SIN-CHN
SCIENTIFIC PRESS PTE.LTD.

Molecular & Cellular Biomechanics 2024, 21(3), 538.
https://doi.org/10.62617/mcb538

Article

Sports biomechanical analysis of knee joint injuries in table tennis players

Wenyan Li*, **Sikuan Ren**

Department of Physical Education, Xinzhou Normal University, Xinzhou 034000, Shanxi, China
*** Corresponding author:** Wenyan Li, lwy19960202@163.com

CITATION

Li W, Ren S. Sports biomechanical analysis of knee joint injuries in table tennis players. Molecular & Cellular Biomechanics. 2024; 21(3): 538. https://doi.org/10.62617/mcb538

ARTICLE INFO

Received: 14 October 2024
Accepted: 21 October 2024
Available online: 12 November 2024

Abstract: Table tennis is a fast-paced, explosive sport that puts a lot of strain and stress on players' lower limbs, particularly their knee joints. This work built a thorough mathematical model to investigate the dynamic and kinematic properties of the knee joint under various motion situations, with the goal of better understanding the biomechanical behavior of the knee joint in table tennis. A model of knee joint motion that takes into account the two degrees of freedom—flexion, extension, and rotation—is put forth based on the concepts of human biomechanics and kinematics theory. This model uses the Newton Euler equation to explain the mechanical behavior of the knee joint and integrates internal forces like muscle forces and external factors like ground reaction forces for torque balance analysis. This study offers a thorough examination of the force distribution and knee joint trajectory in table tennis using numerical simulation techniques. The findings show that the knee joint undergoes considerable compression and shear forces during intense activity, and that the joint's stress properties vary significantly depending on the kind of movement. This finding is a valuable resource for table tennis players' knee joint injury prevention and rehabilitation.

Keywords: table tennis sport; knee joint; biomechanics; mathematical model; sports injuries; numerical simulation

1. Introduction

As a fast-paced, high-intensity competitive sport, table tennis is adored and played by people all over the world. But as the level of competition has continued to rise, so too has the physical strain that athletes must endure during practice and competition, which has resulted in a rise in the prevalence of sports injuries.The knee joint is a high-risk location for sports injuries since it is a major weight-bearing joint in the human body and is essential to table tennis mobility and stability [1]. Table tennis's distinct movement patterns and technical movements (such as emergency stop and start, lateral movement, rotation, etc.) make the knee joint susceptible to repeated stress and asymmetric loads, thereby increasing the risk of injury [2]. Despite the fact that table tennis may have a lower overall incidence of knee joint injuries compared to other high impact sports like football, basketball, etc.Thus, it is theoretically and practically significant to investigate the processes, types, and preventive strategies of knee joint injuries in table tennis players.

The complex anatomical structure and function of the knee joint require it to withstand both impact forces from the ground and cope with its own bending, extension, rotation, and lateral forces during movement, making it highly susceptible to injury during high-intensity exercise [3]. According to the existing literature, knee joint injuries are more common in athletes, especially in high-level athletes, with a higher incidence rate. Specifically for table tennis players, common knee joint injuries include lateral collateral ligament injury, patellar tip disease, patellar tendinitis, and meniscus injury [4]. Although there have been many studies on sports injuries, specialized research on knee joint injuries in table tennis players is relatively limited and lacks systematic and comprehensive analysis.

In order to systematically investigate the mechanism and preventative measures for knee joint injuries in table tennis athletes, this study coupled biomechanical analysis with a retrospective survey of 414 table tennis coaches, team physicians, and participants.This study aims to identify the specific types and patterns of knee joint injuries in table tennis players, analyze the biomechanical causes of these injuries, suggest reasonable and scientific preventive and treatment measures, and offer theoretical support and useful guidance to coaches and medical staff through extensive data analysis and biomechanical modeling.

Despite research examining the mechanics underlying knee joint injuries in athletes, there are still certain limitations and difficulties. First of all, there are many diverse and intricate technical motions in table tennis, and each action has a unique effect on the knee joint. It is challenging to fully expose its biomechanical features with a single research approach [5]. Second, the majority of the research being done on knee joint injuries in table tennis players now concentrates on rehabilitation and post-injury care, with relatively little research being done on injury prevention [6]. Furthermore, the majority of the data used in current study comes from athletes in the West. Due to differences in training methods, physical fitness, and competitive level, Chinese table tennis players may have different injury characteristics and prevention needs, which requires further localization research.

