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The Effects of Brace Stiffness on Knee Joints During Pull-Up Jump Shot Movements in Amateur Female Basketball Players

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Abstract: (1) Background: The pull-up jump shot is a commonly used scoring technique in basketball. This study aimed to investigate the biomechanical effects of knee brace stiffness on knee joint mechanics during the pull-up jump shot in female basketball players and to evaluate the potential risk of non-contact anterior cruciate ligament (ACL) injuries associated with different stiffness levels. (2) Methods: Sixty-six female basketball players performed pull-up jump shot drills while kinematic and kinetic data were collected using a Vicon motion capture system and a Kistler ground reaction force (GRF) plate. (3) Results: A one-way analysis of variance (ANOVA) revealed that both low-stiffness and high-stiffness knee braces significantly reduced knee flexion angles ($p = 0.001$) but increased indirect contact forces in the sagittal plane ($p < 0.01$). Notable differences were observed between low-stiffness and high-stiffness braces, as well as between braced and unbraced conditions. However, no significant differences were detected between the effects of low-stiffness and high-stiffness braces. (4) Conclusions: Athletes should select knee braces based on the intensity of competition and training, and those with ACL concerns should opt for high-stiffness knee braces for enhanced joint stability.

Keywords: stiffness; pull-up jump shot; pull-off phase; landing cushioning phase

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1. Introduction

Basketball is one of the most widely played sports globally, with over 450 million participants worldwide. As sport evolves, the level of competition has increased, resulting in more intense physical confrontations. Notably, the physical demands and intensity of women's basketball have become increasingly comparable to those of men's basketball [1]. Pivotal sports such as basketball are also considered high-risk activities for ACL injuries [2,3]. This is because the knee joint is subjected to high axial and torsional loads during specific tasks in the sport, such as sudden stops, breakthroughs, shooting, and contact with opponents, which can put a great deal of strain on the knee. This change greatly increases the risk of knee injury [4] and may lead to ligament laxity.

The knee joint is the largest and most complex joint in the human body and is also the most susceptible to injury [5]. Epidemiological surveys show that knee injuries account for 14%–33% of all injuries. Damage to tissues such as the meniscus, ligaments, or hyaline cartilage can lead to irreversible osteoarthritis changes in the joint [6]. The characteristics of basketball require athletes to complete many jumps, sudden stops, and other actions. With advancements in basketball techniques, basic skills alone no longer suffice in competitive play, making the pull-up jump shot a critical core skill. This move, which integrates sprinting and jumping, requires explosive power and is essential for scoring. Executing a pull-up jump shot involves athletes creating space from defenders by abruptly stopping, which demands exceptional lower limb strength and coordination to control the knee and ankle joints and minimize impact forces. However, landing with both feet simultaneously generates higher forces on the knee, further elevating the risk of injury [7]. Previous studies on the biomechanical mechanism of anterior cruciate ligament injury found that a smaller knee flexion angle, a larger proximal tibial anterior shear force, quadriceps contraction force, and ground reaction force will increase the load on the ACL; sagittal lower limb biomechanics is closely related to ACL injury [8].

Although men have a higher overall incidence of knee injuries, women are four times more likely to suffer severe knee injuries requiring surgery [9]. This disparity is primarily attributed to anatomical differences, particularly variations in the Q angle. The Q angle is defined as the angle between the femur and the patella, reflecting the alignment of the force vectors between the thigh and calf. Women generally have a larger Q angle. An increased Q angle alters the force line at the knee joint, potentially placing greater stress on the medial side of the knee. As knee valgus increases, the longer force arm exacerbates the knee valgus angle, further influencing the force distribution in the lower limbs [10]. Additionally, a larger Q angle may affect knee joint stability, particularly during sharp turns or rapid stops in athletic activities. This can make the knee more prone to instability, especially during sudden stops, thereby increasing the risk of anterior cruciate ligament (ACL) injury [11,12]. And knee joint lesions often affect the meniscus and ligaments. If left undiagnosed and untreated, these lesions can progressively worsen over time, ultimately leading to cartilage damage, which has minimal potential for healing. Such damage can significantly impact an athlete's sports career. To prevent this from occurring, wearing knee braces during competitions or training is one of the most effective measures [13].

Given the knee's vulnerability, protective measures such as sports knee braces have gained significant attention. These braces reduce ground reaction forces through their elastic materials while providing support [14,15]. Knee braces are categorized by function: braking, impact-resistant, pressure-relieving, and those enhancing physiological function. Braking knee braces, for example, stabilize the knee joint and limit its range of motion without impairing performance, thereby reducing soft tissue injury risk. Semi-rigid knee braces, a type of braking knee brace, effectively protect the knee joint during high-intensity exercise while allowing some freedom of movement. This type of knee brace offers protection without limiting the overall function of the body [16]. Studies had shown that semi-rigid knee braces can improve the kinetics and kinematics of the knee joint, reduce excess knee movement, and thus reduce the probability of injury[17].

