

Article

Biomechanical Analysis on Skilled Badminton Players during Take-Off Phase in Forehand Overhead Strokes: A Pilot Study

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Simple Summary: Different movement speeds can contribute to different joint loading in sports. Joint contact force is the actual force acting on the articular surface, which could predict performance and injury, but is rarely reported for badminton overhead strokes. From the perspective of sports biomechanics, this paper analyzes the characteristics of kinematics and mechanics at each stage of the fast and moderately paced movements and studies the changes in the force of the lower extremity joints caused by the characteristics of the movements at different speeds so that athletes and enthusiasts can clarify the essentials of the movements and prevent sports injuries.

Abstract: Different movement speeds can contribute to different joint loading in sports. Joint contact force is the actual force acting on the articular surface, which could predict performance and injury, but is rarely reported for badminton overhead strokes. Through an approach using musculoskeletal modelling, six male elite badminton players performed forehand overhead strokes at different movement speeds (fast (100%) vs. moderate (90%)). The synchronized kinematics and ground reaction force (GRF) data were measured using a motion capturing system and a force platform. All kinematics and GRF information were input into the AnyBody musculoskeletal modelling to determine the three-dimensional hip, knee and ankle contact forces. Paired *t*-tests were performed to assess the significant differences among the GRF, joint kinematics and contact force variables between the movement speed conditions. The results showed that when compared with the moderate movement condition, participants performing faster stroke movements induced larger first and second vertical peaks and larger first horizontal peak but lower second horizontal peak, and it also led to higher peak ankle lateral and distal contact forces, knee lateral and distal contact forces, and hip distal contact forces. Additionally, fast movements corresponded with distinct joint angles and velocities at the instant of initial contact, peak and take-off among the hip, knee and ankle joints compared with moderate movement speeds. The current results suggest that changes in joint kinematics and loading could contribute to changes in movement speeds. However, the relationship between lower limb joint kinematics and contact forces during overhead stroke is unclear and requires further investigation.

Keywords: inverse dynamical analysis; lower limbs; propulsion; movement speeds



Citation: Cui, X.; Lam, W.K.; Gao, Q.; Wang, X.; Zhao, T. Biomechanical Analysis on Skilled Badminton Players during Take-Off Phase in Forehand Overhead Strokes: A Pilot Study. *Biology* **2022**, *11*, 1401. <https://doi.org/10.3390/biology11101401>

Academic Editor: Anne Deleextrat

Received: 28 July 2022

Accepted: 16 September 2022

Published: 26 September 2022

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1. Introduction

Badminton is one of the most popular sports in the world, and there are over 200 million participants playing at recreational and elite levels [1]. To attain performance proficiency, the players require a high level of technical skills, equipment, tactics and rapid footwork, including lunging, braking, turning, jumping and landing during game plays [2,3]. Efficient footwork allows participants to reach a shuttlecock at the best position quickly and to maintain good body balance for upper limb racket performance [4–8].

Previous studies have investigated the upper limb mechanics in various badminton-specific tasks [9–11]. Barnamehei et al. [11] identified significant differences in upper limb muscular activation and movement coordination between elite and less skilled players during badminton forehand smashes. Zhang et al. [9] found that trunk rotation would contribute higher shuttlecock release speed in a badminton forehand smash. Taha et al. [10] developed a virtual reality training system using Kinect Technology and inertial measurement unit (IMU) for players to learn upper limb mechanics (wrist, elbow and shoulder joint) of the smashing movement and showed improvements in the athletic performances. Koike and Hashiguchi [12] found that an increased racket head speed was related to increased joint torques and shaft-restoring torque of the racket arm during a badminton smash. However, while these studies have predominantly focused on performance and racket mechanics, little attention has been paid to the lower limb mechanics, which are also related to performance and injury.

In badminton, the demanding footwork and movement (e.g., lunging) could induce excessive and repetitive loading [6,7], which is associated with increased risk of joint injuries, stress fractures and micro-damage of cartilage [8]. During the London Summer Olympic Games 2012, about 11% and 7% of the athletes were reported as being injured and experiencing discomfort/illness, respectively [13]. Most of the injuries occurred in the lower extremities, especially the knee joint [14–18]. Forehand overhead stroke is one of the most frequently executed movements in badminton plays and often causes anterior cruciate ligament (ACL) and ankle injuries [19,20]. Therefore, an analysis of lower limb loading is necessary to understand the underlying mechanism of injuries in badminton. To date, previous studies have predominantly investigated the lower limb mechanics in forward lunge landing [4,6,7,21–23], but an investigation of overhead movement tasks is lacking. The knee joint kinematic and valgus moment of badminton players during the landing from overhead stroke [24] and high clear stroke [25] has also been reported. However, these studies did not report on the joint contact forces during the landing or stepping (push-off) phases. Joint moment is the extrinsic force that could be counteracted by intrinsic forces such as muscle forces, and therefore, it is not necessarily equivalent to the actual mechanical burdens on the articular joint interfaces [26]. Joint contact force is the actual force applied on the articular surface that combines the net joint reaction forces and forces generated by the muscles crossing the joint [27]. While Kimura et al. focused only on the landing phase after an overhead stroke, the take-off biomechanics remain unclear. The joint contact forces and/or take-off biomechanics (stepping step) can allow for better prediction on performance and injuries in various movement tasks [22,28,29].

The development of computational simulation platforms in engineering [30–34] allows for the joint contact force to be determined using musculoskeletal human modelling [35]. The modelling has been used to calculate the muscle forces and contraction velocity as well as joint contact forces for volleyball strokes [31], soccer instep passing [32] and badminton lunges [22,36]. Furthermore, it is still questionable how joint contact forces would change in maximum and moderate movement speed conditions. Hence, the objective of this study was to examine lower limb joint contact forces in forehand overhead strokes in maximum and moderate movement speeds. The results of this study can play an important role in injury prevention and performance in badminton overhead strokes.

2. Materials and Methods

2.1. Participants

According to the sample size calculation by Gpower 3.1 software (Informer Technologies, Inc., Los Angeles, CA, USA), six right-handed skilled badminton players (mean age = 25.0 ± 0.9 years, body height = 176.2 ± 1.2 m, body mass = 66.0 ± 3.2 kg) were recruited for this study. They were competitive club-level badminton players with regular training of at least ten years (ranged from 10 to 13 years). The participants were all national first-level badminton players for China. All of them were right-handed players and had no any injuries on their lower limbs, trunk and upper limbs for the past six months. To

prevent fatigue, they were instructed not to engage in strenuous exercise within 24 h before the test. This study was received and granted by the ethical review board of Shenyang Sport University. All participants signed an informed consent form before testing.