In order to make up for the shortcomings of existing research, this study adopted a combination of retrospective investigation and biomechanical analysis to systematically analyze the occurrence and biomechanical mechanisms of knee joint injuries in table tennis players. Retrospective surveys can obtain first-hand information on athletes and coaches through a large number of questionnaires and interviews, comprehensively understanding the incidence, types, and severity of knee joint injuriesBiomechanics analysis reveals in depth the force distribution and injury mechanism of the knee joint during movement through modeling and simulation of typical motion movements [7]. However, there are still some limitations to this study, such as subjective bias in retrospective surveys and the need for simplification and assumptions in establishing biomechanical models, which may affect the accuracy and universality of the results.

Despite the challenges mentioned above, this study has several significant advantages. Firstly, this study has a large sample size, covering table tennis players of different levels, and the data has strong representativeness and reliability. Secondly, the diversity and comprehensiveness of research methods contribute to a comprehensive analysis of the mechanisms underlying knee joint injuries from different perspectives.By combining retrospective investigation and biomechanical analysis, the specific situation and causes of knee joint injuries in table tennis players can be more accurately revealed. In addition, this study focuses on practical application value and proposes targeted prevention and treatment measures, providing practical guidance for coaches, team doctors, and athletes.

2. Preliminary

According to the structure of the human body, the knee joint is the key to people's movement. Whether it is walking or some intense sports in daily life, the knee joint needs to provide support, so it bears a lot of load and faces injury [8]. The knee joint is a dual joint structure composed of the tibiofemoral joint and patellofemoral joint, and is located in the middle of the leg, which is subject to a lot of friction. Without a doubt, the knee joint needs to be given special attention [9].

The knee joint's auxiliary and primary structures. The tibia of the calf and the femur of the thigh are the two bones that make up the knee joint.The lower end of the femur and the higher end of the tibia, together referred to as the joint head and socket, make create the well-known socket-shaped structure that is the knee joint. The human knee joint is created by the combination of the joint head and socket. The knee joint's joint head and socket, particularly the joint socket, are not typical knee joint characteristics. Although its purpose is to increase the knee joint's flexibility, it lacks sufficient stability.

The auxiliary structures of the knee joint are the collateral ligament, cruciate ligament, meniscus, fat, and patella. Their function is to compensate for the shortcomings of auxiliary structures, that is, to enhance the stability of the knee joint [10].

Lateral collateral ligament: It is located on both sides of the knee joint and is divided into two, one is the tibial collateral ligament and the other is the fibular collateral ligament. Its function is to ensure that the knee does not stretch or bend in the opposite direction during movement, causing serious damage [11]. Cross cruciate ligament: The cross cruciate ligament is divided into the anterior cruciate ligament and the posterior cruciate ligament, and is located inside the knee joint. It is used to strengthen fixation when the movement of the thigh and calf is not coordinated, prevent displacement of the thigh or calf, and maintain stability [12].

Meniscus: People who often watch sports games know that they occasionally hear about athletes suffering from meniscus injuries, but their understanding of meniscus is not sufficient.The meniscus is two crescent shaped, thin inside and thick outside fibrocartilage located on the tibia of the knee joint. Its function is like an air cushion, reducing the impact on the knee joint during exercise and minimizing the damage it receives.

Fat pad: The fat pad is the most easily overlooked part of the knee joint that people often overlook. It refers to the synovial membrane that is light yellow in color and grows in the gaps of the knee joint, with a certain amount of fat, so it is called a fat pad.Its function is to reduce the vibration amplitude of the knee joint during movement, thanks to the fat pad promoting the secretion of synovial fluid, which provides good protection for the knee joint.

3. Biomechanical analysis of knee joint movement

Although the movement of the knee occurs simultaneously in two planes, the movement in one plane is so large that it can be considered as approximately the movement of all knees [13]. Furthermore, although the muscle strength on the knee is generated by several muscles, when a single muscle group produces a large force, it can be considered as almost all the muscle strength acting on the knee [14]. Therefore, the movement of the knee confined to a plane and the force generated by a single muscle group can still be understood as knee movement [15].

3.1. Sports biomechanical analysis of tibiofemoral joint

The range of motion of the tibiofemoral joint is approximately 0° to 140° in the sagittal plane, from the maximum knee extension to complete flexion; The range of motion of the tibiofemoral joint in the transverse plane increases as the knee is fully extended to 90 degrees of flexion [16]. When fully extended, the main reason is that the medial condyle of the femur is longer than the lateral condyle, causing the femoral condyle to interlock with the tibial condyle, and there is almost no possibility of movement in this plane [17]. As shown in **Figure 1**, the external rotation range of the knee when flexed 90 degrees is from 0° to 45°, and the internal rotation range is from 0° to 30°. When the knee is flexed above 90 degrees, the range of motion in the transverse plane decreases, mainly due to the limited function of soft tissues; The same pattern can be obtained within the frontal plane [18]. It is almost impossible to have abduction or adduction when the knee is fully extended.When the knee is flexed to 30 degrees, the movement within that plane increases, but regardless of passive abduction or passive adduction, its maximum movement is only a few degrees [19]. Similarly, due to the limitations of soft tissue, when the functional flexion exceeds 30°, the movement within this plane decreases.