During the push-off and landing cushioning phases of a pull-up stop jump shot, the knee joint was at its maximum flexion angle, and the ACL and medial collateral ligament (MCL) are prone to tearing [17]. In addition, during the half squat landing, if the knee joint is adducted or abducted too much, the meniscus may be damaged [18]. And repeated knee flexion may cause hamstring muscle fatigue and loss of strength [19]. Existing research has mostly focused on the effects of knee braces for male athletes or other sports, and there is a lack of in-depth research on the biomechanical properties of female basketball players and their knee brace needs. Given gender differences and different physiological characteristics, female athletes might have different mechanical responses and support needs when using knee braces. Understanding the stiffness requirements of knee braces for female basketball players is crucial for preventing and mitigating knee injuries. This research could provide valuable insights into the protective effects of knee braces and guide athletes and enthusiasts in selecting braces suited to varying competition intensities.

2. Materials and Methods

2.1. Participants

A total sample of 66 amateur college female basketball players (Table 1) (age 22.4 ± 1.5; body mass: 62.05 ± 9.1 kg; height: 168 ± 5.6 cm) was analyzed by using G * Power 3.1.9.6 (Heinrich Heine University, Düsseldorf, Germany) and criteria of 80% power, an alpha level of 0.05, and an effect size of 0.40 [20,21]. This study intended to recruit amateur college female basketball players with the following conditions: (1) Subjects' dominant leg was their right leg (kicking leg). (2) All subjects were required to have no history of lower limb injuries in the past year. Prior to the experiment, they were informed about the study details and provided with an informed consent form, which they signed after giving their consent. The experiment was approved by the Ethics Committee of the University of Ningbo (RAGH20240920).

Table 1. Basic information of the subjects.

Number	Age/Year	Height/cm	Weight/kg	BMI
66	22.4 ± 1.5	168.8 ± 5.6	62.05 ± 9.1	21.71 ± 2.46

2.2. Procedures

2.2.1. Data Collection Procedures

All experiments were conducted in the Sports Biomechanics Laboratory of the Institute of Grand Health, Ningbo University. Before the experiment, all subjects wore tight basketball shorts, and their height and weight were measured. The subjects were informed of the experimental process. The knee brace was worn in the order of no-stiffness, low-stiffness, and high-stiffness. The stiffness of the knee brace was adjusted using the flat springs built into the design. This brand of knee brace features four detachable springs (Figure 1b). When no stiffness is required, no springs are inserted; for low stiffness, two springs are used; and for high stiffness, all four springs are inserted. The springs were positioned in alignment with the wearing direction of the knee brace and provided support through controlled bending deformation. It was used to collect 38 reflective markers attached to the subject [22].

First, the subjects warmed up for 10 min at their own speed. Then, dynamic stretching was performed. Each subject was fully familiar with the stop-and-go jump shot. When collecting biomechanical data, the subject first stepped the pivot leg onto the force plate, and then the other limb stepped onto the force plate. The pivot leg was the limb on the opposite side of the dominant leg [23]. The subject's push-off height was determined to be 1.15 times the subject's height [24] (Figure 1a). The jumping height was determined by a retractable pole, and the subject needs to jump to the height marked by the bell. The action was considered successful when the subject's central leg fully contacted the force platform and reached the specified jump height. Each subject had to complete five valid trials while wearing a knee brace of different stiffness. To minimize the impact of fatigue on the experimental data, a 5 min rest period was provided between each set of tests.

The action data were recorded using a Vicon 3D motion capture system consisting of 10 infrared cameras (Vicon Metrics Ltd., 10 MX-T20 cameras, Oxford, UK, frequency = 200 Hz). Simultaneously, a Kistler three-dimensional ground force plate (Kistler, Winterthur, Switzerland) was used to collect GRFs in three different directions with a sampling frequency of 1000 Hz [25].