2.2. Experimental Procedure

Participants performed all forehand overhead strokes (maximum and moderate speeds) at a biomechanical laboratory that was equipped with a synchronized motion capturing system (Codamotion, Charnwood Dynamics Ltd., Rothley, UK, sampling at 200 Hz) and a force plate (AMTI, Watertown, MA, USA, sampling at 1000 Hz) for the collection of lower limb kinematic and kinetics data. Participants wore the same badminton shoes (Victor SH-P7800, Victor Rackets Corp, Taiwan, China) to avoid potential bias due to footwear worn [37–39]. There were 18 Coda active markers attached firmly to the following anatomical landmarks: left and right sides of the first and fifth metatarsophalangeal joint, heel, lateral malleolus, lateral aspect of the shank and thigh segments, lateral epicondyle of the knee, as well as anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS).

The footwork and overhead stroke movements were demonstrated by the same badminton coach to all participants (Figure 1). Prior to data acquisition, in order to make sure that the participants were familiarized with the experimental process and the deviation in the ground feeling during the actual test, three familiarization trials were conducted for each participant to become familiar with the experimental process before the data acquisition. The participants were given time for warm-up and familiarization with the movement and speed requirement. Upon the auditory signal, the participants were asked to perform one step to the back from the starting position and to land on their right foot on the force plate, followed by an immediate vertical jump for an overhead stroke with a racket at their maximum (fast) and submaximal (moderate) speeds. The participants returned to the starting position immediately after landing [24]. A shuttlecock was suspended 2.8 m (hanging height depended on the player's body height) above the ground to simulate the average hitting point of the stroke [40–43]. A successful trial was defined as the right foot (stepping step) on the middle of the force platform and natural movement for the forehand overhead strokes with a racket in their right hand at the maximum (fast) and submaximal (moderate) movement speeds. Fast movement was defined as the fastest speed to complete the stroke movement with their maximum effort. Moderate movement was defined as 90% of the fast condition. The average fast and moderate movement speeds were $3.51 \text{ m/s} \pm 0.5 \text{ m/s}$ and $3.17 \text{ m/s} \pm 0.8 \text{ m/s}$, respectively. The order of movement speed conditions presented were counterbalanced across all participants. Each participant performed three successful trials for each of the two movement speeds, resulting in a total of six trials for each participant. Both placing the markers and sounding the auditory signals were carried out by the same experimenters.

Spline interpolation was performed for minor missing data points in the Coda Motion (Codamotion cx1, Charnwood Dynamics Ltd., Rothley, UK) analysis kits. Only the take-off/stepping step (right leg) was analyzed in this study. The stance phase was defined as the period from touchdown to take-off (Figure 1). The instants of touchdown and take-off were determined when the vertical GRF first exceeded 10 N and reduced to 10 N, respectively. Kinematic data were filtered through a low-pass Butterworth filter with a cut-off frequency of 10 Hz as it is the standard procedure applied in the AnyBody Modelling System (AMMR5.0, AnyBody Technology A/S, Aalborg, Denmark). All kinematic and kinetic data were input into the musculoskeletal modelling (AnyBody Technology A/S, Aalborg, Denmark) for further processing. We used the AnyBody built-in generic model with seven rigid-body segments; six degrees of freedom; and a total of 159 musculotendinous units, which were scaled to the mass and anthropometries of each participant [22]. Inverse kinematics was used to determine the time-series joint angles that aligned with the stepping step of the overhead stroke movements. Dynamic inconsistency found in the Residual Reduction Algorithm was reduced by small adjustments to the model mass

properties. The hip and ankle joints were modelled as spherical joints, while the knee joint was modelled as a hinged joint to predict the lower-limb joint contact forces. A positive value denoted dorsiflexion (knee/hip extension), pronation (valgus) and internal rotation for the respective joints.



Figure 1. The sequence for the take-off step during a forehand overhead stroke: (A) right foot initially making contact with the ground, (B) peak GRF in the braking phase and (C) instant of take-off.

The analyzed variables were joint angles and angular velocities during the take-off step (at initial contact, peak value and take-off); GRF; and peak sagittal, coronal and transverse hip, knee and ankle contact forces. These variables were selected as they are linked to badminton injuries and performances [4,6,7,21–25,36].

2.3. Statistical Analysis

All statistical analyses were performed in the SPSS software package (SPSS version 16.0, IBM, Armonk, NY, USA). Paired *t*-tests were performed to determine if there were any significant differences between fast and moderate speeds on the test variables (i.e., peak angles, angular velocities, GRF and joint contact forces). Statistical significance was set at $p = 0.05$. Cohen's effect method (Cohen's *d*) was used to calculate effect size. The value < 0.2 indicates a small effect size, close to 0.5 indicates a moderate effect size, and > 0.8 indicates a large effect size.

3. Results

3.1. Joint Kinematics and GRF Variables

Figure 2 shows the hip, knee and ankle joint angles across time in both the fast and moderate movement conditions. The paired *t*-tests (Table 1, Figure 2) indicated that the fast movement condition had a significantly larger ankle dorsiflexion for all events (i.e., at initial contact, min, peak and take-off, $p < 0.05$; $d > 0.8$) but smaller peak pronation ($p = 0.001$; $d > 0.8$) and pronation at take-off ($p = 0.020$; $d > 0.8$) than the moderate movement condition. In addition, the fast movement condition demonstrated smaller peak and initial knee extension angles ($p < 0.001$; $d > 0.8$) and smaller hip peak extension ($p = 0.007$; $d > 0.8$)

and extension at take-off ($p < 0.001$; $d > 0.8$) than the moderate movement condition (Table 1, Figure 2).