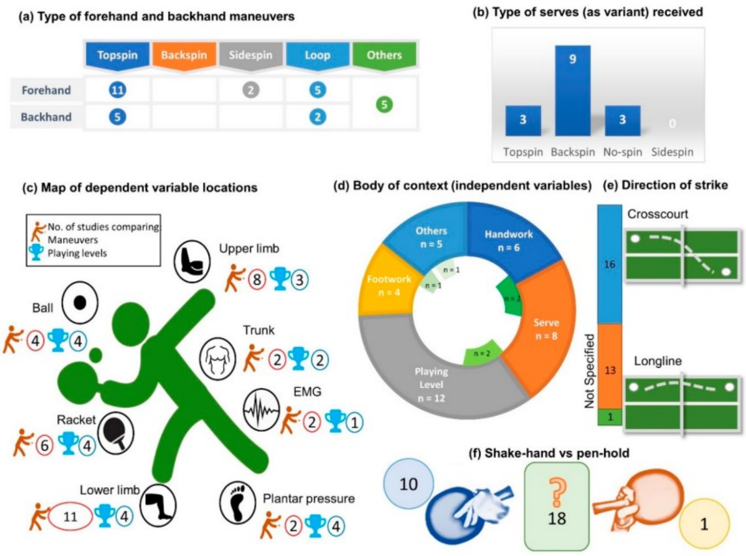

Figure 1. Motion torque.

Joint movement in the knee occurs between the tibial condyle and femoral condyle, as well as between the femoral condyle and patella. The movement between the tibial condyle and the femoral condyle occurs simultaneously in all three planes, but is minimal in the transverse and frontal planes. The movement between the femoral condyle and patella occurs simultaneously on both the frontal and transverse planes.

Dynamics includes static analysis and dynamic analysis. We only analyze the tibiofemoral joint from the perspective of motion. The main forces to be considered in dynamic analysis are muscle body weight connective tissue and external loads, and joint torque is commonly used in dynamic analysis [20].

When developing knee injury prevention strategies for table tennis players, based on actual sports scenarios, the following specific measures can be taken:

Strengthening the leg muscles:

Strong leg muscles, especially quadriceps, hamstrings and calf muscles, can provide better support and stability to the knee joint. Targeted increase in leg strength training, such as deep squats, lunges, leg lifts, etc., can help athletes improve the carrying capacity of the lower limbs and reduce the stress burden on the knee joint in high-speed movements and sharp stops and starts.

Optimize technical movements:

Technical movements such as sharp stops and starts, lateral movements and rotations in table tennis place high stress on the knee joint. Unnecessary stress can be effectively reduced by optimizing movement techniques, especially improving the athlete's posture, movement and rotation. For example, reducing excessive knee flexion during sharp stops and training athletes to use more hip and core strength to share the load during the movement can reduce the risk of knee injury.

Stretching and recovery exercises before and after exercise:

Adequate warm-up and stretching can increase the flexibility and stability of the knee and its surrounding muscles. Athletes are advised to perform dynamic stretching and static stretching before and after training to maintain muscle flexibility and reduce stress pooling during exercise. In addition, recovery exercises such as foam roller massages and ice packs can help reduce fatigue buildup after training, thus reducing the risk of knee injuries.

Protective equipment use:

Athletes may consider wearing a knee brace during high-intensity competition or training to provide additional support to the knee joint, especially during confrontations with intense movements. This not only enhances the stability of the knee joint, but also effectively disperses impact forces and reduces the chances of knee injuries.

These preventive strategies are designed to reduce the risk of knee injuries in table tennis players based on the actual demands of the sport, providing practical solutions to ensure that athletes remain healthy and safe during high-intensity play and training.

Torque is the product of the mass moment of inertia of a body part and the angular acceleration of that part: $T = I^{\times}\alpha$. T is the torque expressed in Newton; I is the moment of inertia of the mass, expressed in Newton's square seconds as $N.m\,sec^{2}$; α is the angular acceleration expressed in radians per square second as r/sec^{2}.

Torque is not only the product of the mass moment of inertia and angular acceleration of the body part, but also the product of the main muscle strength that accelerates the body part and the vertical distance from the instantaneous center of the joint to the force line (force arm): T = Fd. F is the force expressed in Newton; D is the vertical distance expressed in meters.The acceleration of body parts and their mass moment of inertia affect the magnitude of joint forces in a dynamic state.

