldecabres, Richards and De Benito, 2020).

1.2.2 Lower Limb Injury Prevention

To lower the injury risk, players strive to promote their aerobic endurance, agility, strength, speed, and accuracy of action. These abilities are relevant to improved muscle strength, better shock absorption ability in the lower limbs, and better joint stability, exceeding the demands of regular physical activities (Manrique and Gonzalez-Badillo, 2003; Phomsoupha and Laffaye, 2015). Intensive training aims to enhance motor control, a crucial factor for both performance improvement and injury risk reduction. However, these abilities might not be satisfactory innately(Mahieu et al., 2006; Malisoux et al., 2013). To make up for the inherent abilities' deficiency, footwear has emerged as a prevalent research topic, with modifications in shoe design and properties potentially affecting biomechanical responses (Hoitz et al., 2020; Honert et al., 2020; Lam, Wong and Lee, 2020; Teng et al., 2022).

Badminton footwear can improve player performance while preventing excessive load and related injuries by providing optimal shock attenuation and movement stabilization (Park et al., 2009). Injury prevention, performance, and comfort are the most important functional design features for court shoes (Bouché, 2010) (Figure 4). Ironically, being barefoot is often more stable than wearing a shoe; the shoe sole increases the lever arm, imparting an external inversion moment on the subtalar joint (Stacoff et al., 1996). This underscores the challenge in designing footwear that enhances natural stability while providing necessary support (Reinschmidt and Nigg, 2000). Previous research reported that modifications in shoe characteristics, including midsole material, midsole thickness, heel cup height, and heel-to-toe drop, could lead to adjustments in both kinematics and kinetics (Lam et al., 2022; Lin et al., 2022). These adaptations have been observed to affect athletic performance and the susceptibility to potential injuries across various sports (Hoitz et al., 2020; Honert et al., 2020; Lam et al., 2020; Teng et al., 2022). For instance, superior shoe cushioning has been associated with improved impact attenuation (Park et al., 2017; Lam et al., 2017b), further, increased shoe-bending stiffness has been linked to enhanced performance in jumping, sprinting, and agility tasks (Park et al., 2017; Lam et al., 2017b). A related cross-sectional study also highlighted the importance of badminton shoe characteristics (Shen et al., 2022).

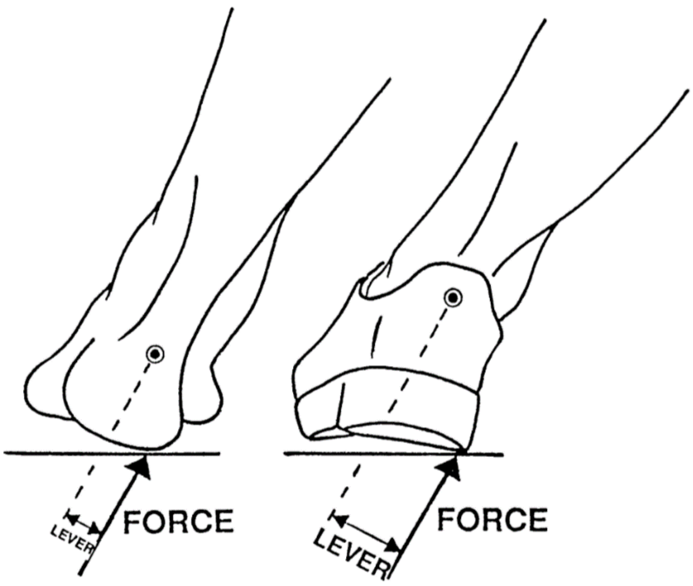


Figure 4. Sideward (lateral) cutting movements barefoot (left) and with a shoe (right) (Bouché, 2017). The shoe sole imparts a greater external inversion moment on subtalar joint than when barefoot.

The significance of sports shoes in injury prevention, performance enhancement, and comfort perception was highlighted (Reinschmidt and Nigg, 2000). As for injury prevention in the design of court shoes, achieving overall stability is crucial to counteract excessive pronation during jumping landings, and particularly, excessive supination during sideward cutting movements (Bouché, 2017). The stability of shoe sole relied on factors such as hardness, thickness, and torsional stiffness. Therefore, shoes with softer soles of mild-to-moderate thickness, possessing torsional flexibility, and allowing for medial and lateral deformation of the sole upon heel contact, may offer optimal benefits (Stacoff et al., 1996).

1.3 Biomechanics of Badminton Footwear

1.3.1 Constructions and Biomechanical Function of Badminton Footwear

The primary function of badminton shoes is to minimize injury risks while maximizing sports performance and comfort (Marchena-Rodriguez et al., 2020). Bouché highlighted the essential features of court shoes, which include: 1) countering excessive pronation during sideward movements, 2) providing sufficient heel and forefoot cushioning for effective shock attenuation and comfort, 3) ensuring moderate bending stiffness in the midfoot region while maintaining torsional flexibility, and 4) offering optimal traction to prevent foot interlocking and slippage (Bouché, 2010). Numerous studies in the literature have focused on biomechanical changes induced by specific shoe feature modifications, aiming to optimize badminton footwear design.

Shoe cushioning and midsole hardness: Designing badminton footwear focuses on managing high impact forces, crucial due to the sport's rapid movements and the inability of soft tissues to sufficiently mitigate these forces in a short time (Nigg, 2010). Shoe cushioning and midsole hardness are integral in altering these impact forces. Softer midsoles, as opposed to harder ones, have been proven to better attenuate impact force, a finding expected to translate to lower impact force peaks in human testing (Kaelin et al., 1985).

The influence of midsole hardness is pivotal in achieving a balance between reducing impact force and enhancing propulsive performance. This balance is crucial for effective cushioning during landing and jumping, with performance often assessed by jump height and agility during takeoff (Lyle et al., 2013). Studies have shown that injured runners experience higher vertical impact peaks compared to uninjured ones, and these peaks are greater with hard midsole conditions (Hreljac, Marshall and Hume, 2000). Landing in harder shoes has been associated with higher impact forces, suggesting that softer footwear can effectively reduce these impact peaks (Hreljac et al., 2000; Zhang et al., 2005; Malisoux et al., 2017).

For athletes recovering from impact injuries, avoiding shoes with harder midsoles is advisable. Excessively high ground reaction forces (GRF) pose a risk for joint pathology, and a high loading rate can further increase this risk (Dufek and Bates, 1990; Ricard and Veatch, 1990; Crossley et al., 1999; Bauer et al., 2001; Irmischer et al., 2004).

Interestingly, despite material tests suggesting that thinner midsoles might compromise shock attenuation, minimalist footwear has been found to have beneficial effects on reducing impact force during running. This reduction in force is attributed to the biomechanical accommodation that occurs with thin soles in high-impact-force activities, particularly considering the role of foot pronation. The subtalar and transverse tarsal joints, crucial in dynamic activities, are primarily involved in foot pronation and supination, with excessive pronation identified as a contributing factor in running injuries (Messier and Pittala, 1988; Rolf, 1995; Nigg, 2001). Quantitative studies have highlighted the necessity for more sophisticated multisegment foot models to comprehensively understand the interplay between shoe design and foot kinematics in sports (Leardini et al., 2007).

Forefoot bending stiffness: The overall stiffness in the forefoot region of sports footwear, known as forefoot bending stiffness, is a crucial feature that significantly influences athletic performance (Stefanyshyn and Wannop, 2016). The stiffness can be tailored using materials such as high-density EVA midsoles and carbon fiber plates, making it essential for agility-based sports like basketball and badminton (Park et al., 2017). Studies have shown that increasing forefoot stiffness can enhance performance in forward acceleration and jumping, attributed to more efficient energy use during movement (Stefanyshyn and Fusco, 2004; Wannop et al., 2015).

In terms of injury prevention, heightened forefoot stiffness can be instrumental in managing and preventing metatarsophalangeal (MTP) joint injuries, such as turf-toe, by limiting excessive forefoot extension (Clanton and Ford, 1994; McCormick and Anderson, 2009). This stiffness modification not only aids in treatment but also serves as a preventative measure against injuries, particularly in high-impact sports (Crandall et al., 2015). Further, it can alleviate stress on other foot areas, potentially preventing injuries like metatarsal stress fractures (Arndt et al., 2003).

The specific bending stiffness requirements vary across sports due to differences in movement dynamics. For instance, badminton shoes might require distinct stiffness properties compared to running or sprinting shoes, reflecting the sport's unique movement patterns. This tailored approach ensures that athletes receive both the performance benefits and injury prevention advantages specific to their sport's demands.

Shoe heel: In the realm of badminton, the design of the shoe heel plays a pivotal role in biomechanical functions, particularly during the critical phase of initial contact in lunging movements. A study focusing on the impact of shoe sole design on lunge skill performance in badminton highlights the significance of heel curvature in altering landing impacts and joint coordination (Guanchun et al., 2021). The rounded heel design, as opposed to the standard heel, has been observed to modify the dynamics of initial ground contact, thereby influencing the biomechanical interaction between the player and the court surface.

This alteration in landing impact is crucial as it directly affects the coordination between the knee and ankle joints. The structure of the shoe heel, particularly its curvature, plays a significant role in how these joints work together during the rapid and complex movements inherent in badminton (Guanchun et al., 2021). Improved heel curvature in badminton shoes is suggested as a plausible method to enhance movement coordination, which is essential for efficient and injury-free performance in the sport.

Furthermore, the biomechanical implications of shoe heel design extend to performance optimization and injury prevention. Appropriate shoe design can improve performance and attenuate impact forces effectively during lunges, thereby reducing the risk of joint injuries (Phomsoupha and Laffaye, 2015; Kesilmiş and Akın, 2019). The shoe heel, as the primary interface between the foot and the ground, is instrumental in ensuring effective movement coordination, a critical factor in the efficiency and safety of sports activities (Guanchun et al., 2021).

In conclusion, the biomechanical function of the shoe heel in badminton is multifaceted, encompassing the modification of landing impacts, enhancement of joint coordination, optimization of performance, and reduction of injury risks. The design of the shoe heel, especially its curvature, emerges as a key factor in achieving these biomechanical objectives in the sport of badminton.

Existing studies have explored the crucial aspects of badminton footwear design, with a focus on shoe cushioning and midsole hardness, forefoot bending stiffness, and heel design. These areas have been the primary focus of recent research aimed at optimizing the design of badminton shoes. The studies collectively highlight the importance of these features in enhancing athletic performance, ensuring comfort, and reducing injury risks.

1.3.2 Torsional Stiffness and Arch Support in Badminton Footwear

In the realm of badminton footwear design, torsional stiffness and arch support play crucial roles in both performance enhancement and injury prevention.

Torsion of the foot is defined as the rotation of the forefoot relative to the rearfoot in the frontal plane (eversion/inversion) (Kälin et al., 1989; Stacoff et al., 1989), with the motion occurring mainly at the transverse talar (Chopart's) and tarso-metatarsal (Lisfranc's) joints (Kälin et al., 1989; Segesser et al., 1989; Ferrandis et al., 1994). The transverse talar joint is comprised of the talonavicular and calcaneocuboid joints, while the tarso-metatarsal joint contains the cuboid, all three cuneiforms and all metatarsals (Kapandji, 1987; Debrunner and Jacob, 1998). These joints allow rotation in all three planes (frontal, transversal, sagittal) with the majority of motion occurring in the frontal plane. The passive range of motion has been reported as 15°–20° eversion and 35°–40° inversion during manual fixation of the rearfoot (Figure 5) (Debrunner and Jacob, 1998).

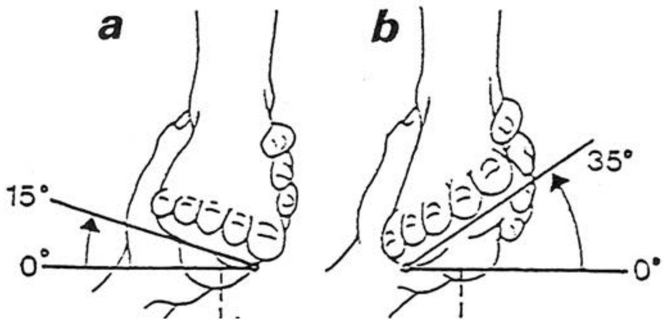


Figure 5. Torsional movements of the foot: (a) eversion of the forefoot, and (b) inversion of the forefoot (Debrunner and Jacob, 1998).

By altering the torsion of the foot when wearing footwear, non-sagittal plane kinematics of the forefoot, rearfoot and shank may be altered. Some research indicates that heightened torsional stiffness in footwear used for basketball, handball, or soccer may increase ankle joint eversion torque, increasing ankle injury risks (Graf and Stefanyshyn, 2013; Graf et al., 2017). In contrast, Luethi et al. suggested that shoes with greater torsional stiffness can lead to reduced lateral ground reaction forces, lessened ankle inversion angles, and lower internal resistive force (Luethi et al., 1986). Furthermore, a study focusing on tennis forehand strokes revealed that shoe torsional stiffness significantly impacts forefoot inversion, with shoes exhibiting maximum torsional stiffness presenting a notable rise in peak ankle inversion angles (Martin et al., 2022). These observations present conflicting insights into the connection between shoe torsional stiffness and the ankle injury risk during sports activities. It's essential to highlight that whether a stronger or weaker shoe torsional stiffness would lead to inversion motion at the ankle, disrupting force absorption balance, and amplifying the risk of ankle injuries. However, despite the potential significance of torsional stiffness on sports performance and predisposition to injuries, there is an absence of biomechanical research specifically on badminton shoe torsional stiffness. Hence, discerning the exact role of torsional stiffness in improving sports performance and reducing injury risks to the lower limbs in badminton remains underexplored.

In addition to the inherent characteristics of shoes, removable insoles that offer functions such as shock absorption, slip resistance, and arch support have attracted considerable attention in recent years, aiming to prevent sports injuries and improve sports performance. Research has reported that more than half of basketball players use insoles with medial arch support during matches (Losito, 2017). For female basketball players, arch support could potentially reduce stress on their lower limbs (Peng et al., 2015). Evidence suggested that baseball pitchers wearing insoles with arch support experience better foot and knee stability (Chen et al., 2016). Biomechanically, arch support insoles enlarge the contact area of the foot with the insole and increase the pressure at the medial longitudinal arch. This enhancement augments foot posture control and improves sensory perception during movement, effectively reducing ground impact, thereby augmenting lower limb stability and preventing lower limb injuries (Davidson, 2010; Arastoo et al., 2014). However, a conflicting study noted that insoles with arch support might exacerbate the ankle joint's maximum inversion during landing, signifying injury risks (Yu et al., 2007). The differing findings could be due to variations in test protocols or differences in arch support height. Given this, there's a need to explore the effects of varying arch support heights, particularly in the context of badminton.

In conclusion, while the impact of torsional stiffness and arch support on injury risk and performance is evident, further specific research in the context of badminton is essential to optimize these elements for the sport's unique demands.

1.4 Research Gaps and Study Justification

1.4.1 Gender properties of badminton shoes

Badminton is one of the most popular recreational sports worldwide. Biomechanical research of badminton sneakers typically focuses on kinematic (Park et al., 2017) and kinetic (Lam et al., 2017b) variables associated with performance injuries in badminton. High-speed cameras and force platforms are frequently used to quantify movement characteristics and joint loading. However, these would cost enormous financial and human resources. In contrast, retrospective studies in hospital and clinics tend to underestimate the incidences and types of injuries (Garrick, 1987), since injured amateur players often do not seek medical help, especially in the case of minor injuries (e.g. blisters, ankle sprain). Moreover, retrospective studies can employ personal interviews and structured questionnaires (Feit and Berenter, 1993), which can allow researchers to gather a vast amount of data using reasonable human and financial resources. In addition to performance and injury perspectives, Llana et al. (Llana et al., 1998) raised the issue of the comfort of sport shoes. These fundamentals can be used in the design and development process of athletic shoes to improve shoe quality and specific function.

The functional requirements of a shoe are multifaceted. While the shoe is the only interface of the human body in contact with the ground, functional shoe constructions for good control, ground support, grip ability and agility are suggested to improve sports performance (Park et al., 2009). Inappropriate shoes and shoe fitting can cause several foot problems (Høy et al., 1994), such as blisters, squeezed toes, and soft tissue bruises (Park et al., 2009). The function of badminton shoes aims at minimizing the injury risks (Marchena-Rodriguez et al., 2020), whilst maximizing sports performance and comfort. Sport shoe characteristics for running, gym, football, basketball, and tennis have been previously studied using questionnaires (Brauner, Zwinzscher and Sterzing, 2012; Althoff and Hennig, 2014; Sterzing et al., 2014; Apps et al., 2015; Hoitz et al., 2020), but information for badminton has not been established. In addition, compared to males, a lower maximal stiffness and higher elasticity within the heel pad have been noted in females (Alcántara-Ayala, 2002). Furthermore, previous studies showed males have a significantly larger plantar fascia and heel fat pad thickness compared to females (Mickle, Steele and Munro, 2008; Taş, Korkusuz and Erden, 2018). Several investigations show that female feet were not just a scaled down version of male feet (Wunderlich and Cavanagh, 2001; Krauss et al., 2008) and female feet were characterized by a higher arch, shallower first toe, shorter length of the outside ball and smaller instep circumference. Other etiological factors including hip Q-angle, foot shape, body mass, muscle strength are different between genders (Althoff and Hennig, 2014), which results in distinct biomechanical alternations and thereby different footwear requirements between males and females

(Apps et al., 2015). Therefore, it can be assumed that badminton shoes need to be optimized with reference to these characteristics between genders in badminton. To date, there is a lack of research on badminton shoes based on gender-specific foot morphology.

Furthermore, badminton players exhibit high asymmetry in their movements, particularly in the functional differences between the dominant and non-dominant legs. In this non-contact sport, rapid forward lunges result in the dominant leg bearing a significantly greater load than the non-dominant leg (Mundermann, Stefanyshyn and Nigg, 2001). Therefore, it is crucial to examine the specific characteristics of badminton shoes for both the dominant and non-dominant sides.

1.4.2 Torsional Stiffness of Badminton Footwear

As for injury prevention in the design of court shoes, achieving overall stability is crucial to counteract excessive pronation during jumping landings, and particularly, excessive supination during sideward cutting movements (Bouché, 2017). The stability of shoe sole relied on factors such as hardness, thickness, and torsional stiffness. Therefore, shoes with softer soles of mild-to-moderate thickness, possessing torsional flexibility, and allowing for medial and lateral deformation of the sole upon heel contact, may offer optimal benefits.

Specifically for the development of badminton footwear, 'flexibility' and 'stability' are important factors that directly affect athletic performance and injury risk (Barton, Bonanno and Menz, 2009; Hong et al., 2016). 'Flexibility' refers to the shoe's features to maintain the natural posture of the foot or torsion difficulty between the forefoot and rearfoot. Reduced torsion might induce injuries due to excessive rearfoot eversion (Segesser et al., 1989; Segesser and Nigg, 1993). 'Stability' involves restricting excessive foot motion and providing stable motion control, especially in sports like badminton that require rapid directional changes and complex footwork (Yu et al., 2023), which also contributes to improved athletic performance. Furthermore, achieving a balance between flexibility and stability is essential in badminton footwear design, especially considering the dynamic demands of fast-paced sports and potential injuries.

The foot fixation or “blocking” played a pivotal role in the mechanism underlying ankle sprains and other injuries in racquet sports (Reinschmidt and Nigg, 2000). Moreover, anecdotal evidence suggested that increased rotational traction may contribute to overload injuries, highlighting the importance of minimizing rotational resistance (Reinschmidt and Nigg, 2000).

The term “foot torsion” refers to the rotational displacement between the forefoot and the rearfoot within the frontal plane (Stacoff et al., 1989). However, the existing literature presented conflicting findings regarding the relationship between shoe torsional stiffness and the risk of ankle injuries during sports activities. Graf and Stefanyshyn (Graf and Stefanyshyn, 2013; Graf et al., 2017) documented that increased torsional stiffness in footwear worn during basketball, handball, or soccer led to higher ankle valgus torque, thereby increasing the susceptibility to ankle injuries (Stacoff et al., 1989; Graf et al., 2017). Further, Luethi et al. found a reduced lateral ground reaction force, decreased ankle inversion angle, and diminished internal resistive force with shoes exhibiting greater stiffness (Luethi et al., 1986). It is important to note that excessive torsional stiffness may limit natural ankle movements, potentially leading to reduced foot flexibility.

Caroline Martin et al (Martin et al., 2022) investigated the impact of shoe torsional stiffness on ankle biomechanics during tennis forehand strikes, and found that shoe torsional stiffness significantly influenced the varus motion in the forefoot. Notably, the study revealed a significant increase of the maximal ankle varus angle with the stiffest shoes, potentially increasing the vulnerability of the lateral ankle sprains.

Despite the potential implications of torsional stiffness on sports performance and injury risk, a notable lack of biomechanical literatures on the torsional stiffness of badminton shoes was found. Consequently, the precise role of torsional stiffness in improving sports performance and mitigating risks of foot and ankle injuries in badminton remain elusive.

1.4.3 Arch Support of Badminton Footwear

Research has reported that more than half of basketball players use insoles with medial arch support during matches (Losito, 2017). For female basketball players, arch support could potentially reduce stress on their lower limbs (Peng et al., 2015). Evidence suggested that baseball pitchers wearing insoles with arch support experience better foot and knee stability (Chen et al., 2016). Biomechanically, arch support insoles enlarge the contact area of the foot with the insole and increase the pressure at the medial longitudinal arch. This enhancement augments foot posture control and improves sensory perception during movement, effectively reducing ground impact, thereby augmenting lower limb stability and preventing lower limb injuries (Davidson, 2010; Arastoo et al., 2014). However, a conflicting study noted that insoles with arch support might exacerbate the ankle joint's maximum inversion during landing, signifying injury risks (Yu et al., 2007). The differing findings could be due to variations in test protocols or differences in arch support height. Given this, there's a need to explore the effects of varying arch support heights, particularly in the context of badminton.

1.5 Objectives

In my thesis, I would like to draw up three research questions that have been unanswered so far in the relevant.

The First Research Question of This Thesis: Given the predominant focus on biomechanical studies in the evaluation of badminton footwear features, what are the subjective perspectives and requirements of athletes regarding footwear characteristics, and how might these subjective factors differ between genders? Additionally, considering the asymmetric demands of badminton, are there discrepancies in footwear needs and reported lower limb injuries between an athlete's dominant and non-dominant legs?

