

Dynamic Finite Element Simulation Analysis of Table Tennis Hitting

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Abstract: The process of hitting a table tennis ball involves complex dynamic behaviors, in which the ball's velocity, spin, and deformation characteristics directly affect the shot outcome. Based on the finite element simulation method, this study establishes a simplified model of the interaction between the table tennis ball and the racket. Two typical hitting patterns are simulated in the research: one dominated by impact namely the fast attack technique, while the other dominated by friction, referring to the loop drive stroke. The results indicates that in the impact mode with a normal speed of 20 m/s, the table tennis ball attains a maximum speed of 45 m/s, along with a spin of about 450 rpm. By comparison, in the friction mode with a tangential speed of 20 m/s, the ball spins at about 900 rpm but has a lower outgoing ball velocity at about 9 m/s. The simulation clearly reveals the dynamic patterns of ball deformation, energy transfer, and the evolution of the ball's motion state. It also verifies the regulatory effect of hitting angle and speed on the ball release. This research provides quantitative evidence for the scientific training and equipment optimization in table tennis, while also demonstrating the practical value of finite element simulation in the field of sports engineering.

Keywords: Table tennis; Finite element simulation; Ball dynamics; Spin; Speed

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1. Research background

Table tennis, renowned as the “national sport” of China, is an indoor racket game that enjoys widespread popularity worldwide, across all age groups. Originating in the late 19th century in the United Kingdom, it was initially conceived as an after-dinner leisure activity played on dining tables, using cigar box lids as paddles and champagne corks as balls. Consequently, it was originally known by that name. With the continuous advancement in equipment, such as the invention of the hollow celluloid ball, the emergence of rackets with rubber pimples or sponge rubber, along with the refinement of rules, table tennis has gradually developed into a highly technical, fast-paced and highly variable competitive sport with strong spectator appeal. In 1926, the International Table Tennis Federation (ITTF) was established, followed by the launch

of the first World Table Tennis Championships, marking the sport's move toward standardization and internationalization. As illustrated in **Figure 1**, athletes are engaged in table tennis competition. In 1988, table tennis was officially included as an Olympic sport. For many years, the Chinese table tennis team has occupied a dominant position in international competitions, which has helped boost the sport's spread and growth nationwide^[1].



Figure 1. Table tennis.

The essence of table tennis can be summed up as follows: two or four players stand on opposite sides of a net, using rackets to alternately hit a hollow plastic ball. This ball measures about 40 mm in diameter and weighs roughly 2.7 g. Early versions of the ball were made of celluloid. The basic way to score is to legally hit the ball over the net onto the opponent's side of the table, leaving rivals unable to return properly or directly commit faults. The sport is characterized by high speed, with professional players able to hit the ball at speeds above 100 km/h. It also features intense ball spin that peaks at 150 rad/s, alongside rich and changeable tactical layouts during actual matches^[2]. **Figure 2** presents the basic spin forms of table tennis. By adjusting the force applied and the racket angle when the rubber contacts the ball, players can produce multidimensional spin, such as combinations of basic spin, and control the ball's landing point, which helps them gain a technical advantage in play. The process of hitting a ball involves complex physical phenomena, including ball deformation, energy transfer, and frictional mechanics. Traditional training methods rely on experience and high-speed image analysis, making it difficult to quantify the dynamic mechanisms upon at the instance of impact^[3,4].

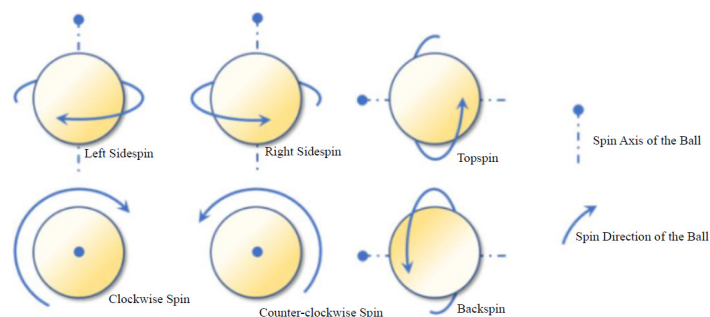


Figure 2. The basic spin form of a table tennis ball.