Increasing the angular acceleration of body parts will result in a proportional increase in joint torque.

The patella provides two important biomechanical functions for the knee: it extends the quadriceps muscle arm throughout the range of motion to help the knee straighten, and improves pressure distribution on the femur by increasing the contact surface between the patella and femur.

When the knee is fully flexed to fully extended, the effect of the patella on the length of the quadriceps muscle arm also changes. When fully flexed, the anterior displacement of the quadriceps tendon within the intercondylar fossa of the patella is minimal, and its effect on the length of the quadriceps muscle arm is minimal (approximately 10% of the total length of the force arm). When the knee is extended, the patella lifts from the intercondylar fossa, resulting in significant tendon displacement. When extended to 45°, the quadriceps muscle arm length rapidly increases, and at this point, the patella elongates the force arm by about 30%. Continuing to straighten the knee, the quadriceps muscle strength and arm length slightly decrease. At the last 45 degrees of extension, as the length of the lever arm decreases, the quadriceps muscle must apply a greater force to maintain the same knee torque.

3.2. Mathematical model of motion

In table tennis, the knee joint is subjected to a complex combination of forces and motion patterns. In order to analyze the impact of these forces on the knee joint, a systematic biomechanical model needs to be established. The following is a simplified mathematical model based on the principles of human biomechanics and kinematics, used to analyze the movement and force situation of the knee joint in table tennis.

3.2.1. Model assumptions

1) Rigid body assumption: The various parts of the human body are considered as rigid bodies, and the motion at each joint is considered as relative motion between the rigid bodies.
2) Two degree of freedom system: The movement of the knee joint mainly considers two degrees of freedom: flexion, extension, and rotation.
3) Simplify the mechanical model: ignore the complex mechanical behavior of soft tissues such as muscles and ligaments, and mainly consider external forces and joint reaction forces.

3.2.2. Joint kinematics

The position and angle of the knee joint during movement can be described by the following equation:

$$\theta(t) = \theta_0 + \omega t + \frac{1}{2}\alpha t^2 \tag{1}$$

wherein:

$\theta(t)$ is the knee joint angle (in radians) at time *t*;

θ_0 is the initial angle;

ω is the angular velocity (radians per second);

α is the angular acceleration (radians/second ^2).

The force exerted on the knee joint during movement can be described by the Newton Euler equation. Assuming the mass of the leg is m and the position of the center of gravity is *r*, the force balance equation for the leg is:

$$m \times r(t) = F_{ext}(t) - F_{int}(t) \tag{2}$$

wherein:

$r(t)$ is the linear acceleration of the leg;

$F_{ext}(t)$ is an external force (such as ground reaction force);

$F_{int}(t)$ is the internal joint reaction force.

The torque balance equation of the knee joint is as follows:

$$I \times \theta(t) = \sum\tau(t) \tag{3}$$

wherein:

I is the moment of inertia of the knee joint;

$\theta(t)$ is the angular acceleration of the knee joint;

$\sum\tau(t)$ is the total torque acting on the knee joint.

The total torque acting on the knee joint can be decomposed into external torque and muscle torque:

$$\tau_{\text{total}I}(t) = \tau_{ext}(t) + \tau_{\text{muscie}}(t) \tag{4}$$

Ground reaction force (GRF) is one of the main external forces, which can be described by the forces during the gait cycle:

$$F_{GRF}(t) = Mg - Mr(t) \tag{5}$$

wherein:

M is the total mass of the athlete;

g is the acceleration due to gravity;

$Mr(t)$ is the inertial force of the leg.

The internal reaction force of the knee joint is mainly provided by muscle force and ligament force, which can be solved by the torque balance equation of the muscles:

$$\tau_{\text{muscle}}(t) = F_{\text{muscle}}(t) \times d_{\text{moment}} \tag{6}$$

wherein:

$F_{\text{muscle}}(t)$ is the force produced by muscles;

d_{moment} arm is the length of the force arm.

The above equation can be solved numerically to obtain the motion state and force situation of the knee joint during the movement process. Finite element analysis or multi-body dynamics simulation software (such as Open Sim, SPSS) can be used for detailed analysis.

3.3. Randomized controlled trials (RCTs) validated assessments

Randomized controlled trial (RCT) design:

The effectiveness of these measures can be assessed more scientifically through RCTs. In the design, the athletes can be randomly divided into an intervention group and a control group, and the intervention group receives the specific preventive measures proposed in this paper (e.g., strengthening the training of the muscles around the knee joint, optimizing the technical movements of the sport, etc.), while the control group adopts the traditional training methods or does not carry out any special intervention. The study needs to regularly track the incidence of knee injuries, injury recovery time, changes in athletic performance and other indicators of the two groups of athletes, and compare the differences between the two groups in order to quantify the effectiveness of these measures.