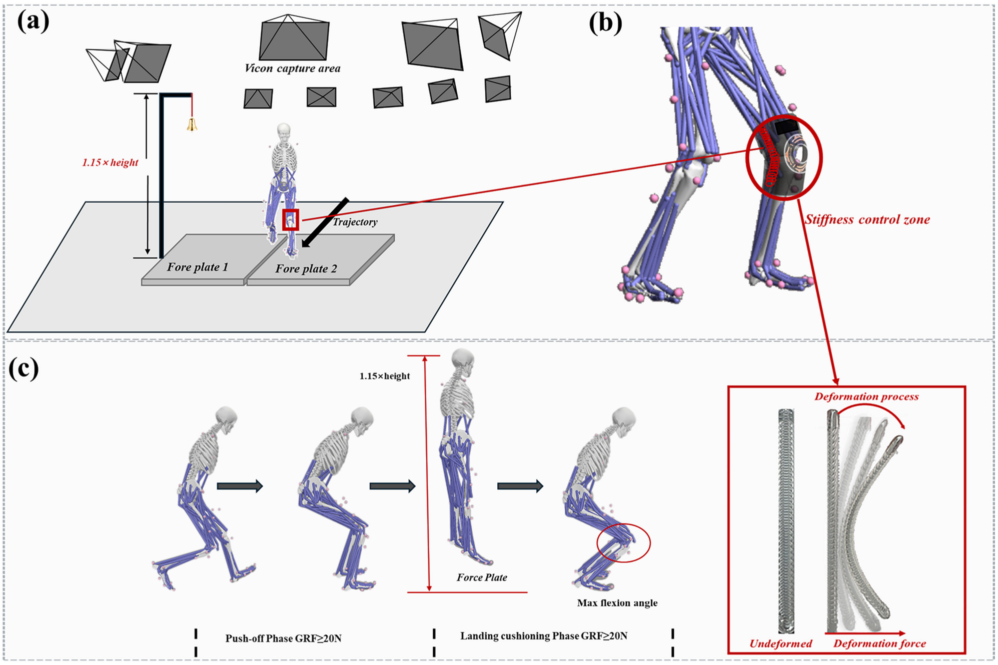

Figure 1. (**a**) Schematic diagram of the experimental setup. The arrows indicate the trajectory of the subjects' movements. A marker pole is positioned next to the force platform to ensure consistent take-off height. (**b**) Knee brace diagram: There are four removable spring devices on both sides for adjusting the stiffness of the knee brace. (**c**) The pull-off phase and landing cushioning phase are distinguished. The first phase began when the GRF was ≥ 20 N and ended when the subjects had fully jumped off the force plate. The second phase began when the subject's foot contacted the force plate upon landing with the GRF ≥ 20 N.

2.2.2. Data Processing Procedures

In the pull-up jump shot movement, the knee joint is prone to reaching its maximum flexion angle during the push-off and landing cushioning phase, increasing the risk of ACL and MCL tears [7]. During semi-squat landings, excessive knee abduction or adduction can lead to meniscus injuries [26]. Therefore, this study divides the stop-jump shot into two phases for analysis (Figure 1c).

The two instances of knee flexion during the movement were identified as critical stages for ACL injury risk [27]. Kinematic and kinetic data captured using Vicon were exported in C3D format, then processed in MATLAB version 2019b (The MathWorks, Natick, MA, USA) by converting to the coordinate system, applying low-pass filtering, extracting data, and formatting it into kinematic and ground reaction force datasets. The C3D files were subsequently converted into TRC and MOT formats using MATLAB and then imported into Open Sim 4.1 for the calculation of biomechanical parameters [25].

The selected indicators include the landing cushioning phase's first peak of VGRF and peak VGRF loading rate (VLR); the knee joint angle corresponding to the IC moment (initial contact, IC, is defined as the moment of ground contact); the maximum knee joint angle and range of motion (ROM) of the knee joint in two phases; knee joint moments in three planes corresponding to the peak VGRF; knee joint work in the sagittal plane; and knee joint contact force. The model was scaled to match the participants' body measurements using the 2392 model. Data filtering was conducted with a fourth-order zero-lag Butterworth filter at cutoff frequencies of 15 Hz and 50 Hz [28]. According to previous studies, the flexion and extension, adduction and abduction, and internal rotation and external rotation of the knee joints were defined as negative (−) and positive (+), respectively. The Open Sim workflow adhered to established protocols. First, marker weights in the model were manually adjusted, and the model was scaled to match the subjects' anthropometric characteristics. This process ensured that the root mean square error between the experimental markers and the virtual markers was less than 0.02 m, with a maximum error not exceeding 0.04 m. Next, inverse kinematics was used to calculate joint angles by minimizing errors between experimental and virtual markers, followed by inverse dynamics to determine joint torques [29,30].In this study, we used a weight static optimization technique to estimate the knee indirect contact force, and joint work was calculated using angular velocity and joint torque [29].

2.2.3. Data Analysis

The data were expressed as mean ± standard deviation (M ± SD). The Kolmogorov–Smirnov (K-S) test was applied to assess whether the kinematic and kinetic data followed a normal distribution. If the data were normally distributed, a one-way analysis of variance (one-way ANOVA) was conducted to test for differences among knee braces with different stiffness levels. The homogeneity of variance was assessed using Levene's test. If the assumption of homogeneity of variances was violated, Tamhane's T2 method was used for post hoc comparisons. If the data did not follow a normal distribution, the Kruskal–Wallis H test was used for nonparametric analysis. Statistical analyses were performed using SPSS 27 (IBM, USA), with the significance level set at $\alpha = 0.05$ [31].

3. Results

3.1. Pull-Off Phase

3.1.1. Kinematics

The kinematic analysis revealed that the knee joint was in a flexed position at the initial contact (IC) moment of the jump shot under all knee brace stiffness conditions. Significant differences in knee flexion angle were observed among the brace conditions ($p = 0.001$). Additionally, the knee adduction angle exhibited significant differences ($p = 0.001$), while no significant differences were found in the knee rotation angle (Table 2). When landing with no-stiffness knee braces, the knee joint experienced the maximum internal rotation angle, while wearing low-stiffness and high-stiffness knee braces results in smaller knee joint internal rotation angles compared to the no-stiffness condition. During the whole push-off phase, no significant differences were observed in the maximum knee flexion angle among knee braces with different stiffness levels. Similarly, there were no significant differences between low-stiffness and high-stiffness knee braces in terms of the maximum knee flexion angle or the maximum internal and external rotation angles. However, significant differences were found in the maximum knee flexion angles ($p < 0.001$), and the ROM of the knee in the sagittal, frontal, and horizontal planes was significantly different ($p = 0.007$, $p = 0.001$, $p = 0.003$) (Table 2).

