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**Research article**

# Influence of Torsional Stiffness in Badminton Footwear on Lower Limb Biomechanics

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## Abstract

Torsional stiffness of athletic footwear plays a crucial role in preventing injury and improving sports performance. Yet, there is a lack of research focused on the biomechanical effect of torsional stiffness in badminton shoes. This study aimed to comprehensively investigate the influence of three different levels of torsional stiffness in badminton shoes on biomechanical characteristics, sports performance, and injury risk in badminton players. Fifteen male players, aged 22.8 ± 1.96 years, participated in the study, performing badminton-specific tasks, including forehand clear stroke [left foot (FCL) and right foot (FCR)], 45-degree sidestep cutting (45C), and consecutive vertical jumps (CVJ). The tasks were conducted wearing badminton shoes of torsional stiffness measured with Shore D hardness 50, 60, and 70 (referred to as 50D, 60D, and 70D, respectively). The primary biomechanical parameters included ankle, knee, and MTP joint kinematics, ankle and knee joint moments, peak ground reaction forces, joint range of motion (ROM), and stance time. A one-way repeated measures ANOVA was employed for normally distributed data and Friedman tests for non-normally distributed data. The 70D shoe exhibited the highest ankle dorsiflexion and lowest ankle inversion peak angles during 45C task. The 60D shoe showed significantly lower knee abduction angle and coronal motions compared to the 50D and 70D shoes. Increased torsional stiffness reduced stance time in the FCR task. No significant differences were observed in anterior-posterior and medial-lateral ground reaction forces (GRF). However, the 70D shoe demonstrated higher vertical GRF than the 50D shoe while performing the FCR task, particularly during 70% - 75% of stance. Findings from this study revealed the significant role of torsional stiffness in reducing injury risk and optimizing performance during badminton tasks, indicating that shoes with an intermediate level of stiffness (60D) could provide a beneficial balance between flexibility and stability. These findings may provide practical references in guiding future badminton shoe research and development. Further research is necessary to explore the long-term effects of altering stiffness, considering factors such as athletic levels and foot morphology, to understand of the influence of torsional stiffness on motion biomechanics and injury prevalence in badminton-specific tasks.

**Key words:** Badminton, footwear, torsional stiffness, biomechanics, footwork.

## Introduction

Badminton is a high-intensity non-contact racquet sport (Phomsoupha and Laffaye, 2020; Yu and Mohamad, 2022), requiring athletes to perform intermittent abrupt stops, jumps, lunges, and rapid directional changes, thus placing significant demands on the quick reflexes, agile movements, and high-velocity striking abilities (Manrique and Gonzalez-Badillo, 2003; Phomsoupha and Laffaye, 2015). However, the repetitive and rapid nature of the lunges and jumping movements may subject the lower extremity to considerable impact loads, thus increasing the risk of excessive strain and stress in the joints (Shariff et al., 2009; Mei et al., 2017; Yu et al., 2021, 2023a). Specifically, during the jumping of badminton, the early contact involves high magnitudes of vertical and horizontal impact forces, resulting in substantial joint torques and stress in the ligaments, thereby elevating the susceptibility of injuries (Abian-Vicen et al., 2014; Lam et al., 2018). Remarkably, within the realm of badminton, lower limb injuries account for 58% of the total injury cases, with over 50% injuries in the ankle and knee joints (Phomsoupha and Laffaye, 2020).

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., 2017), further, increased shoe-bending stiffness has been linked to enhanced performance in jumping, sprinting, and agility tasks (Park et al., 2017; Lam et al., 2017). A related cross-sectional study also highlighted the importance of badminton shoe characteristics (Shen et al., 2022).

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,

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possessing torsional flexibility, and allowing for medial and lateral deformation of the sole upon heel contact, may offer optimal benefits (Stacoff et al., 1996).

Specifically for the development of badminton footwear, 'flexibility' and 'stability' are important factors that directly affect athletic performance and injury risk (Barton et al., 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., 2023b), which also contributes to improved athletic performance (Graf et al., 2017). 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. Therefore, this study is aimed to comprehensively investigate the influence of torsional stiffness in badminton shoes on the biomechanical characteristics, sports performance, and injury risk of lower limbs during badminton-specific tasks. The current study hypothesized that increasing torsional stiffness of badminton shoes would enhance the stability of lower limb joints during badminton footwork and improve performance in badminton-specific actions.

## Methods

### 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-β) 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 et al., 2019; Hülsdünker et al., 2020; Dzulfakar et al., 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.

### Footwear

Three pair 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 in the midfoot region. 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 unit, with value of 50D, 60D, and 70D assigned to the respective shoes (Figure 1a). Additionally, a torsional plate made of thermoplastic polyurethane (TPU) was incorporated into each shoe design (Figure 1b), contributing to the variation in torsional characteristics.