Complement of empirical research methods:

In addition to RCTs, the long-term effects of different preventive and therapeutic measures can be analyzed through prospective cohort studies or cross-sectional surveys. Empirical models are developed to analyze the effectiveness of measures through long-term follow-up of different groups of athletes, collecting data on the frequency of knee injuries, treatment efficacy, and recurrence rates. Combining data on athletes' training intensity, technical movement characteristics, and sports history can provide a more detailed assessment of effectiveness.

Effectiveness assessment indicators:

In RCTs or empirical studies, it is recommended to set the following assessment indicators to quantify the effectiveness of the measures:

Knee injury incidence: by comparing the intervention group with the control group, analyze whether the intervention significantly reduces the risk of knee injury in athletes.

Athletic performance: To assess whether the preventive measures affected the athletes' athletic ability by testing the changes in their athletic performance.

Rehabilitation effect: For athletes who have been injured, the effectiveness of the treatment measures was assessed by observing the speed of rehabilitation, the degree of pain relief and the recurrence rate.

Expand sample diversity:

It is recommended that athletes from different regions, ethnicities and training backgrounds be included in RCTs or other empirical studies to ensure broad applicability of the findings. By comparing the responses of different populations, the generalizability and effectiveness of the measures can be further validated.

By including RCTs and other empirical methods of effect assessment, not only can we provide more adequate empirical support for the proposed preventive and therapeutic measures, but we can also enhance the scientific validity and credibility of the study. This will provide important guidance for coaches, athletes, and medical personnel in applying these measures in actual athletic training.

4. Test objects

The research mainly focuses on table tennis athletes, coaches, and team doctors from provinces, cities, and colleges with good development of table tennis in China. A retrospective research method was used to conduct a questionnaire survey on the research subjects. Pearson correlation analysis was used to evaluate the consistency of coaches, team doctors, and athletes' perceptions of knee joint injuries in table tennis players. The comparison of counting data adopts x^2 test. All statistical analyses were performed using SPSS11.0 for Windows professional software on a computer.

5. Research results

5.1. Types and composition of knee joint injuries in table tennis players

Among 350 table tennis players, there were 225 cases of knee joint injuries, accounting for 29.49% of the total number of injuries. The types and composition of injuries are shown in **Table 1**.

Table 1. Statistics of scientific names and composition of injuries in taekwondo athletes.

Serial number	Injury name	Number of cases (%)	Composition ratio (%)
1	Injury of collateral ligament	55	24.44
2	Patellar apex disease and patellar tendinitis	34	15.11
3	Meniscus injury	30	13.33
4	Fat pad inflammation	29	12.89
5	Knee joint tear	26	11.56
6	Synovitis	18	8.0
7	Patellar chondropathy	18	8.0
8	Cruciate ligament rupture	12	5.33
9	Support for injured individuals	3	1.33
	Total	225	100

According to **Table 1**, excellent table tennis players in China rank first in terms of lateral collateral ligament injuries (55 cases, accounting for 24.44%) in knee joint injuries; Patellar apex disease and patellar tendinitis (34 cases, accounting for 15.11%) ranked second; Meniscus injury (30 cases, accounting for 13.33%) ranks third.

5.2. Consistency analysis of coaches, team doctors, and athletes' perceptions of knee joint injuries in table tennis players

This article analyzes the consistency of coaches, team doctors, and athletes' cognition of knee joint injuries from three aspects: knee joint injuries during single action exercises, knee joint injuries during offensive competitions, and knee joint injury cognition during defensive competitions. The results are shown in **Tables 2–4**.

Table 2. Consistency of knee joint injury cognition in single action exercises.

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
Sportsman	Number of people	301	-	49	89	-	2	61	190	-	220	-	83	36	46
	Proportion (%)	27.95	-	4.55	8.26	-	0.19	5.66	17.64	-	20.43	-	7.71	3.34	4.27
Teachers and Medical Education Teams	Number of people	55	-	8	16	-	0	11	34	-	40	-	15	6	8
	Proportion (%)	28.49	-	4.15	8.29	-	0	5.69	17.62	-	20.73	-	7.77	3.11	4.14

Table 3. Consistency of cognitive recognition of knee joint injuries during offensive matches.