Finite element simulation technology provides a new approach to overcoming this limitation. As an advanced numerical simulation technique, finite element analysis works by dividing complex continuous entities into many tiny, interconnected simple elements called finite elements. By building a computational model, specifying material properties (such as elastic modulus, density, Poisson’s ratio), boundary conditions, and loads, and using physical laws to solve for responses (displacement, stress, strain, etc.) of each element and node, the detailed behavior of the entire model under the applied forces is obtained, as shown in **Figure 3**. Taking table tennis hitting as an example, the finite element method can discretize the ball, the racket’s rubber–sponge layers, and even the blade into finite elements. Boundary conditions can be prescribed (fixing the racket handle), and impact scenarios can be simulated in which the ball is returned or struck at specified velocities and angles. The governing equations, based on Newtonian mechanics and material constitutive relations, are then solved to obtain the fundamental dynamic behavior of the ball-racket interaction during the hitting process ^[5,6].

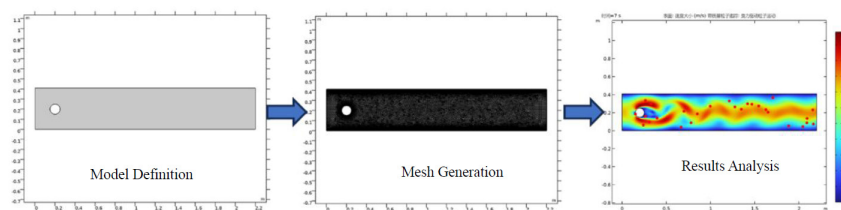


Figure 3. Finite element analysis method.

This study aims to develop a simplified model for the interaction between the table tennis ball and the racket by using dynamic finite element simulation. This model allows to simulate the dynamic process at the exact moment of impact, and analyze the effects of key factors, such as shot speed, angle, equipment properties on the shot outcome (i.e., ball speed and spin). The significance of this study lies in:

- (1) Advancing scientific understanding: This study provides quantitative scientific evidence for the biomechanics and equipment mechanics of table tennis, and converts the empirical “hand feel” into computable physical quantities;
- (2) Assisting training and equipment optimization: It offers potential guidance for the mechanical optimization of technical movements in table tennis practice and for design improvements by equipment manufacturers;
- (3) Developing integrated competencies: This study effectively integrates knowledge from physics (mechanics, materials), mathematics (modeling, computation), computer science (simulation software), and sports science. In doing so, it strengthens core research skills, including literature review, model development, numerical computation, result analysis, and scientific writing;
- (4) Access to cutting-edge tools: Finite element analysis is a core tool widely used in engineering and science. This study provides a valuable opportunity for early exposure and hands-on experience.

2. Research content

2.1. Basic dynamics analysis of table tennis hitting

Table tennis hitting is a highly coordinated kinetic chain, involving the synergistic movement of multiple body segments and the precise interaction between the racket and the ball. As shown in **Figure 4**, according to the principles of sports biomechanics, the complete stroke can be divided into the following six basic steps:

- (1) Ready positioning: The player adjusts the relative position between the body and the incoming ball through footwork, thereby creating optimal conditions for the stroke;
- (2) Backswing: A preparatory motion in which the racket is moved backward and downward, or laterally backward before hitting the ball;
- (3) Swinging toward the ball: The phase in which the racket accelerates from the backswing position toward the ball, typically in a forward-upward (or forward-downward) trajectory;
- (4) Contact: The moment when the racket touches and collides with the ball;
- (5) Follow-through: The phase in which the racket continues along its original trajectory after hitting the ball;
- (6) Recovery: The phase in which the player rapidly returns to the ready position in preparation for the next stroke.

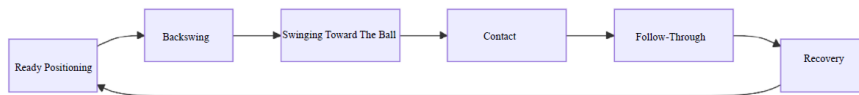


Figure 4. Basic steps of the table tennis hitting process.

According to the speed and power of the shot, table tennis shots are mainly classified into fast attacks, loop shots, defensive shots, etc. Fast attacks primarily rely on impact between the racket and the ball, aiming for high-speed, low-arc shots. The loop shot is characterized by intense friction between the racket and the table tennis ball. The ball has very strong spin while maintaining a relatively high speed and high arc. Defensive shots, on the other hand, rely on using momentum to return the ball, with lower speed and minimal spin variation.

From a dynamical perspective, the table tennis stroke can be primarily characterized as a coupled process of impact and friction between the racket and the ball. As shown in **Figure 5**, the ball strikes the racket with a velocity v . When the racket speed is normal, that is, perpendicular to the racket face, the interaction is dominated by impact, corresponding to a fast attack. When the speed of the racket is tangential to the racket face (i.e., parallel to the surface), the interaction is dominated by friction, corresponding to the loop drive. In actual hitting, different angles of the racket face significantly affect the ball's motion state (direction of speed, form of spin). To simplify the analysis, the subsequent simulations model the ball–racket interaction within a two-dimensional plane.