The First Objective of This Thesis: To conduct a cross-sectional survey to assess the differences in shoe requirements, reported problems/complaints, and pain locations between male and female badminton players, as well as to compare the footwear feature needs of players' dominant and non-dominant legs. The results from this study will aid in understanding the requirements for badminton footwear and the mechanisms of foot pain, providing insights for recommendations on footwear features.

The Second Research Question of This Thesis: Building on the identification of gender-related differences in badminton footwear needs, this study extends to assess the influence of torsional stiffness—a critical but less examined feature of badminton shoes—on the biomechanics of the lower limbs. How does torsional stiffness impact the performance and injury risk during badminton-specific footwork, particularly concerning the stability and performance of the foot and lower limb joints?

The Second Objective of This Thesis: To empirically assess the effects of varying torsional stiffness levels, with Shore D hardness values of 50, 60, and 70 (denoted as 50D, 60D, and 70D, respectively), in badminton footwear on the biomechanical functioning of the lower limbs during badminton-specific movements. This entails a detailed analysis of ankle, knee, and MTP joint kinematics, moments, and ground reaction forces to determine how these variables are influenced by footwear torsional stiffness. The study aims to establish an evidence-based understanding of how stiffness variations can affect players' performance and the incidence of injuries, ultimately guiding the design of badminton shoes that optimize the balance between flexibility and stability for enhanced athletic performance and reduced injury risk.

The Third Research Question of This Thesis: Building upon the previous study that investigated the biomechanical impact of 50D, 60D, and 70D torsional stiffness levels in badminton shoes, how do more finely graduated torsional stiffness levels (55D, 60D, and 65D), along with varying arch support heights, affect the lower limb joint kinematics, kinetics, and contact forces in badminton athletes? Further, is there a compound effect of these finely differentiated levels of torsional stiffness when combined with different arch support heights on the risk and mechanism of injury, as well as on the optimization of performance in badminton?

The Third Research Objective of This Thesis: To determine the combined effects of varying torsional stiffness levels (55D, 60D, and 65D) and arch support heights on lower limb biomechanics using OpenSim musculoskeletal modeling, with a focus on their influence on joint kinematics, kinetics, and contact forces during badminton-specific movements. This objective will explore the potential synergistic or antagonistic interactions between torsional stiffness and arch support height in badminton footwear, assessing their implications for athletic performance optimization and injury prevention in the sport.

2. METHODS

2.1 Gender properties of badminton shoes

2.1.1 Study design and participants

This cross-sectional study was conducted at a recreational badminton match at Li-Ning Company (Beijing, China) in October 2019, with a total of 2,000 participants. The basic inclusion criteria were: above 18 years old and had been regularly participating in badminton for the past six months. The exclusion criteria were: lower limb surgery or neurological injury. The supervised questionnaire contained the basic profile (height, weight, age and racket-hand/dominant leg), the importance of shoe properties, shoe complaints, and pain or discomfort across foot regions. Ethical approval was approved by the institutional Human Research Ethics Committee (IRB-2019-BM-0013) in accordance with the Declaration of Helsinki principles.

2.1.2 Sample size

The sample size for this study was calculated using the online Sample Size Calculator (Raosoft Inc., Seattle, WA, USA, raosoft.com) with a 5% margin of error, 95% confidence interval, and 50% response distribution. A total of 500 recreational badminton players was approached while 326 returned their responds with their consent and participated in the study (response rate 65.2%)

2.1.3 Data validity and collection

A total of 78 self-assessment items in the “importance of shoe properties”, “shoe complaints” and “pain or discomfort in different foot regions” sections of this study were assessed using the Likert scale, which showed a good reliability and validity to measure subjective perception (Isherwood, Wang and Sterzing, 2021; Matthias, Banwell and Arnold, 2021). The reliability levels of the subscales were as follows: importance of shoe properties (Cronbach’s α=0.94), shoe complaints (Cronbach’s α=0.96), pain or discomfort across foot regions (Cronbach’s α=0.63). Therefore, the reliability of the questionnaire in our study was acceptable. Bartlett spherical test and KMO (Kaiser-Meyer-Olkin) test were performed to ensure that the data characteristics were suitable for factor analysis. In the sample adequacy test, the KMO value of 0.812 is greater than 0.5, indicating that the questionnaire data was suitable for factor analysis. The Bartlett’s test result was $X^2 = 25553.553$, df = 3003, P = 0.000 < 0.05, confirming the validity of the questionnaire.

The questionnaire was completed by participants under the supervision of researchers, who provided guidance to ensure the validity of the data. In this study, the role of the researchers was to explain the definitions of the footwear and foot related terminology in order to avoid the misunderstanding of the technical terms, especially for the participants with little anatomy and/or footwear construction knowledge and to prevent the participants from random answers and missing answers, which greatly ensured the quality of the questionnaire.

The questionnaire, specifically designed for this study, was categorized into four sections: (1) participant profile, (2) importance of shoe properties, (3) shoe complaints, (4) pain or discomfort in different foot regions (Figure 6). All of the questionnaires were conducted in Chinese when the participants had completed the competition.

In section one, participant profiles regarding gender, age, height, weight, racket-hand/ dominant leg were obtained. Section two and three required respondents to indicate subject's rating on the importance of shoe properties and shoe complaints, respectively.

In section two, the importance of shoe properties was selected as the common shoe requirements during gameplays, which was established based on the previous studies on footwear properties in running, basketball and gym training (Alcántara-Ayala, 2002; Lam, Sterzing and Cheung, 2011; Brauner et al., 2012; Apps et al., 2015). The assessed variables were overall evaluation of shoe, heel cushioning, forefoot cushioning, arch support, forefoot bending stiffness, traction/grip, durability, and stability. All respondents indicated their preferences on the 9-point Likert scale (1: extremely unimportant, 2: very unimportant, 3: unimportant, 4: somewhat unimportant, 5: neutral, 6: somewhat important, 7: important, 8: very important, 9: extremely important).

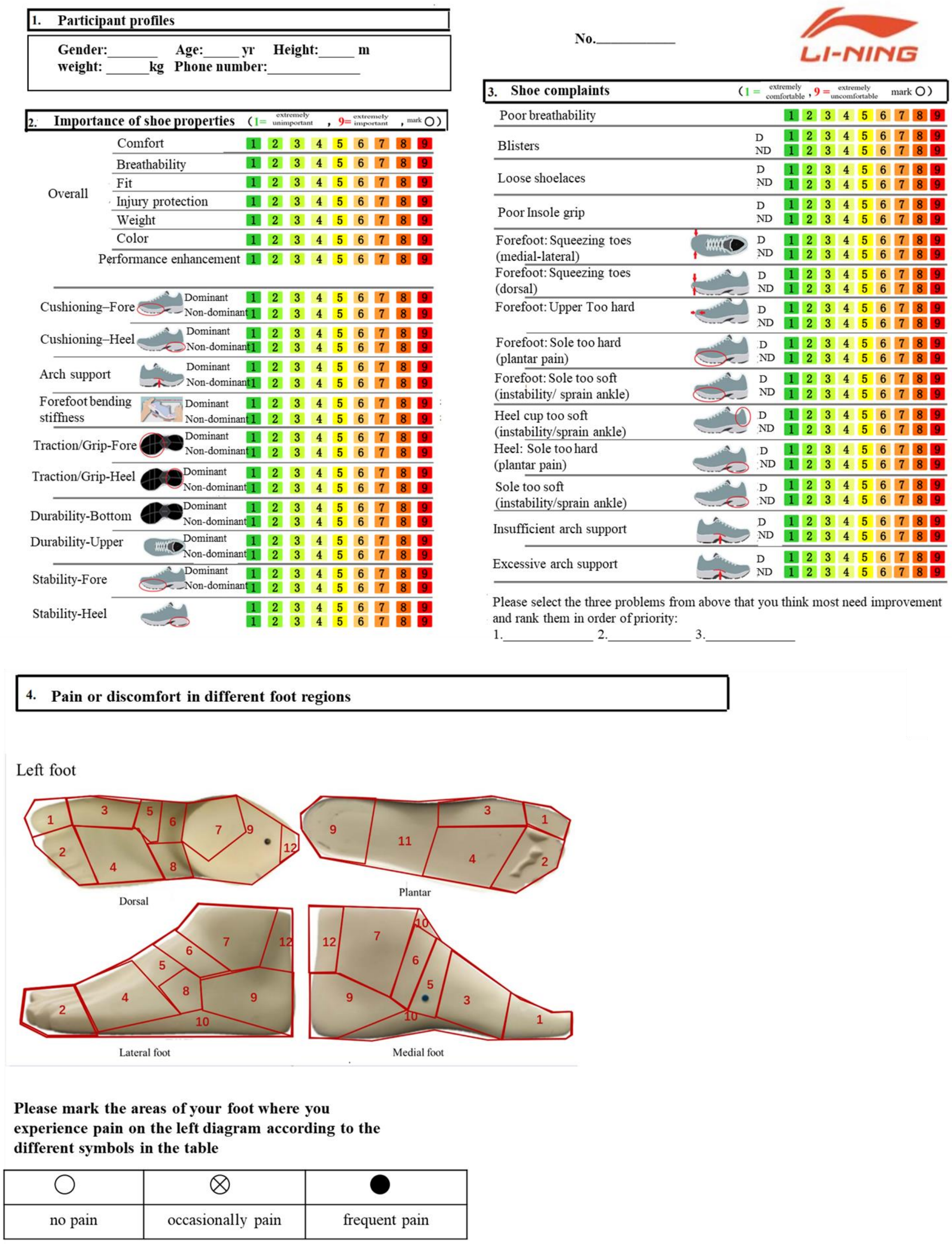


Figure 6. Chinese questionnaire

In section three, the footwear complaint was defined as any footwear problems encountered in badminton, including poor breathability, blisters, loose shoelaces, poor insole grip, forefoot squeezing toes (media-lateral), forefoot squeezing toes (dorsal), forefoot upper too hard, forefoot sole too hard (plantar pain), forefoot sole too soft (instability/sprain ankle), heel cup too soft (instability/sprain ankle), insufficient arch support, and excessive arch support. All of the shoe properties and footwear complaints were extracted from the previous studies on footwear comfort perception (Lam et al., 2011; Brauner et al., 2012; Apps et al., 2015; Honert et al., 2020) as well as advice from badminton coaches. All respondents gave their rating on the 9-point Likert scale (1: extremely comfortable, 2: very comfortable, 3: comfortable, 4: somewhat comfortable, 5: neutral, 6: somewhat uncomfortable, 7: uncomfortable, 8: very uncomfortable, 9: extremely uncomfortable).

In section four, respondents were asked to indicate any pain or discomfort at 12-foot regions (Figure 7), including hallux, other four toes, first metatarsophalangeal MTP, second-fifth MTP, cuneiform bone, cuboid bone, navicular bone, talus, heel, soft tissues of the foot, arch, and Achilles' tendon, as described in previous studies (Gefen et al., 2000; Wunderlich and Cavanagh, 2001; Chen, Lee and Lee, 2015). The degree of pain/discomfort was assessed by 3-point Likert scale (no pain, occasionally pain, and frequent pain) (Llana et al., 2002) for the dominant and non-dominant feet, respectively.

In addition, the subjective assessment was determined for respective dominant and non-dominant legs, as badminton is considered as a highly asymmetrical sport that results in uneven loading and movement characteristics. The sensitive dominant side was more suitable for athletes to use during competition, which may lead to the larger discrepancy of the strength and movement characteristics between dominant and non-dominant legs. Therefore, we also evaluated the requirements for footwear and pain on the dominant and the non-dominant sides (Nadzalan et al., 2018).

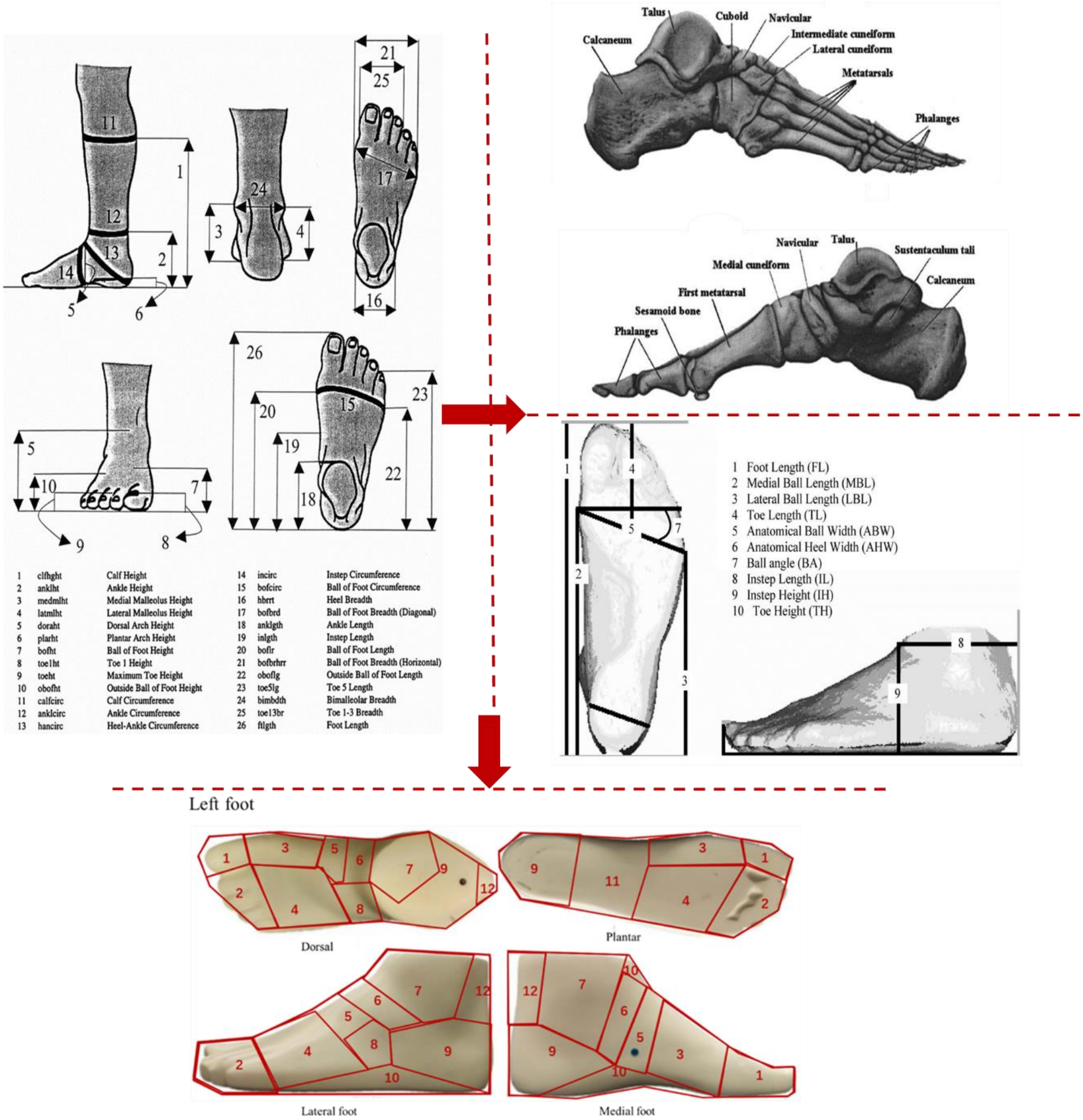


Figure 7. Diagram of the foot regions (Left foot), 1-Hallux, 2-Other four toes, 3-First MTP, 4-2nd-5th MTP, 5-cuneiform bone, 6-navicular bone, 7-Talus, 8-Cuboid bone, 9-Heel, 10-Soft tissues of the foot, 11-Arch, 12-Achilles' tendon (Gefen et al., 2000; Wunderlich and Cavanagh, 2001; Chen et al., 2015).

2.1.4 Data analysis

The data obtained were shown as means and standard deviations, as well as frequencies. The self-reported Likert scale was considered as non-parametric in nature. Moreover, additional Shapiro-Wilk tests showed that the data violated the normal distribution ($P < 0.05$). Therefore, the gender differences in all variables were analyzed using the Mann-Whitney U test, and the differences between the dominant and non-dominant feet were analyzed using the Wilcoxon Signed Ranks Test. The significance level was set at $P < 0.05$. All statistical analyses were conducted using SPSS 21.0 (SPSS Inc., Chicago, IL, USA).

2.2 Torsional Stiffness of Badminton Footwear

2.2.1 Participants

Fifteen male players participated in the study, with anthropometrics of age = 22.8 (1.96) years, height = 1.77 (0.04) m, mass = 74.2 (7.65) kg, AHI (arch height index) = 0.25 (0.04), ASI (arch stiffness index) = 0.82 (0.09). Prior to the recruitment of participants, the G*power software (Faul et al., 2007) was used for power analysis to determine the number of participants required to obtain an effect size of 0.25, which was based on anticipated differences informed by preliminary research and existing literature (Teng et al., 2022). The alpha error probability was set at a common threshold of less than 0.05 to uphold the stringency of statistical testing. In pursuit of high sensitivity to detect true effects, the study sought a power ($1-\beta$) exceeding 0.95. Through these parameters, using a one-way repeated measures ANOVA in G*power, it was established that a minimum sample size of 15 subjects was required to accomplish sufficient power for this study. This determination aligns with standard practices for ensuring reliable and valid results within biomechanical research. Specific inclusion criteria included 1) active competitive badminton players, evidenced by participation of official matches, 2) engagement in badminton-related activities more than three times per week, 3) definition of right-hand and right-leg as the dominant limb, and 4) a shoe size of 9 US with uniform test footwear. Particular exclusion criteria included 1) any history of lower extremity injuries in the past six months that may affect sport performance, and 2) prior experience with the specific shoe model used in this study to avoid familiarity bias.

During the recruitment phase, each participant underwent a balance recovery test (Virgile and Bishop, 2021). In this procedure, the same testing assistant administered a sudden push to the participants' upper spine from behind, prompting them to step forward to regain balance. The first leg to move in response was designated as the dominant leg (Hoffman et al., 1998). Moreover, the hand a participant instinctively used to grasp a badminton racket was determined as the dominant hand (Hülsdünker, Ostermann and Mierau, 2019; Hülsdünker, Gunasekara and Mierau, 2020; Dzulfakar, Shufaian and Sharir, 2022). As a result, all qualifying participants reported right-side dominance.

Ethical considerations were also meticulously followed, which was approved from the Ethics Committee in the University. Participants were informed of the requirements and procedures with obtained consent.

2.2.2 Footwear

Three pairs of badminton shoes with a shoe size of US 9.0 (SSRC-AT-23, Li-Ning, Beijing, China) were specifically customized for this study to ensure consistency in the upper and sole materials, structure, and size in all footwear conditions. The primary modification was the torsional stiffness of the shoes. To achieve this, the shoes were intentionally altered, resulting in three distinct levels of torsional stiffness. The quantification of torsional stiffness was carried out using Shore D hardness units, with values of 50D, 60D, and 70D assigned to the respective shoes (Figure 8a). Additionally, a torsional plate made of the same thermoplastic polyurethane (TPU) was incorporated into each shoe design (Figure 8b), contributing to the variation in torsional characteristics.

(a) (b)

Figure 8. Constructions of shoe conditions (a) and the torsion plate location (b)

The biomechanical properties of the shoes, particularly the torsional stiffness, were quantified using a standardized methodology based on the GB/T 32024-2015 standard by the China National Light Industry Council (China National Light Industry Council, 2015) The toe section of the shoe was secured, and the heel section was elevated along the outsole's flexion line by 30°/10° to mimic physiological conditions. A controlled rotational motion was applied around the longitudinal axis at a consistent velocity, and the maximum torque required for inward and outward rotation to the predetermined angles was measured. This procedure allowed for the precise calculation of torsional stiffness in Newton meters (N*m), providing a clear, quantifiable differentiation between shoe conditions (China National Light Industry Council, 2015). The torsional performance data for each shoe condition were presented in Table 1.

Table 1. Description of shoe conditions.

Shoe conditions	Internal torque (30°) [Nm/ °]	External torque (10°) [Nm/ °]	Weight (g)
50D	3.63	1.42	325
60D	3.94	1.72	325
70D	4.47	1.90	325

2.2.3 Movement tasks

The kinematic data were collected using the Vicon motion analysis system (Vicon, Oxford Metrics, Oxford, UK) equipped with the VERO series cameras. This setup included 8 VERO cameras, operating at a sampling frequency of 200Hz. The kinetic data were obtained using the KISTLER force plates (Kistler, Switzerland) at a sampling frequency of 1000Hz. The kinematic and kinetic data were collected simultaneously.

Forehand Clear Stroke (Left Foot and Right Foot): The forehand clear stroke is a crucial element in badminton, significantly affecting both the pace and strategy of the game (Ahmed and Ghai, 2020). This technique requires intricate lower limb movements, especially notable in the twisting motion of the foot when generating propulsive force (Lee, Xie and Teh, 2005). The movement serves as a valuable measure in this study to explore how different shoe torsional stiffness impact the biomechanical response.

During the forehand clear stroke, participants wore the three pairs of badminton shoes and performed five valid trials with each pair (a total of 15 trials) in a randomized order. The specific requirements for the movement were as follows, during the preparation phase, participants stood with their feet shoulder-width apart and slightly bent knees. At the initiation, participants shifted the weight center to the right, quickly pushed right foot towards the right rear, and then stepped back to ensure that the right foot landed on the force plate (A) (Figure 9). After completion of the stroke, participants immediately ensured that the left foot landed on the force plate (B) (Figure 9), indicating a successful completion of the trial.

