Biomechanics of Table Tennis

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Table tennis is a popular recreational and competitive sports at all levels. Recent research on table tennis maneuvers identified the differences between playing levels and between maneuvers using parameters which included ball and racket speed, joint kinematics and kinetics, electromyography, and plantar pressure distribution. Different maneuvers underlined changes on body posture and lines of movement which were accommodated particularly by the racket face angle, trunk rotation, knee and elbow joint movements, and thus different contributions of muscles. Higher-level players produced ball and strike at higher accuracy and repeatability but not necessarily lead to higher speed. In addition, higher-level players utilize superior whole-body coordination and footwork to compromise between agility and stability for a quality strike. Strengthening shoulder and wrist muscles could enhance the speed of the strike while personalized training shall be considered since motor coordination and adaptation vary among individuals.

Keywords: kinematics ; kinetics ; table tennis ; ping pong ; racket

1. Introduction

Table tennis is one of the most famous competitive and recreational sports worldwide [1]. A previous survey estimated that almost 300 million people participate in table tennis across countries [2], while a recent report indicated that China has more than 300 million recreational table tennis players [3]. In 2016, another survey reported about 100 thousand people aged 16 or over have played table tennis for at least 30 minutes a week in England. In the United States, more than 16 million people have played table tennis [4]. By 2016, there were 40 million competitive table tennis players registered worldwide [1].Table tennis was originated from lawn tennis on the dining table during winter with improvised equipment since 1880s [5]. In 1883, Ralph Slazenger is believed to describe a game mechanism by passing ball over a net and with reference to ordinary tennis to be played indoor (Great Britain Patent, No. 3156, dated 26 Jun 1883). The game is played on a standard rectangular table using a lightweight hollow ball and small rackets (bats). To win a game, the player has to hit a ball over the net and land on the opponents' table until the one cannot return the ball properly. A good understanding of movement, ball and racket mechanics would be insightful to produce effective strokes.

Table tennis is a competitive sport which requires technical preparation, tactics, mental and motor training [6]. Players with higher technical capability demonstrate good coordinated movement with controlled strike power, which yield adequate speed and spin on the ball in limited decision time [7][8]. To master the stroke, professional players have to rotate the trunk efficiently and place excellent foot drive in response to various ball conditions [7]. Whole-body coordination plays an important role in table tennis, as biomechanics of lower extremities is closely related to upper limb performance [9]. An incorrect technique would alter movement mechanics and thus joint loading that are related to risk potential of injury. A retrospective study found that about one-fifth of table tennis players suffered from shoulder injuries [10]. Although numerous studies have investigated the biomechanics of table tennis maneuvers, their methods and protocols were generally inconsistent. Therefore, a direct comparison across studies is not feasible. Furthermore, players of different skill levels may perform table tennis maneuvers with unique techniques and patterns. To identify the general characteristics of higher-level players, an investigation has to be conducted properly mapping playing levels with different maneuvers. Such information can help in designing sport-specific training programs in table tennis.

2. Classification of Movement Stage or Phase

While some biomechanical studies adopted the maximum or submaximal performance effort of strokes, the majority of these studies divided a stroke into movement sub-phases or targeted to selected events for subsequent analyses. Typically, a stroke was classified into backswing and forward-swing phases, targeted on the specific time points at the termination, backward-end and forward-end [6][8][11][12][13][14][15][16][17]. A few biomechanical studies [7][16][18][19][20][21] focused on the instant at ball impact which was used to determine the velocity of the racket and ball, while some other studies investigated the biomechanics at pre-impact and post-impact stages [19][21][22][23], and over a longer period of time before and after the instant of ball contact [6][7][23][24]. Some other studies endeavored that the pelvic and hip rotations were correlated with the racket velocity at ball impact and thus focused on the starting time of the pelvic forward rotation [21][22].