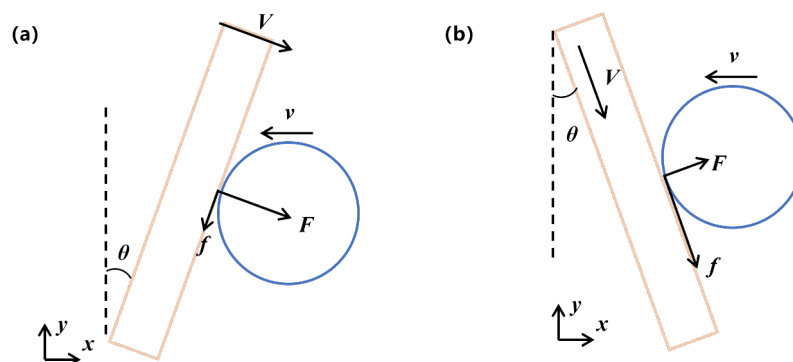


Figure 5. Analysis of the dynamics of table tennis hitting. (a) Impact-dominated; (b) Friction-dominated.

2.2. Finite element analysis of table tennis hitting

2.2.1. Basic process of finite element simulation analysis

The basic process of the finite element simulation analysis is illustrated in **Figure 6**. The main steps are:

- (1) Construct a physical model of the structure based on the designed underwater rapid-impact device;
- (2) Define the connections between components in the model (e.g., whether they are independent or bonded);
- (3) Assign corresponding materials to each structure in the model, including density, Young's modulus, Poisson's ratio and other basic properties of the materials;
- (4) Introduce the physical field according to the actual simulation requirements. The physical field mainly used in the simulation of this project is the solid mechanics physical field for analyzing the motion and collision of the structure;
- (5) After selecting the physical fields, the objects that need to be calculated for each physical field are defined based on the roles of individual structures during device operation as identified in the theoretical analysis;
- (6) Configure the basic parameters for each physical field and the boundary conditions of the structure, such as whether the connection mode of the device is free or motion-constrained;
- (7) Generate the computational mesh, and select suitable element types according to the structural features, with additional treatment for geometrically complex regions where necessary;
- (8) Set up the study mode (e.g., time-domain or frequency-domain analysis) and define the solver required for the computation;
- (9) Extract the calculated simulation data for post-processing.

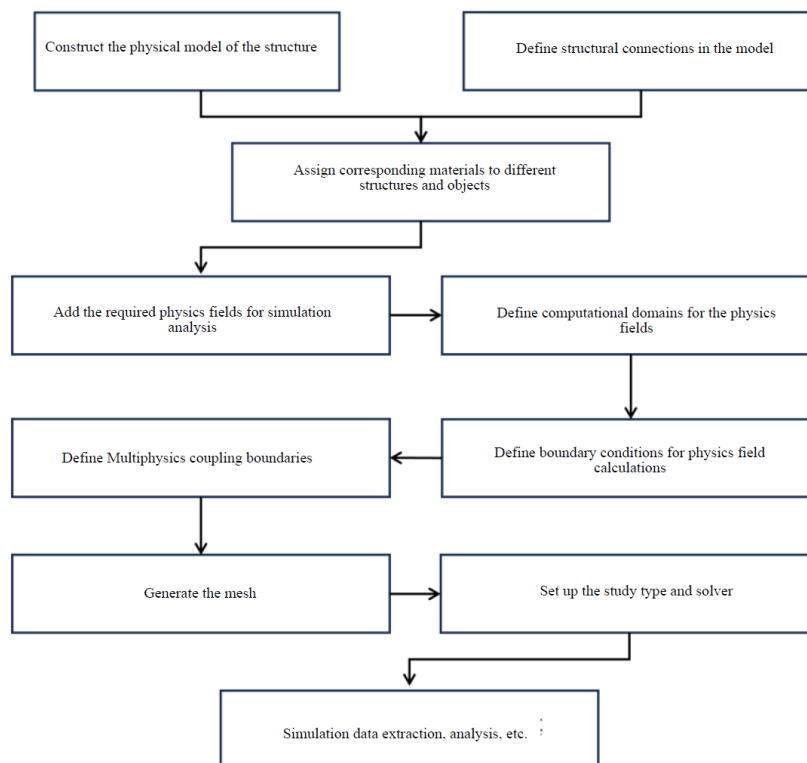


Figure 6. Basic process of finite element analysis.