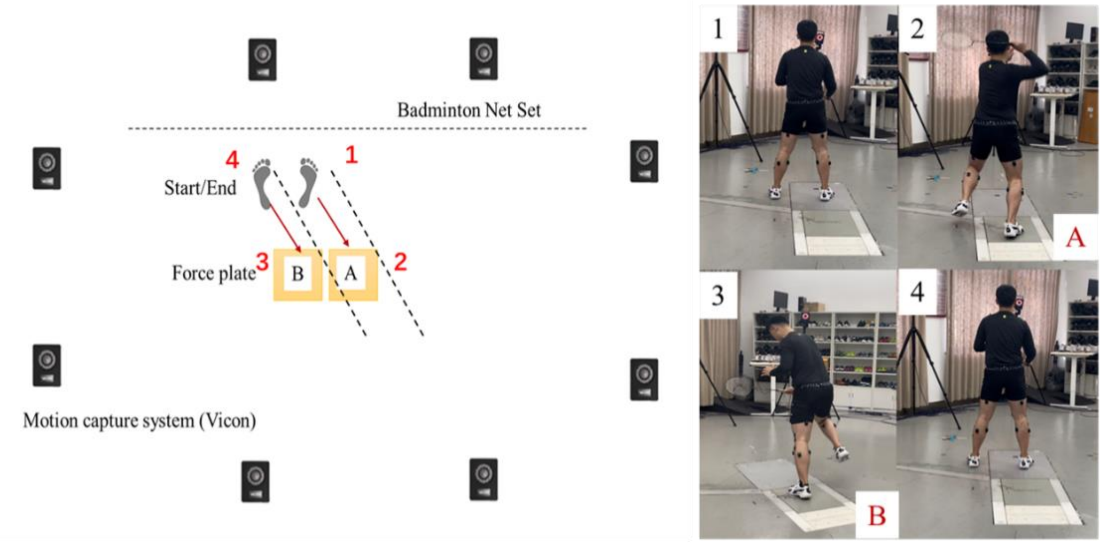


Figure 9. Laboratory simulation and route for forehand clear stroke

45-Degree Sidestep Cutting (45C): While the 45C is not the most commonly employed footwork in badminton, this movement plays a strategic role during the game. Players employ the footwork in specific scenarios to change the motion direction, thus creating challenges for the opponents and increasing opportunities for more effective shots. The effectiveness of 45C lies in the flexibility, accuracy and speed, highlighting the need for athletic precision. The strategic importance and physical demands placed on badminton players makes the 45C an essential motion included in this study (Zhang et al., 2023). By analyzing this movement, insights into how torsional stiffness of shoes may affect cutting biomechanics during quick and reactive movements could be reported (Yu et al., 2023)

At the initiation of the 45C acquisition, the participant moved forward in a straight line, ensuring that the left foot landed on the designated force plate upon reaching it. Subsequently, the participant exerted maximum effort to execute a precise 45-degree cut to the right. Finally, deceleration and stopping were executed along the direction of the sidestep cutting, facilitating controlled movement, and maintaining positional stability (Figure 10).

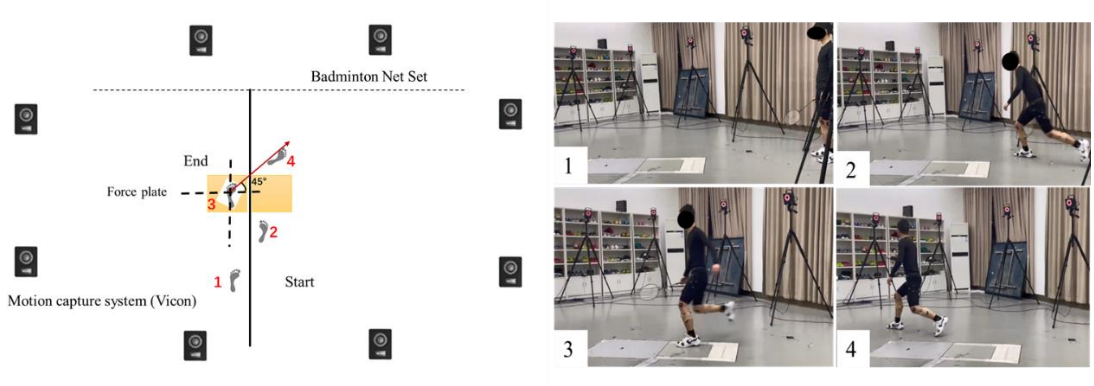


Figure 10. Laboratory simulation and route for 45C

Consecutive Vertical Jumps (CVJ): CVJ are pivotal in badminton, directly linked to both offensive and defensive plays (Akdogan et al., 2022). As a cornerstone of on-court agility and dynamic performance, the CVJ task in this study was specifically chosen to scrutinize the footwear's performance under repetitive, high-impact conditions, thus highlighting the shoes' ability to absorb shock and assist in efficient energy transfer during continuous jumps (Hoffman et al., 1998; Kam et al., 2021). This inclusion explores not just the protection property of badminton shoes during the strenuous actions but also how variations in torsional stiffness may affect the mechanics and safety of common, high-frequency movements in badminton.

At the onset of the CVJ task, participants were instructed to position the right leg on the designated force platform, with the left leg stationary on the adjacent floor surface. Unlike standard vertical jumps measuring the height, the CVJ approach in this study prioritized the dynamic nature of multiple successive jumps, crucial in badminton performance. Participants were required to execute five consecutive jumps, exerting maximal effort without aiming for a specific height, focusing instead on continuous, smooth movement. This technique was chosen to simulate the rapid, inherent repetitive movements in competitive badminton. Ensuring the right foot's accuracy on the force platform was crucial for valid data of each trial, with the left foot remaining off the force platform interference. This method focused on collecting data related to lower limb joint angles, ROM, and ground reaction forces, providing a holistic view of performance than a singular focus on jump height.

2.2.4 Procedures

Prior to the actual data acquisition, participants were instructed to perform a 5-minute self-selected warm-up protocol and familiarize with the experimental protocol, especially the placement of the right foot on the force platform in all test movements (Forehand Clear Stroke, 45C, and CVJ). After becoming familiar with the protocol, participants wore uniform socks and tights, and the experimental assistants were responsible for pasting the 38 reflective markers according to a previous musculoskeletal marker set model (Delp et al., 2007), as illustrated in the Figure 11.

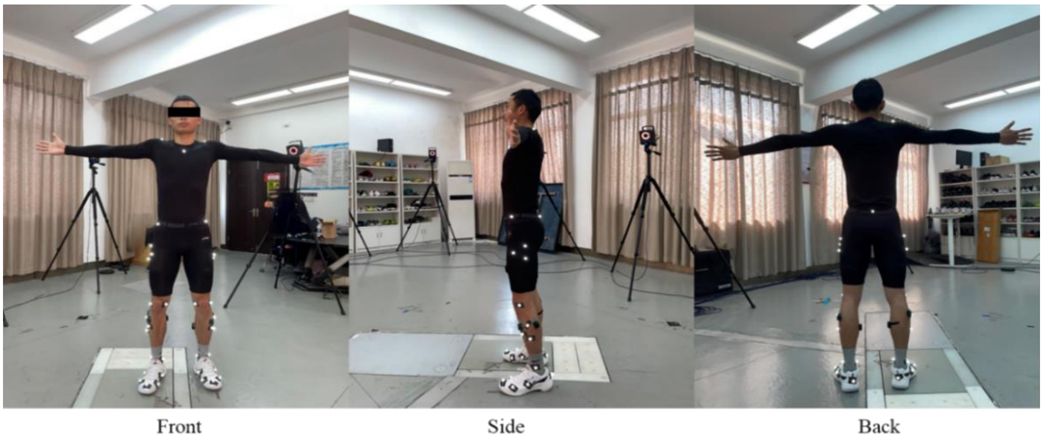


Figure 11. The front, side, and back positions of marker set

During the tests, participants were asked to perform five trials for each of the Forehand Clear Stroke, 45C, and CVJ tasks in each of the three test shoe conditions (50D, 60D, and 70D). In total, participants performed 60 trials (five valid trials × four movements × three shoes). One-minute and ten-minute breaks were prescribed between trials and between different shoe conditions to minimize the influence of fatigue (Lam et al., 2019b).

For the purpose of consistency and maintaining the integrity of the test conditions, all participants used standardized equipment during the experiment, including rackets and badminton shuttlecocks of uniform model and brand, ensuring that performance differences were attributable to the shoe conditions rather than variances in equipment. Both the shoes and movement conditions were randomized across participants, which ensured that each participant was randomly assigned different shoe conditions and movement tasks, without adhering to any predetermined sequence, thereby enhancing the impartiality and validity of the results.

2.2.5 Data Processing

The kinematic and kinetic data were collected and recorded synchronously using Vicon Nexus software (Oxford Metrics Ltd, Oxford, UK). Following the marker labelling process, the data were exported to the Visual 3D (three-dimensional) software (C-Motion Inc., Germantown, USA) for the calculation and extraction of all the required parameters. To enhance data quality, a fourth-order Butterworth bi-directional filter with cut-off frequencies of 12 and 100 Hz was employed to smooth the kinematic and kinetic data (Nigg et al., 2009). Joint angles, range of motion (ROM), joint moments, were computed using Visual 3D software. Joint moments were calculated using an inverse dynamics analysis and presented as the resultant internal joint moments in the sagittal, transverse, and frontal planes (Lam et al., 2015b). Additionally, the ground reaction force data were standardized by body weight (BW) to account for individual variations. The zero degree of joint was established with reference to the static standing position.

The primary variables of analysis included ankle, knee, and MTP kinematics, ankle and knee joint moments, peak ground reaction forces in the anterior-posterior, medial-lateral, and vertical directions, ROM, and stance time.

2.2.6 Statistical analysis

Statistical analyses were conducted using SPSS 27.0 (IBM Corp., Armonk, NY, USA) statistical analysis software. Prior to hypothesis testing, the normality of data distribution for continuous variables was assessed using the Shapiro-Wilk test, accompanied by visual inspections of Q-Q plots. This step was vital as subsequent parametric analyses, including the one-way repeated measures analysis of variance (ANOVA), requiring the data to adhere to a normal distribution. The ANOVA was performed at a significance level of 0.05 to determine any statistically significant differences between the 50D, 60D, and 70D shoe conditions. Sphericity assumptions were checked using Mauchly's sphericity test, and if violated, Greenhouse-Geisser's test was employed to adjust the significance of the main effects. The effect size was measured using partial eta-squared (η^2) for ANOVA and interpreted as small ($0.1 \leq \eta2 < 0.06$), medium ($0.06 \leq \eta^2 < 0.14$), and large ($\eta^2 \geq 0.14$) (Cohen, 2013). In the case of a significant main effect, Bonferroni-adjusted post hoc tests were used to compare the different shoe conditions. Non-normally distributed data were analyzed using a Friedman test, followed by a post-hoc Bonferroni correction. Statistical parametric mapping based on the one-dimensional statistical parametric mapping (SPM1d) package for MATLAB (MathWorks, Natick, MA, USA) was employed to compare the vertical ground reaction force during the forehand clear stroke (right foot) (FCR). Specifically, the vGRF was compared between the 50D vs. 70D conditions (Pataky, 2012). The significance level was set at 0.05.

2.3 Torsional Stiffness and Arch Support Variations in Badminton Footwear

2.3.1 Participants

The study utilized the G*power software for a preliminary power analysis (Faul et al., 2007), setting the alpha below 0.05 and the power of the t-test at 0.8. Based on a Two-way repeated-measures ANOVA, a minimum of 12 participants was required. Fifteen male players, averaging 22.86 (±1.96) years in age, 1.77 (±0.04) m in height, and 74.2 (±7.65) kg in weight, participated in the study. All participants had extensive badminton experience and a dominant right leg. None reported injuries in the past 6 months or had previously worn the specific shoe model used in the experiment. The university's ethics committee approved the study, and all participants provided informed consent.

2.3.2 Footwear

For this study, Li Ning Company specially developed three models of badminton shoes, all in US size 9.0 (SSRC-AT-23, Li Ning, Beijing, China). The primary differentiation among these shoes was their soles' torsional stiffness, aimed at assessing the impact of varying stiffness levels on player performance. The torsional stiffness of the entire sole, measured in Shore D hardness units, was set at 55D, 60D, and 65D, respectively, for the three shoe models (see Figure 12a). The torsion plates, responsible for this variation in stiffness, were all fabricated from the same of thermoplastic polyurethane (TPU) (refer to Figure 12b). Aside from the differences in torsional stiffness, the test shoes shared consistent design and characteristics.

(a) (b)

Figure 12. Constructions of shoe conditions (a) and the torsion plate location (b).

Performance tests were conducted on the shoes with varying torsional stiffness levels. The testing procedure involved fixing the forefoot of the shoe and elevating the heel section along the outsole flexion line by 30°/10°. Subsequent movements around the longitudinal axis were executed at a predetermined speed to quantify the maximum torque needed to reach specific inward and outward rotation angles. Torque is defined as the force exerted in the vertical direction multiplied by the distance to the center of rotation, and it's quantified in Newton-meters (N*m). Table 2 displays the torsional performance data of each shoe condition.

Table 2. Description of shoe conditions.

Shoe conditions	Internal torque (30°) [Nm/ °]	External torque (10°) [Nm/ °]	Weight (g)
55D	3.84	1.86	325
60D	3.94	1.72	325
65D	3.86	1.77	325

2.3.3 Arch support insoles

The present study employed an insole with an original thickness of 5mm, fabricated from polyurethane (PU). The arch region showcased a cut-out feature, designed to accommodate arch support pads of various elevations, made from Thermoplastic Rubber (TPR) (Figure 13). Three distinct heights of insoles were tested (Figure 14): Figure 14a, when combined with the primary insole, yielded a flat profile, indicative of no arch support (NS). Figure 14b exhibited a 5mm elevation over 14a, representing low support (LS), while Figure 14c was elevated by 8mm in comparison to 3a, denoting high support (HS). With the exception of the differences in the height of the arch support inserts, all other design elements remained consistent.

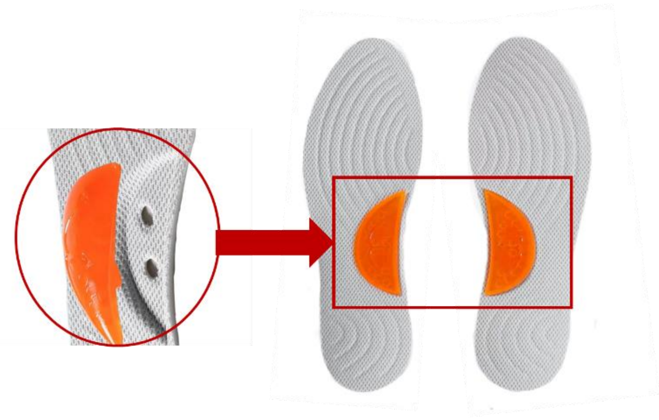
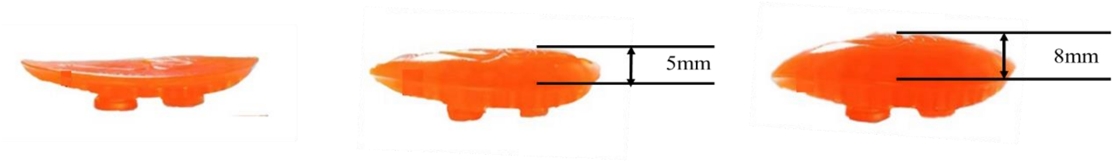


Figure 13. Placement method of the arch support inserts.



(a)- No support (b)- low support (c)- High support

Figure 14. Arch support inserts of varying heights. (a) No support, (b) Low support, (c) High support.

2.3.4 Movement tasks

Test Movement One: FCR. Participants were required to wear shoes with each variation of insole height and torsional stiffness, performing five successful trials for each, resulting in a total of 45 trials. A trial was marked successful when the right foot accurately contacted the force plate's center and balance was maintained upon landing. Specific movement instructions were: During the preparation phase, participants stood with feet shoulder-width apart and knees slightly bent. At initiation, they shifted their weight to the right, rapidly extending the right foot towards the right rear, before stepping back to ensure the right foot made contact with the force plate (refer to Figure 15). Upon completion of the stroke and the landing of the left foot, participants returned to their original stance, indicating the trial's end.

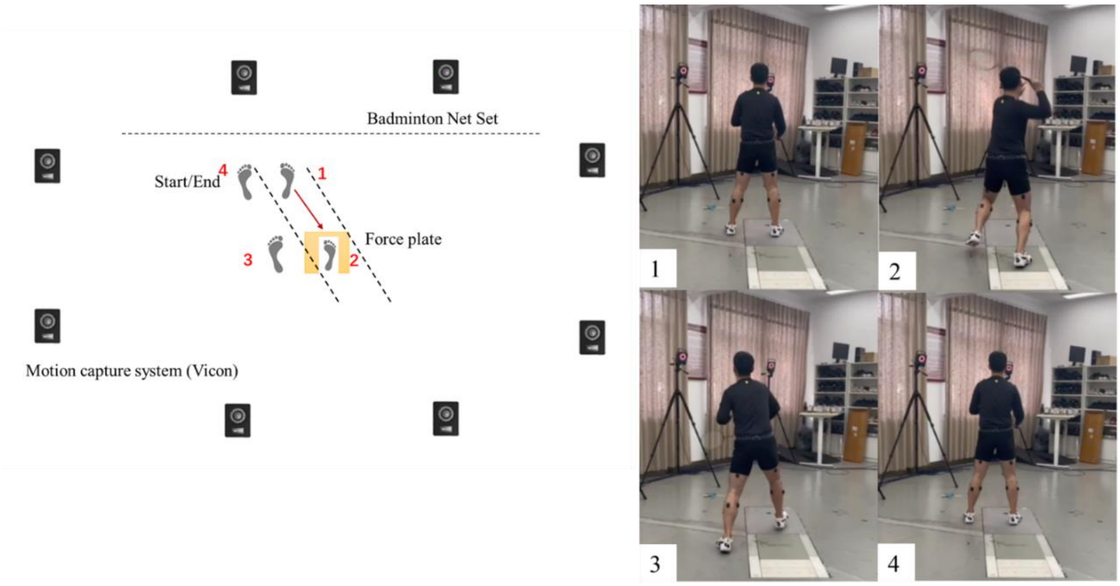


Figure 15. Laboratory trajectory of the FCR

Test Movement Two: 45C. The number of trials was consistent with the FCR. The collection criteria were as follows: Initially, participants advanced straight forward, ensuring that the left foot centered on the force plate upon arrival (Figure 16). Subsequently, with maximal effort, participants cut out at a 45-degree angle to the right using their right foot. Lastly, data was considered valid if participants decelerated following the cutting direction and came to a stop while maintaining body stability.

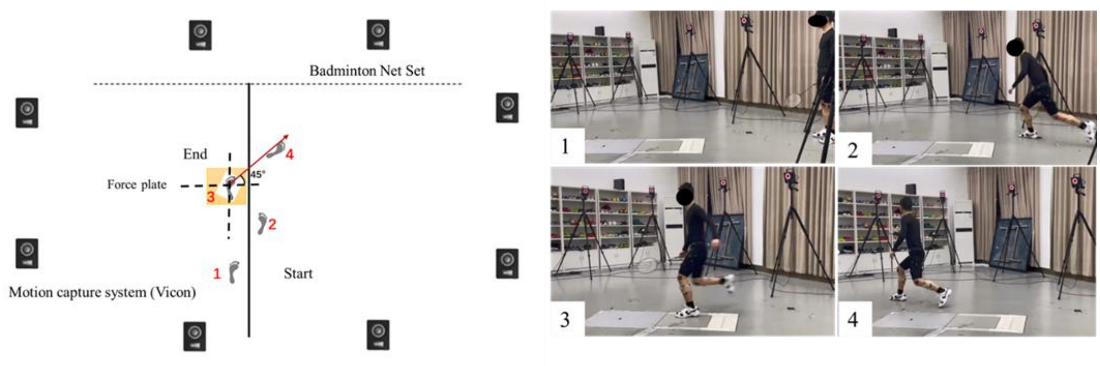


Figure 16. Laboratory trajectory of the 45C

2.3.5 Experimental equipment and protocol

Kinematic data was collected using the Vicon motion analysis system (Vicon, Oxford Metrics, Oxford, UK) with 8 cameras at a sampling rate of 200Hz.

Concurrently, kinetic data was captured using the KISTLER force platform (Kistler, Switzerland) at a frequency of 1000Hz. Muscle activities from ten muscles were recorded at 1000Hz with the Trigno wireless surface electromyography system (Delsys, Boston, MA, United States). These muscles included five from each leg: rectus femoris, biceps femoris, tibialis anterior, medial gastrocnemius, and lateral gastrocnemius. The specific electrode placement is illustrated in Figure 17. The Gait 2392 model in OpenSim (Stanford University, Stanford, CA, USA) was employed for musculoskeletal modeling. A total of 38 reflective markers with a diameter of 14mm were positioned as depicted in Figure 17.

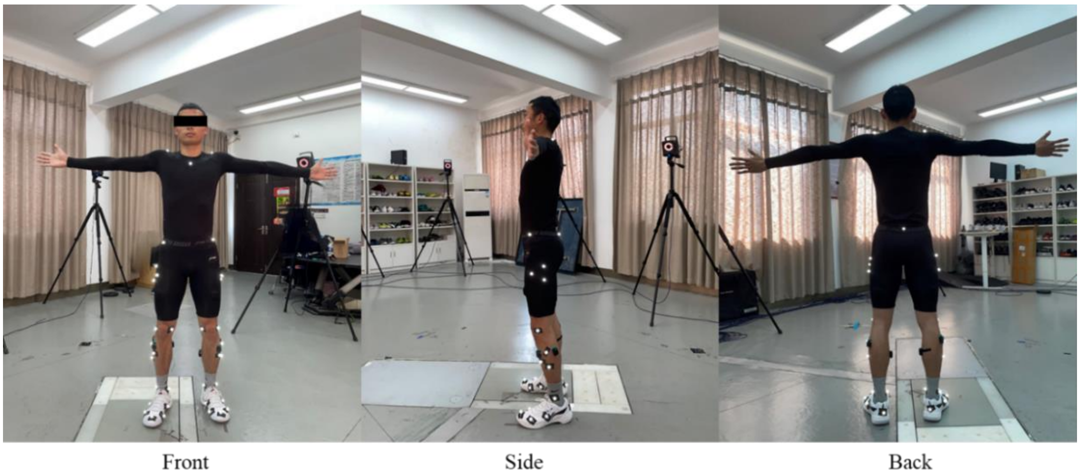


Figure 17. The front, side, and back positions of markers and EMG electrodes

Prior to data collection, participants were instructed to undertake a self-selected 5-minute warm-up routine and familiarize themselves with the testing protocols, particularly the foot positioning on the force plat during all test movements. After understanding the procedure, they wore standardized socks and tight-fitting clothes, and the assistant placed the 38 reflective markers according to the Gait 2392 model (Delp et al., 2007).

For the actual testing, each participant was asked to perform the tasks in shoes with three different torsional stiffnesses (55D, 60D, and 65D) and with three types of insoles with varying arch heights (NS, LS, and HS). This resulted in a total of 90 trials for each participant: 5 trials for each combination of 2 tasks, 3 types of shoes, and 3 types of insoles. One-minute rest intervals were given between trials, and ten-minute rests were allocated between different shoe and insole conditions to minimize fatigue (Lam et al., 2019b). The sequence of shoe, insole, and movement conditions was randomized for each participant.