Table 2. The knee joint's IC moment angle, maximum angle, peak moment in three planes, and sagittal plane.

Variables		No Stiffness	Low Stiffness	High Stiffness	*p*	F
Pop						
IC Angle (°)	flexion	−27.98 (7.11)	−26.65 (3.3) #	−25.58 (4.03) ^	**0.001**	5.452
	adduction	−0.58 (1.31)	0.46 (1.11) #	0.45 (1.67) ^	**0.001**	5.452
	external rotation	−7.14 (0.91)	−5.18 (2.04)	−2.11 (2.20)	0.325	1.165
Max Angle (°)	flexion	−100.17(12.39)	−98.54(12.81) #	−98.83(9.14) ^	0.062	2.499
	adduction	−0.60(3.95)	6.76(0.81) # *	4.39(1.65) ^	**0.001**	4.767

	external rotation	−16.92(5.68)	−12.73(6.09)	−9.78(7.52)	0.955	0.108
ROM (°)	sagittal	100.83(2.84)	107.05(4.83) #	107.27(5.12) ^	**0.007**	6.256
	frontal	20.52(1.30)	13.34(0.75) #	12.96(1.91) ^	**0.001**	8.305
	horizontal	22.24(1.12)	22.16(1.23) *	19.87(1.91) ^	**0.003**	7.601
Moment (Nm/kg)	flexion	−0.62 (1.82)	1.16 (2.51)	−2.68 (3.28)	**0.004**	5.353
	adduction	0.11 (0.32)	0.07 (0.23)	0.04 (0.25)	**0.100**	2.182
	external	−0.25 (0.29)	0.97 (2.77)	0.76 (0.88)	**0.004**	5.993
Lcp						
IC Angle (°)	flexion	−11.12 (1.58)	−15.1 (2.82) #	−14.4 (2.79) ^	**0.001**	2.351
	adduction	6.39 (1.54)	5.18 (1.53) #	5.12 (1.53) ^	**0.006**	5.500
	external rotation	−4.32 (5.48)	−6.17 (3.11) #	−6.25 (2.55) ^	0.176	1.773
Max Angle (°)	flexion angle	−93.43(5.68)	−98.56(8.31) #	−99.74(10.33) ^	**0.001**	10.93
	adduction	6.17(1.32)	6.06(0.84)	5.91(4.01)	0.067	2.886
	internal rotation	19.91(2.25)	17.04(1.53) #	16.11(1.31) ^	**0.001**	13.490
ROM (°)	sagittal	58.50(5.46)	67.12(8.43) #	68.65(10.07) ^	**0.022**	4.439
	frontal	15.41(1.93)	8.49(1.64) #	9.09(0.93) ^	**0.001**	6.004
	horizontal	8.34(3.31)	6.28(2.15)	6.85(2.43)	0.223	1.587
Moment (Nm/kg)	flexion	1.22 (1.86)	−0.15 (0.40)	0.99 (0.62) ^	0.941	0.133
	adduction	1.15 (0.84)	−1.78 (2.85) #	−1.47 (2.59) ^	**0.048**	3.211
	external rotation	0.88 (1.01)	0.14 (1.60) #	0.09 (1.06) ^	**0.001**	7.458

Note: The bold represent significant differences, with $p < 0.05$. "#" represents the interaction effect between no and low. "^" represents the interaction effect between no and high. "*" represents the interaction effect between low and high.

3.1.2. Kinetics

The results for the kinetics in our study indicated that significant differences in knee flexion moments were observed under peak ground reaction force conditions with different stiffness knee braces ($p = 0.004$) (Table 3). No significant differences were found in the adduction moments or rotation moments.

Table 3. Knee joint work in the sagittal plan in two phases.

Variables		**No Stiffness**	**Low Stiffness**	**High Stiffness**	***p***	**F**
Pop						
Work (J)	Joint positive work	5.57 (2.3)	1.42 (0.72) #	1.23 (0.55) ^	**<0.01**	5.708
	Joint negative work	−8.75 (3.12)	−4.77 (4.31) # *	−4.11 (3.63) ^	**<0.01**	12.082
Lcp						
Work (J)	Joint positive work	1.25 (1.48)	0.70 (0.49)	0.40 (0.23) ^	**0.012**	4.709
	Joint negative work	−2.94 (2.13)	−1.81 (0.61) #	−1.63 (0.35) ^	0.591	0.530

Note: The bold represent significant differences, with $p < 0.05$. "#" represents the interaction effect between no and low. "^" represents the interaction effect between no and high. "*" represents the interaction effect between low and high.