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
Sportsman	Number of people	301	-	49	89	-	2	61	190	-	220	-	83	36	46
	Proportion (%)	27.95	-	4.55	8.26	-	0.19	5.66	17.64	-	20.43	-	7.71	3.34	4.27
Teachers and Medical Education Teams	Number of people	55	-	8	16	-	0	11	34	-	40	-	15	6	8
	Proportion (%)	28.49	-	4.15	8.29	-	0	5.69	17.62	-	20.73	-	7.77	3.11	4.14

Table 4. Consistency of knee joint injury cognition in game defense.

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
Sportsman	Number of people	209	-	149	55	11	18	67	-	80	201	73	97	-	-
	Proportion (%)	23.36	-	15.20	5.61	1.12	1.83	6.84	-	8.16	20.51	7.44	9.89	-	-
Teachers and Medical Education Teams	Number of people	42	-	27	10	2	3	12	-	14	36	13	17	-	-
	Proportion (%)	23.86	-	15.34	5.68	1.14	17.05	6.82	-	7.95	20.45	7.39	9.65	-	-

According to **Tables 2–4**, coaches, team doctors, and athletes have a high degree of consistency in their understanding of knee joint injuries in table tennis players.

5.3. The correlation between table tennis players' technical movements and knee joint injuries

Among the 414 valid questionnaires, almost all respondents unanimously believed that there was a link between completing technical movements and knee joint injuries, as shown in **Table 5**.

Table 5. Statistical results of the correlation between table tennis players' completion of leg techniques and knee joint injuries.

		A	B	C	D	E	F	G	H	I	J	K	L	M	N
Sportsman	Number of people	121	77	-	-	103	113	-	245	8	1	19	-	191	117
	Proportion (%)	12.16	7.74	-	-	10.35	11.36	-	24.62	0.80	0.10	1.91	-	19.19	11.76
Teachers and Medical Education Teams	Number of people	22	14	-	-	18	20	-	44	1	0	3	-	34	21
	Proportion (%)	12.43	7.91	-	-	10.17	11.30	-	24.86	0.56	0	1.69	-	19.21	11.86

According to **Table 5**, among the surveyed subjects, 356 people believed that horizontal kicking could easily cause knee joint injuries in table tennis players during single action practice, followed by double flying kicking (260 people); Horizontal kicking (271 times) is the most likely to cause knee joint injuries in table tennis players during game attacks, followed by double flying kicking (237 times).

Side kicks (289 times) are most likely to cause knee joint injuries in table tennis players during game defense, followed by back kicks (225 times).Among the surveyed subjects, horizontal kicking (770 times) was considered the most likely cause of knee joint injury in table tennis players, followed by side kicking (513 times), and double flying kicking (498 times) ranked third.

The survey results generally believe that knee joint injuries in table tennis players are closely related to kicking movements. It is not difficult to see from the statistical results that the technical movements that cause knee joint injuries in table tennis players are mainly horizontal kicking and side kicking [21].

5.4. Action effect

In this study, we focused on analyzing the biomechanical properties of the knee joint in table tennis using forward and backward impact techniques, and compared the range of motion (ROM) and mechanical load patterns of different athletes when performing these techniques. As shown in **Figure 2**, for the forehand topspin technique, the range of abduction/adduction of the shoulder joint is 38° in the disabled athlete group and 32 (15)° in the control group. Through SPM (Statistical Parameter Mapping) analysis, significant differences (p < 0.001) were observed between the disabled athlete group and the control group throughout the entire waveform from the start to the end of the shot.This result indicates that there are significant differences in shoulder joint movement patterns among different groups during the forehand topspin hitting process, which may be related to differences in technical movement habits and physical functions. For the backhand topspin technique, the range of motion of the shoulder joint is 35° in the disabled athlete group and 24(16)°in the control group.Disabled athletes exhibit significantly different movement patterns during the ball preparation stage (p < 0.001) and the follow-up stage (p = 0.014) (**Figure 2**). These differences reflect that disabled athletes may need to use different exercise strategies to compensate for the limitations of their physical abilities when striking the backhand, in order to achieve effective hitting.