2.3.6 Musculoskeletal Model

The musculoskeletal model employed in this study was the generic OpenSim model, Gait 2392, which comprises 10 rigid bodies, 23 degrees of freedom, and 92 muscles (Au and Dunne). Kinematic data and ground reaction forces collected were processed and converted into TRC and MOT files in MATLAB R2022b (MathWorks, Natick, MA, USA)）. Subsequent data processing followed the established workflow in OpenSim v4.3 (Delp et al., 2007). Initially, the model was scaled according to the anthropometric data of each participant, which was obtained from static marker positions and body weight. This ensured that the root mean square error between the experimental and virtual markers was less than 0.02 meters, with a maximum error of less than 0.04 meters. Subsequently, using inverse kinematics, joint angles were determined that minimized the discrepancy between the calibrated and virtual markers. This was followed by the computation of joint moments through inverse dynamics. Thereafter, the static optimization algorithm was executed, leveraging the least squares sum of muscle activations to deduce the extent of muscle activations and muscle forces (Delp et al., 2007; DeMers, Pal and Delp, 2014; Mei et al., 2019). Ultimately, the muscle forces were employed to calculate joint contact forces.

2.3.7 Data and Statistical Analysis

Prior to experimental testing, maximal voluntary contraction (MVC) of the muscles was evaluated using isometric strength assessments. Using the Delsys EMG signal analysis software, the raw EMG signals were processed with a fourth-order Butterworth band-pass filter in a frequency range of 100 to 500 Hz. Subsequent amplitude analysis was conducted via root mean square (RMS) calculations, which then produced MVC and normalized activity values for each motion. EMG activity levels were calculated by comparing the RMS amplitude to the MVC's RMS amplitude, ranging from 0 (indicating no activation) to 1 (indicating full activation). The muscle activation levels derived from experimental measurements were contrasted with those obtained via the static optimization algorithm to validate the model.

This study focused on simulations from the standing phase of each test action. Analyzed variables encompassed joint angles, moments, and contact forces of the hip, knee, and ankle joints. Joint moments were standardized by body weight (Nm/kg), while joint contact forces were standardized by body weight (%BW).

Statistical analyses were conducted using SPSS 27.0 (IBM Corp., Armonk, NY, USA). Data normality was verified using the Shapiro-Wilk test. Sphericity was assessed using Mauchly’s test, and if assumptions were violated, the Greenhouse-Geisser correction was applied. Effect sizes were measured with the partial eta squared (η^2) and were interpreted as small ($0.01 \leq \eta^2 < 0.06$), medium ($0.06 \leq \eta^2 < 0.14$), and large ($\eta^2 \geq 0.14$). For each test variable, a separated 3 x 3 two-way repeated measures ANOVA (Torsional Stiffness x Arch Support height) was used to identify any significant differences ($p < 0.05$). Post-hoc Bonferroni tests were carried out where main effects were significant.

3. RESULTS

3.1 Gender properties of badminton shoes

3.1.1 Characteristics of the participants

A total of 326 recreational badminton players, comprising 200 males and 126 females, all of whom are Chinese citizens, participated in the experiment. The mean ages were 30.9±11.8 years for males and 33.18±12.1 years for females. The average weight was recorded at 67±12.5 kg for males and 67±13.19 kg for females, with corresponding heights of 1.77±0.05 m and 1.71±0.14 m, respectively. The calculated body mass index (BMI = weight in kg / [height in m] ^2) was 23.3±3.4 for males and 21.3±2.7 for females. The participants were randomly recruited from the badminton tournament, which was held over a month.

3.1.2 Importance of shoe properties

In Table 3, both males and females rated shoe fit as the most important variable, followed by shoe comfort and injury protection. The Mann-Whitney U test showed significant differences in the importance of some shoe features between males and females. Females reported higher importance of forefoot cushioning, comfort, breathability, colour and upper durability than males (*p* =0.002, 0.032, 0.043, 0.049< 0.05).

Table 3. Importance of shoe properties between genders.

Shoe function			Male (points) Mean ±SD	Rank	Female (points) Mean ±SD	Rank	*P*
Overall	Comfort		8.25±1.5	2	8.66±0.86	2	0.002*
	Breathability		7.37±1.89	22	7.83±1.54	14	0.032*
	Fit		8.38±1.48	1	8.73±0.57	1	0.103
	Injury protection		8.24±1.58	3	8.55±0.88	3	0.344
	Weight		7.10±1.87	24	7.33±1.64	24	0.412
	Color		5.57±2.55	27	6.48±2.19	27	0.002*
	Performance enhancement		7.7±1.82	14	7.47±1.82	23	0.172
Cushioning–Fore		D	7.79±1.61	10	8.20±1.19	5	0.043*
		ND	7.79±1.6	11	7.96±1.46	11	0.482
Cushioning–Heel		D	7.98±1.55	6	7.97±1.56	10	0.928
		ND	7.62±1.71	16	7.83±1.52	15	0.312
Arch support		D	7.43±1.82	19	7.55±1.64	20	0.797
		ND	7.38±1.65	20	7.52±1.65	21	0.816
Forefoot bending stiffness		D	7.37±1.70	23	7.60±1.60	19	0.242
		ND	7.38±1.65	21	7.52±1.61	22	0.431
Traction/Grip-Fore		D	8.11±1.44	5	8.24±1.26	4	0.497
		ND	8.16±1.37	4	8.18±1.31	6	0.964
Traction/Grip-Heel		D	7.79±1.67	12	7.86±1.41	13	0.715
		ND	7.68±1.68	15	7.83±1.45	16	0.700
Durability-Bottom		D	7.48±1.80	18	7.73±1.54	18	0.303
		ND	7.57±1.72	17	7.75±1.53	17	0.474
Durability-Upper		D	6.53±2.18	26	7.02±1.92	25	0.049*
		ND	6.69±2.25	25	7.02±1.64	26	0.326
Stability-Fore		D	7.93±1.58	7	8.17±1.25	7	0.403
		ND	7.89±1.60	8	8.13±1.30	8	0.374
Stability-Heel		D	7.88±1.64	9	7.98±1.43	9	0.854
		ND	7.72±1.72	13	7.93±1.42	12	0.530

D= dominant; ND= non-dominant; SD= standard deviation. *Indicates a significant difference, $P < 0.05$.

Wilcoxon Signed Ranks Test was used to compare the importance of shoe characteristics between dominant and non-dominant sides, respectively (Table 4). For males, heel cushioning and heel stability were more important (p = 0.000, 0.010), while the upper durability was less important on the dominant side (p = 0.002) compared with the non-dominant side. For females, forefoot cushioning on the dominant shoe was significantly more important than the non-dominant shoe (p = 0.019).

Table 4. Importance of shoe properties between dominant and non-dominant sides.

Shoe function		Male (points) (Mean± SD) Dominant	Non-dominant	*p*	Female (points) (Mean ±SD) Dominant	Non-dominant	*p*
Cushioning-Fore		7.79±1.61	7.79±1.6	0.88	8.20±1.19	7.96±1.46	0.019*
Cushioning-heel		7.98±1.55	7.62±1.71	**0.000** *	7.97±1.56	7.83±1.52	0.102
Arch support		7.43±1.82	7.38±1.65	0.753	7.55±1.64	7.52±1.65	0.543
Forefoot bending stiffness		7.37±1.70	7.38±1.65	0.829	7.60±1.60	7.52±1.61	0.083
Traction/Grip-Fore		8.11±1.44	8.16±1.37	0.55	8.24±1.26	8.18±1.31	0.440
Traction/Grip-Heel		7.79±1.67	7.68±1.68	0.057	7.86±1.41	7.83±1.45	0.641
Durability-Bottom		7.48±1.80	7.57±1.72	0.33	7.73±1.54	7.75±1.53	0.815
Durability-Upper		6.53±2.18	6.69±2.25	**0.002** *	7.02±1.92	7.02±1.64	0.904
Stability-Fore		7.93±1.58	7.89±1.60	0.598	8.17±1.25	8.13±1.30	0.714
Stability-Heel		7.88±1.64	7.72±1.72	**0.010** *	7.98±1.43	7.93±1.42	0.265

*Indicates a significant difference, $p < 0.05$.

3.1.3 Shoe problems/complaints

Descriptive statistics showed that none of the shoe problems were extremely serious, however individual differences were large (Table 5). By ranking the severity of shoe problems, plantar pain attributed to “sole too hard” of non-dominant foot was considered as the most serious footwear problem by both males and females. In addition, for males, the second most crucial factor was also the plantar pain attributed to “sole too hard” of the dominant foot. For females, the next shoe problem ranking was squeezing toes (medial- lateral), forefoot upper, and sole too hard on the dominant foot (Table 5).

Table 5. Shoe problems/complaints between genders

Shoe problems/complaints			Male (points) Mean ±SD	Rank	Female (points) Mean ±SD	Rank	*P*
Poor breathability			4.75±2.69	5	4.50±2.72	11	0.444
Blisters	D		4.26±2.92	21	3.98±3.18	23	0.275
	ND		4.45±2.98	12	4.02±3.11	22	0.158
Loose shoelaces	D		4.37±2.81	14	4.28±2.96	14	0.694
	ND		4.45±2.81	13	4.24±2.93	15	0.520
Poor insole grip	D		4.56±3.00	8	4.56±3.02	7	0.945
	ND		4.47±2.97	11	4.52±3.03	9	0.832
Forefoot: Squeezing toes (medial-lateral)		D	4.68±2.97	6	4.68±3.10	2	0.899
		ND	4.61±3.01	7	4.63±3.09	6	0.865
Forefoot: Squeezing toes (dorsal)		D	4.11±2.93	25	4.53±3.10	8	0.288
		ND	4.18±2.92	22	4.45±3.08	13	0.521
Forefoot: Upper too hard		D	4.49±2.89	10	4.67±3.12	3	0.708
		ND	4.55±2.91	9	4.66±3.08	5	0.905
Forefoot: Sole too hard (plantar pain)		D	4.92±2.98	2	4.67±2.88	4	0.373
		ND	4.95±3.00	1	4.69±2.90	1	0.366
Forefoot: Sole too soft (instability/ sprain ankle)		D	4.28±2.90	19	4.10±3.01	19	0.492
		ND	4.31±2.96	15	4.07±2.96	21	0.415
Heel cup too soft (instability/sprain ankle)		D	4.31±2.85	16	4.22±2.94	16	0.659
		ND	4.28±2.86	20	4.19±2.97	17	0.603
Heel: Sole too hard (plantar pain)		D	4.90±2.80	3	4.52±3.05	10	0.216
		ND	4.87±2.79	4	4.46±3.03	12	0.192
Sole too soft (instability/sprain ankle)		D	4.17±2.87	23	3.85±2.99	24	0.231
		ND	4.15±2.88	24	3.80±2.98	25	0.177
Insufficient arch support		D	4.31±2.75	17	4.09±2.77	20	0.459
		ND	4.29±2.65	18	4.13±2.81	18	0.552
Excessive arch support		D	3.90±2.65	26	3.29±2.70	26	0.018*
		ND	3.87±2.67	27	3.29±2.67	27	0.017*

D= dominant; ND= non-dominant. *Indicates a significant difference, $p < 0.05$.

The Mann-Whitney U test reported that the shoe problem of excessive arch support on both dominant and non-dominant sides were significantly higher in males than females (p =0.017, 0.018, Table 5). Wilcoxon Signed Ranks test showed no significant difference between dominant and non-dominant sides (Table 6).

Table 6. Shoe problems/complaints between dominant and non-dominant sides.

Shoe problems/complaints		Male (points)			Female (points)		
		Dominant	Non-dominant	*P*	Dominant	Non-dominant	*P*
Blisters		4.26±2.92	4.45±2.98	0.089	3.98±3.18	4.02±3.11	0.940
Loose shoelaces		4.37±2.81	4.45±2.81	0.174	4.28±2.96	4.24±2.93	0.417
Poor insole grip		4.56±3.00	4.47±2.97	0.106	4.56±3.02	4.52±3.03	0.739
Forefoot: Squeezing toes (medial-lateral)		4.68±2.97	4.61±3.01	0.402	4.68±3.10	4.63±3.09	0.206
Forefoot: Squeezing toes (dorsal)		4.11±2.93	4.18±2.92	0.279	4.53±3.10	4.45±3.08	0.066
Forefoot: Upper Too hard		4.49±2.89	4.55±2.91	0.901	4.67±3.12	4.66±3.08	0.556
Forefoot: Sole too hard sole ±plantar pain		4.92±2.98	4.95±3.00	0.321	4.67±2.88	4.69±2.90	0.496
Forefoot: Sole too soft (instability/ sprain) ankle		4.28±2.90	4.31±2.96	0.694	4.10±3.01	4.07±2.96	0.832
Heel cup too soft (instability/sprain) ankle		4.31±2.85	4.28±2.86	0.820	4.22±2.94	4.19±2.97	0.357
Heel: Sole too hard (plantar pain)		4.90±2.80	4.87±2.79	0.391	4.52±3.05	4.46±3.03	0.070
Heel: Sole too soft (instability/sprain) ankle		4.17±2.87	4.15±2.88	0.623	3.85±2.99	3.80±2.98	0.052
Insufficient arch support		4.31±2.75	4.29±2.65	0.812	4.09±2.77	4.13±2.81	0.163
Excessive arch support		3.90±2.65	3.87±2.67	0.383	3.29±2.70	3.25±2.67	0.336

3.1.4 Pain or discomfort in different foot regions.

The foot regions with occasional pain or frequent pain were distributed in the forefoot, followed by rearfoot and midfoot regions (Table 7). The gender difference results showed that occasional pain in the hallux on both dominant and non-dominant feet was more likely in females than males (p = 0.017, 0.032). On the other hand, the heel frequent pain on the dominant and non-dominant sides of males were significantly higher than that of females (p = 0.009, 0.023). Similarly, the soft tissue of the foot on the dominant side was significantly higher in males than females (p = 0.028).

Table 7. Foot pain/ discomfort locations between genders.

Foot regions		NP (%)		OP (%)		FP (%)		*p* - values
		male	female	male	female	male	female	Male vs. female
Hallux	D	87.5	77	10	21.4	2.5	1.6	0.017*
	ND	89	80.2	8	16.7	3	3.2	0.032*
Other toes	D	93	87.3	6	11.9	1	0.8	0.088
	ND	94	93.7	4.5	6.3	1.5	0	0.926
1^{st} MTP	D	76.5	76.2	21	20.6	2.5	3.2	0.747
	ND	74.5	78.6	22.5	19	3	2.4	0.669
2^{nd}-5^{th} MTP	D	84.5	81.7	14	15.1	1.5	3.2	0.484
	ND	89	87.3	10.5	11.9	0.5	0.8	0.638
Cuneiform bone	D	97.5	95.2	2.5	2.4	0	2.4	0.259
	ND	96	95.2	2.5	4.8	0.5	0	0.418
Navicular bone	D	98.5	99.2	1.5	0	0	0.8	0.580
	ND	99.5	97.6	0.5	2.4	0	0	0.569
Talus	D	95.5	90.5	4.5	8.7	0	0.8	0.070
	ND	96.5	97.6	3.5	2.4	0	0	0.950
Cuboid bone	D	100	99.2	0	0.8	0	0	0.208
	ND	97.5	97.6	2	1.6	0.5	0.8	0.950
Heel	D	70.5	84.1	23	9.5	6.5	6.3	0.009*
	ND	77.5	88.1	16.5	6.3	6	5.6	0.023*
Soft tissues	D	93	98.4	6.5	1.6	0.5	0	0.028*
	ND	95	96.8	4.5	2.4	0.5	0.8	0.435
Arch	D	96.5	96	3.5	2.4	0	1.6	0.807
	ND	96	95.2	3	4	1	0.8	0.747
Achilles' tendon	D	99	94.8	1	1.6	0	0	0.640
	ND	99.5	100	0.5	0	0	0	0.427

D = Dominant; ND = Non-dominant; NP= no pain, OP= occasional pain, FP= frequent pain; *indicates a significant difference, $p < 0.05$.

3.2 Torsional Stiffness of Badminton Footwear

This part investigated the biomechanical effects of various torsional stiffness in badminton shoes on lower limb motion during four specific movements. To ensure clarity in research outcomes, the indicators are categorized into variables on stability, performance, and ground reaction forces. The research findings demonstrate significant variations in the measured indicators among different tasks performed with different torsional stiffness conditions. These findings suggest that the lower extremities show various biomechanical characteristics when performing different tasks. In this study, data from the participants' left legs were collected for the 45C and Forehand Clear Stroke (left foot) (FCL) tasks, while data from their right legs were collected for the FCR and CVJ tasks.

3.2.1 Stability variables

Table 8 and 9 presented the stability variables for the 45C and FCL tasks, showing notable differences among participants under different torsional stiffness conditions, primarily involving ankle and knee joint movements in both the sagittal and coronal planes.

Regarding the 45C task, the results revealed a significant increase in the peak ankle dorsiflexion angle for the 70D shoes compared to the 50D and 60D shoes. Additionally, the peak ankle inversion angle was significantly smaller for the 70D shoes compared to the 60D and 50D shoes. The ROM of the ankle in the sagittal plane was greater for the 50D shoes than for the 70D shoes, while in the coronal plane, the ankle ROM was greater for the 60D shoes compared to the 50D shoes. Furthermore, the ROM of the knee in the coronal plane was significantly smaller for the 60D shoes compared to both the 50D and 70D shoes. Additionally, significant differences were observed in the metatarsophalangeal joint motion in the sagittal plane between the 50D shoes and both the 60D and 70D shoes (Table 8).

Table 8. Stability variables (Mean± SD) during 45C tasks by different footwear conditions.

Variables (°)		50D	60D	70D	F	*p*	η^2
Max. ankle angle	Dorsiflexion	**17.57 ±2.20^{c}**	**17.39 ±2.27^{c}**	**22.18 ±2.22$^{a, b}$**	17.258	**<0.001**	0.570
	Plantarflexion	17.74 ±6.88	14.15 ±6.27	14.07 ±6.12	3.709	0.075	0.209
	Inversion	2.40 ±2.29	2.16 ±2.63	8.40 ±1.01	3.466	0.056	0.302
	Eversion	**13.16 ±1.93^{c}**	**13.83 ±1.82^{c}**	**3.96 ±2.72$^{a, b}$**	9.502	**<0.001**	0.919
	Internal rotation	10.52 ±3.73	11.18 ±2.40	11.25 ±2.17	0.285	0.754	0.020
	External rotation	12.92 ±5.10	10.88 ±5.31	12.22 ±6.40	0.799	0.456	0.035
ROM of ankle	Sagittal plane	**36.44 ±8.36^{c}**	33.93 ±7.98	**30.71 ±3.94^{a}**	4.098	**0.027**	0.226
	Coronal plane	**15.87 ±6.15^{b}**	**9.09 ±1.24^{a}**	12.36 ±5.04	6.181	**0.01**	0.436
	transverse plane	20.60 ±6.46	17.77 ±4.36	19.77 ±4.53	0.407	0.53	0.019
Max. knee angle	Flexion	48.22 ±6.94	51.42 ±5.81	52.78 ±5.17	/	0.174	/
	Adduction	**8.48 ±5.11^{b}**	**3.17 ±1.05$^{a, c}$**	**8.21 ±2.22^{b}**	/	**<0.001**	/
	Abduction	2.69 ±3.98	2.82 ±2.57	2.76 ±2.70	0.007	0.961	0.001
	external rotation	14.74 ±4.37	2.82 ±2.57	2.76 ±2.70	0.635	0.54	0.055
ROM of knee	Sagittal plane	37.69 ±7.98	39.06±3.01	41.40 ±4.96	1.543	0.23	0.093
	Coronal plane	**9.99 ±3.73^{b}**	**5.82 ±1.74$^{a, c}$**	**10.97 ±4.56^{b}**	/	**<0.001**	/
	Transverse plane	16.15 ±4.40	12.18 ±3.91	14.72 ±5.69	2.775	0.084	0.201
Max. MTP angle	Dorsiflexion	**16.61±3.42$^{b, c}$**	**9.08 ±7.04^{a}**	**7.58 ±5.29^{a}**	25.61	**<0.001**	0.574
	Plantarflexion	**1.91 ±1.34$^{b, c}$**	**7.66 ±4.51^{a}**	**9.82 ±4.14^{a}**	31.23	**<0.001**	0.647
ROM of MTP	Sagittal plane	17.89 ±2.80	17.04 ±3.40	17.40 ±2.34	0.65	0.53	0.033

[a] indicates a significant difference from 50D ($p < 0.05$), [b] indicates a significant difference from 60D ($p < 0.05$), and [c] indicates a significant difference from 70D ($p < 0.05$). $\boldsymbol{\eta^2}$ represents partial eta squared.

In the case of the FCL task, the results indicated a significant increase in the peak ankle dorsiflexion angle for the 60D shoes compared to the 50D shoes. Additionally, the ROM of the knee in the coronal plane was significantly smaller for the 70D shoes compared to the 50D and 60D shoes (Table 9).

Table 9. Stability variables (Mean± SD) during FCL tasks by different footwear conditions.

Variables (°)		50D	60D	70D	F	*p*	η^2
Max. ankle angle	Dorsiflexion	**16.91 ±2.50[b, c]**	**22.10 ±2.90[a]**	**21.58 ±5.83[a]**	10.11	**<0.001**	0.403
	Plantarflexion	23.50 ±7.72	25.75 ±7.24	23.09 ±1.63	0.71	0.507	0.073
	Eversion	**8.08 ±1.16[c]**	**7.68 ±1.97[c]**	**12.77±1.68[a, b]**	5.44	**0.011**	0.295
	Internal rotation	7.13 ±2.18	5.67 ±8.15	6.92 ±4.56	0.31	0.735	0.025
	External rotation	3.31 ±3.52	5.34 ±6.61	5.67 ±2.02	1.14	0.335	0.081
ROM of ankle	Sagittal plane	38.60 ±7.24	43.04 ±9.87	44.06 ±7.79	2.58	0.092	0.139
	Coronal plane	12.46 ±2.53	10.53 ±0.80	11.16 ±3.03	2.88	0.072	0.161
	Transverse plane	9.79 ±2.31	10.12 ±2.11	10.75 ±2.16	0.58	0.569	0.050
Max. knee angle	Flexion	**33.80 ±6.24[a]**	**41.24 ±4.25[b]**	40.23 ±3.84	8.11	**0.003**	0.448
	Extension	10.02 ±4.77	12.90 ±5.04	10.56 ±3.11	1.15	0.338	0.103
	Adduction	**11.85 ±4.64[c]**	10.71 ±5.29	**6.63 ±4.06[a]**	6.91	**0.004**	0.347
	External rotation	13.25 ±4.52	14.74 ±5.95	14.73 ±5.87	0.38	0.684	0.023
ROM of knee	Sagittal plane	27.01 ±4.50	27.78 ±8.70	29.67 ±4.63	0.57	0.572	0.054
	Coronal plane	**9.27 ±3.31[c]**	**9.69 ±3.78[c]**	**5.20 ±1.40[a, b]**	14.87	**<0.001**	0.534
	Transverse plane	14.06 ±2.75	13.40 ±3.41	15.33 ±2.87	1.81	0.181	0.101
Max. MTP angle	Dorsiflexion	**28.11 ±8.37[c]**	23.07 ±4.28	**21.99 ±4.52[a]**	4.87	**0.016**	0.273
ROM of MTP	Sagittal plane	24.01 ±6.42	23.40 ±3.41	22.79 ±3.16	0.21	0.814	0.016

[a] indicates a significant difference from 50D ($p < 0.05$), [b] indicates a significant difference from 60D ($p < 0.05$), and [c] indicates a significant difference from 70D ($p < 0.05$). $\boldsymbol{\eta^2}$ represents partial eta squared.