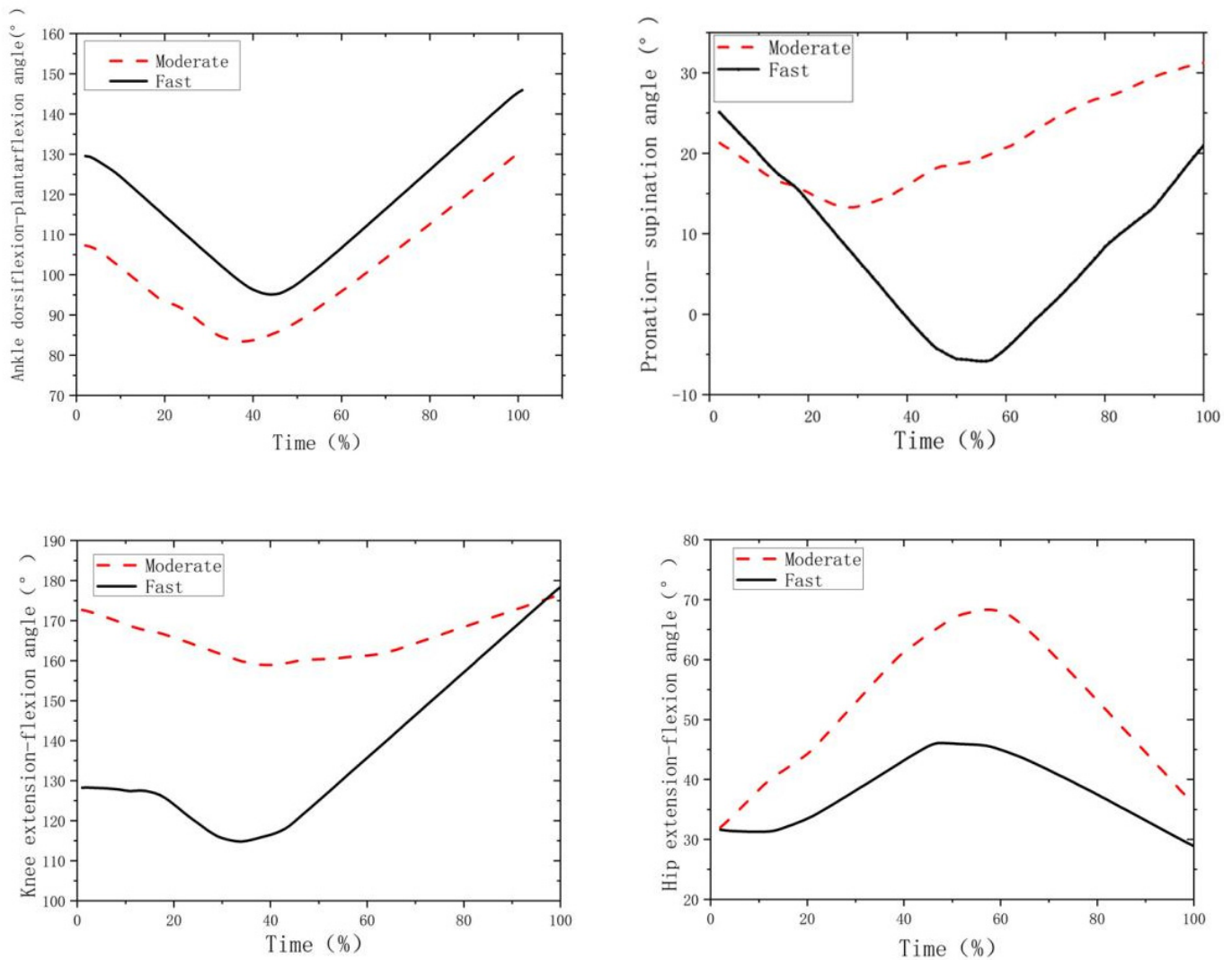


Figure 2. The curves of hip, knee and ankle joint angles across time.

Table 1. The hip, knee and ankle joint angles (°) in each event.

Variable	Event	Fast	Moderate	Cohen's d
Ankle dorsiflexion-plantarflexion angle	Initial contact	128.26 ± 5.38 **	107.30 ± 2.83	4.87
	Min	94.30 ± 1.77 **	81.61 ± 3.77	4.30
	Take-off	145.95 ± 4.45 **	131.15 ± 6.26	2.72
Pronation-supination angle	Initial contact	25.11 ± 6.15	21.32 ± 5.30	0.66
	Min	-5.86 ± 3.39 **	13.29 ± 2.54	6.39
	Take-off	21.62 ± 4.21 *	31.39 ± 4.62	2.21
Knee extension-flexion angle	Initial contact	128.26 ± 5.38 **	172.70 ± 4.65	8.83
	Min	114.78 ± 11.21 **	159.13 ± 9.14	4.33
	Take-off	178.37 ± 1.24	176.6 ± 1.05	1.54
Hip extension-flexion angle	Initial contact	31.61 ± 5.05	32.00 ± 3.52	0.08
	Peak	46.09 ± 6.38 **	68.32 ± 3.21	4.40
	Take-off	28.5 ± 6.76 **	34.89 ± 3.22	1.20

Dorsiflexion (+)/plantarflexion (-); pronation (+)/supination (-); extension (+)/flexion (-). * represents significant difference with $p \leq 0.05$; ** represents significant difference with $p \leq 0.01$.

Figure 3 shows the hip, knee and ankle angular velocities during the fast and moderate movements. Compared to moderate movement (Table 2, Figure 3), the fast movement led to a higher knee extension but smaller hip extension velocities at initial contact ($p < 0.001$; $d > 0.8$), higher peak knee extension velocity ($p < 0.001$; $d > 0.8$), as well as higher knee flexion ($p < 0.001$; $d > 0.8$) and ankle plantarflexion at take-off ($p = 0.033$; $d > 0.8$).