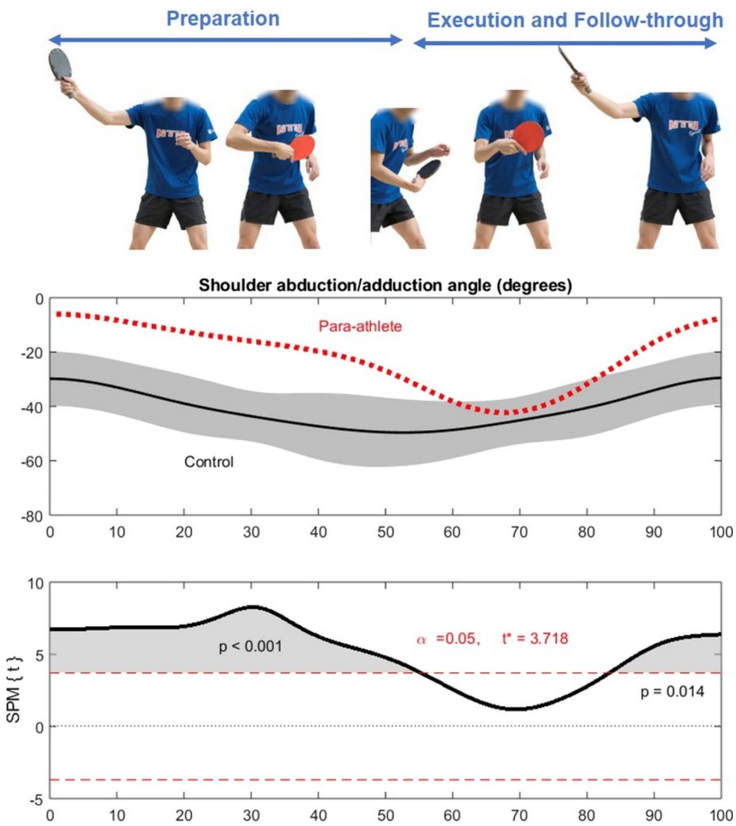

Figure 2. Numerical analysis.

With the use of these numerical analysis results, we were able to identify variations in the mechanical characteristics and movement patterns of the knee joint in table tennis as well as offer valuable resources for the training and recovery of athletes from various backgrounds. We advise maximizing technical motions, lowering the risk of sports injuries, and enhancing the stability and flexibility training of the shoulder and knee joints during training, especially for athletes with disabilities. Meanwhile, by refining the parameters of the mathematical model and integrating it with real-world sports data, we can raise the model's prediction accuracy, create more scientific training and recovery regimens for table tennis players, and improve both their athletic performance and career longevity.

6. Conclusion

In order to shed light on the unique load patterns and mechanical behaviors of table tennis on the knee joint, this work develops a biomechanical mathematical model of the knee joint in table tennis and thoroughly examines the dynamic and kinematic properties of the knee joint in various sporting scenarios. The findings of the study show that during strong table tennis motions, the knee joint experiences considerable shear and compression stresses. It also exhibits notable variations in force characteristics depending on the technical action. This study identifies possible risk factors for knee joint injuries in table tennis players through a thorough investigation of knee joint forces under various workout modalities. The knee joint is the most common location of injury for table tennis players, accounting for 29.49% of all injuries sustained by study participants. The most common injuries among them were meniscus injuries (13.33%), patellar tendinitis and disease (15.11%), and lateral collateral ligament injuries (24.44%).

Author contributions: Conceptualization, WL and SR; methodology, WL; software, WL; validation, WL; formal analysis, WL; investigation, WL; resources, WL; data curation, WL; writing—original draft preparation, WL; writing—review and editing, WL; visualization, WL; supervision, WL; project administration, WL; funding acquisition, SR. All authors have read and agreed to the published version of the manuscript.

Ethical approval: Not applicable.

Funding: This research was funded by the project entitled "The influence of physical activity on college students' smartphone dependence behavior: the chain mediation effect of emotional intelligence and self-control" led by Shanxi Provincial Education Department, grant number 2024W159.

Conflict of interest: The authors declare no conflict of interest.

References

1. Irawan, R., Azam, M., Rahayu, S., Setyawati, H., Adi, S., Priyono, B., & Nugroho, A. (2023). Biomechanical Motion of the Tennis Forehand Stroke: Analyzing the Impact on the Ball Speed Using Biofor Analysis Software. Physical Education Theory and Methodology, 23(6), 918-924.
2. Rigozzi, C. J., Vio, G. A., & Poronnik, P. (2023). Application of wearable technologies for player motion analysis in racket