2.2.2. Finite element simulation of the hitting process

As illustrated in **Figure 7**, geometric models are constructed for two representative stroke scenarios. The table tennis racket is simplified as a rectangular prism of $80 \times 80 \times 10 \text{ mm}^3$, and the ball is a shell with an inner diameter of 19 mm and an outer diameter of 20 mm. In terms of material, to reduce the computational load of the finite element simulation, the material of the racket is simply set to oak board with the following basic parameters: density 630 kg/m^3 , Young's modulus 12.4 GPa , Poisson's ratio 0.3 ; the table tennis ball is defined as a hyperelastic material with the following basic parameters: density 1020 kg/m^3 , Lamé parameter λ : 8 GPa and μ : 0.8 GPa . The hyperelastic model adopted for the ball material is the Neo-Hookean model. In terms of physical fields and boundary conditions, the solid mechanics physics field is employed. The racket is assigned normal and tangential initial velocities to simulate impact-dominated hitting and friction-dominated hitting, respectively. In addition, to simulate the swinging motion, the boundary condition is set such that one side of the racket maintains a swing displacement before and after the stroke, analogous to a player's hand maintaining motion after hitting the ball. As illustrated in **Figure 8**, the configuration corresponding to the impact-dominated case is presented as an example.

Furthermore, in terms of meshing, **Figure 9** illustrates the graded mesh established for the table tennis hitting process (taking the impact-dominated case as an example). It can be observed that since the table tennis ball undergoes significant deformation during impact, the mesh on the ball is noticeably finer to ensure sufficient computational accuracy. Meanwhile, to save computational time and resources, and to improve efficiency, the mesh on the racket part is relatively coarser.

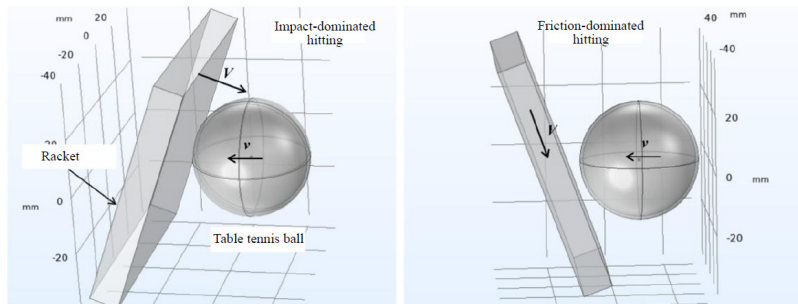


Figure 7. Table tennis ball hitting simulation model.

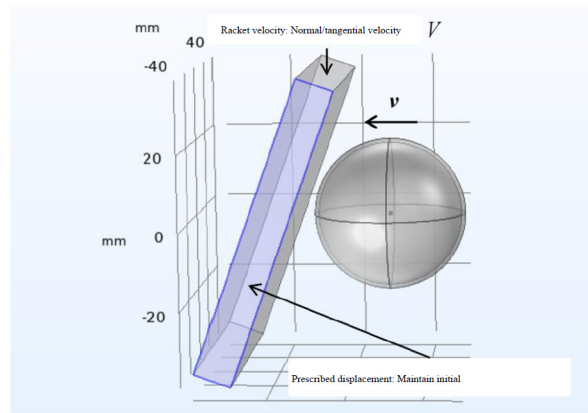


Figure 8. Setting of physical field boundary conditions during table tennis hitting.

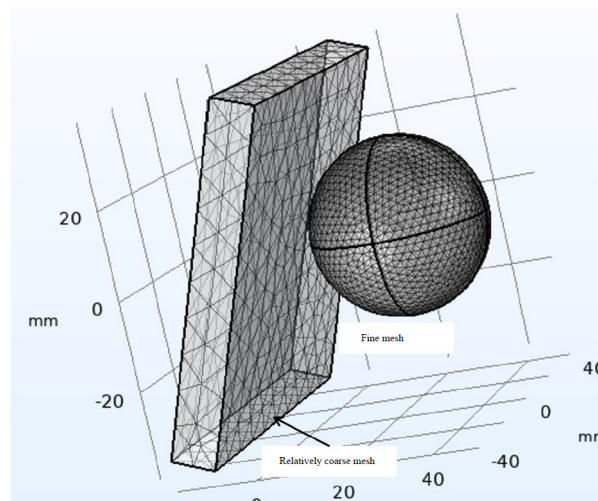


Figure 9. Meshing of the table tennis hitting process.