Since knee flexion is the predominant motion throughout the entire movement, this study focused on analyzing the work performed by the knee joint during flexion. The results indicate significant differences in knee flexion work when wearing knee braces of different stiffness levels. The highest negative work was observed with the high-stiffness knee brace. No significant differences were found in the positive work between the low-stiffness and high-stiffness knee braces (Table 3). The no-stiffness knee brace resulted in the greatest positive work. Furthermore, significant differences in knee joint contact forces were observed between the no-stiffness knee brace and both the low-stiffness knee brace ($p < 0.001$) and the high-stiffness knee brace ($p = 0.005$), but no significant difference was found between the low-stiffness and high-stiffness knee braces (Table 3).

3.2. Landing Cushioning Phase

3.2.1. Kinematics

During the landing cushioning phase, significant differences were observed in the knee flexion angles at the IC moment when wearing knee braces of different stiffness levels ($p < 0.001$), as well as in the adduction angles ($p < 0.005$). However, no significant differences were found in the knee rotation angles (Figure 2). And there were no significant differences observed in knee flexion range of motion between the knee braces of different stiffness levels. However, significant differences were found in the sagittal and frontal planes of ROM ($p = 0.022$, $p = 0.001$), and no significant difference was found in the horizontal plane ($p = 0.223$) (Table 2).

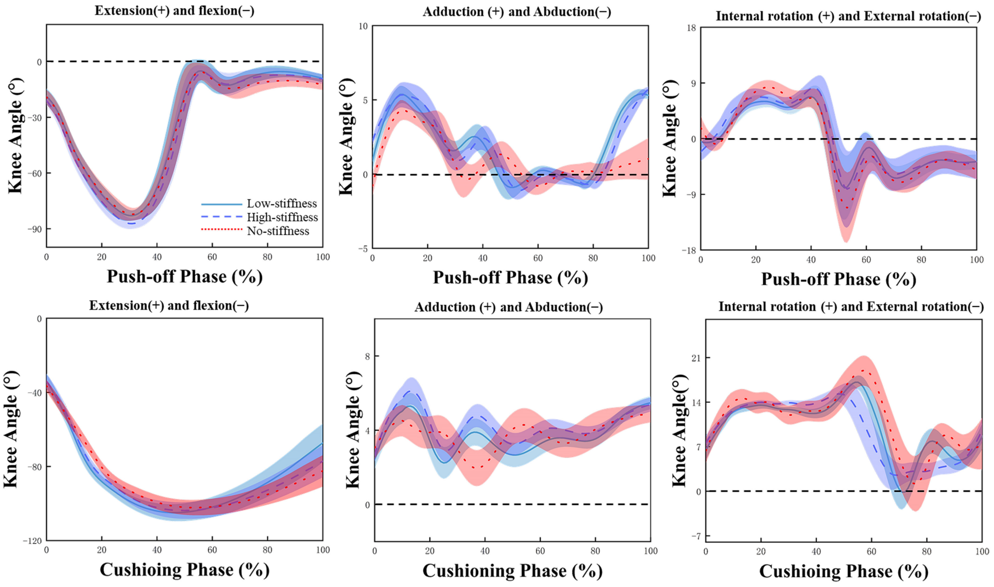

Figure 2. The knee joint angle in the sagittal, frontal, and horizontal planes during the pull-off phase and landing cushioning phase. The black dashed line represents a value of 0.

3.2.2. Kinetics

At the peak of VGRF, significant differences were observed in the VGRF across knee braces with different stiffness levels ($p = 0.004$) (Figure 3). Furthermore, significant differences were found in the knee flexion moment ($p = 0.048$), adduction moment ($p = 0.001$), and external rotation moment ($p = 0.001$) at the peak of the ground reaction force (GRF) (Figure 4). Significant differences were observed in the peak loading rate of the GRF across knee braces with different stiffness levels ($p = 0.006$). When comparing the negative work performed by the knee joint under different stiffness conditions, significant differences were found between the no-stiffness knee brace and both the low-stiffness and high-stiffness knee braces. However, no significant difference was observed between the low-stiffness and high-stiffness knee braces. For positive work, significant differences were found between the no-stiffness and high-stiffness knee braces (p = 0.004) (Table 3). The analysis revealed that the knee joint contact force was significantly higher under the no-stiffness knee brace condition compared to both the low-stiffness and high-stiffness knee braces. No significant differences in knee joint contact force were found between the low-stiffness and high-stiffness knee braces (Table 4).