Table 10 and 11 presented the results of stability variables in the FCR and CVJ tasks, respectively, under different torsional stiffness shoe conditions. In the case of the FCR task, the results revealed significant differences in ankle joint angles. The peak angles of ankle inversion, adduction, abduction, and external rotation were significantly smaller for the highest torsional stiffness shoes (70D) compared to the lowest torsional stiffness shoes (50D). However, only the peak angle of ankle internal rotation was significantly smaller for the moderate torsional stiffness shoes (60D). Furthermore, the range of motion (ROM) of the knee joint in both the coronal and transverse planes was significantly greater for the lowest torsional stiffness shoes (50D) compared to both the moderate (60D) and highest (70D) torsional stiffness shoes. Additionally, the peak dorsiflexion angle of the metatarsophalangeal joint followed the same pattern, with significantly smaller angles observed for the highest torsional stiffness shoes (70D) compared to the lowest (50D) and moderate (60D) torsional stiffness shoes (Table 10).

Table 10. Stability variables (Mean± SD) during FCR tasks by different footwear conditions

Variables (°)		50D	60D	70D	F	*p*	η^2
Max. ankle angle	Dorsiflexion	25.30 ±2.28	24.77 ±1.69	23.12 ±2.38	3.46	0.05	0.239
	Inversion	**14.38 ±1.18[c]**	12.68 ±1.10	**7.73 ±1.87[a]**	4.88	**0.038**	0.328
	Eversion	5.35 ±2.06	5.32 ±0.68	7.76 ±2.85	0.88	0.429	0.081
	Internal rotation	14.25 ±1.11	**15.51 ±1.07[c]**	**12.71 ±2.21[b]**	8.50	**0.003**	0.486
ROM of ankle	Sagittal plane	40.02 ±4.59	37.91 ±4.91	38.67 ±3.25	1.21	0.312	0.070
	Coronal plane	19.73 ±1.57	18.00 ±1.61	15.48 ±1.85	3.42	0.053	0.255
	Transverse plane	16.42 ±2.72	13.43 ±0.98	11.29 ±1.06	/	0.105	/
Max. knee angle	Flexion	54.23 ±4.13	53.47 ±3.93	53.14 ±3.94	0.34	0.714	0.015
	Adduction	**6.35 ±2.80[c]**	5.27 ±0.81	**4.24 ±1.28[a]**	4.71	**0.046**	0.300
	Abduction	**18.85 ±4.79[c]**	15.15 ±2.06	**11.11 ±4.25[a]**	15.00	**<0.001**	0.518
	Internal rotation	8.63 ±5.43	6.74 ±5.49	4.19 ±3.20	3.49	0.081	0.212
	External rotation	**33.03 ±2.70[c]**	30.00 ±7.43	**25.61 ±4.71[a]**	8.25	**0.002**	0.371
ROM of knee	Sagittal plane	34.43 ±7.96	39.18 ±13.01	39.95 ±10.49	/	0.092	/
	Coronal plane	**23.91±3.57 [b, c]**	**19.24 ±3.37[a]**	**14.65 ±4.53[a]**	19.14	**<0.001**	0.578
	Transverse plane	**39.50 ±7. 15[b, c]**	**32.85 ±2.10[a]**	**30.07 ±5.00[a]**	10.52	**<0.001**	0.447
Max. MTP angle	Dorsiflexion	**21.43 ±3.56[c]**	**23.06 ±7.57[c]**	**16.91±2.02[a, b]**	/	**0.02**	/
ROM of MTP	Sagittal plane	17.99 ±2.53	16.82 ±2.56	16.71 ±1.68	1.08	0.362	0.11

[a] indicates a significant difference from 50D ($p < 0.05$), **[b]** indicates a significant difference from 60D ($p < 0.05$), and **[c]** indicates a significant difference from 70D ($p < 0.05$). $\boldsymbol{\eta^2}$ represents partial eta squared.

Regarding the CVJ task, the results indicated significant differences in the ROM of ankle and knee joints. The activity of the ankle joint in the sagittal plane was significantly greater for the lowest torsional stiffness shoes (50D) compared to the highest torsional stiffness shoes (70D). Similarly, the ROM of the knee joint in the sagittal plane was significantly greater for the moderate torsional stiffness shoes (60D) compared to the lowest torsional stiffness shoes (50D) (Table 11).

Table 11. Stability variables (Mean± SD) during CVJ tasks by different footwear conditions

	Variables (°)	50D	60D	70D	F	*p*	η^2
Ankle	Max. Dorsiflexion	22.66 ±7.10	21.27 ±8.61	19.83 ±8.29	/	0.472	/
	Max. Plantarflexion	37.39 ±2.35	35.15 ±4.14	34.72 ±3.04	2.88	0.072	0.161
	ROM of sagittal plane	**60.05 ±7.42[c]**	56.42 ±5.71	**54.55 ±8.53[a]**	5.74	**0.008**	**0.277**
Knee	Max. Flexion	56.38 ±5.40	53.27 ±5.62	54.89 ±6.58	0.66	0.525	0.045
	ROM of sagittal plane	**49.57 ±10.33[b]**	**39.84 ±3.30[a]**	46.13 ±13.45	4.64	**0.021**	0.297

[a] indicates a significant difference from 50D ($p < 0.05$), [b] indicates a significant difference from 60D ($p < 0.05$), and [c] indicates a significant difference from 70D ($p < 0.05$). η^2 represents partial eta squared.

3.2.2 Performance variables

The results showed that the peak knee extension moment during the 45C task was significantly greater for the 70D shoes compared to the 50D shoes (Table 12). Furthermore, the peak knee internal rotation moment during the execution of the FCL was significantly greater for the 70D shoes compared to the 50D shoes (Table 13). Additionally, participants wearing the 70D shoes demonstrated significantly higher peak ankle plantarflexion and eversion moments during the execution of the FCR compared to those wearing the 50D and 60D shoes (Table 14).

Table 12. Sports performance variables (Mean± SD) during 45C tasks by different conditions

Variables		50D	60D	70D	F	*p*	η^2
Max. ankle moment (Nm/BW)	Plantarflexion	2.36±0.47	2.56±0.53	2.41±0.43	2.699	0.083	0.144
	Inversion	0.53 ±0.11	0.50 ±0.09	0.54 ±0.11	1.02	0.374	0.073
	External rotation	0.29 ±0.09	0.33 ±0.13	0.33 ±0.08	1.778	0.192	0.139
Max. knee moment (Nm/BW)	Flexion	1.63±0.44	2.04 ±0.06	1.64±0.32	3.981	0.053	0.443
	Extension	**0.60 ±0.10[c]**	0.76 ±0.10	**0.88 ±0.05[a]**	9.293	**0.008**	0.699
	Adduction	0.88 ±0.20	1.02 ±0.19	1.08 ±0.10	/	0.276	/
	Abduction	0.36 ±0.18	0.39 ±0.18	0.40 ±0.18	0.131	0.879	0.016
	Internal rotation	0.40 ±0.05	0.41 ±0.03	0.39 ±0.06	0.627	0.545	0.065
Stance time (s)		**0.47 ±0.10[b]**	**0.39 ±0.05[a]**	0.42 ±0.06	7.367	**0.005**	0.251

[a] indicates a significant difference from 50D ($p < 0.05$), [b] indicates a significant difference from 60D ($p < 0.05$), and [c] indicates a significant difference from 70D ($p < 0.05$). η^2 represents partial eta squared.

Table 13. Sports performance variables (Mean± SD) during FCL tasks by different conditions.

Variables		50D	60D	70D	F	*p*	η^2
Max. ankle moment (Nm/BW)	Plantarflexion	2.44±0.17	2.94±0.68	3.25±0.97	/	0.307	/
	Inversion	0.90 ±0.29	0.77 ±0.16	0.80 ±0.22	1.27	0.294	0.074
	External rotation	0.53 ±0.20	0.76 ±0.09	0.67 ±0.29	2.68	0.122	0.196
Max. knee moment (Nm/BW)	Flexion	1.16 ±0.36	1.02 ±0.12	1.05 ±0.25	0.95	0.403	0.079
	Extension	1.05 ±0.28	1.12 ±0.48	1.37±0.34	2.91	0.076	0.209
	Adduction	1.01 ±0.33	1.06 ±0.31	1.22 ±0.34	2.52	0.098	0.153
	Internal rotation	**0.37 ±0.10^{c}**	0.47 ±0.14	**0.48 ±0.11^{a}**	4.58	**0.022**	0.294
Stance time (s)		0.61 ±0.09	0.60 ±0.07	0.57 ±0.12	0.94	0.403	0.059

^{a} indicates a significant difference from 50D ($p < 0.05$), ^{b} indicates a significant difference from 60D ($p < 0.05$), and ^{c} indicates a significant difference from 70D ($p < 0.05$). η^2 represents partial eta squared.

Table 14. Sports performance variables (Mean± SD) during FCR tasks by different conditions

Variables		50D	60D	70D	F	*p*	η^2
Max. ankle moment (Nm/BW)	Plantarflexion	**3.78±0.51^{c}**	**3.48±0.41^{c}**	**4.24±0.20$^{a, b}$**	7.89	**0.018**	0.467
	Eversion	**0.67 ±0.19^{c}**	**0.73±0.24^{c}**	**0.90 ±0.23$^{a, b}$**	7.45	**0.004**	0.427
	External rotation	0.29 ±0.06	**0.35 ±0.09^{c}**	**0.23 ±0.08^{b}**	9.68	**0.002**	0.548
Max. knee moment (Nm/BW)	Flexion	0.70±0.24	0.91 ±0.37	0.84 ±0.38	1.73	0.193	0.098
	Extension	2.03±0.22	1.68±0.44	2.17±0.51	/	0.165	/
	Adduction	0.67 ±0.29	0.63 ±0.17	0.78 ±0.19	2.91	0.071	0.172
	Abduction	0.76 ±0.34	0.75 ±0.33	1.00 ±0.36	2.22	0.127	0.137
	Internal rotation	0.17 ±0.08	0.16 ±0.12	0.15 ±0.03	2.22	0.127	0.137
	External rotation	**0.39 ±0.10^{c}**	**0.36 ±0.12^{c}**	**0.51±0.10 $^{a, b}$**	7.56	**0.003**	0.368
Stance time (s)		**0.53 ±0.12^{c}**	**0.52 ±0.08^{c}**	**0.46±0.06$^{a, b}$**	6.49	**0.011**	0.255

^{a} indicates a significant difference from 50D ($p < 0.05$), ^{b} indicates a significant difference from 60D ($p < 0.05$), and ^{c} indicates a significant difference from 70D ($p < 0.05$). η^2 represents partial eta squared.

Figure 18 presented the stance time for participants wearing badminton shoes with varied levels of torsional stiffness during the 45C, FCL, and FCR tasks. The figure depicted that participant exhibited different stance times when performing various tasks in badminton. Specifically, during the 45C task, the stance time was shortest for the 60D shoes among the three torsional stiffness levels, and it was significantly lower than the duration for the 50D shoes. In the case of the FCR task, the stance time decreased as torsional stiffness increased, and participants wearing the 70D shoes demonstrated a significantly lower stance time than those wearing the 50D and 60D shoes.

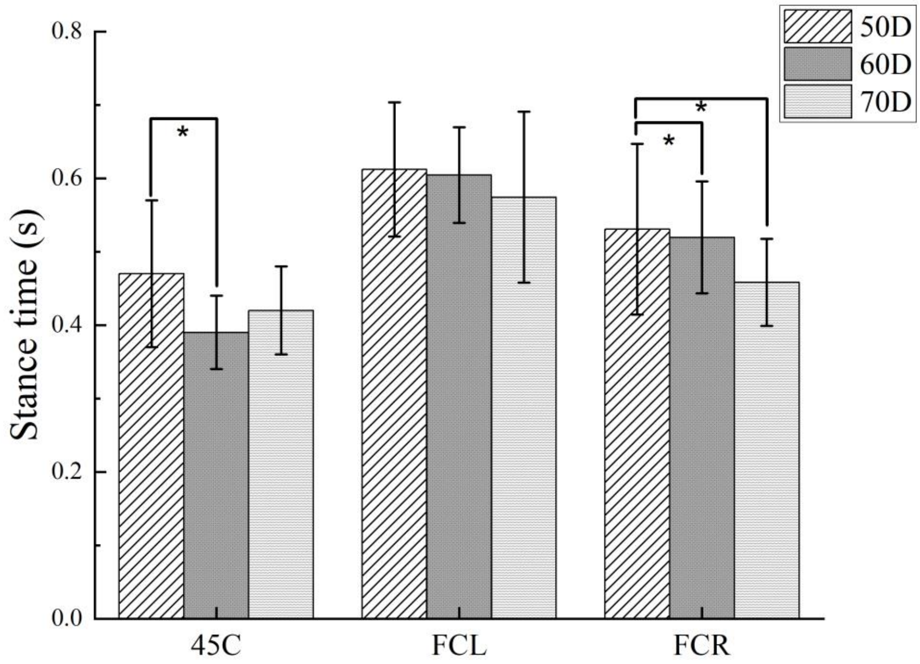


Figure 18. Bar graph showing stance times at 45C, FCL, and FCR, * = significant difference at $p < 0.05$.

3.2.3 Ground reaction force variables

Through statistical analysis of ground reaction force variables in three directions for various movements under different footwear conditions, no significant differences were observed in the anterior-posterior and medial-lateral directions (Table 15). However, concerning the vertical ground reaction force, the 70D shoes showed a significantly higher value compared to the 50D shoes. To further examine this, a statistical parametric mapping analysis using MATLAB's SPM1D package was conducted to compare the vertical ground reaction force between the 50D and 70D shoes during the execution of the FCR task. Figure 19 illustrates a significant difference between the 50D and 70D shoes during the stance phase at 70%-75%.

Table 15. Ground reaction force variables (Mean± SD) by different footwear conditions.

GRF Variables (BW)		50D	60D	70D	F	p	η^2
Anterior-posterior	45C	0.45 ±0.16	0.48 ±0.10	0.52 ±0.10	1.89	0.167	0.100
	FCL	0.46 ±0.11	0.48 ±0.11	0.46 ±0.13	0.17	0.847	0.015
	FCR	0.40 ±0.11	0.36 ±0.16	0.40 ±0.16	2.02	0.153	0.134
Medial-lateral	45C	0.54 ±0.05	0.50 ±0.09	0.50 ±0.13	1.14	0.338	0.094
	FCL	0.37 ±0.07	0.39 ±0.07	0.41 ±0.06	2.19	0.131	0.135
	FCR	0.37 ±0.04	0.38 ±0.06	0.35 ±0.04	2.50	0.1	0.152
Vertical	45C	1.87 ±0.27	1.98 ±0.29	1.82 ±0.23	3.18	0.054	0.158
	FCL	2.15 ±0.26	2.12 ±0.16	2.26 ±0.14	2.87	0.075	0.181
	FCR	**1.89 ±0.08**[c]	2.02 ±0.13	**2.04 ±0.12**[a]	/	**0.042**	/
	CVJ	2.35 ±0.41	2.55 ±0.08	2.50 ±0.14	1.86	0.198	0.144

[a] indicates a significant difference from 50D ($p < 0.05$), [b] indicates a significant difference from 60D ($p < 0.05$), and [c] indicates a significant difference from 70D ($p < 0.05$). η^2 represents partial eta squared, BW = Body weight.

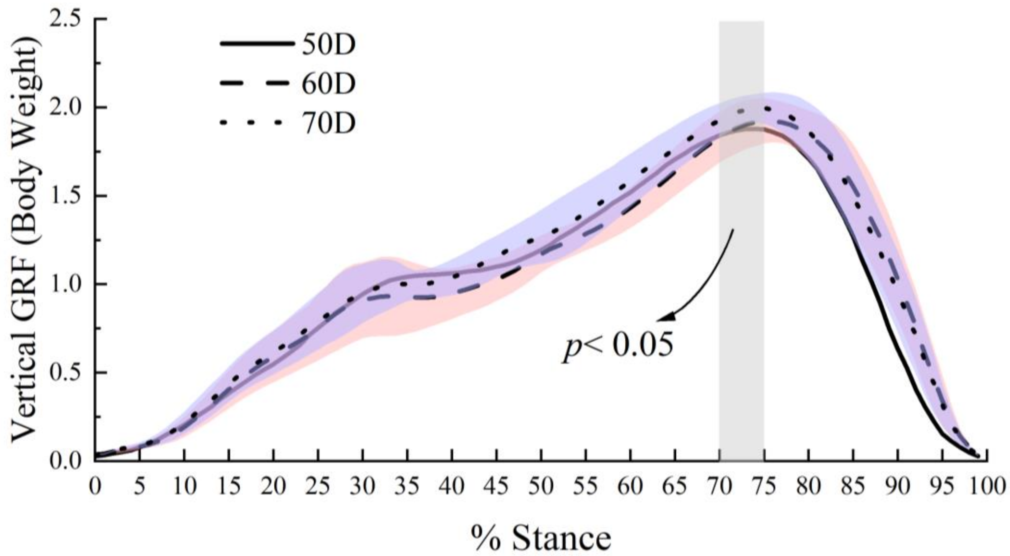


Figure 19. FCR's Vertical ground reaction force of different footwear conditions, with the grey areas indicating significant differences as increasing from 50D to 70D.

3.3 Torsional Stiffness and Arch Support Variations in Badminton Footwear

3.3.1 Model Validation

Figure 20 presents the comparison between muscle activation levels, as computed by the OpenSim static optimization tool, and the experimentally recorded EMG signals during the 45C task. This includes muscles such as the tibialis anterior, gastrocnemius medial, gastrocnemius lateral, rectus femoris, and biceps femoris. The consistency between the OpenSim musculoskeletal model's computed lower limb muscle activation for the 45C task and the experimental EMG signals underscores the relative credibility of our OpenSim model's data in this study.

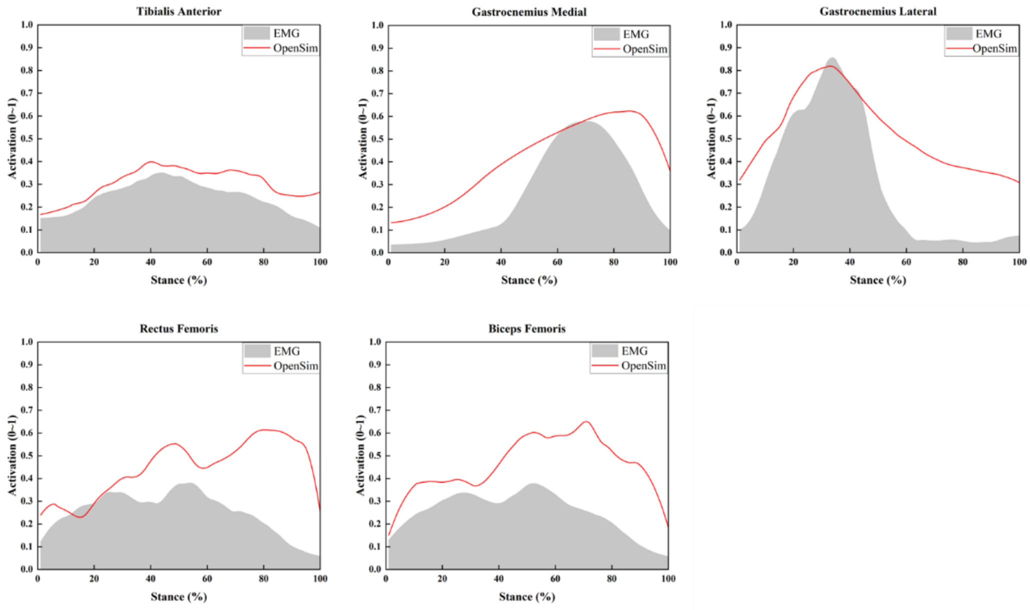


Figure 20. Comparison of tibialis anterior, gastrocnemius medial, gastrocnemius lateral, rectus femoris and biceps femoris muscle activation level obtained by EMG signal and OpenSim optimization algorithm.

3.3.2 Joint Angles

During the 45C task, the kinematics of the hip joint revealed significant variations as illustrated in Figure 21. In the horizontal plane, there was a notable interaction between arch support and torsional stiffness for peak hip internal rotation angles ($p < 0.05$). Specifically, under a torsional stiffness of 65D, the HS condition notably reduced the internal rotation angle compared to the NS and LS conditions. Moreover, as arch support increased, there was a clear reduction in the peak internal rotation angle at 65D.

For the knee joint, Figure 21 highlights the significant influences observed for both the peak external rotation and abduction angles due to arch support and torsional stiffness. The abduction angle displayed significant variations ($p < 0.01$) with the NS condition at 65D showing a notable reduction compared to the LS and HS conditions. In terms of external rotation, significant changes were evident (p = 0.027), particularly at the NS level where 60D showed a marked reduction in angle compared to both 55D and 65D.

Regarding the ankle joint, the kinematic analysis during the 45C task indicated that while the interaction between arch support and torsional stiffness for the peak dorsiflexion angle wasn't statistically significant (p = 0.233), notable variations were observed across the conditions. Under the 65D condition, the NS setting showed a significant differentiation in dorsiflexion angle from the other arch support settings. Furthermore, an increase in the dorsiflexion angle at 65D was noted with a rise in the arch support level (Figure 21).