**Figure 1**. 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 |

## Movement tasks

The kinematic data were collected using the Vicon motion analysis system (Vicon, Oxford Metrics, Oxford, UK) with 8 cameras 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 et al., 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 2). After completion of the stroke, participants immediately ensured that the left foot landed on the force plate (B) (Figure 2), indicating a successful completion of the trial.

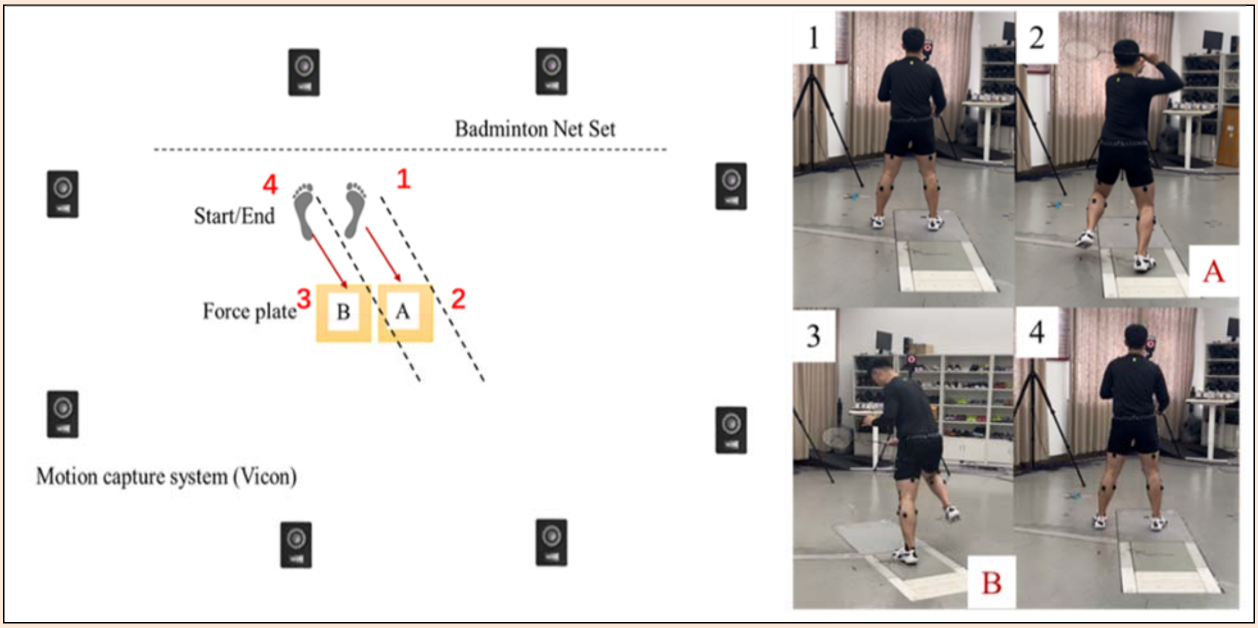


**Figure 2. Laboratory simulation and route for forehand clear stroke.**

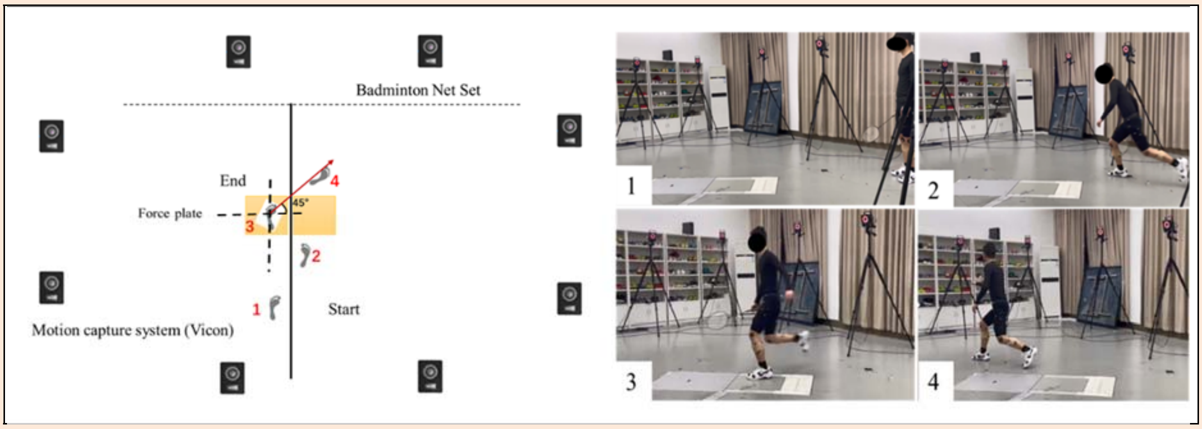


**Figure 3.** **Laboratory simulation and route for 45C.**

*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., 2023b)

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 3).