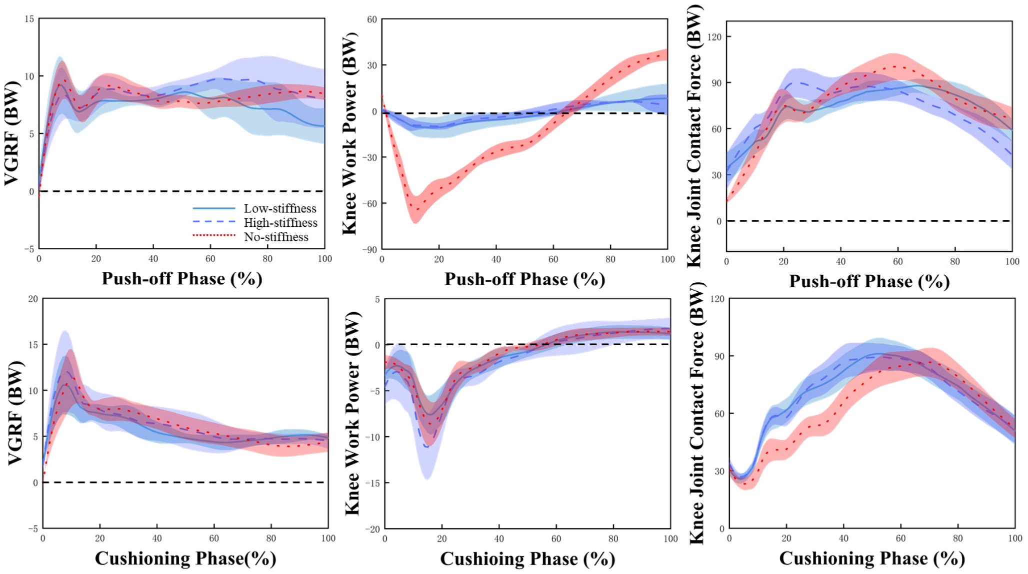

Figure 3. VGRF in two phases. And knee sagittal contact force and knee joint work power in the sagittal plane. The black dashed line represents a value of 0.

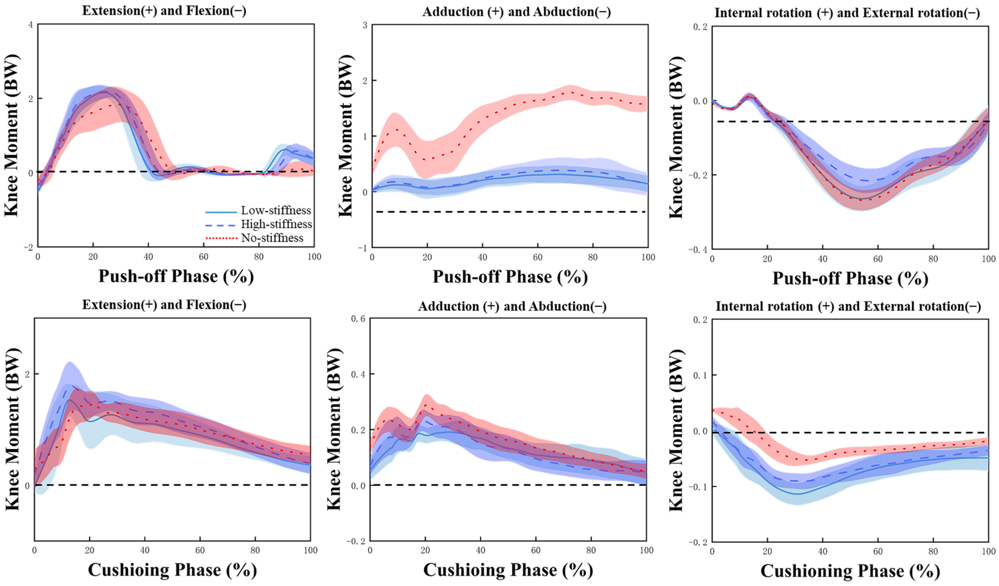

Figure 4. The knee joint moment in the sagittal, frontal, and transverse planes during the pull-off phase and landing cushioning phase. The black dashed line represents a value of 0.

Table 4. Knee joint contact force in two phases and VGRF and VLR in Lcp.

Variables(N)	No Stiffness	Low Stiffness	High Stiffness	*p*	F
Pop					
Knee joint contact force (BW)	1.89 (0.61)	2.78 (0.36) #	2.53 (0.54) ^	**0.001**	6.180
Lcp					
VGRF (BW)	2.15(0.73)	2.08(0.79)	1.95(0.63)	**0.004**	5.892
VLR (BW)	0.74(0.43)	0.71(0.37)	0.58(0.43)	**0.006**	6.293
Knee joint contact force (BW)	9.16 (1.36)	11.21 (2.27) #	11.93 (2.09) ^	**<0.01**	11.408

Note: The bold represent significant differences, with $p < 0.05$. "#" represents the interaction effect between no and low. "^" represents the interaction effect between no and high.

4. Discussion

This study examined the knee joint biomechanics of female basketball players during the push-off and landing cushioning phases of a pull-up jump shot while wearing knee braces with varying stiffness levels. The results revealed significant differences in knee joint flexion and adduction angles, range of motion in the sagittal and coronal planes, knee adduction moment, positive work, and joint contact force between conditions with and without high-stiffness knee braces.