3. Research on Playing Levels

3.1. Ball and racket performance

Ball speed, accuracy, and repeatability are suggested to be the key indicators of playing level. Ball speed and accuracy were significantly correlated with player ranking in a competition [25]. Higher-level players would produce higher ball speed and accuracy, which could be due to significantly shorter duration and lower variability of duration in the forward swing phase [14][15][23][26].

However, racket speed at impact was not significantly different between playing levels (advanced vs. intermediate), although players with higher-level can rotate the trunk effectively to produce a greater racket acceleration at ball impact [19]. Similarly, another study found that while there was only a slight difference in ball speed comparing higher- and lower-level players, players with higher-level demonstrated higher accuracy of ball target placement and made fewer errors in training and competition [27].

On the other hand, inexperienced players showed lower consistency in ball speed and accuracy during within-day trials and between-day trials [25]. Compared to the intermediate players, advanced players showed a smaller variance of joint angle that affected the racket vertical angle during forehand topspin stroke [26]. Furthermore, a lower variability in racket orientation and movement direction could be the reason for more successful returns and higher accuracy of the ball bounce location [23]. An uncontrolled manifold analysis suggested that higher-level players exploited a higher degree of redundancy to maintain a consistent racket angle at ball impact [26]. In brief, higher-level players exhibited higher accuracy and reproducibility on ball and racket mechanics but may not necessarily produce higher ball speed than lower-level players.

3.2. Upper limb performance

Higher racket speed and faster ball rotation are the key attributes of an attacking shot and these could be determined by the kinematics/kinetics of the upper extremity as well as the efficiency of energy transfer through the upper arm [28][29]. Higher-level players showed significantly larger maximum shoulder internal rotation, elbow varus, and wrist radial deviation torques, in addition to the maximum joint torque power at the shoulder joint in both internal and external rotation directions [29]. Higher angular velocity of the wrist joint contributed to a higher ball and racket speed during drop shot service, while that also produced higher racket speed during long shot service [30].

Moreover, higher-level players rotated the lower trunk (pelvis) efficiently contributing to higher racket speed at ball impact [19]. Meanwhile, the racket horizontal velocity at ball impact was related to the hip axial rotation torque at the playing side (i.e., racket side), while the racket vertical velocity was correlated with the backward tilt torque and upward hip joint forces [21]. In contrast, players with shoulder impingement syndrome demonstrated sub-optimal coordination and movement patterns of the shoulder girdle [31]. These players significantly reduced muscle activity of the serratus anterior and supraspinatus muscles, which was compensated by increased the overall muscle activity and earlier firing activation of the upper trapezius [31]. Whole-body coordination and movement would play an important role in driving a speedy ball impact.

3.3. Lower limb performance

When executing forehand topspin loop, higher-level players increased the knee external rotation, hip flexion and decreased ankle dorsiflexion during the backward end, and increased hip extension and internal rotation, decreased ankle and knee internal rotation during the forward end phase. There was an overall increase in ankle sagittal RoM as well as hip sagittal and coronal RoM [11]. When performing backhand crosscourt loop against backspin ball, higher-level players increased ankle dorsiflexion, eversion and external rotation, increased knee flexion and abduction and increased hip flexion, adduction, and external rotation at the beginning of backswing, as well as increased ankle dorsiflexion, knee flexion, reduced hip flexion but increased abduction at the end of swing [12]. During cross-step footwork, higher-level players executed superior foot motor control, as indicated by a smaller RoM of forefoot-rearfoot and ankle joints and higher relative load on the plantar toes, lateral forefoot and rearfoot regions [17]. The study also demonstrated smaller forefoot plantarflexion and abduction during cross-step ending but larger forefoot dorsiflexion and adduction during forward end [17]. Effective coordination of lower limb facilitates better upper body rotation in higher-level players [24].

Inter-individual and intra-individual variabilities of kinematic parameters could be quite high for table tennis players but players attempted to minimize variability at critical moments, such as the ball impact instant [16]. The higher inter-individual variability could also imply that the technique of coordination movement is rather individual. Adopting or imitating a particular training regime has to pay more attention.