3. Results and discussion

A transient analysis is performed on the finite element simulation models of the two stroke patterns, covering the entire stroke event, including the instant before the stroke, the stroke phase, and the instant after the stroke.

3.1. Analysis of results for the impact-dominated model

In this mode, the racket attack angle is set to 20° , and the racket speed is prescribed as 20 m/s in the normal direction. Such a velocity can generally be achieved through coordinated whole-body force generation (e.g., leg drive, torso rotation, and arm swing), which significantly increases the swing speed. Meanwhile, the table tennis ball is set with a right-to-left velocity of 5 m/s. To simplify the system in the simulation, this velocity is represented as an additional relative velocity between the ball and the racket; specifically, this horizontal velocity is superimposed on the racket motion.

As shown in **Figure 10**, at 0 ms, the racket moves at high speed towards a stationary ball. At around 0.2 ms, the racket touches the ball. The left side of the table tennis ball begins to gain a certain speed, while the right side remains stationary due to inertia. As time progresses, the ball reaches its maximum deformation at 0.3 ms, at which point the velocity of the entire ball significantly exceeds the racket speed. At around 0.4 ms, the ball begins to leave the racket. **Figure 11** presents the strain distribution of the ball during the stroke process, where the deformation of the ball corresponds to the variation of ball velocity.

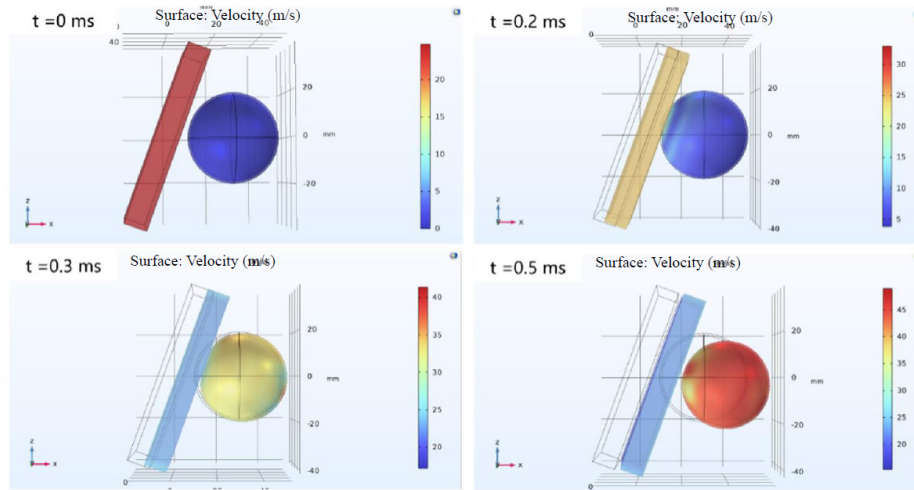


Figure 10. Simulated velocity distribution during the impact-dominated table tennis hitting process.

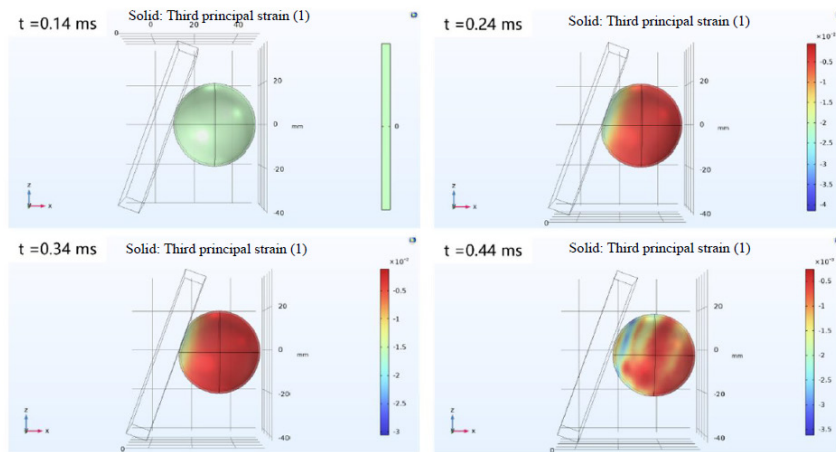


Figure 11. Strain distribution of the table tennis ball during the impact-dominated table tennis hitting process.