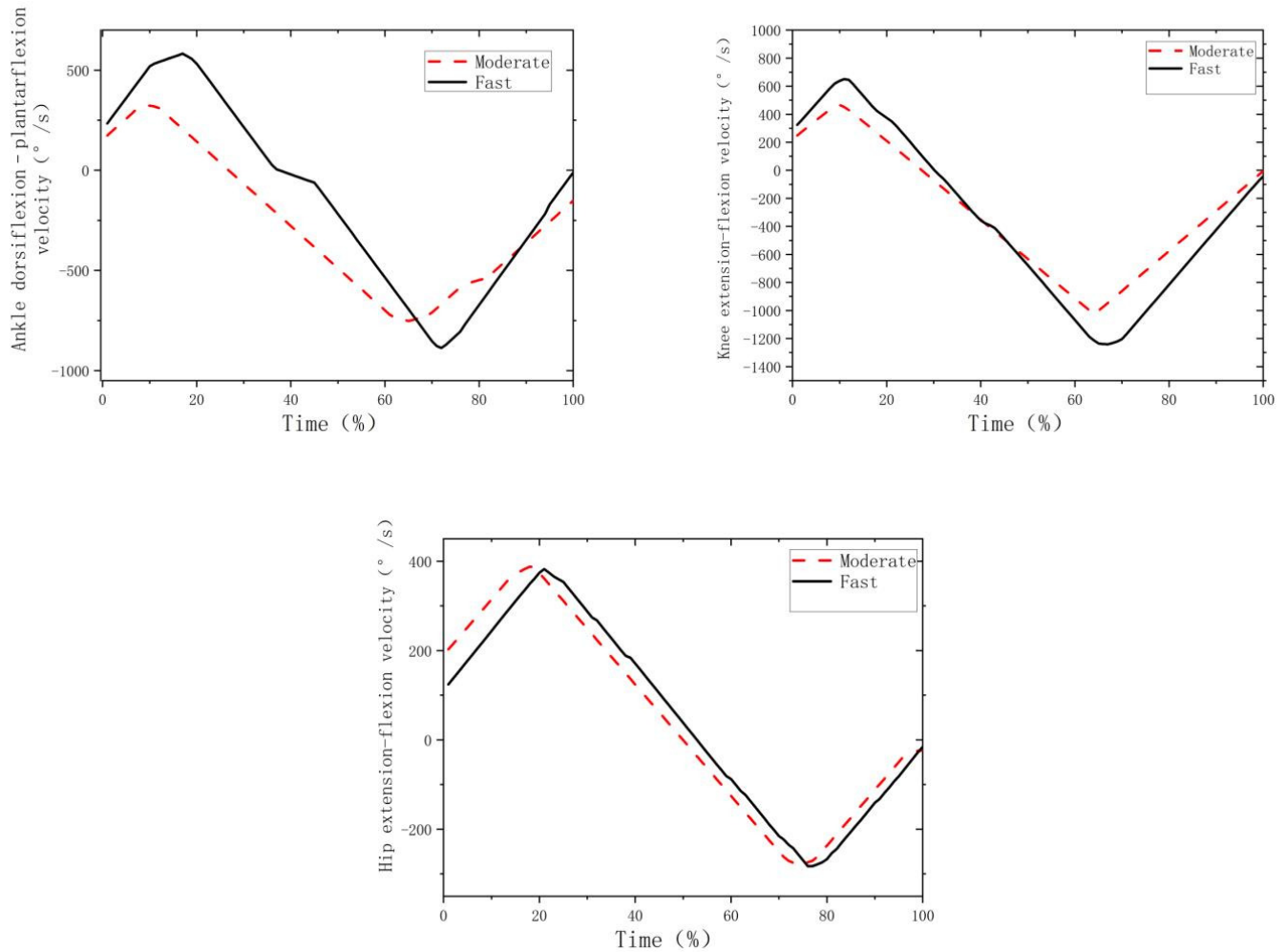


Figure 3. The curves of hip, knee and ankle angular velocities across time.

Table 2. The hip, knee and ankle angular velocities (°/s) in each event.

Variable	Event	Fast	Moderate	Cohen's <i>d</i>
		Mean	Mean	
Ankle dorsiflexion–plantarflexion velocity	Initial contact	233.80 ± 40.74	173.59 ± 52.57	1.28
	Peak	582.02 ± 177.225 **	323.24 ± 6.19	2.06
	Min	−886.967 ± 104.937 *	−752.22 ± 45.375	1.66
Knee extension–flexion velocity	Initial contact	324.09 ± 44.23 *	248.16 ± 23.38	2.14
	Peak	651.08 ± 89.71 **	465.78 ± 19.85	2.85
	Min	−1240.31 ± 75.98 **	−1016.00 ± 49.58	3.49
Hip extension–flexion velocity	Initial contact	123.93 ± 24.28 **	202.36 ± 27.06	3.05
	Peak	382.44 ± 35.69	387.79 ± 48.99	0.12
	Min	−282.81 ± 46.49	−277.34 ± 57.57	0.10

Dorsiflexion (+)/plantarflexion (−); extension (+)/flexion (−). * represents significant difference with $p \leq 0.05$; ** represents significant difference $p \leq 0.01$.

For the GRF variables (Table 3), the fast movement condition had significantly higher first vertical ($p = 0.005$; $d > 0.8$) and horizontal ($p = 0.007$; $d < 0.8$) GRF peaks than the

moderate movement condition. Additionally, the fast movement indicated a significantly higher second vertical GRF peak ($p = 0.001$; $d > 0.8$) but smaller second horizontal peak ($p = 0.010$; $d > 0.8$) than the moderate movement.

Table 3. Vertical and horizontal GRF data (BW).

Variable	Event	Fast	Moderate	Cohen's <i>d</i>
Vertical GRF	First peak	2.16 ± 0.14 **	1.59 ± 0.17	3.66
	Valley	1.49 ± 0.06	1.32 ± 0.11	1.91
	Second peak	2.29 ± 0.03 **	1.87 ± 0.05	10.18
Horizontal GRF	First peak	1.54 ± 0.21 **	1.43 ± 0.29	0.43
	Valley	1.26 ± 0.20	1.14 ± 0.17	0.64
	Second peak	1.18 ± 0.24 **	1.45 ± 0.14	1.37

** represents significant difference with $p \leq 0.01$.

3.2. Joint Contact Force Variables

Figure 4 shows the medial–lateral and proximal–distal contact forces of the ankle, knee and hip joints. Compared to the moderate movement condition (Table 4), the fast movement produced a higher peak knee lateral contact force ($p = 0.008$; $d > 0.8$) and ankle lateral contact force ($p < 0.001$; $d < 0.8$). Additionally, the fast movement generated a higher first peak knee and hip distal contact forces ($p < 0.001$; $d > 0.8$), higher peak ankle distal contact force ($p = 0.001$; $d > 0.8$), higher valley knee and hip distal contact force ($p = 0.001$; $d > 0.8$) as well as higher second peak knee distal contact force ($p = 0.001$; $d > 0.8$) than the moderate movement condition (Figure 4 and Table 4).

Table 4. The hip, knee and ankle medial–lateral and proximal–distal contact forces (N/BW) in each analyzed event.

Variable	Event	Fast	Moderate	Cohen's <i>d</i>
Ankle medial–lateral force	Peak	1.99 ± 0.34 **	1.68 ± 3.95	0.11
Ankle proximal–distal force	Peak	−11.46 ± 0.48 **	−9.83 ± 0.13	4.63
Knee medial–lateral force	Peak	2.23 ± 0.05 **	2.05 ± 0.05	3.6
Knee proximal–distal force	First peak	−7.70 ± 0.64 **	−7.49 ± 0.26	0.42
	Valley	−7.68 ± 0.26 **	−7.16 ± 0.18	2.32
	Second peak	−7.94 ± 0.79 **	−7.23 ± 0.47	1.09
Hip medial–lateral force	Peak	2.04 ± 0.20	2.21 ± 0.13	1.00
Hip proximal–distal force	First peak	−7.86 ± 0.15 **	−6.02 ± 0.18	11.10
	Valley	−6.81 ± 0.86 **	−5.50 ± 0.56	1.80
	Second peak	−7.48 ± 0.24	−7.66 ± 0.21	0.79

Medial (−)/lateral (+); proximal (+)/distal (−). ** represents significant difference with $p \leq 0.01$.