sports: A systematic review. International Journal of Sports Science & Coaching, 18(6), 2321-2346.
3. Kumar, S., & Das, R. (2024). Championing Olympic Excellence: A Bibliometric Analysis of Biomechanics Impacting Tennis Performance on the World Stage. Physical Education Theory and Methodology, 24(3), 494-503.
4. Fadier, M., Touzard, P., Lecomte, C., Bideau, B., Cantin, N., & Martin, C. (2023). Do serve distance and net height modify serve biomechanics in young tennis players?. International Journal of Sports Science & Coaching, 18(5), 1513-1520.
5. Maheshwari, A., Pal, S., & Pandey, G. (2023). Electromyographic evaluation of upper extremity muscles during forehand and backhand table tennis drives. Journal of Physical Education and Sport, 23(6), 1425-1431.
6. Israel, J. S., Loushin, S. R., Tetzloff, S. U., Ellenbecker, T., Kaufman, K. R., & Kakar, S. (2024). Wrist Motion Assessment in Tennis Players using Three-Dimensional Motion Capture and Dynamic Electromyography. Journal of Wrist Surgery, 13(03), 264-271.
7. Ju, Y. Y., Chu, W. T., Shieh, W. Y., & Cheng, H. Y. K. (2024). Elbow, wrist kinematics and shock transmission of backhand stroke in wheelchair tennis players. Sports Biomechanics, 23(4), 402-416.
8. Fong, D. T., Mok, K. M., Thompson, I. M., Wang, Y., Shan, W., & King, M. A. (2023). A lateral ankle sprain during a lateral backward step in badminton: A case report of a televised injury incident. Journal of Sport and Health Science, 12(1), 139-144.
9. Martin, C., Touzard, P., Horvais, N., Puchaud, P., Kulpa, R., Bideau, B., & Sorel, A. (2023). Influence of shoe torsional stiffness on foot and ankle biomechanics during tennis forehand strokes. European Journal of Sport Science, 23(6), 914-924.
10. Wood, D., Reid, M., Elliot, B., Alderson, J., & Mian, A. (2023). The expert eye? An inter-rater comparison of elite tennis serve kinematics and performance. Journal of Sports Sciences, 41(19), 1779-1786.
11. Grosdent, S., Colman, D., Demoulin, C., Kaux, J. F., Roussel, N., & Vanderthommen, M. (2023). Lumbopelvic motor control in elite tennis players with and without a history of low back pain. Science & Sports, 38(8), 836-844.
12. AbdulsalamWaheeb, A., Tawfeeq, M. I., Raheem, B. A., & Dakheel, H. O. (2024). Comparison Of The Performance Of The Forehandkick (Straight And Accompanied By Forward Rotation) In Terms Of Accuracy And Speed Among The Players Of The National Team (Advanced Category) In Tennis. International Development Planning Review, 23(1), 138-148.
13. Ramasamy, Y., Usman, J., Sundar, V., Towler, H., & King, M. (2024). Kinetic and kinematic determinants of shuttlecock speed in the forehand jump smash performed by elite male Malaysian badminton players. Sports biomechanics, 23(5), 582-597.
14. Nasar, Z., Adnan, M., Zia, M., Qundeel, H. S., & Rahman, M. U. (2024). FREQUENCIES OF SPORT-SPECIFIC INJURIES IN PESHAWAR'S SPORTS COMPLEX. Rehman Journal of Health Sciences, 6(1), 50-56.
15. Özaltın, G. E., Talu, B., & Öktem, U. (2023). Functional Outcomes of Motor Learning Interventions in Anterior Cruciate Ligament Injuries. Arşiv Kaynak Tarama Dergisi, 32(1), 33-41.
16. Crotti, M., Heering, T., Lander, N., Fox, A., Barnett, L. M., & Duncan, M. J. (2024). Extrinsic risk factors for primary noncontact anterior cruciate ligament injury in adolescents aged between 14 and 18 years: A systematic review. Sports Medicine, 54(4), 875-894.
17. Waldzinska, E., Rytelewski, M., & Waldziński, T. (2023). Assessment of the impact of physiotherapy on the frequency of injuries in tennis. Polish Journal of Applied Sciences, 9(1), 22-28.
18. Brich, Q., Casals, M., Crespo, M., Reid, M., & Baiget, E. (2024). Quantifying Hitting Load in Racket Sports: A Scoping Review of Key Technologies. International Journal of Sports Physiology and Performance, 19(6), 519-532.
19. Alsaeed, R., Hassn, Y., Alaboudi, W., & Aldywan, L. (2023). Biomechanical analytical study of some obstacles affecting the development of football players. International Journal of Physical Education, Sports and Health, 10(3), 342-346.
20. Davis, J., Doyle, B., Ishii, H., & Jayanthi, N. (2023). SPORRT—A Comprehensive Approach to the Assessment and Non-Operative Management of Overuse Knee Conditions in Youth Athletes. Current Reviews in Musculoskeletal Medicine, 16(12), 627-638.
21. Emma Farnsworth, Natalie Gomez, Herlandt Lino, Rigoberto Florez, Brendan Rooney, Darren Narayan. Realizing the Asymmetric Index of a Graph, Journal of Combinatorial Mathematics and Combinatorial Computing, Volume 121. 17-29. DOI: https://doi.org/10.61091/jcmcc121-02.