As hypothesized, the knee flexion angle was inversely related to knee brace stiffness, though significant differences were only observed in the range of motion in the horizontal plane between the low- and high-stiffness braces. Previous studies had shown that a larger knee flexion angle at the IC moment increased the risk of soft tissue injuries, including ACL injuries, meniscal tears, MCL injuries, and chronic knee osteoarthritis [32]. Smaller flexion angles, on the other hand, can reduce the load on the ACL. A study that simulated the pull-up jump shot motion also indicated that female athletes exhibit a larger knee joint flexion angle upon landing compared to male athletes [33]. According to Nunley's research, when the knee flexion angle of females increased from 22.3° to 27.6°, the angle between the patellar tendon and the tibia decreased from an average of 19° to 17.4°, which significantly reduced the load on the ACL [34]. Additionally, during the push-off and landing cushioning phases, knee extensors must generate greater positive work to increase jump height. Joint work reflects the timing, magnitude, and energy transfer by muscles, ligaments, and other tissues [35]. This work mainly depends on muscle fibers' contractile power during rapid contractions. Our study found that knee joint work across both phases of the pull-up jump shot followed a consistent pattern. At a given jump height, greater positive joint work indicated higher demands for kinetic energy and speed. Notably, knee joints with high-stiffness knee braces exhibited lower flexion moments and positive work, suggesting that high-stiffness braces may reduce the muscle force required by the knee joint during takeoff after landing, potentially lowering injury risks [36].

Our study revealed that compared to no-stiffness and low-stiffness knee braces, wearing high-stiffness knee braces significantly reduced the abduction angle of the knee joint. Consequently, knee braces can help prevent patellofemoral pain syndrome, with high-stiffness braces being more effective than low-stiffness ones. Furthermore, high-stiffness knee braces enhance frontal plane stability of the knee joint, reduce the pressure on the medial meniscus and medial cartilage, and lower the risk of injury. It had been shown that for every 1° increase in knee abduction angle, the knee joint load increased by 1.7 Nm [34]. Previous studies had demonstrated a correlation between reduced knee abduction and alleviated osteoarthritis pain [37], while excessive tibial external rotation may lead to degeneration of the knee's soft tissues, contributing to chronic knee osteoarthritis. This suggested that wearing knee braces may help prevent osteoarthritis and alleviate knee pain [38].

The elastic constraint provided by low-stiffness knee braces is weaker than that of high-stiffness braces, resulting in a less effective reduction in knee valgus angles. However, it should be noted that while high-stiffness knee braces effectively decrease valgus angles and reduce valgus loading, they may compromise the knee joint's ability to dissipate and absorb ground reaction forces. This limitation could lead to the transmission of impact forces to more proximal segments of the body.

During the push-off and landing cushioning phases, the ROM of the knee angle in the sagittal plane was positively correlated with knee brace stiffness. Higher stiffness levels in the knee braces resulted in greater knee joint ROM throughout these phases. In landing scenarios, the increased knee flexion ROM is often attributed to the enhanced sense of stability provided by the knee braces. This added sense of security can reduce athletes' fear of movement and may lower the pre-activation and protective response of the quadriceps. As a result, the biceps femoris and other knee flexors become more dominant, leading to an increased knee flexion ROM [39,40]. Alternatively, the knee brace might alter the proprioception of the knee joint by compressing the proprioceptors around the knee, thereby modifying the knee joint's proprioceptive feedback [41,42], this, in turn, might lead the knee joint to adopt a safer landing strategy. Liu's study had shown that a greater knee flexion angle allows for a longer landing buffer time, facilitating the absorption of GRF [43].

Our study also identified significant differences in VGRF during the landing cushioning phase across different knee brace stiffness levels. As the stiffness of the knee brace increased, the peak VGRF decreased, which is also related to ACL injury. Some studies had shown that during the landing phase, the peak VGRF is positively correlated with the peak forward GRF, and the peak forward GRF was further positively correlated with the anterior shear force applied to the tibia [44]. Therefore, peak VGRF was considered a key indicator of ACL load. While some studies had suggested that wearing knee braces did not significantly alter the magnitude of peak VGRF during impact activities, others had reported changes in peak VGRF, possibly due to variations in the types of knee braces used. Upon ground contact, the GRF exerts pressure on the body, with the loading rate reflecting the speed at which the body absorbs these forces [45].

Compared to no stiffness, both low-stiffness and high-stiffness knee braces resulted in lower loading rates, with the high-stiffness knee brace exhibiting the smallest loading rate. External loads played a crucial role in determining the load experienced by the ACL [46]. A higher loading rate indicated that the body absorbs more GRF in a shorter period, which can impose excessive strain on the joint and increase the risk of injury, particularly during the landing cushioning phase of a pull-up jump shot. Wearing high-stiffness knee braces can effectively absorb and dissipate these impact forces, thereby reducing the risk of knee injuries. Cerulli's study had found that during the landing cushioning phase, the ACL experiences the highest stress [47]. This result is consistent with the trend observed in our study.

This study indicated that during both phases, significant differences were observed in the knee flexion moment at peak VGRF when wearing knee braces of different stiffness levels. As shown in the results, when a no-stiffness knee brace was worn, the knee flexion moment was greater than that with low-stiffness and high-stiffness braces. This could be attributed to the GRF, which caused the quadriceps to generate a larger knee extension moment to counteract the GRF and maintain dynamic stability of the knee joint. In Lee's [7] study, subjects who wore hinged knee braces during depth jumps showed an 18% reduction in peak anterior–posterior force on the knee joint. Therefore, wearing high-stiffness knee braces helps reduce the load on the ACL. During the landing phase of the stop-and-jump shot, there was a significant correlation between the anterior shear force at the proximal tibia, peak knee flexion moment, and VGRF; female athletes exhibited a trend of synchronized increases in peak tibial anterior shear force and peak knee flexion moment [48].