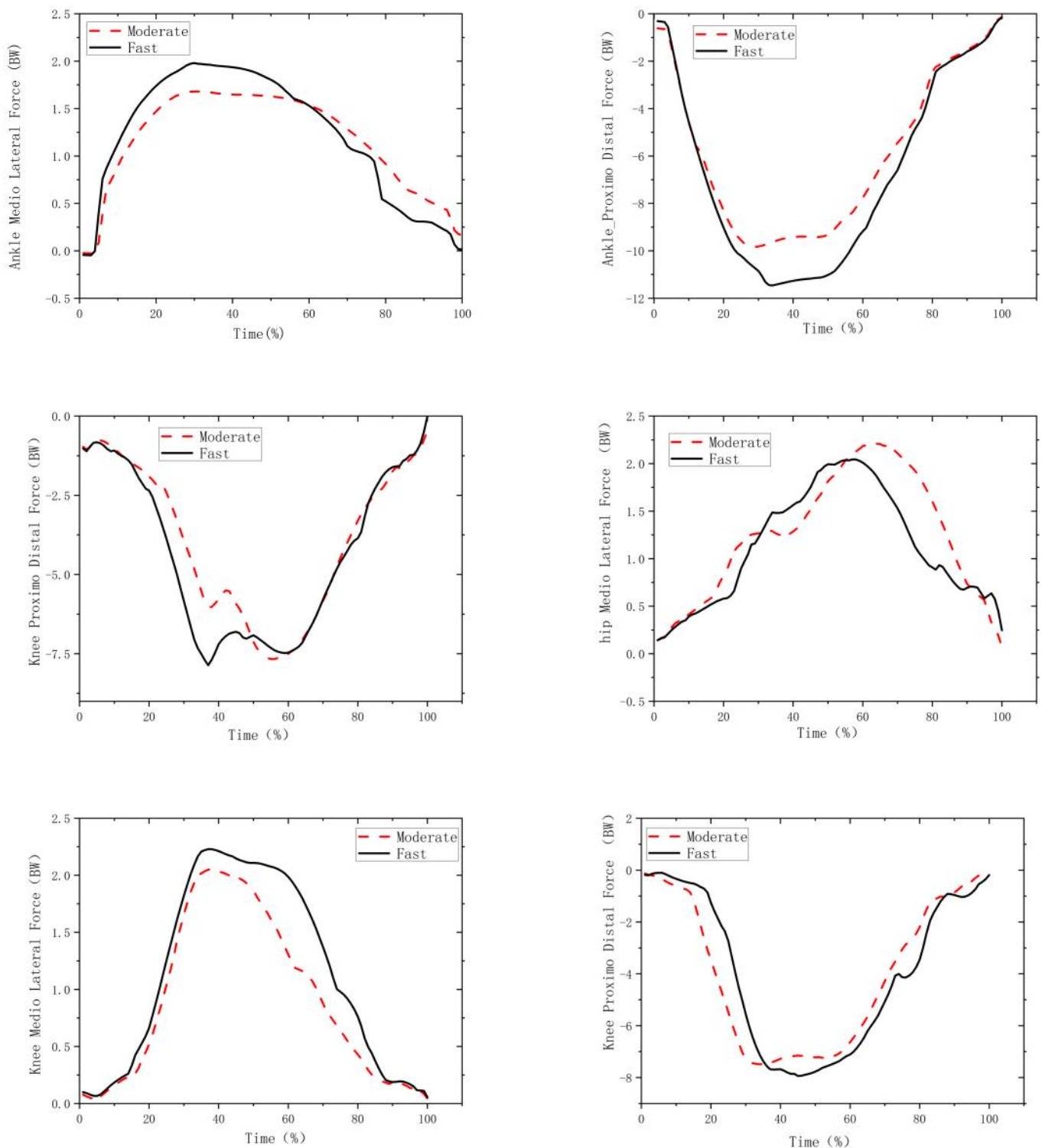


Figure 4. The curves of the medial–lateral (left) and proximal–distal (right) contact forces of ankle (upper), knee (middle) and hip (bottom) joints across time.

4. Discussion

Through an approach using musculoskeletal modelling, this study examined the differences in ground reaction forces and lower limb joint contact forces during the take-off step in forehand overhead strokes with fast and moderate movements. The key results are summarized as follows: (1) Fast speed movement led to larger ankle dorsiflexion and knee extension velocity but smaller hip extension velocity at initial contact. (2) Fast movement

displayed smaller peak ankle pronation, knee flexion and hip flexion but higher peak ankle dorsiflexion velocity and peak knee extension velocity. (3) Fast movement exhibited larger ankle dorsiflexion; smaller ankle pronation and hip extension angles; and higher plantarflexion, knee flexion and hip flexion velocities during take-off. (4) Fast movement induced larger first and second vertical peaks, larger first horizontal peak but lower second horizontal peak. (5) Fast movement led to higher peak ankle lateral and distal contact forces, higher knee lateral and distal contact forces, and higher hip distal contact forces than moderate movement conditions.

4.1. GRF, Joint Kinematics and Contact Forces in Braking Phase (Initial Contact, Peak)

Larger first vertical and horizontal GRF peaks were found in the fast movements. Exposure to repetitive and rapid overhead strokes places higher loads on the lower extremities of the athletes, resulting in higher lower extremity injuries [43]. Additionally, the hip joint angle variation changed little when the participants completed their overhead stroke with faster movement speeds. The fast speed movement condition had a larger peak hip distal force than the moderate, which suggested a fast force transmission along the direction of motion [44,45]. The hip joint appears to be an important technical factor influencing forehand overhead strokes and injuries during early landing period. At the knee joint, the fast movement condition showed a larger maximum knee angular velocity, which may relate to a larger knee distal (+2.8%) and lateral (+8.8%) contact forces during fast movement. The increase in joint contact force and joint velocity is attributed to the higher risk of knee joint injury [46], which shows a strong association between the joint contact force and the knee angular velocity. Therefore, reducing contact force and/or knee angular velocity would prove important in order to protect knee joints from injuries.

The foot in fast movements changed from pronation to supination, but the foot in moderate movements only showed decreasing pronation angle across the stance phase. The inconsistent change in coronal foot motion resulted in different forces acting on the ankle, for which fast movement condition had a higher ankle distal (+16.6%) and lateral (+18.4%) contact forces than the moderate movements. The higher ankle joint contact force is related to more ankle injuries [47]. However, it can be seen from Figure 4 that both the horizontal GRF and medial–lateral ankle contact force in the fast movement condition decreased faster than those in the moderate movement condition, indicating that the angle changing from pronation to supination could have delayed the action time of the lateral contact force. This is in line with a previous running study that argued that overpronation at the early stance phase of running delayed the peak of vertical GRF [48]. Considering the special physiological structure of ankle joint, strengthening exercises should be considered to protect the medial and lateral ligaments to prevent injury. While the longitudinal impact on injury risks for athletes is uncertain, the findings from the present study confirm that fast movements induce higher impact forces during forehand overhead stroke activities.