Figures 12, 13 and 14 illustrate the variations of parameters during the stroke. **Figure 12** presents the velocity distribution of the racket and ball. Once the racket hits the ball, the ball velocity increases rapidly according to the impulse-momentum theorem. At the same time, the racket's velocity drops a little, which is simply the result of the reaction force. As the swing process continues, the racket velocity gradually recovers. At this point, the ball velocity becomes significantly higher than the horizontal velocity of the racket. After the ball leaves the racket, its velocity remains nearly constant. Since the racket has a certain attack angle, the friction during the hitting also gives the ball some spin, as shown in **Figure 13**. **Figure 14** shows the energy changes of the ball during the hitting process. The kinetic energy change in the ball corresponds to the variation of ball velocity, while the change in its potential energy reflects the deformation of the ball.

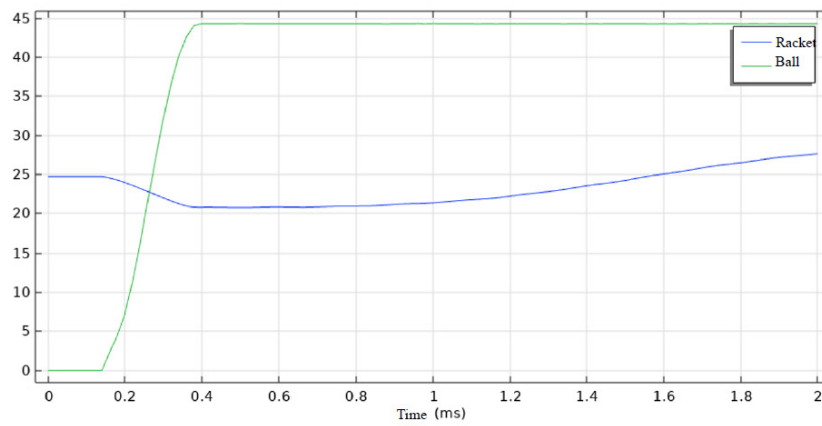


Figure 12. Velocities of the racket and table tennis ball during the impact-dominated hitting process.

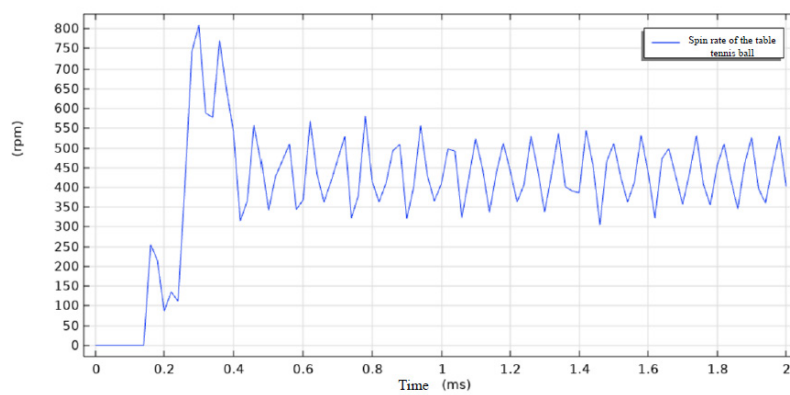


Figure 13. Spin rate of the table tennis ball during the impact-dominated hitting process.

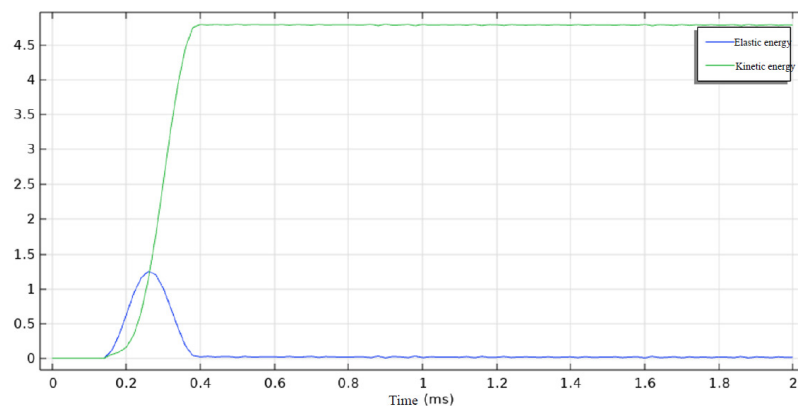


Figure 14. Energy of the table tennis ball during the impact-dominated hitting process.

3.2. Analysis of results of the friction-dominant model

In this mode, the racket is set with an attack angle of -20° and a tangential velocity of 20 m/s. Meanwhile, the table tennis ball is configured with a right-to-left velocity of 5 m/s. To simplify the system in the simulation,

this velocity is treated as an additional relative velocity between the ball and the racket. Specifically, this horizontal velocity is added to the racket.