The difference between low-stiffness and high-stiffness braces lies mainly in the mechanical properties. There was no obvious change in the internal and external rotation angles of the knee joint at the IC moment, which might be because the knee joint plays a horizontal fixation role when wearing protective gear of different stiffness. Previous studies on basketball-specific movements had pointed out that in the pull-up stop jump shot, the athlete's front foot often lands in an "external rotation" posture; that is, the knee joint is abducted. Both low-stiffness and high-stiffness knee braces effectively mitigate excessive knee joint abduction, prevent misalignment of the femoral-tibial force vector, and reduce ACL load. This study found that both types of braces decreased the maximum knee flexion angle compared to conditions without a knee brace, aligning with findings from previous research [49]. Therefore, wearing knee braces with a certain level of stiffness can help prevent patellofemoral pain. This suggested that high-stiffness knee braces can enhance knee joint stability in the coronal plane, reduce the pressure on the medial meniscus and medial cartilage, and lower the risk of injury [50]. In Hewett's study it was shown that during vertical jumping movements, the external rotation moment at the knee also increases the risk of ACL injuries [51]. Wearing both low-stiffness and high-stiffness knee braces effectively enhances knee stability during the landing phase, helping to prevent injuries associated with excessive knee abduction. However, the differences between low-stiffness and high-stiffness braces are minimal, as both types significantly reduce the knee abduction angle during the two phases. This finding suggested that high-stiffness knee braces can improve frontal plane stability of the knee joint, reduce pressure on the medial meniscus and medial cartilage, and thereby lower the risk of injury [34]. Previous studies had indicated that the reduction in knee abduction is associated with a decrease in the severity of knee osteoarthritis pain [52]. This meant that high-stiffness knee braces can prevent knee osteoarthritis and alleviate pain, making them suitable for athletes with existing knee injuries in high-intensity basketball games.

The hypothesis of this study proposed that wearing high-stiffness knee braces could reduce the indirect contact forces on the knee joint; however, the experimental results were contrary to this assumption. This may be because knee braces with stiffness levels (both low and high) somewhat restrict the natural ROM of the knee joint. Such restriction could lead to alterations in movement patterns, thereby increasing the contact force within the joint. When the knee joint is restricted by a stiff brace, the range of motion is reduced, concentrating forces in a specific area and resulting in higher local contact forces. This finding is consistent with previous research [53]. Further studies are needed to balance the support effects of knee braces with their interference in the joint's natural motion to avoid potential joint overload caused by the brace. This issue remains an area worth deeper exploration in future research.

Several limitations of the current study should be acknowledged. First, this experimental study was conducted in a laboratory setting, which may not fully replicate the pull-up jump shot movements and intensity of the athletes in real game scenarios. Future research should aim to explore real game environments and investigate the effects of knee braces with different stiffness levels on lower limb biomechanics using more diverse methodologies. And as a tool to protect the knee joint, there is also a certain uncertainty in the frequency of wearing knee braces. Whether long-term wearing of knee braces is more helpful for the knee joint requires more detailed long-term studies. Additionally, the use of instruments such as infrared reflective marker balls placed on the subjects may have influenced their performance during exercise. Future studies could monitor athletes during actual games using wearable devices to more accurately investigate the knee joint injury mechanisms in female basketball players. And the subjects of this experimental study were amateur female basketball players, which is a limitation for most female basketball players. In future studies, we will continue to explore the impact of different stiffness knee braces on the biomechanics of the knee joints of female professional basketball players. Lastly, finite element analysis has been extensively used in sports biomechanics to simulate the impact of equipment on human tissues [54–56]. We will also integrate this approach to study the biomechanical effects of knee braces with varying stiffness on the internal mechanical states of knee joints, elucidating their protective mechanisms.

5. Conclusions

This study delved into the biomechanical effects and changes in the knee joint of female basketball players wearing knee braces with different stiffness levels during the stop-jump shooting movement. Most of the indicators suggest that both low-stiffness and high-stiffness knee braces are effective in reducing the risk of knee injuries during both the takeoff and landing phases. However, the differences between the low-stiffness and high-stiffness knee braces are minimal. Both low-stiffness and high-stiffness knee braces can, to some extent, limit knee flexion, thereby enhancing knee stability. Therefore, in basketball games, wearing either a high-stiffness or low-stiffness knee brace can provide some degree of protection to the knee joint, with the choice depending on the intensity of the game. If an athlete has a history of knee injury, it is recommended to wear a high-stiffness knee brace during competition to prevent further damage. However, wearing a brace with stiffness may lead to increased indirect contact forces on the knee joint, which requires further research to balance these potential trade-offs in future studies.

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Data Availability Statement: The data that support the findings of this study are available on reasonable request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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