4.2. GRF, Joint Kinematics and Contact Forces in Propulsion Phase (Take-off, Min)

When performing a step back followed by vertical jump for an overhead stroke, participants may experience higher horizontal backward inertia prior to the take-off event. Athletes performing overhead strokes in the fast movement manner induced larger second vertical GRF peaks but smaller second horizontal GRFs than in the moderate movement condition, suggesting that higher efficiency is required to transfer horizontal inertia to the vertical force component. The range of hip motion was generally smaller in the fast movement condition compared with moderate movement condition. The fast movement condition appears to complete the hip movement more stably, resulting in a higher hip proximal contact force. In other words, the faster the movement speed, the higher the contact forces acting on the hip.

The range of knee angular velocity and the proximal–distal contact force were generally larger in the fast movement condition than in the moderate movement condition. In the running literature, kinematic variability of the lower limbs during movements has been

linked to injury occurrences [49,50]. It is argued that lower variability may be indicative of localized mechanical stress on a certain body and higher variability may help re-distribute the load and, hence, prevent overuse injury [50]. This may imply that knee joint could be the key joint in the take-off. The knee medial–lateral force generally declined with contact time, which indicated that knee joint would play an important role in pushing the body in an upward movement [51]. It is also consistent with the human body structure to ensure the stability of the knee joint to produce effective force transmission upward. Liu et al.'s study [52] found that different take-off postures and techniques led to different force generation, and the knee bending angles were the key factor in generating an upward force. It was consistent with the conclusion that higher ranges of knee motion were required to generate higher/rapid jumping forces in the fast movement condition than moderate movements [53]. In a sprinting study, Liu (2008) showed that the GRF passed through the front of the joint center of knee before the instant of sprint take-off. The hind leg muscle produced significant bending torque in order to counteract this moment, which may increase the likelihood of an injury of the hind leg muscle. Such rapid/strenuous action was similar to the leg take-off movement in our study; therefore, more attention should be paid to hind leg mechanics to prevent sports injuries.

No observed differences were found in the ankle joints during take-off, but higher ankle angular velocity was found in the fast movement condition than the moderate movements. The foot changed from supination to pronation in the fast movement condition; it only increased the pronation amplitude in the moderate movement condition, and the ankle distal contact force was larger in the fast speed condition than that in the moderate movements. This indicates that the movement speed caused a larger downward ankle contact force, which was beneficial for athletes in order to perform rapid/effective jumps.

4.3. Experimental Limitation

Although this pilot study provided a theoretical basis for the lower limb mechanics during forehand overhead strokes, several limitations should be considered. First, a larger sample size with various genders and playing levels would be needed for a more comprehensive analysis to generalize the take-off joint mechanics amongst athletes. Second, the isolated and preplanned movement trials were measured in the laboratory. In realistic badminton game plays, the movements are rather unanticipated and consecutive to the preceding movements. The information collected from studying realistic movements would be valuable in sport training and performance. Third, we did not measure electromyography as well as upper limb and racket mechanics. Future studies could examine the relationship among racket, upper and lower limb mechanics to underlying mechanisms and strategies associated with the faster and slower overhead stroke movements.

5. Conclusions

Assessing different movement speeds may be valuable in analyzing sporting performances. With the increase in movement speed, larger joint contact forces were determined at all hip, knee and ankle joints. However, distinct joint angles and velocities were exhibited among the hip (smaller angle–larger velocities), knee (larger velocities) and ankle, suggesting that different joint coordination strategies should be utilized to achieve higher movement speeds. The larger joint contact forces possibly contributed to higher pressure on joint stability and muscle forces. Although fast movement speed of the forehand overhead stroke is always encouraged in offensive play, the information on take-off characteristics could be useful in predicting the performances and potential risks of hip, knee and ankle joints and could be insightful for designing training regimes.

Author Contributions: Conceptualization, X.C. and X.W.; methodology, X.C.; validation, W.K.L. and Q.G.; investigation, X.C. and Q.G.; writing—original draft preparation, X.C. and W.K.L.; writing—review and editing, T.Z.; visualization, X.W.; supervision, X.W. and T.Z.; funding acquisition, X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Shenyang Sport University (Word of Ethics (2020) No. 1) for studies involving humans.

Informed Consent Statement: Written informed consent to publish this paper has been obtained from the patients.