During the friction-dominated hitting process, the racket moves mainly along the tangential direction. As shown in **Figure 15**, the racket touches the ball at around 0.71 ms, during which the ball is subjected to a substantial frictional force. As contact proceeds, the ball reaches its maximum deformation at 0.83 ms and begins to leave the racket at around 1 ms. **Figure 16** shows the strain distribution of the ball during the hitting process. The deformation of the ball corresponds to the variation of ball velocity.

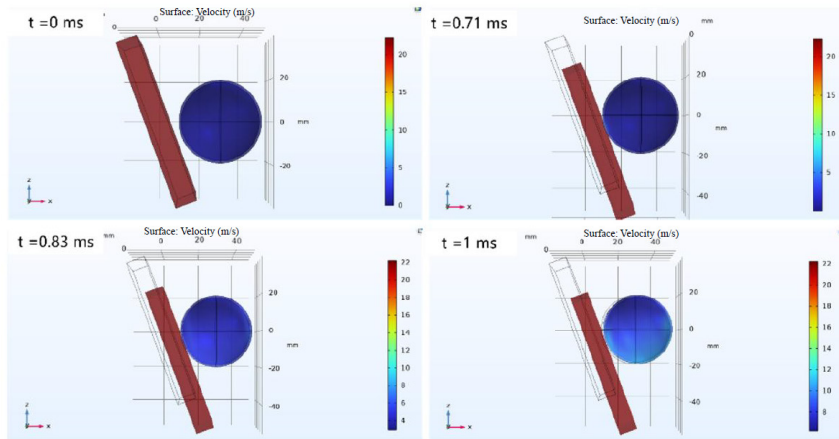


Figure 15. Simulated velocity distribution of the friction-dominated hitting process.

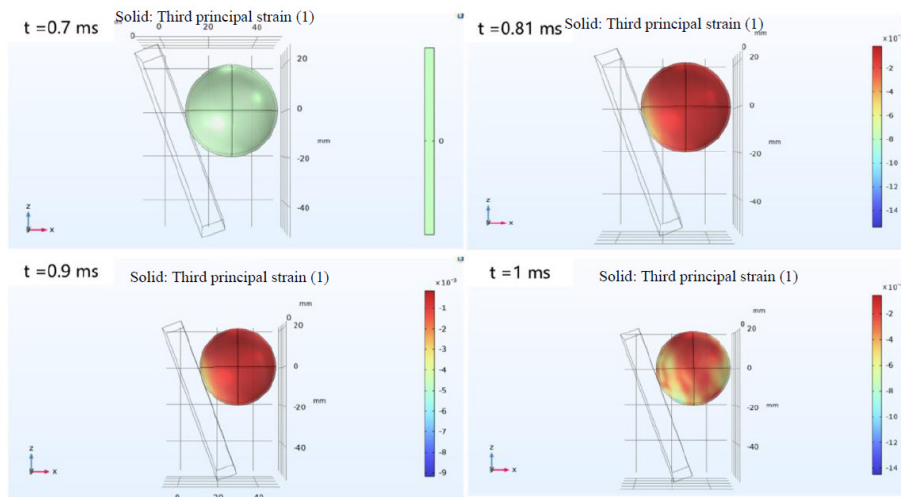


Figure 16. Strain distribution of the table tennis ball during the friction-dominated table tennis hitting process.

Figures 17, 18 and 19 show the variations of parameters during this hitting process. **Figure 17** shows the velocity distribution of the ball and racket. Since the process is friction-dominated, the ball speed is not very high, and the racket velocity only fluctuates slightly during the hitting process. **Figure 18** presents the spin of the ball during this process. The rotational speed of the ball is significantly higher than that in the impact-dominated hitting process. **Figure 19** shows the energy variation of the ball during this hitting process. The changes in the kinetic energy of the table tennis ball in accordance with its velocity variation,

while the changes in its potential energy reflect the deformation of the ball.