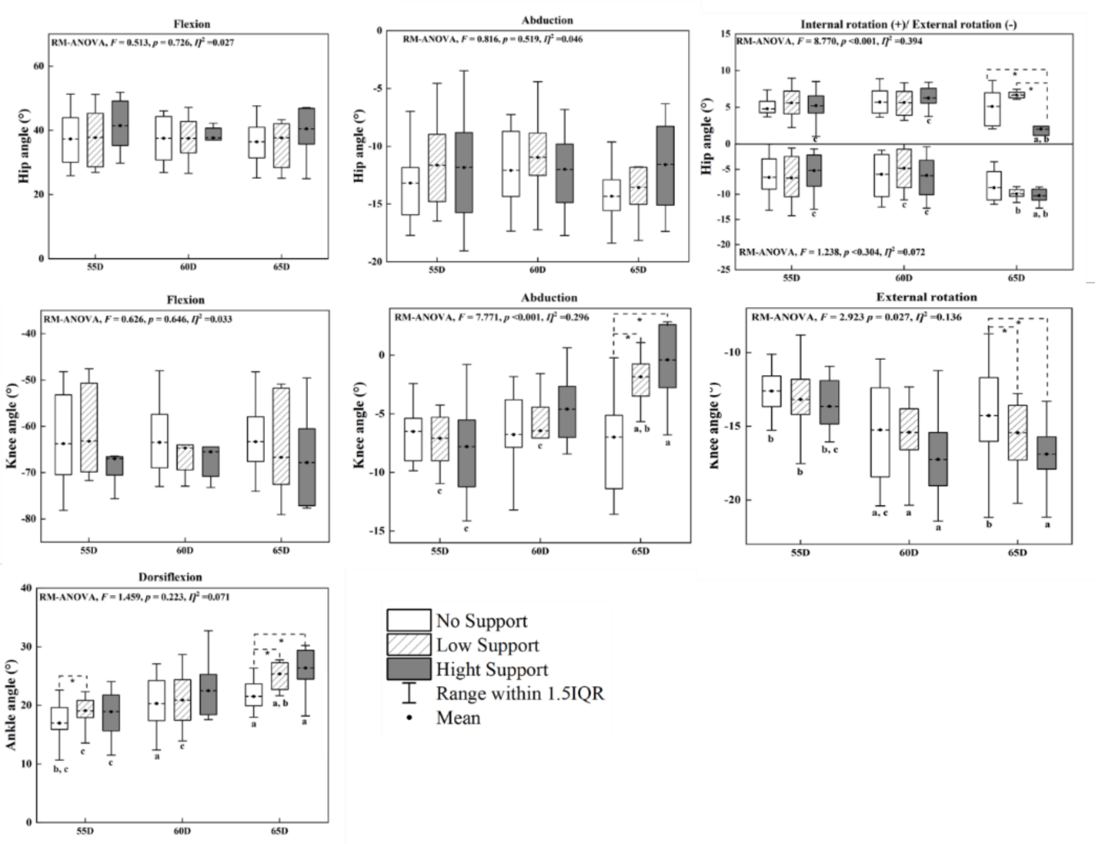


Figure 21. Peak angles for the ankle, knee, and hip joints during the 45C task across three different torsional stiffness conditions and three insole variations, * indicates statistical differences between the various arch support insoles with constant torsional

stiffness ($p < 0.05$). Different letters a, b, and c indicates statistical differences between the torsional stiffness levels when the arch support elevation remains constant ($p < 0.05$).

During the FCR task (Figure 22), the hip joint's kinematics showed specific patterns. For peak extension angles, the interaction between arch support and torsional stiffness wasn't significant ($p = 0.058$). However, at 65D, the NS condition exhibited lower angles than both LS and HS. In the peak abduction angles, there was a significant interaction ($p = 0.001$). At 65D, the HS angles were reduced compared to those at 60D and were also lower than the NS and LS conditions. The hip internal rotation peak angles presented significant differences ($p = 0.001$) with variations emerging depending on the arch support and torsional stiffness combination.

For the knee joint, interactions between arch support and torsional stiffness for peak flexion angles were clear ($p = 0.025$). At 55D, angles in the HS condition were reduced compared to LS, and at 60D, the LS angles were smaller than NS. Moreover, in the LS condition, angles at both 60D and 65D were reduced compared to 55D. When looking at peak knee adduction angles, there were significant interactions ($p = 0.003$). The HS condition at 65D showed larger angles than both NS and LS, with each arch support revealing specific trends at different torsional stiffness levels.

Regarding the ankle joint, peak dorsiflexion angles highlighted significant interactions ($p = 0.031$). In the HS setting at 60D, the angles were greater than those under the NS condition. Conversely, in the NS condition, the angle at 60D was diminished compared to both 55D and 65D.

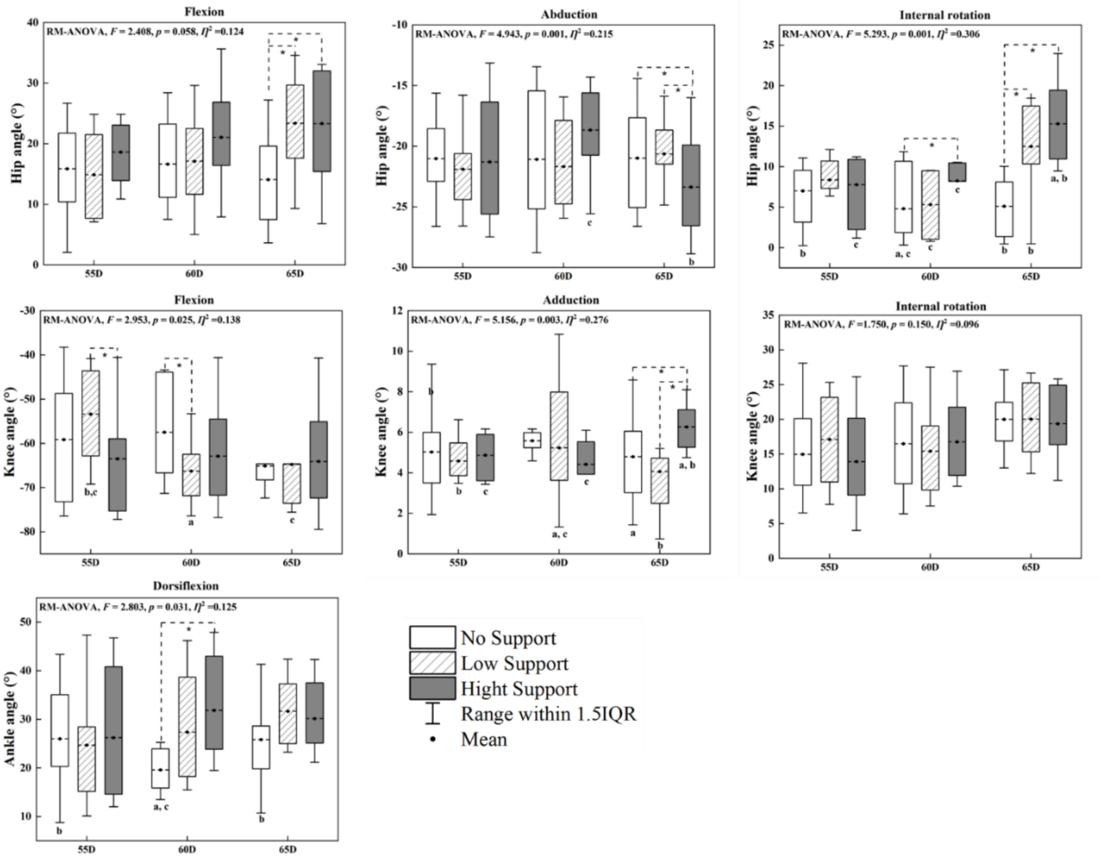


Figure 22. Peak angles for the ankle, knee, and hip joints during the FCR task across three different torsional stiffness conditions and three insole variations, * indicates statistical differences between the various arch support insoles with constant torsional stiffness ($p < 0.05$). Different letters a, b, and c indicates statistical differences between the torsional stiffness levels when the arch support elevation remains constant ($p < 0.05$).

3.3.3 Joint Moments.

In the analysis of the 45C task, Figure 23 delineates the joint moment outcomes for the hip joint in the sagittal plane. There wasn't a pronounced interaction between arch support and torsional stiffness ($p = 0.415$). Nonetheless, significant differences were observed in the peak extension moments. Specifically, at 60D, moments in the HS condition were significantly lower than in NS. Similarly, at 65D, the HS condition showed moments lower than both NS and LS. Notably, no statistical differences were observed in the joint moments for both the knee and ankle joints.

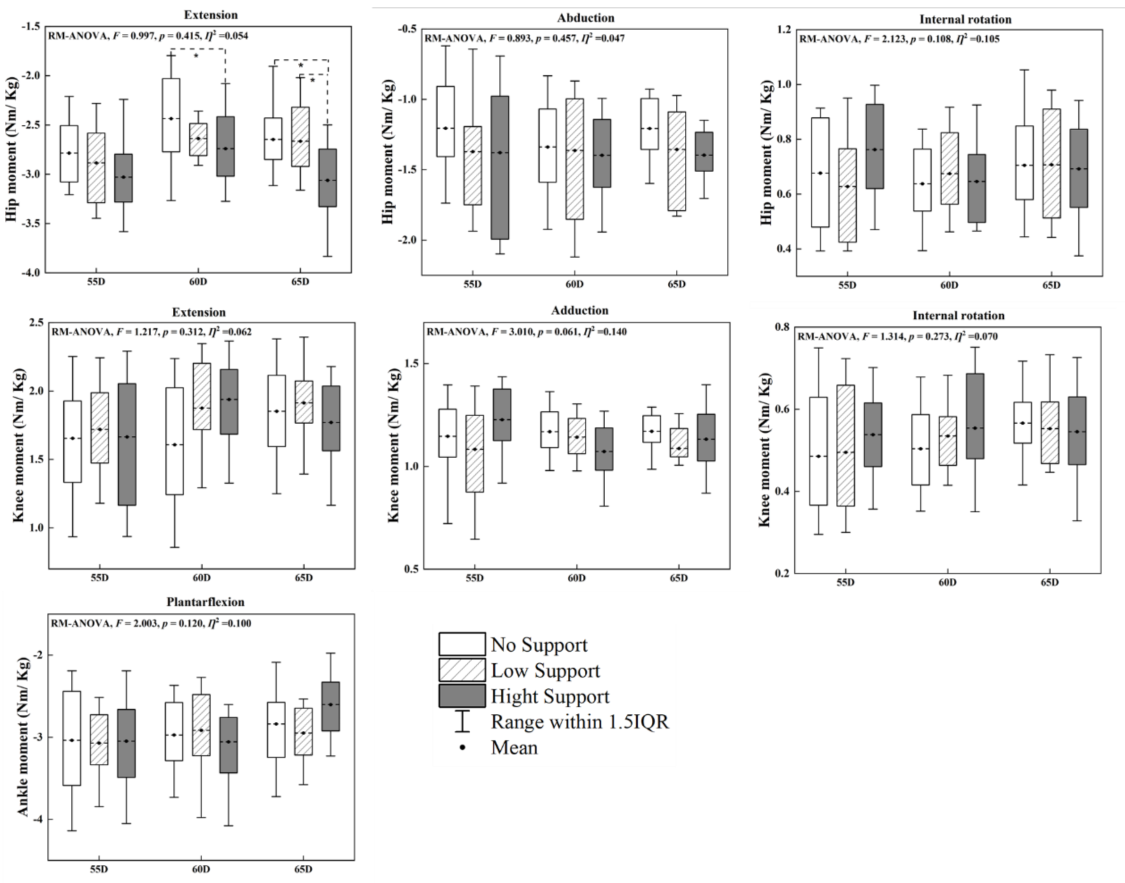


Figure 23. Peak moments for the ankle, knee, and hip joints during the 45C task across three different torsional stiffness conditions and three insole variations, * indicates statistical differences between the various arch support insoles with constant torsional stiffness ($p < 0.05$). Different letters a, b, and c indicates statistical differences between the torsional stiffness levels when the arch support elevation remains constant ($p < 0.05$).

Joint moment results for the FCR movement illustrated interactions (Figure 24). At the hip joint, a significant interaction was observed between arch support and torsional stiffness for peak extension moments (p = 0.017). Specifically, with 65D torsional stiffness, the moments in the LS condition were significantly reduced compared to both NS and HS. Moreover, within the LS condition, moments at 65D were reduced relative to 55D.

For the knee joint, peak extension moments presented a significant interaction (p < 0.001). At 55D, moments in LS were significantly reduced relative to both NS and

HS, and at 60D, moments in NS were lower than those in HS. Additionally, for LS, moments at 55D were reduced compared to those at both 60D and 65D. Although the interaction for peak abduction moments wasn't statistically significant (*p* = 0.196), moments in LS were greater than those in HS at 55D. For peak external rotation moments, a significant interaction emerged (*p* = 0.005): at 60D, moments in NS were lower than those in LS and HS, and within NS, moments at 55D were higher compared to those at both 60D and 65D.

For the ankle joint, the interaction between arch support and torsional stiffness for peak plantarflexion moments was significant (*p* = 0.038). Moments in the NS condition at 65D were reduced compared to those in HS, and in the NS condition, moments at 55D exceeded those at 65D.

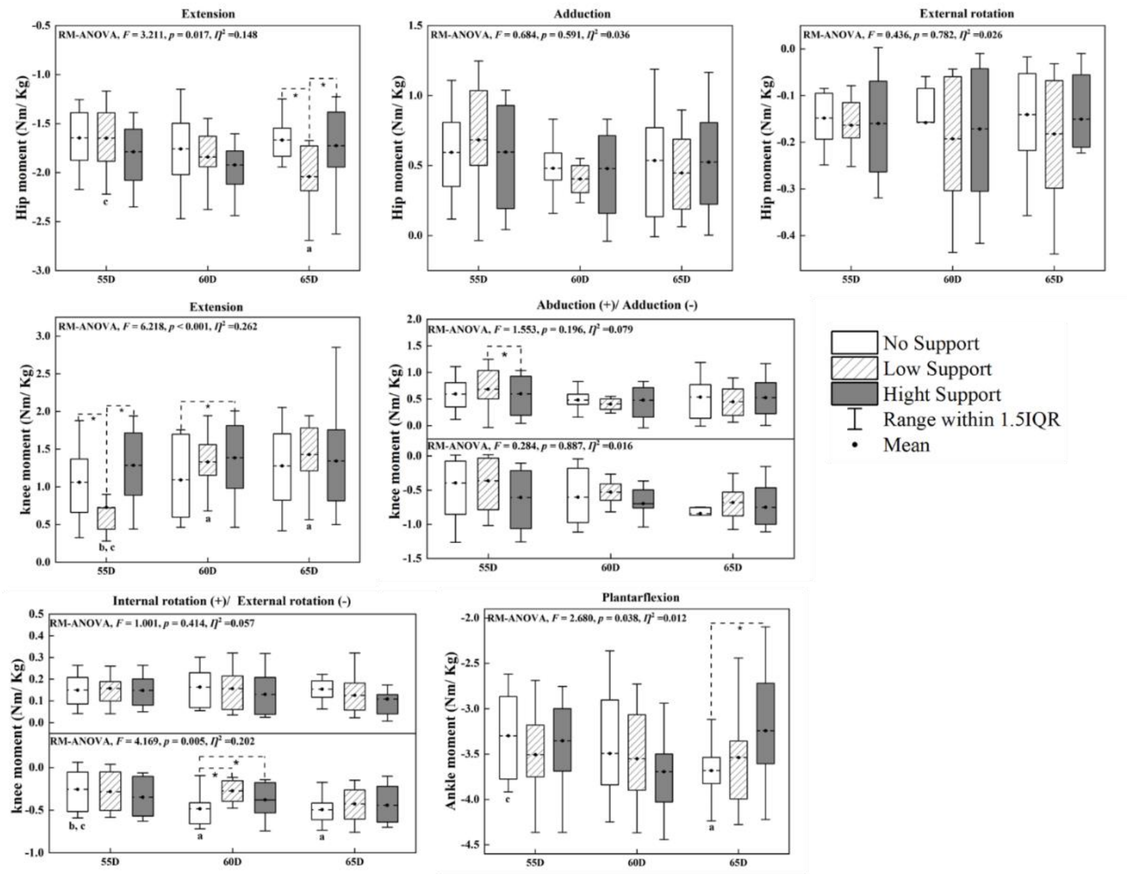


Figure 24. Peak moments for the ankle, knee, and hip joints during the FCR task across three different torsional stiffness conditions and three insole variations, * indicates statistical differences between the various arch support insoles with constant

torsional stiffness ($p < 0.05$). Different letters a, b, and c indicates statistical differences between the torsional stiffness levels when the arch support elevation remains constant ($p < 0.05$).

3.3.4 Joint Forces

During the 45C task, joint contact forces in the hip and knee did not show any interaction between foot arch support height and torsional stiffness. Moreover, post-hoc tests revealed no significant differences in joint contact forces with respect to foot arch support height or torsional stiffness.

In the ankle joint, when analyzing joint contact forces in the anterior-posterior direction, no significant interaction was found between foot arch support height and torsional stiffness ($p = 0.251$). However, post-hoc analysis indicated that at 65D, the peak contact force in the LS condition was significantly greater than in the NS condition (see Figure 25).

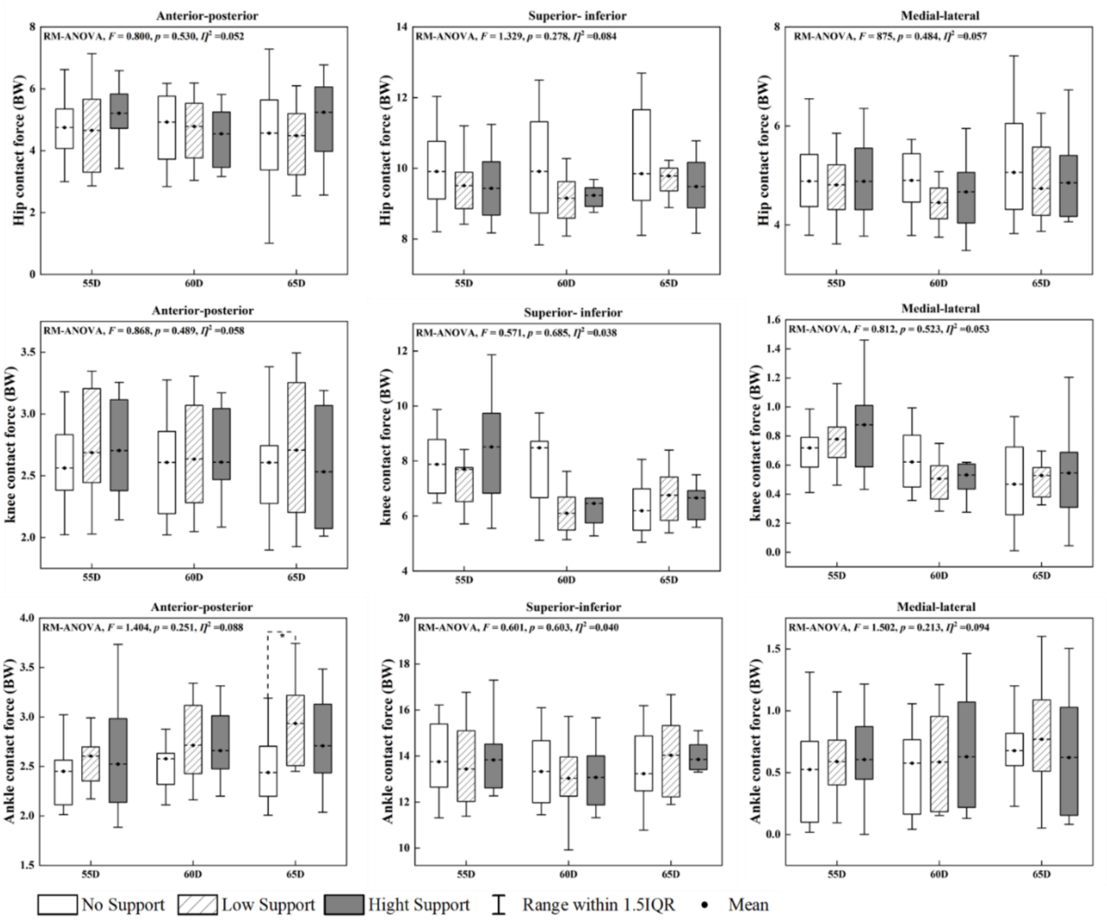


Figure 25. Peak joint contact forces for the ankle, knee, and hip joints during the 45C

task across three different torsional stiffness conditions and three insole variations, * indicates statistical differences between the various arch support insoles with constant torsional stiffness ($p < 0.05$). Different letters a, b, and c indicates statistical differences between the torsional stiffness levels when the arch support elevation remains constant ($p < 0.05$).

During the FCR task, the statistical analysis of joint contact forces showed no significant interactions between arch support height and torsional stiffness across all joint variables (Figure 26). However, post-hoc analysis revealed that for the peak joint contact forces in the knee's Medial-Lateral Direction, the values under the HS at 60D torsional stiffness were significantly greater than both NS and LS.