Data Availability Statement: The data presented in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Phomsoupha, M.; Laffaye, G. The Science of Badminton: Game Characteristics, Anthropometry, Physiology, Visual Fitness and Biomechanics. *Sports Med.* **2015**, *45*, 473–495. [[CrossRef](#)] [[PubMed](#)]
2. Faude, O.; Meyer, T.; Rosenberger, F.; Fries, M.; Huber, G.; Kindermann, W. Physiological characteristics of badminton match play. *Eur. J. Appl. Physiol.* **2007**, *100*, 479–485. [[CrossRef](#)] [[PubMed](#)]
3. Li, D.; Gao, R.; Dong, L.; Lam, W.-K.; Zhang, F. A novel 3D re-entrant unit cell structure with negative Poisson's ratio and tunable stiffness. *Smart Mater Struct.* **2020**, *29*, 6. [[CrossRef](#)]
4. Kuntze, G.; Sellers, W.I.; Mansfield, N. Bilateral ground reaction forces and joint moments for lateral sidestepping and crossover stepping tasks. *J. Sports Sci. Med.* **2009**, *8*, 1–8.
5. Kuntze, G.; Mansfield, N.; Sellers, W. A biomechanical analysis of common lunge tasks in badminton. *J. Sports Sci.* **2010**, *28*, 183–191. [[CrossRef](#)]
6. Lam, W.K.; Ryue, J.; Lee, K.K.; Park, S.K.; Cheung, J.T.M.; Ryu, J. Does shoe heel design influence ground reaction forces and knee moments during maximum lunges in elite and intermediate badminton players? *PLoS ONE* **2017**, *12*, e0174604. [[CrossRef](#)]
7. Lam, W.K.; Ding, R.; Qu, Y. Ground reaction forces and knee kinetics during single and repeated badminton lunges. *J. Sports Sci.* **2017**, *35*, 587–592. [[CrossRef](#)]
8. Hong, Y.; Wang, S.J.; Lam, W.K.; Cheung, J.T.-M. Kinetics of Badminton Lunges in Four Directions. *J. Appl. Biomech.* **2014**, *30*, 113–118. [[CrossRef](#)]
9. Zhang, Z.; Li, S.; Wan, B.; Visentin, P.; Jiang, Q.; Dyck, M.; Li, H.; Shan, G. The Influence of X-Factor (Trunk Rotation) and Experience on the Quality of the Badminton Forehand Smash. *J. Hum. Kinet.* **2016**, *53*, 9–22. [[CrossRef](#)]
10. Taha, Z.; Hassan, M.S.S.; Yap, H.J.; Yeo, W.K. Preliminary Investigation of an Innovative Digital Motion Analysis Device for Badminton Athlete Performance Evaluation. In *Engineering of Sport 11. Procedia Engineering*; Jansen, A.J., Ed.; Elsevier Science Bv: Amsterdam, The Netherlands, 2016; Volume 147, pp. 461–465.
11. Barnamehei, H.; Ghomsheh, F.T.; Cherati, A.S.; Pouladian, M. Upper Limb Neuromuscular Activities and Synergies Comparison between Elite and Nonelite Athletics in Badminton Overhead Forehand Smash. *Appl. Bionics Biomech.* **2018**, *2018*, 6067807. [[CrossRef](#)]
12. Koike, S.; Hashiguchi, T. Dynamic contribution analysis of badminton-smash-motion with consideration of racket shaft deformation (a model consisted of racket-side upper limb and a racket). In *Engineering of Sport 10. Procedia Engineering*; James, D., Choppin, S., Allen, T., Wheat, J., Fleming, P., Eds.; Elsevier Science Bv: Amsterdam, The Netherlands, 2014; Volume 72, pp. 496–501.
13. Engebretsen, L.; Soligard, T.; Steffen, K.; Alonso, J.M.; Aubry, M.; Budgett, R.; Dvorak, J.; Jegathesan, M.; Meeuwisse, W.H.; Mountjoy, M.; et al. Sports injuries and illnesses during the London Summer Olympic Games 2012. *Br. J. Sports Med.* **2013**, *47*, 407–414. [[CrossRef](#)] [[PubMed](#)]
14. Hewett, T.E.; Myer, G.D.; Ford, K.R.; Heidt, R.S., Jr.; Colosimo, A.J.; McLean, S.G.; Van Den Bogert, A.J.; Paterno, M.V.; Succop, P. Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study. *Am. J. Sports Med.* **2005**, *33*, 492–501. [[CrossRef](#)]
15. Shariif, A.H.; George, J.; Ramlan, A.A. Musculoskeletal injuries among Malaysian badminton players. *Singap. Med. J.* **2009**, *50*, 1095–1097.
16. Goh, S.L.; Mokhtar, A.H.; Ali, M.R.M. Badminton injuries in youth competitive players. *J. Sports Med. Phys. Fit.* **2013**, *53*, 65–70.
17. Lin, C.-F.; Hua, S.-H.; Huang, M.-T.; Lee, H.-H.; Liao, J.-C. Biomechanical analysis of knee and trunk in badminton players with and without knee pain during backhand diagonal lunges. *J. Sports Sci.* **2015**, *33*, 1429–1439. [[CrossRef](#)] [[PubMed](#)]
18. Herbaut, A.; Delannoy, J.; Foissac, M. Injuries in French and Chinese regular badminton players. *Sci. Sports* **2018**, *33*, 145–151. [[CrossRef](#)]
19. Kimura, Y.; Ishibashi, Y.; Tsuda, E.; Yamamoto, Y.; Tsukada, H.; Toh, S. Mechanisms for anterior cruciate ligament injuries in badminton. *Br. J. Sports Med.* **2010**, *44*, 1124–1127. [[CrossRef](#)]
20. Sasaki, S.; Nagano, Y.; Ichikawa, H. Loading differences in single-leg landing in the forehand- and backhand-side courts after an overhead stroke in badminton: A novel tri-axial accelerometer research. *J. Sports Sci.* **2018**, *36*, 2794–2801. [[CrossRef](#)]
21. Mei, Q.; Gu, Y.; Fu, F.; Fernandez, J. A biomechanical investigation of right-forward lunging step among badminton players. *J. Sports Sci.* **2017**, *35*, 457–462. [[CrossRef](#)]