*Consecutive Vertical Jumps (CVJ):* CVJ are pivotal in badminton, directly linked to both offensive and defensive plays (Barton et al., 2009; 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; Lam et al., 2018). 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, range of motion (ROM), and ground reaction forces, providing a holistic view of performance than a singular focus on jump height.

## 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 4.

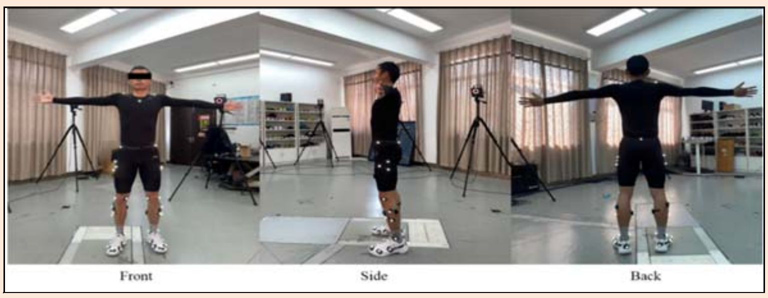


**Figure 4.** **The front, side, and back positions of marker set.**

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., 2019).

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.

### 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 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., 2015). Additionally, the ground reaction force (GRF) 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.

### 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 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 ($\eta^2$) for ANOVA and interpreted as small ($0.1 \leq \eta 2 < 0.06$), 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 SPM1D package for MATLAB (MathWorks, Natick, MA, USA) was employed to compare the vertical ground reaction force (vGRF) 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.

## Results

This study 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.

### Stability variables

Table 2 and Table 3 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 2).

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 3).

**Table 2.** Stability variables (Mean± SD) during 45C tasks by different footwear conditions.

| Variables (°) | | 50D | 60D | 70D | F | P | $\eta^2$ |
|---|---|---|---|---|---|---|---|
| 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). $\eta^2$ represents partial eta squared.

**Table 3.** Stability variables (Mean± SD) during FCL tasks by different footwear conditions.

| Variables (°) | | 50D | 60D | 70D | F | P | $\eta^2$ |
|---|---|---|---|---|---|---|---|
| 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). $\eta^2$ represents partial eta squared.

Table 4 and Table 5 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 4).

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 5).

**Table 4. Stability variables (Mean± SD) during FCR tasks by different footwear conditions.**

| Variables (°) | | 50D | 60D | 70D | F | P | $\eta^2$ |
|---|---|---|---|---|---|---|---|
| **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). **$\eta^2$** represents partial eta squared.

**Table 5. Stability variables (Mean± SD) during CVJ tasks by different footwear conditions.**

| Variables (°) | | 50D | 60D | 70D | F | P | $\eta^2$ |
|---|---|---|---|---|---|---|---|
| **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 |

## 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 6). 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 7). 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 8).

**Table 6. Sports performance variables (Mean± SD) during 45C tasks by different footwear conditions.**

| Variables | | 50D | 60D | 70D | F | P | $\eta^2$ |
|---|---|---|---|---|---|---|---|
| **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). **$\eta^2$** represents partial eta squared.

**Table 7. Sports performance variables (Mean± SD) during FCL tasks by different footwear conditions.**

| Variables | | 50D | 60D | 70D | F | P | $\eta^2$ |
|---|---|---|---|---|---|---|---|
| **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). **$\eta^2$** represents partial eta squared.

**Table 8.** **Sports performance variables (Mean± SD) during FCR tasks by different footwear conditions.**

| Variables | | 50D | 60D | 70D | F | P | $\eta^2$ |
|---|---|---|---|---|---|---|---|
| **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). **$\eta^2$** represents partial eta squared.

Figure 5 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.

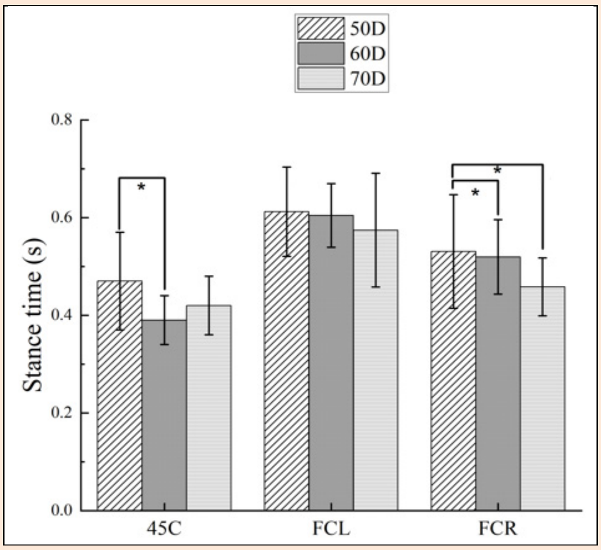


**Figure 5.** **Bar graph showing stance times at 45C, FCL, and FCR.** * = significant difference at p < 0.05.

## 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. 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 6. illustrates a significant difference between the 50D and 70D shoes during the stance phase at 70% - 75%.