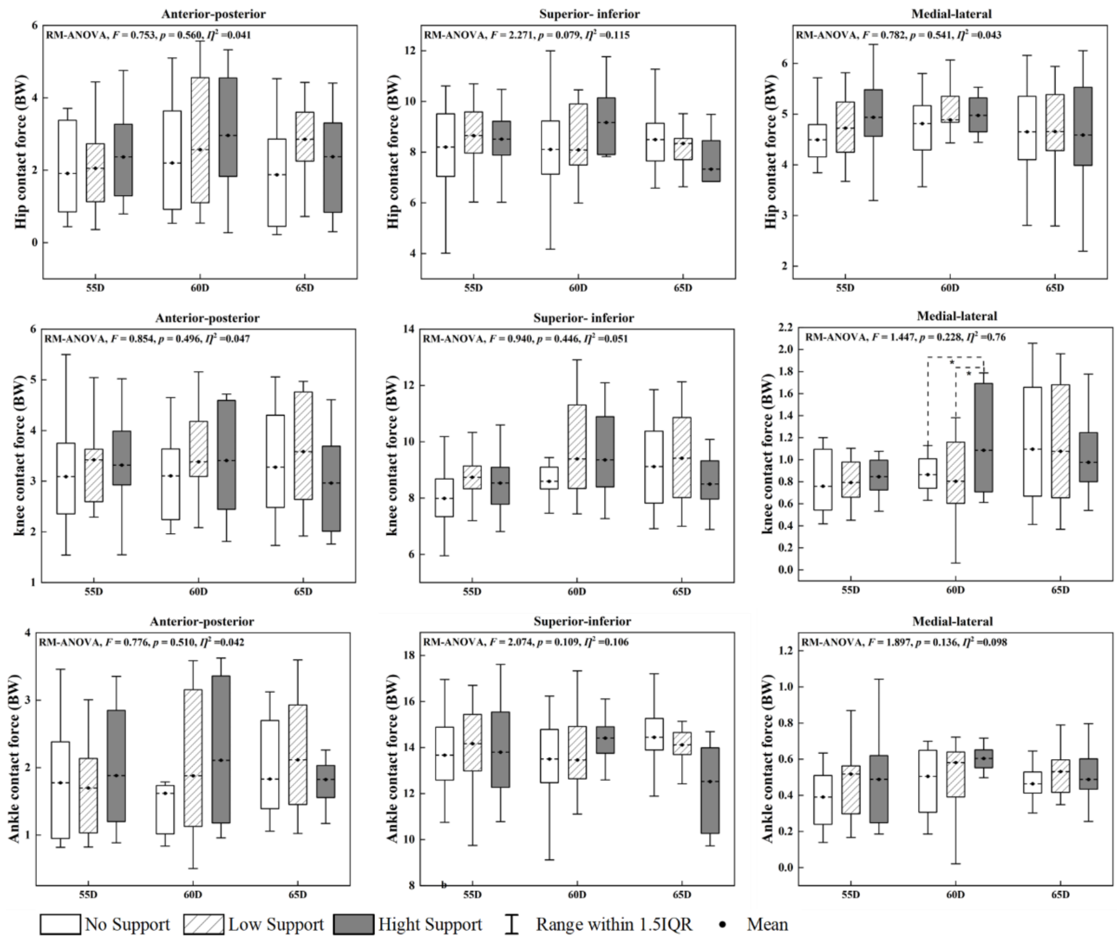


Figure 26. Peak joint contact forces for the ankle, knee, and hip joints during the FCR task across three different torsional stiffness conditions and three insole variations, * indicates statistical differences between the various arch support insoles with constant torsional stiffness ($p < 0.05$). Different letters a, b, and c indicates statistical

differences between the torsional stiffness levels when the arch support elevation remains constant ($p < 0.05$).

4. DISCUSSION

4.1 Gender properties of badminton shoes

Badminton requires athletes to perform substantial explosive movements on joint loading (Phomsoupha and Laffaye, 2015; Nadzalan et al., 2018), which could be related to various extremely rapid and intense activities during the game (Bravo-Sánchez et al., 2020). The foot is susceptible to considerable high amount of pressure, which increases the risks of potential foot injuries (Lam et al., 2020). Badminton shoes are clearly different from other sports shoes, and they must be functionally suitable for the characteristics of badminton players (Park et al., 2017). The basic requirements of badminton footwear usually focus on the soles, the weight and appearance (Nadzalan et al., 2018; Lam et al., 2022). It is generally believed that the correct shoe shape is obtained by matching shoe shape to foot shape (Miller and Redwood, 1976). Therefore, consideration of the gender differences in foot shape is essential to the proper design of both male and female footwear (Wunderlich and Cavanagh, 2001). However, it is still questionable if male and female athletes would demonstrate different footwear requirements, foot complaints and foot injury locations, since there are considerable anthropometrical and biomechanical differences between genders. The objective of this cross-sectional survey was to investigate the shoe requirements, shoe problems/complaints and pain locations in males and females using supervised questionnaires. As a non-contact sport, badminton has obvious laterality in its lower limbs. Badminton involves repeated rapid forward lunges; the dominant leg bears a greater load than the non-dominant leg. Therefore, the dominant and non-dominant side characteristics of badminton shoes should also be examined (Mundermann et al., 2001). The results from this part can provide insights for badminton footwear development.

Our results showed that the fit and comfort of badminton shoes were recognized as the most important shoe feature in both males and females. This is similar to previous research on running, soccer, gym, basketball and tennis footwear, which also reported fit and comfort as the most important shoe features (Brauner et al., 2012; Althoff and Hennig, 2014; Sterzing et al., 2014; Apps et al., 2015; Park et al., 2017). Moreover, another research studying shoe comfort during standing tasks, preferred footwear conditions were shown to result in the lowest levels of lower extremity and back pain. In addition to injuries, it has been suggested (Nigg, Nurse and Stefanyshyn, 1999; Nigg, 2001)that footwear comfort is related to sport performances MENDELEY CITATION PLACEHOLDER 0. Some studies have found significant improvements in running economy when wearing their most comfortable/preferred shoe conditions (Luo et al., 2009).

Shoe fit is a prerequisite to shoe comfort as well as sports performance, fatigue and injury prevention (Sterzing et al., 2009, 2014; Schubert, Oriwol and Sterzing, 2011). Comfortable fit is also considered essential for shoe performance (Luximon, Goonetilleke and Tsui, 2003; Frederick and Wojcieszak, 2005; Au and Goonetilleke, 2007). Fit and comfort are closely related to shoe design (Lam, Fung and Poolton, 2015a). Although shoe fit and comfort were ranked as important by both genders, the higher importance of fit and comfort was found in female players. One possible explanation is that females may have different foot shape, with wider forefoot and narrower heel, compared with males (Frey, 2000; Wunderlich and Cavanagh, 2001; Krauss et al., 2008). However, most female sports shoes are scaled down versions of male shoes (Frey, 2000), resulting in potential concerns on shoe fit. Another explanation is due to the higher hallux valgus angles found in females than males (Hardy and Clapham, 1951; JORDAN and BRODSKY, 1951; Piggott, 1960; Mann and Coughlin, 1981; Schemitsch and Horne, 1989; Coughlin and Jones, 2007), which would result in more sensitivity to shoe upper pressures exerted on the hallux and therefore higher frequency of discomfort of the female hallux.

In this part, females reported importance for shoe color, dominant forefoot cushioning and upper durability than the males, suggesting that colour should be always considered in female footwear. Biomechanically, the function of shoes is minimally affected by color. From the cognitive science perspective, colour can influence human cognition, perception and behavior, which may in turn have a great impact on motor performance (Elliot et al., 2007; Feltman and Elliot, 2011; Sorokowski, Sorokowska and Witzel, 2014; Nigg et al., 2015). The earliest study investigating the color of badminton shoes (Liang and Li, 2018) indicated that badminton shoes should concentrate on exciting colors (e.g. red) and material combinations, which could help to improve the wearer's sports performance perception.

Compared to males, females have wider pelvis width, which is associated with greater genu valgus, greater external tibial torsion and a greater Q-angle. Previous work has shown that female athletes have higher knee injury rates than male athletes in many court sports such as basketball and soccer (Hootman, Dick and Agel, 2007), which is partly consistent with our survey results. Our female respondents rated shoe cushioning as one of the important shoe features in badminton and the need for shoe cushioning was more important in the dominant leg compared with the non-dominant leg to lower the impact of the lower limbs during exercises. Since females have narrower heel and higher medial arch than males (Krauss et al., 2008), females prefer shoes with better upper fit and durability.

Based on our shoe problem/complaints findings, there were no gender differences found for most of shoe problems/complaints in regular sports. Due to the different anatomical structures of male and female feet, female arches are higher than males. Excessive arch support causes excessive ankle varus, which is suggested to increase the risk of ankle sprain (Xiong et al., 2010; Kristianslund, Bahr and Krosshaug, 2011). Subjectively, athletes exhibit differences in perceived shoe stiffness based on mechanical properties. As a result, soft soles were more popular than hard soles, and shoes with a stiffer forefoot were considered particularly uncomfortable for recreational athletes (Sterzing et al., 2013). Our foot discomfort and pain results showed that the plantar region was the most susceptible to discomfort or pain regardless of gender. Together with the findings from the "importance of shoe properties" section, which showed a higher demand on fore-foot cushioning. Moreover, our recreational badminton athletes complained of hard forefoot soles. Wearing shoes may alter cutaneous proprioception, mainly due to mechanoreceptors on the plantar surface (Aboutorabi et al., 2016; Alghadir, Zafar and Anwer, 2018). The cutaneous proprioception is one of the most important sensory systems to regulate the postural stability (Lord, Clark and Webster, 1991). Furthermore, ankle proprioception is a key part of the feedback loop that is regulated by the central nervous system to maintain a stable upright posture while standing quietly. In a similar vein, badminton shoes might affect this proprioceptive process by changing the structure of the shoe, which could alter the sensory inputs on the foot and thus influence postural strategy (Hausselle et al., 2021). In the future, forefoot cushioning should be improved together with the individual perception to minimize the potential risk of foot and lower-limb injuries.

4.2 Torsional Stiffness of Badminton Footwear

The purpose of this study was to investigate the influence of badminton shoes with different torsional stiffness levels on lower limb biomechanical characteristics, as well as on performance and injury risk during several typical badminton tasks. Injuries are a prevalent occurrence in the badminton, with a significant proportion of overused injuries primarily affecting the lower extremities (Fahlström, Björnstig and Lorentzon, 1998b). Research study reported that approximately 58% of badminton-related injuries were localized to the lower limbs (Boesen et al., 2011). In the context of injury prevention, considering the design of court shoes, it is crucial to ensure that shoes exhibit certain characteristics (Reinschmidt and Nigg, 2000). One important consideration is the need for shoes to provide adequate stability, effectively addressing excessive pronation and particularly excessive supination (Bouché, 2010).

This study revealed that during the execution of the 45C task, there was a reduction in the peak ankle inversion angle as the torsional stiffness increased. Notably, the 50D shoes exhibited the highest range of motion in the sagittal and horizontal planes at the ankle joint, suggesting that increasing the torsional stiffness of badminton shoes could potentially improve ankle joint stability during badminton, consequently decreasing the risk of ankle injuries. Conversely, the peak knee abduction angle and coronal plane motion were significantly lower for the 60D shoes compared to the 50D and 70D shoes. According to the mechanism of anterior cruciate ligament (ACL) injury in the knee joint, excessive knee abduction angles have been associated with ACL injuries (Kimura et al., 2012). Consequently, during the execution of the 45C task, the 60D shoes demonstrated the lowest risk of ACL injury.

Additionally, our findings indicated that an increase in torsional stiffness of badminton shoes led to a decrease in dorsiflexion angle at the MTP joint. Previous research has demonstrated that wearing appropriately fitted badminton shoes could enhance push-off efficiency by reducing peak dorsiflexion angles and plantar flexor muscle lengthening angles at the MTP joint, thereby improving the sports performance (Wei et al., 2009). Therefore, increasing torsional stiffness effectively may not only enhance sports performance and improve stability during the motion of the MTP joint, ultimately lowering the risk of injuries.

To gain a more comprehensive understanding of the biomechanical characteristics influenced by the torsional stiffness of badminton shoes, our study further examined the FCL task and the 45C task that also involved the data collection of the left leg. The FCL task represented another common movement in badminton requiring rapid and agile responses (Zhao and Li, 2019).

Our observations during the FCL task brought new considerations to light. We observed that the peak ankle dorsiflexion angle increased with the 60D shoes, indicating enhanced ankle joint mobility and range of motion. This increase may be attributed to the specific characteristics of the 60D shoes, which seem to strike a balance between flexibility and torsional stiffness. In this footwork of reliant on the left leg for optimal execution, the 60D shoes allow for greater ankle joint mobility, leading to increased peak dorsiflexion and inversion angles during the FCL task, possibly offering players a competitive edge in moments that demand quick directional changes (Zhao and Li, 2019). On the contrary, the 70D shoes resulted in a different interplay of biomechanics and performance, which significantly reduced the ROM of the knee in the coronal plane compared to the 50D and 60D shoes, suggesting a more constrained knee movement. The higher midfoot torsional stiffness associated with the 70D shoes appeared to limit transverse displacement and subsequent knee motion in the coronal plane, resulting in a smaller ROM, which might have deficiencies for movements that rely on knee flexibility, such as badminton lunge (Mei et al., 2017; Lam et al., 2020)These findings may highlight the influence of different torsional stiffness levels on ankle and knee kinematics during the FCL task.

Regarding the FCR task, the results revealed significant differences in ankle joint angles among various shoe conditions, highlighting the influence of torsional stiffness on ankle biomechanics. Characterized by higher torsional stiffness, the 70D shoes exhibited restricted ankle inversion, adduction, abduction, and external rotation, resulting in smaller peak angles. This restriction in ankle motion may contribute to improved ankle joint stability during badminton activities. However, it is important to consider the implications for injury prevention, as global stabilization of the ankle joint may limit its range of motion and potentially increase forces on proximal joints. Winter (Winter, 1984) demonstrated that changes in kinematics and kinetics in one joint can affect other joints within the kinetic chain. These ankle restrictions during functional tasks may lead to increased forces on proximal joints, such as the knee and hip, as compensation for forces were not absorbed by the ankle joint. Previous studies by DiStefano et al. (DiStefano et al., 2008) and Stoffel et al. (Stoffel et al., 2010) suggested that alterations in proximal joint kinematics and kinetics may increase the risk of injury in those joints. Our findings are consistent with previous literature (DiStefano et al., 2008; Stoffel et al., 2010), demonstrating that while the 70D shoes could maintain ankle stability, which may inadvertently impose additional stress on the knee joint. This underscores the necessity in athletic footwear design to comprehensively consider the intrinsic interconnectedness within the lower limb kinetic chain (Nicola and Jewison, 2012), aiming to achieve a balance between joint protection and athletic performance. An integrative evaluation of footwear should not only focus on the stability of a single joint but also explore how various designs impact the biomechanical characteristics of the entire kinetic chain (Farzadi et al., 2017).

Furthermore, the knee abduction angle in the 70D shoes was significantly smaller than in the 50D shoes. Numerous studies have determined through biomechanical analysis, injury video analysis, and simulation studies that an increase in knee abduction angle and moment increases the risk of ACL injury(Hewett et al., 1999; Olsen et al., 2004; Krosshaug et al., 2007; Koga et al., 2010). Hewett et al (Hewett et al., 2005b) reported in a prospective cohort study on badminton that female athletes with increased knee abduction angle and knee abduction moment had an increased risk of ACL injury during the landing phase, suggesting a possible relationship between torsional stiffness and the incidence of ACL injuries. Our research supported this relation, proposing that footwear with optimized torsional stiffness not only improved sport performance but also served as a preventative strategy against common musculoskeletal injuries in badminton, particularly the ACL injury (Alentorn-Geli et al., 2009).

The analysis of stability data obtained from the CVJ task yielded significant findings concerning the range of motion (ROM) exhibited by the ankle and knee joints. Specifically, a comparative analysis of different shoe conditions revealed notable variations. The findings showed that shoes with lower torsional stiffness facilitated greater ankle joint mobility during the CVJ task in the sagittal plane. While this augmented mobility might allow for more continuous moment and adaptability during badminton sport, which may also introduce a higher risk of ankle-related injuries (Gleim and McHugh, 1997).

Additionally, an examination of the knee joint ROM in the sagittal plane indicated that shoes with moderate torsional stiffness (60D) exhibited a significantly smaller ROM compared to shoes with the lowest torsional stiffness (50D). The results suggested that shoes with intermediate torsional stiffness reached an optimal balance between flexibility and stability, thereby enhancing overall performance and reducing the injury risk during dynamic movements such as the CVJ task.

Within this study, it was found that the 70D shoes exhibited significantly higher peak knee extension moment during the 45C task, peak knee internal rotation moment during the execution of the FCL, and peak knee external rotation moment during the execution of the FCR, as compared to the 50D shoes. These findings regarding knee joint dynamics suggested that the 70D shoes showed enhanced efficiency in managing impact forces, enabling immediate execution of tasks with greater mechanical output (Kuntze et al., 2010). These results provided partial support for the maximal dynamic hypothesis (Markovic and Jaric, 2007), indicating that the musculoskeletal system of the lower limb aimed to optimize dynamic output. These revelations have certain implications for the sports industry, suggesting that strategic modifications in shoe torsional stiffness could revolutionize training protocols, footwear customization, and injury prevention methodologies, ultimately safeguarding athlete well-being while pushing the boundaries of their athletic performance (Davids et al., 2003; Barton et al., 2009; Van Wilgen and Verhagen, 2012).

The analysis of stance time in this study revealed that participants demonstrated shorter stance time during the FCR task while wearing shoes with increased torsional stiffness. This finding was particularly advantageous for rapid direction changes in competitive sports, where the speed of direction changes significantly influenced game outcomes (Hughes and Meyers, 2005; Fernandez, Mendez-Villanueva and Pluim, 2006). However, in the case of the 45C task, it was observed that the shortest stance phase duration occurred with the 60D shoes, rather than the 70D shoes. Thus, in the context of badminton, the identical torsional stiffness may yield varying performance outcomes during different badminton movements.

The statistical analysis of ground reaction force variables in three directions during various movements under different shoe conditions had no significant differences in the anterior-posterior and medial-lateral directions. However, a notable disparity was observed in the vertical ground reaction force, with the 70D shoes exhibiting significantly higher values compared to the 50D shoes. This difference was particularly evident during the stance phase, specifically at 70%-75%. In the FCR movement, this phase corresponded to the push-off stage, where the greater vertical ground reaction force in 70D shoe could provide enhanced propulsive power. This outcome facilitated rapid propulsion, quick preparation for following reactive actions, thus improving overall sports performance.

4.3 Torsional Stiffness and Arch Support Variations in Badminton Footwear

Badminton demands intricate footwork skills and emphasizes both the dominant and non-dominant legs (Shen et al., 2022; Yu and Mohamad, 2022). Given this context, our study, by focusing on two common badminton footwork patterns, 45C and FCR, delved into the impact of arch support height (no support, low support and high support) and differing torsional stiffness (55D, 60D and 65D) in badminton shoes on lower limb biomechanics. Furthermore, we explored the potential complex relationship between arch support and torsional stiffness, especially the biomechanical characteristics changes in the hip, knee, and ankle joints. Our findings indicate that there are statistically significant interactions between the arch support heights and the torsional stiffness of badminton shoes concerning joint angles and torque characteristics. However, the interaction between joint contact force and high arch support relative to torsional stiffness was not statistically significant.

This study's joint kinematic analysis offers a deeper understanding of how variations in insole arch support and torsional stiffness impact joint movement. In the 45C task, 65D torsional stiffness combined with the HS condition resulted in decreased hip joint internal rotation. This indicates that heightened arch support could curtail undesirable hip joint internal rotation, which in turn may reduce the potential for injuries like hip impingement (Boutris et al., 2018) or acetabular labral tear (Kang, Hwang and Cha, 2009). Data from the FCR task aligns with these findings. When compared to the NS and LS conditions at 65D, the HS condition demonstrated reduced extension angles. This underscores the influence of elevated arch support on the hip joint's range of motion. This may serve to reduce the risk of injuries from excessive hip abduction (Kuhns et al., 2017). Furthermore, during the FCR task while wearing 65D, there was an observed increase in hip joint flexion angles as the arch support elevated. Previous studies have suggested that enhanced hip flexion, in the presence of increased support, can decrease the risk of ACL injuries (Blackburn and Padua, 2008; Larwa et al., 2021). This increased hip flexion during badminton activities likely represents a biomechanical adaptation to deceleration, abrupt stops, and sudden directional changes, enhancing overall body stability.

The kinematic outcomes of the knee joint, as presented in Figure 8, demonstrate significant variations in peak external rotation and abduction angles during the 45C task. Notably, the abduction angle under the 65D NS condition exhibited a substantial decrease compared to both the LS and HS conditions. This highlights the biomechanical changes in the knee joint due to varying levels of arch support. Non-contact mechanisms (where the knee isn't directly impacted) predominantly account for anterior cruciate ligament (ACL) injuries, making up approximately 70% of all ACL-related incidents, especially during lateral cutting maneuvers in sports activities (Griffin et al., 2000). A study by Kiapour et al. suggests that an elevation in knee abduction angles may amplify the risk of non-contact ACL injuries (Kiapour et al., 2016). Furthermore, with a consistent arch support level, peak abduction angles of the knee joint rise with increased torsional stiffness, indicating that excessive torsional rigidity might also heighten the ACL injury risk in the knee. While evaluating external rotation, data revealed differences, particularly within the 60D NS condition, where there was a significant reduction in the peak rotation angle compared to 55D and 65D. Excessive rotational movement in the knee is linked to meniscal tears during court sports (Jayanthi and Esser, 2013; Fu et al., 2018). This suggests that maintaining an appropriate torsional stiffness could play a crucial role in preventing knee injuries during athletic activities. During the FCR task, the kinematic results of the knee joint clearly manifested significant interactions between arch support and torsional stiffness, especially regarding peak flexion angles. Specifically, at a torsional stiffness of 50D, the HS condition displayed a notably reduced peak flexion angle compared to LS. When the torsional stiffness was set to 60D, the flexion peak angle of LS was substantially lower than NS. Such data patterns suggest that increasing arch support can lead to diminished knee flexion angles. Research has shown that athletes, during intense badminton footwork in training or competitions, augment knee flexion to compensate for dynamic stability (Huang et al., 2014). Our findings propose that elevating arch support could potentially counterbalance the necessity for knee flexion, thereby reducing the impact and stress on the joint, ensuring a smoother center of mass transition. This could aid in averting joint overuse injuries caused by high-intensity and swift movements (Willson et al., 2005). On the other hand, we also observed that peak knee flexion angles could be modulated by torsional stiffness. Specifically, under the LS condition, flexion angles at 60D and 65D were significantly lower than at 55D. This insinuates that increased torsional stiffness in badminton shoes might assist in decreasing adverse joint loads during intense movements or rapid directional shifts (Lees, 2003). Such protective properties reduce the likelihood of acute injuries during sports activities, like sprains and tears, often occurring when joint stability is compromised (Salzmann et al., 2017). However, this might also hinder an athlete's agility and fluidity of movement, particularly during high-intensity and rapid matches. Therefore, striking a balance is pivotal: providing sufficient stability to lower the risk of joint injuries, without overly restricting the athlete's range of motion.