22. Nielsen, M.H.; Lund, J.N.; Lam, W.-K.; Kersting, U.G. Differences in impact characteristics, joint kinetics and measurement reliability between forehand and backhand forward badminton lunges. *Sports Biomech.* **2020**, *19*, 547–560. [[CrossRef](#)]
23. Lam, W.-K.; Lee, K.-K.; Park, S.-K.; Ryue, J.; Yoon, S.; Ryu, J. Understanding the impact loading characteristics of a badminton lunge among badminton players. *PLoS ONE* **2018**, *13*, e0205800. [[CrossRef](#)] [[PubMed](#)]
24. Kimura, Y.; Ishibashi, Y.; Tsuda, E.; Yamamoto, Y.; Hayashi, Y.; Sato, S. Increased knee valgus alignment and moment during single-leg landing after overhead stroke as a potential risk factor of anterior cruciate ligament injury in badminton. *Br. J. Sports Med.* **2012**, *46*, 207–213. [[CrossRef](#)] [[PubMed](#)]
25. Park, S.-K.; Lam, W.K.; Yoon, S.; Lee, K.-K.; Ryu, J. Effects of forefoot bending stiffness of badminton shoes on agility, comfort perception and lower leg kinematics during typical badminton movements. *Sports Biomech.* **2017**, *16*, 374–386. [[CrossRef](#)] [[PubMed](#)]
26. Walter, J.P.; D’Lima, D.D.; Colwell, C.W.; Fregly, B.J., Jr. Decreased knee adduction moment does not guarantee decreased medial contact force during gait. *J. Orthop. Res.* **2010**, *28*, 1348–1354. [[CrossRef](#)]
27. Winter, D. *Biomechanics and Motor Control of Human Movement*, 4th ed.; John Wiley & Sons: Hoboken, NJ, USA, 2009. [[CrossRef](#)]
28. Wang, X.; Ma, Y.; Hou, B.Y.; Lam, W.-K. Influence of Gait Speeds on Contact Forces of Lower Limbs. *J. Health Eng.* **2017**, *2017*, 6375976. [[CrossRef](#)]
29. Lam, W.-K.; Jia, S.-W.; Baker, J.S.; Ugbohue, U.C.; Gu, Y.; Sun, W. Effect of consecutive jumping trials on metatarsophalangeal, ankle, and knee biomechanics during take-off and landing. *Eur. J. Sport Sci.* **2020**, *21*, 53–60. [[CrossRef](#)]
30. Zhao, T.Y.; Ma, Y.; Zhang, H.Y.; Pan, H.G.; Cai, Y. Free vibration analysis of a rotating graphene nanoplatelet reinforced pre-twist blade-disk assembly with a setting angle. *Appl. Math. Model.* **2021**, *93*, 578–596. [[CrossRef](#)]
31. Zhao, T.; Li, K.; Ma, H. Study on dynamic characteristics of a rotating cylindrical shell with uncertain parameters. *Anal. Math. Phys.* **2022**, *12*, 97. [[CrossRef](#)]
32. Zhao, T.Y.; Jiang, L.P.; Pan, H.G.; Yang, J.; Kitipornchai, S. Coupled free vibration of a functionally graded pre-twisted blade-shaft system reinforced with graphene nanoplatelets. *Compos. Struct.* **2021**, *262*, 113362. [[CrossRef](#)]
33. Zhao, T.Y.; Cui, Y.S.; Pan, H.G.; Yuan, H.Q.; Yang, J. Free vibration analysis of a functionally graded graphene nanoplatelet reinforced disk-shaft assembly with whirl motion. *Int. J. Mech. Sci.* **2021**, *197*, 106335. [[CrossRef](#)]
34. Zhao, T.Y.; Yan, K.; Li, H.W.; Wang, X. Study on theoretical modeling and vibration performance of an assembled cylindrical shell-plate structure with whirl motion. *Appl. Math. Model.* **2022**, *110*, 618–632. [[CrossRef](#)]
35. Damsgaard, M.; Rasmussen, J.; Christensen, S.T.; Surma, E.; de Zee, M. Analysis of musculoskeletal systems in the AnyBody Modeling System. *Simul. Model. Pract. Theory* **2006**, *14*, 1100–1111. [[CrossRef](#)]
36. Chen, T.L.-W.; Wang, Y.; Wong, D.W.-C.; Lam, W.-K.; Zhang, M. Joint contact force and movement deceleration among badminton forward lunges: A musculoskeletal modelling study. *Sports Biomech.* **2020**, 1–13. [[CrossRef](#)] [[PubMed](#)]
37. Jurkoč, J.; Michnik, R.; Czapla, K. Mathematical modelling as a tool to assessment of loads in volleyball player’s shoulder joint during spike. *J. Sports Sci.* **2017**, *35*, 1179–1186. [[CrossRef](#)]
38. Quan, W.; Ren, F.; Sun, D.; Fekete, G.; He, Y. Do novice runners show greater changes in biomechanical parameters? *Appl. Bionics Biomech.* **2021**, *2021*, 8894636. [[CrossRef](#)]
39. Greene, B.R.; McGrath, D.; O’Neill, R.; O’Donovan, K.J.; Burns, A.; Caulfield, B. An adaptive gyroscope-based algorithm for temporal gait analysis. *Med. Biol. Eng. Comput.* **2010**, *48*, 1251–1260. [[CrossRef](#)]
40. Doherty, C.; Bleakley, C.; Hertel, J.; Caulfield, B.; Ryan, J.; Delahunt, E. Single-leg drop landing motor control strategies following acute ankle sprain injury. *Scand. J. Med. Sci. Sports* **2015**, *25*, 525–533. [[CrossRef](#)]
41. Dupré, T.; Funken, J.; Muller, R.; Mortensen, K.R.L.; Lysdal, F.G.; Braun, M.; Krahl, H.; Potthast, W. Does inside passing contribute to the high incidence of groin injuries in soccer? A biomechanical analysis. *J. Sports Sci.* **2018**, *36*, 1827–1835. [[CrossRef](#)]
42. Shiming, L.; Zhao, Z.; Bingjun, W.; Brandie, W.; Gongbing, S. The relevance of body positioning and its training effect on badminton smash. *J. Sports Sci.* **2017**, *35*, 310–316.
43. Cronin, J.; McNair, P.J.; Marshall, R. Lunge performance and its determinants. *J. Sports Sci.* **2003**, *21*, 49–57. [[CrossRef](#)]
44. Wang, Y.; Niu, W.; He, Y.; Pei, B.Q.; Fan, Y.B. Experimental study on the half-squat parachute landing for driving and validating the inverse dynamic simulation. *J. Med. Biomech.* **2010**, *25*, 257–261+72. (In Chinese)
45. Yu, B.; Lin, C.-F.; Garrett, W.E. Lower extremity biomechanics during the landing of a stop-jump task. *Clin. Biomech.* **2006**, *21*, 297–305. [[CrossRef](#)]
46. Lin, P.E.; Sigward, S.M. Contributors to knee loading deficits during gait in individuals following anterior cruciate ligament reconstruction. *Gait Posture* **2018**, *66*, 83–87. [[CrossRef](#)] [[PubMed](#)]
47. Hunt, K.J.; Goeb, Y.; Behn, A.W.; Criswell, B.; Chou, L. Ankle Joint Contact Loads and Displacement with Progressive Syndesmotom Injury. *Foot Ankle Int.* **2015**, *36*, 1095–1103. [[CrossRef](#)] [[PubMed](#)]
48. Williams, D.S.; McClay, I.S.; Hamill, J.; Buchanan, T.S. Lower Extremity Kinematic and Kinetic Differences in Runners with High and Low Arches. *J. Appl. Biomech.* **2001**, *17*, 153–163. [[CrossRef](#)]
49. Donoghue, O.A.; Harrison, A.J.; Coffey, N.; Hayes, K. Functional Data Analysis of Running Kinematics in Chronic Achilles Tendon Injury. *Med. Sci. Sports Exerc.* **2008**, *40*, 1323–1335. [[CrossRef](#)]
50. Gruber, A.H.; Derrick, T.R.; Hamill, J. Impact Shock Attenuation is Increased with Rearfoot Running Compared to Forefoot Running. *Med. Sci. Sports Exerc.* **2012**, *44*, 772–773.
51. Caruntu, D.I.; Moreno, R. Human Knee Inverse Dynamics Model of Vertical Jump Exercise. *J. Comput. Nonlinear Dyn.* **2019**, *14*, 12. [[CrossRef](#)]

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52. Liu, W.G.; Liu, X.Z.; Li, Q. Dynamic Analysis of Different Forms of Vertical Jump in Ordinary Crowd. *J. Beijing Univ. Phys. Educ.* **2003**, *26*, 45–47+79. (In Chinese)
 53. Janicijevic, D.; Knezevic, O.M.; Mirkov, D.M.; Pérez-Castilla, A.; Petrovic, M.; Samozino, P.; García-Ramos, A. The force–velocity relationship obtained during the squat jump exercise is meaningfully influenced by the initial knee angle. *Sports Biomech.* **2020**, *9*, 1136–1145. [[CrossRef](#)]