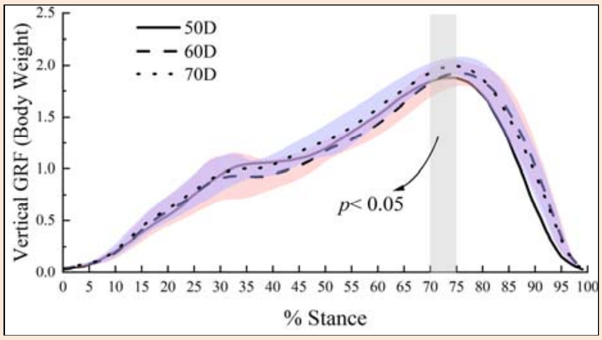


**Figure 6.** **FCR's Vertical ground reaction force of different footwear conditions, with the grey areas indicating significant differences as increasing from 50D to 70D.**

## Discussion

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 et al., 1998). 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 sports performance (Wei et al., 2009). Therefore, increasing torsional stiffness effectively may not only enhance sports performance but also 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, which 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 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., 2005) 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 et al., 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.

While this study provides several valuable insights, there are some limitations need to be elaborated. Firstly, the study design was conducted in a controlled laboratory setting for data consistency, which might not fully reflect the varied, high-intensity conditions of actual competitive badminton games. Badminton's high-intensity and unpredictability, involving rapid changes in speed, direction, and strategy, could elicit certain biomechanical responses that might differ from those observed in our study. While we made an attempt to correlate impact loading profiles with IMU sensors, which may lay foundation for next step with wearables to monitor and predict loading accumulation in complex badminton training and competition scenarios (Yu et al., 2023a). Furthermore, our research did not investigate the long-term effects of wearing shoes with different torsional stiffness levels. Factors such as adaptation over time and the impact on performance and injury rates during prolonged periods were not within the scope of this study. The research was also constrained to lower limb biomechanics and did not account for the comprehensive kinetic chain and the upper body's contributions to badminton movements. Future studies could explore the holistic biomechanical effects across various skill levels, age groups, and competitive settings. Additionally, analyzing the long-term implications of footwear characteristics on performance and injury prevalence could further enrich this field.

Despite these limitations, this study provided valuable insights into the relationship between the torsional stiffness of badminton shoes and lower limb biomechanics. Our findings reported that increasing the torsional stiffness of footwear may enhance the stability of the ankle joint, potentially reducing the risk of certain injuries. However, it should be noted that stiffer torsional stiffness may restrict essential, possibly shifting the stress to other joints.

## Conclusion

In conclusion, we investigated the role of torsional stiffness in badminton shoes on lower limb biomechanics, performance, and injury risks. Our findings revealed noticeable effects on ankle and knee kinematics during various typical badminton movements. An increased torsional stiffness appeared to enhance ankle joint stability, potentially lowering the possibility of ankle issues. Shoes with a medium stiffness (60D) achieved a favorable compromise between flexibility and stability, contributing to maximal overall performance and minimized injury occurrences. In contrast, the stiffest shoes restricted ankle ROM, though assisted in handling impact forces and showed increased vertical ground reaction forces, which might contribute to stronger propulsion and quicker movements. The observations highlighted the potential benefits of intermediate torsional stiffness in maintaining balance between stability and flexibility, which may influence sport performance and reduce injury risk. For more comprehensive information, future research shall consider different athletic capabilities and foot shapes to explore further and longitudinal relationship between shoe properties, biomechanics, and injury risks in badminton.

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## Key points

- This study investigated the dose-response effect of the torsional stiffness in badminton shoes on the biomechanical performance of badminton footwork.
- Shoes with an intermediate torsional stiffness of 60D seemed to demonstrate a favourable compromise, suggesting a balance between flexibility and stability during play.
- There was a noticeable increase in the propulsion force with enhanced torsional stiffness during the forehand clear stroke, hinting at the potential for improved motion performance.

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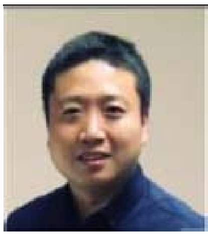

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