The ankle joint is often considered a pivotal aspect in athletic movements. Alterations in footwear can induce significant biomechanical changes at the ankle (Lam et al., 2019a). In the context of a 45C task, observed variations in dorsiflexion angles under different conditions can be attributed to a combination of arch support and torsional stiffness. Notably, even though this interaction might not be statistically significant, distinct variations under certain conditions, particularly when torsional stiffness is 55D and 65D, reveal that peak ankle dorsiflexion angles increase with heightened arch support. This aligns with previous research (Nagano and Begg, 2021; Zhao et al., 2021). Enhanced arch support has been shown to elevate swing foot clearance and improve the distribution of foot-ground impact forces (Silver-Thorn et al., 2011; Ventura, Klute and Neptune, 2011). Furthermore, dorsiflexion at heel contact diminishes impact shock by harnessing the elastic energy absorbed by the extended Achilles tendon, subsequently alleviating knee stresses (Lichtwark and Wilson, 2007; Ventura et al., 2011). A similar trend was evident during the FCR task when wearing badminton shoes with a torsional stiffness of 60D. However, when the arch support height remains consistent, the peak ankle dorsiflexion angle also increases as torsional stiffness escalates. Torsion of the foot is typically defined as the relative rotation between the forefoot and rearfoot in the frontal plane(Stacoff et al., 1989). This might be due to the ankle joint's movement in the frontal plane being restricted when shoe torsional stiffness increases, prompting the ankle to compensate with increased dorsiflexion. Such adaptations might bolster ankle stability during high-intensity activities (Graf and Stefanyshyn, 2013).

The 45C task, which targeted the non-dominant leg, did not exhibit notable differences in joint moments. This might suggest that the biomechanical responses of the non-dominant leg during certain activities could differ from those of the dominant leg (Van der Harst, Gokeler and Hof, 2007; Wang and Fu, 2019). Alternatively, the influence of footwear characteristics might differ for the non-dominant leg (Shen et al., 2022). However, a contrasting picture emerged during the FCR task that targeted the dominant leg. Although no significant interactions were observed among the hip, knee, and ankle joint moments concerning arch support and torsional stiffness, post-hoc comparisons revealed significant disparities under certain conditions. Specifically, with a constant torsional stiffness, the peak extension moments at the hip and knee joints for the LS condition were notably lower than those for NS and HS. In the context of the FCR task, a lower arch support might contribute to the reduction of hip and knee extension moments. While a greater extension moment is recognized as a factor enhancing athletic performance, potentially leading to elevated anterior knee forces, it may also result in increased ACL loading (Nasseri et al., 2020). This implies that appropriate arch support can optimize biomechanical efficiency while potentially mitigating risks associated with excessive joint loadings, safeguarding the athlete from potential injuries.

In the assessment of joint contact forces during the 45C and FCR tasks for the hip, knee, and ankle joints, no evident interaction between foot arch support height and torsional stiffness was observed. However, a closer examination of the data revealed that under specific tasks and torsional rigidity, foot arch support height had a notable influence on joint contact forces. Specifically, during the FCR task, the joint contact forces in the medial-lateral direction of the knee at a torsional stiffness of 60D demonstrated that values generated in the HS condition significantly surpassed those in the NS and LS configurations. This suggests that the elevated arch support, at this particular torsional stiffness, may induce the knee joint to endure amplified pressure or load in the medial-lateral direction. This increased joint contact force might result from the high arch support altering the transmission pathway of the ground reaction forces to some extent or modifying the pressure distribution between the foot and the ground, leading to distinct biomechanical responses in the knee joint.

4.4 Limitations

This dissertation, while providing valuable insights into the biomechanics of badminton footwear, acknowledges several limitations across its studies. The first study may have been influenced by the variability in athletes' footwear and was limited to recreational adult players, potentially not representing the diverse needs of players at different skill levels. The second and third studies, conducted in controlled laboratory settings, might not fully capture the complexities and unpredictability of actual badminton gameplay, thereby limiting the ecological validity of the findings. These studies also did not consider the long-term effects of footwear torsional stiffness and focused primarily on lower limb biomechanics, omitting the comprehensive kinetic chain and upper body contributions. Additionally, the third study's small sample size, primarily comprising college students, and its focus on short-term responses in specific footwork patterns, may limit the generalizability of the results. Across all studies, factors such as player fatigue, psychological stress, court surface variations were not examined, presenting avenues for future research. Despite these constraints, the dissertation contributes significantly to the understanding of performance enhancement and injury mitigation in badminton, highlighting the potential of footwear as a critical factor in athlete performance and safety.

5. CONCLUSIONS

The dissertation begins by addressing badminton shoe demands, highlighting that good fit and comfort are crucial, especially noting clear differences in shoe feature demand between genders. This finding led to the recommendation for female-specific shoes, considering the distinct anthropometrical differences between genders. This initial study provided a comprehensive perspective on shoe demands, problems, and discomfort locations, acknowledging the subtleties of leg-dominance and gender differences in badminton footwear preferences.

Building upon these insights, the second study focused on the role of torsional stiffness in badminton shoes, exploring its impact on lower limb biomechanics, performance, and injury risks. The results indicated that increased torsional stiffness enhances ankle joint stability, potentially reducing ankle issues, with medium stiffness (60D) shoes striking a favorable balance between flexibility and stability. This balance is crucial for maximizing performance and minimizing injury occurrences, though the stiffest shoes were found to restrict ankle range of motion while assisting in handling impact forces.

The third study extends the research scope by analyzing the combined effects of different torsional stiffness levels and arch support heights in badminton footwear. This segment demonstrates how proper arch support significantly impacts the biomechanics of lower limb joints during demanding athletic maneuvers. Increased arch support is associated with a reduction in adverse biomechanical movements in the hip during specific activities, such as the 45C tasks, but yields contrasting results in FCR tasks, highlighting the variation in injury risks associated with different types of movement. Additionally, the study emphasizes the significance of torsional stiffness, particularly at 65D, which correlates with reduced unfavorable joint motions. However, excessive torsional rigidity could hinder natural movements, underscoring the need for a balanced approach in athletic footwear design. The intricate relationship between arch support and torsional stiffness emerges as a pivotal finding, suggesting that these elements should be considered in tandem to achieve an optimal biomechanical response and effectively mitigate injury risks.

In conclusion, this dissertation emphasizes the paramount importance of optimizing badminton footwear design through comprehensive consideration of arch support and torsional stiffness. These studies collectively illuminate the complexity of footwear characteristics and their profound implications on stability, comfort, and overall athletic performance. They pave the way for future research to explore these variables' long-term effects, their specific impacts across different athlete levels and age groups, and the necessity of a holistic approach in sports footwear design to enhance athletic performance and minimize injury risks.

NEW SCIENTIFIC THESIS POINTS

1st Thesis point

I experimentally revealed, based on the data of 326 recreational badminton players regarding their shoe properties, complaints, and foot discomforts (Figures 27A), that while both genders prioritize shoe fit and comfort, females place additional importance on aspects such as breathability (by 6.24%), color (by 16.32%), forefoot cushioning (by 5.26%), and upper durability (by 7.50%) compared to males (Figure 27B). These findings indicate clear gender-based disparities in shoe requirements, with noticeable differences in shoe problems/complaints and foot discomfort between genders. Such insights underline the necessity for gender-specific shoe designs in badminton, tailored to address the unique anatomical and biomechanical aspects of male and female players.

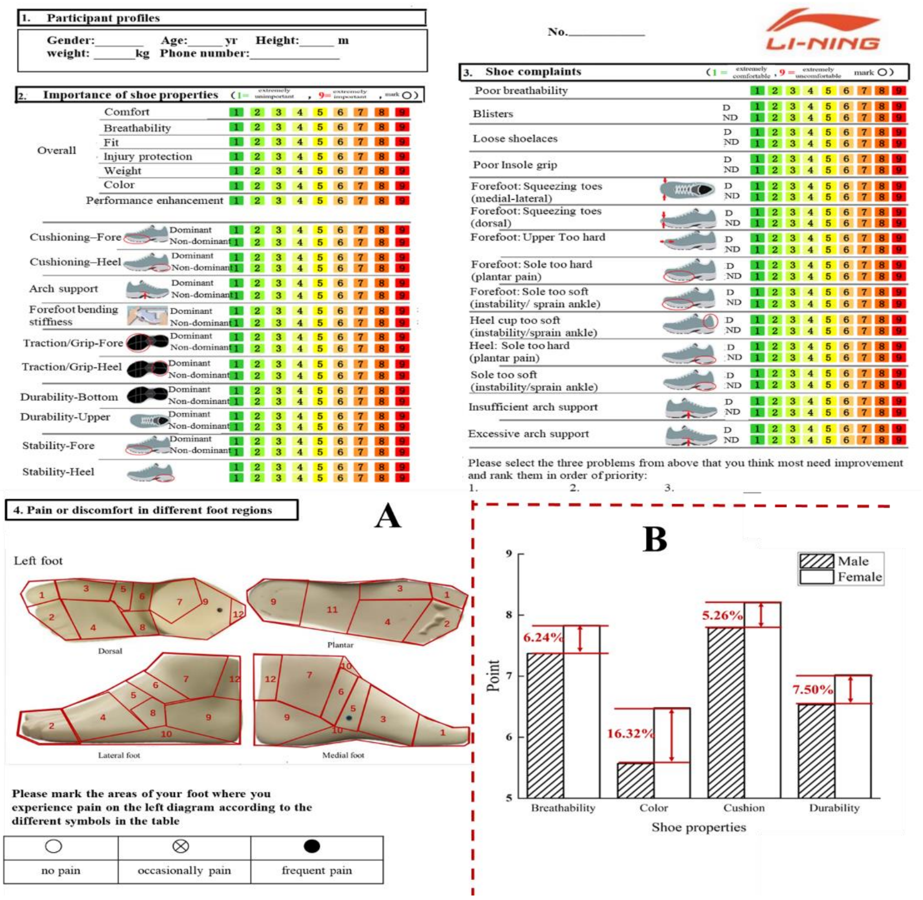


Figure 27. This cross-sectional survey questionnaire (A) and difference of shoe properties between genders (B).

Related articles to the first thesis point:

1. **Shen, S.,** Lam, W.-K., Teng, J., Jia, S.-W., Baker, J. S., Ugbolue, U. C., Fekete, G., & Gu, Y. (2022). Gender and leg-dominance differences in shoe properties and foot injuries in badminton: a cross-sectional survey. *Journal of Foot and Ankle Research*, 15(1), 26. **IF: 2.96, Q2**

2. Xia, Y., **Shen, S.,** Jia, S.-W., Teng, J., Gu, Y., Fekete, G., Korim, T., Zhao, H., Wei, Q., & Yang, F. (2023). Gender differences in footwear characteristics between half and full marathons in China: a cross-sectional survey. *Scientific Reports*, 13(1), 13020. **IF: 4.997, Q1**

2nd Thesis point

I experimentally deduced that shoes with medium stiffness (60D) offer an optimal balance between flexibility and stability, reducing the stance time by 17% compared to 50D (Figure 28B), thereby enhancing performance and reducing injury risk. In contrast, shoes with higher stiffness (70D) show restricted ankle range of motion, however provide increased vertical ground reaction forces (an increase of cca. 8% compared to 50D) (Figure 28C) potentially aiding in quicker movements. Therefore, I can conclude that an intermediate level of torsional stiffness in badminton shoes offer the best balance for sports performance and injury prevention, suggesting the need for further research on the long-term effects of varying shoe stiffness and its relation to different athletic levels and foot morphologies.

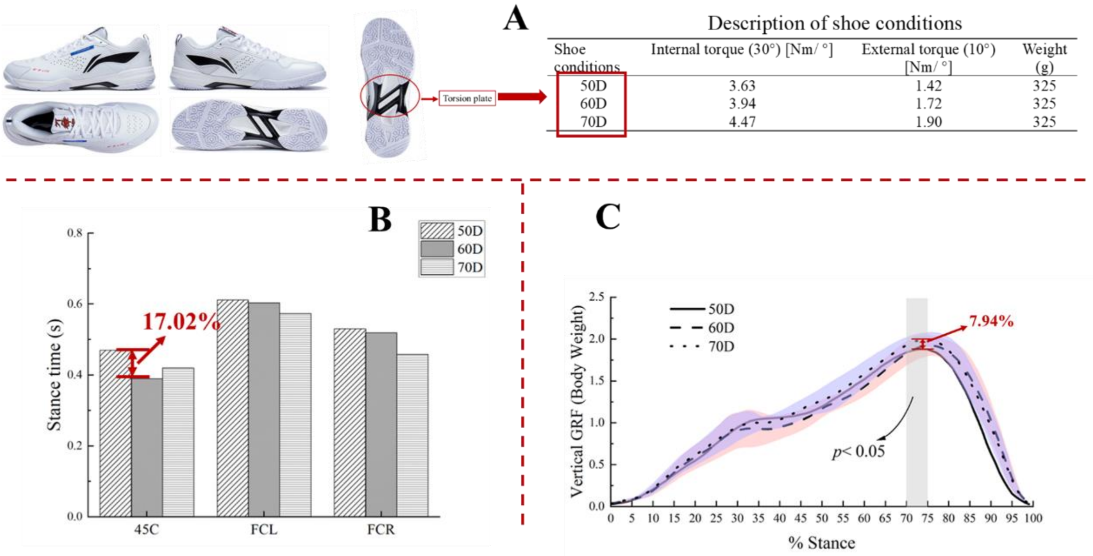


Figure 28. Shoe construction (A) and biomechanical parameters with Impact on Stance Times (B) and vertical ground reaction Forces (C)

Related articles to the second thesis point:

1. **Shen, S.,** Teng, J., Fekete, G., Mei, Q., Zhao, J., Yang, F., & Gu, Y. (2024). Influence of Torsional Stiffness in Badminton Footwear on Lower Limb Biomechanics. *Journal of Sports Science and Medicine*, 23(1), 196-208. **IF: 4.017, Q1**
2. **Shen, S. Q.,** He, Y. Q., Zhang, Y., Fekete, G., & Zhou, Z. X. (2020).

Biomechanical analysis of long distance running on different sports surfaces. *Journal of Biomimetics, Biomaterials and Biomedical Engineering*, 45, 31–39. **IF: 0.69, Q4**

3. Zhang, Y. Y., **Shen, S. Q.,** Baker, J. S., & Gu, Y. D. (2018). Effects of different hardness in bionic soles on lower limb biomechanics. *Journal of Biomimetics, Biomaterials and Biomedical Engineering*, 39, 1–12. **IF: 0.69, Q4**

3rd Thesis point

I numerically demonstrated, by means of OpenSim musculoskeletal modeling, that increased arch support significantly reduces hip internal rotation peak angles during specific badminton tasks like 45-degree sidestep cutting (HS vs. NS: -60.25%, HS vs. LS: -69.57%) (Figure 29-a), potentially lowering hip injury risks. In contrast, during other tasks such as forehand clear stroke executed with the right foot, increased arch support may adversely affect performance (LS vs. NS: +135.83%, HS vs. NS: +199.44%) (Figure 29C-b), indicating variable injury risks with different movements. Additionally, enhanced arch support improves ankle dorsiflexion peak angles (45C: LS vs. NS: +17.88%, HS vs. NS: +22.58%; FCR: HS vs. NS: +39.62%) (Figure 29C-c, d), which is beneficial for foot clearance and impact force distribution. However, it is also associated with higher knee abduction angles, suggesting a potential risk for non-contact ACL injuries.

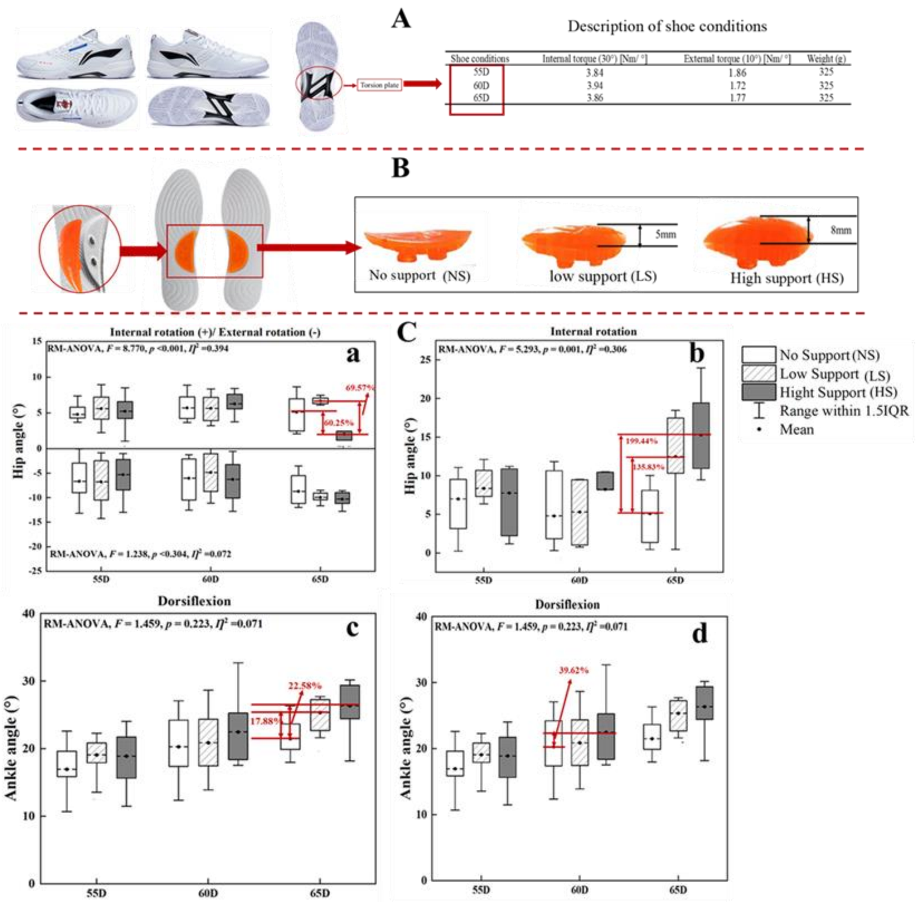


Figure 29. Combination of shoe construction (A), arch support structure (B), and peak hip internal rotation & ankle dorsiflexion angles (C).

Related articles to the third thesis point:

1. **Shen, S.,** Teng, J., Fekete, G., Mei, Q., Zhao, J., Yang, F., & Gu, Y. (2024). Influence of Torsional Stiffness in Badminton Footwear on Lower Limb Biomechanics. *Journal of Sports Science and Medicine*, 23(1), 196-208. **IF: 4.017, Q1**
2. Teng, J., Qu, F., **Shen, S.,** Jia, S.-W., & Lam, W.-K. (2022). Effects of midsole thickness on ground reaction force, ankle stability, and sports performances in four basketball movements. *Sports Biomechanics,* 1–14. **IF: 2.896, Q1**

LIST OF PUBLICATIONS

Articles related to this thesis

1. **Shen, S.,** Lam, W.-K., Teng, J., Jia, S.-W., Baker, J. S., Ugbolue, U. C., Fekete, G., & Gu, Y. (2022). Gender and leg-dominance differences in shoe properties and foot injuries in badminton: a cross-sectional survey. *Journal of Foot and Ankle Research*, 15(1), 26. **IF: 2.96, Q2**

2. **Shen, S. Q.**, He, Y. Q., Zhang, Y., Fekete, G., & Zhou, Z. X. (2020). Biomechanical analysis of long distance running on different sports surfaces. *Journal of Biomimetics, Biomaterials and Biomedical Engineering*, 45, 31–39. **IF: 0.69, Q4**

3. **Shen, S.,** Teng, J., Fekete, G., Mei, Q., Zhao, J., Yang, F., & Gu, Y. (2024). Influence of Torsional Stiffness in Badminton Footwear on Lower Limb Biomechanics. *Journal of Sports Science and Medicine*, 23(1), 196-208. **IF: 4.017, Q1**

4. Xia, Y., **Shen, S.,** Jia, S.-W., Teng, J., Gu, Y., Fekete, G., Korim, T., Zhao, H., Wei, Q., & Yang, F. (2023). Gender differences in footwear characteristics between half and full marathons in China: a cross-sectional survey. *Scientific Reports*, 13(1), 13020. **IF: 4.997, Q1**

5. Teng, J., Qu, F., **Shen, S.,** Jia, S.-W., & Lam, W.-K. (2022). Effects of midsole thickness on ground reaction force, ankle stability, and sports performances in four basketball movements. *Sports Biomechanics,* 1–14**. IF: 2.896, Q1**

6. Zhang, Y. Y., **Shen, S. Q.,** Baker, J. S., & Gu, Y. D. (2018). Effects of different hardness in bionic soles on lower limb biomechanics. *Journal of Biomimetics, Biomaterials and Biomedical Engineering*, 39, 1–12. **IF: 0.69, Q4**

Other publications

1. Teng, J., **Shen, S.,** & Qu, F. (2023). Study on the Effect of Midsole Thickness of Basketball Shoes on Sprint and Shuffle. *Journal of Beijing Sport University*, (08),123-132. **IF: 2.896.**

2. Zhao, H., Teng, J., Song, G., Fu, X., Pan, X., **Shen, S.,** Yan, Y., & Liu, C. (2023).

The optimal exercise parameters of Tai Chi on the effect of glucose and lipid metabolism in patients with type 2 diabetes mellitus: A meta-analysis. *Complementary Therapies in Medicine*, 102995. **IF: 3.335, Q1**

3. Zhao, H., Cheng, R., Song, G., Teng, J., **Shen, S.,** Fu, X., Yan, Y., & Liu, C. (2022). The effect of resistance training on the rehabilitation of elderly patients with sarcopenia: A meta-analysis. *International Journal of Environmental Research and Public Health*, 19(23), 15491. **IF: 4.641, Q2**
4. Zhao, H., Cheng, R., Teng, J., Song, G., Huang, C., Yuan, S., Lu, Y., **Shen, S.,** Liu, J., & Liu, C. (2022). A Meta-Analysis of the Effects of Different Training Modalities on the Inflammatory Response in Adolescents with Obesity. *International Journal of Environmental Research and Public Health*, 19(20), 13224. **IF: 4.641, Q2**
5. Xu, D., Lu, Z., **Shen, S.,** Fekete, G., Ugbolue, U. C., & Gu, Y. (2021). The Differences in lower extremity joints energy dissipation strategy during landing between athletes with symptomatic patellar tendinopathy (PT) and without patellar tendinopathy (UPT). *Molecular & Cellular Biomechanics*, 18(2), 107. **IF: 0.138, Q4**
6. Feng, Y., **Shen, S.,** & Song, Y. (2021). Ultrasound Comparison of the Abductor Hallucis Muscle Between Normal and Hallux Valgus Feet After Long-Distance Running: A Pilot Study. *Journal of Medical Imaging and Health Informatics*, 11(8), 2106–2109. **IF: 0.659, Q4**
7. Li, S. D., **Shen, S. Q.,** Teo, E. C., & Liang, M. J. (2020). Bionic Footwear Effect to Lower Limb Locomotion in Biomechanical Analysis. *Journal of Biomimetics, Biomaterials and Biomedical Engineering*, 47, 105–115. **IF: 0.69, Q4**
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