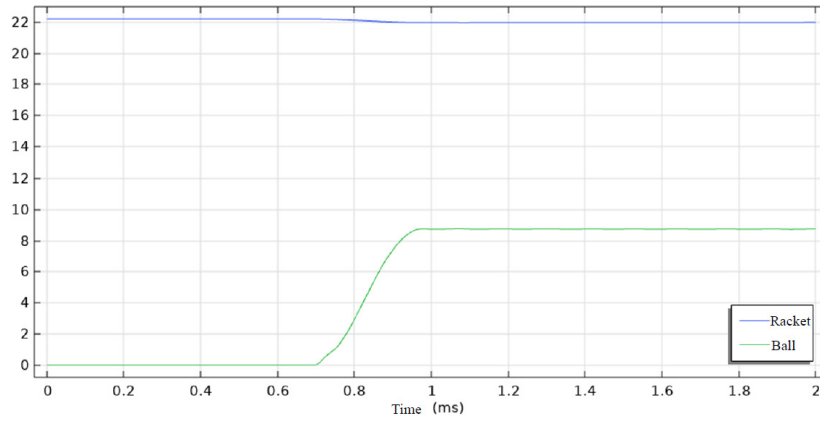


Figure 17. Velocities of the racket and table tennis ball during the friction-dominated table tennis hitting process.

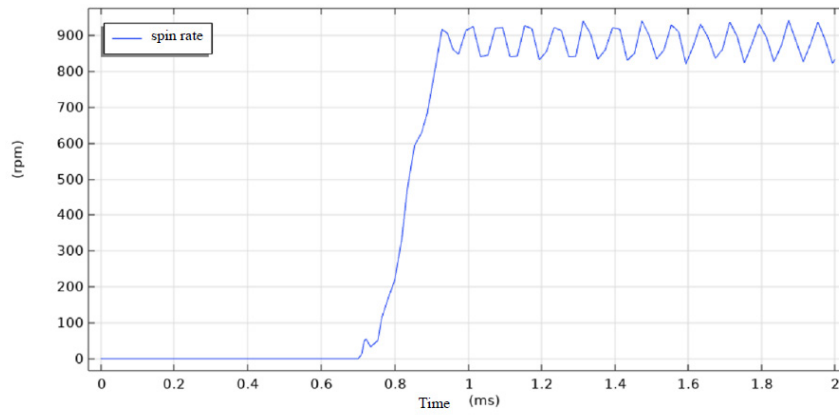


Figure 18. Spin rate of the table tennis ball during the friction-dominated hitting process.

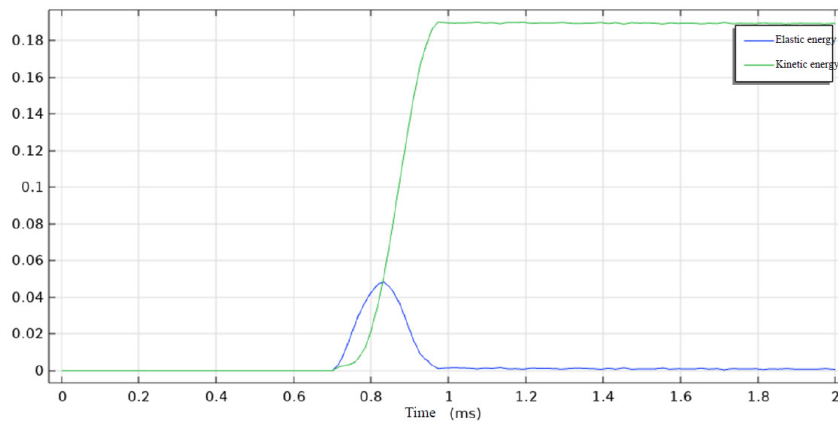


Figure 19. Energy of the table tennis ball during the friction-dominated stroke process.

4. Conclusion

This study, through finite element simulation method, systematically analyzes the dynamic behavior during table tennis hitting process. It explores the mechanical traits and movement patterns of two typical hitting modes: impact-dominated and friction-dominated. In the fast attack mode dominated by impact, the racket moves at a normal velocity of 20 m/s and creates a prominent impact effect. This propels the ball away at 45 m/s, while its rotational speed settles near 450 rpm. Meanwhile, the loop drive technique depends mainly on friction. When the racket moves at a tangential velocity of 20 m/s, it brings about intense ball rotation around 900 rpm, though the ball travels at a much lower outgoing speed of roughly 9 m/s. The simulation results present the dynamic process of ball deformation, energy conversion, as well as the variation of velocity and rotation. These findings offer a mechanical foundation for scientific table tennis training. They also converts players' intuitive hitting feelings into physical data, and further show that the finite element method holds real promise in sports engineering research. In the future, subsequent research can integrate actual equipment parameters and human motion data to establish a more refined hitting simulation model. This will deliver more in-depth theoretical support for technical improvement and sports equipment development.

Disclosure statement

The author declares no conflict of interest.

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