Plantar pressure was used to evaluate foot loading among different playing levels. When performing forehand loop during the backward end phase, higher-level players displayed larger plantar pressure excursion in the medial-lateral direction but smaller in the anterior-posterior direction, accompanied by the increased contact areas at midfoot and rearfoot regions while decreased contact area at lesser toe region [8][11]. During forward end, higher-level players similarly decreased the plantar pressure excursion in the anterior-posterior direction compared with intermediate players. The contact areas were increased for midfoot, rearfoot, and forefoot regions while decreased at the hallux region [8][11]. The change of plantar pressure excursion and contact area could reflect the strategy in compromising dynamic stability and agility in different movement directions.

4. Research on Different Maneuvers

4.1. Ball and racket kinematics

Compared to topspin serves, returning backspin serves demonstrated significantly higher resultant and vertical racket velocities at ball impact [18][22], which could be contributed greatly by the wrist extension [18]. A possible explanation is that backspin serves tend to be treated back-low owing to the spin, resulting in a greater upward velocity of the shoulder joint center [22]. Moreover, the peak shoulder torques in all directions, as well as elbow valgus torque, were significantly larger against backspin, in addition to the peaks of the upper trunk right axial rotation and extension velocities [22]. Returning a spinning ball also alters the moving distance and velocity of the racket in the upward-downward direction, as compared to an ordinary stroke or a stroke with higher power. Hitting back a backspin serve could be of higher mechanical demanding than that of topspin serve.

Comparing between the returns between light and heavy backspin serves, the heavy spin would direct the racket to be more open [19] and higher maximum loading at elbow and shoulder joints which might result in higher work done at the racket arm [29]. However, higher-level players showed a higher amount of energy transfer of the elbow for a light spin compared to intermediate players, but the opposite was true for the heavy spin [29], implying significant interaction effect between ball spin and playing level.

On the other hand, a heavier racket could impose higher demand on the wrist extension torque, but did not influence the trunk and racket arm kinematics and kinetics [20]. Returning frequent ball serves at higher frequency could result in a lower racket speed at impact possibly since pelvis and upper trunk rotations were not responsive enough. Table tennis players managed to identify the differences in ball spin, frequency and mass, and accommodated by tilting the racket face and adjusted the power output of the upper limb joints.

4.2. Upper limb biomechanics

Comparing forehand and backhand strokes, racket speed during ball impact was similar but presented differences in the upward and forward velocity components [6]. Forehand stroke lasts slightly longer duration for whole movement cycle and individual phases, and noticeably longer total traveling distance of the racket. This could be because forehand had a greater body involvement while the arm and trunk movement RoM in backhand stroke is limited. Forehand stroke would produce more energy, whilst a longer backswing phase in the high-force condition would generate higher force and longer contact time with the balls [6]. The racket velocity produced by forehand and backhand strokes could also be different. During forehand stroke, the racket velocity was correlated with angular velocities of internal arm rotation and shoulder adduction, whereas the racket velocity was correlated with angular velocities of arm abduction and shoulder rotation during a backhand stroke [7].

A longline forehand topspin produced larger ball rotation, compared to the crosscourt topspin shot. At the instant of the maximum velocity of racket in a forehand topspin stroke, players put their racket more inclined whilst maintaining a more flexed knee and elbow posture, in addition to a more pronounced trunk rotation [32]. Other maneuvers including loop, flick, fast break, and curling ball were also studied [18][33][34]. Compared to curving ball, fast breaking significantly reduced racket speed during ball impact [34]. While the flick maneuver was specified as an attack when the ball is closed to the net, there were no detailed explanations on the moves of the fast break and curling ball in which we believed that they could be the flick/drop shot and topspin/sidespin loop maneuvers, respectively. On the other hand, aggressive strokes exhibited greater muscle activities [33]. During smash, biceps femoris, gluteus maximus, gastrocnemius, and soleus muscles were highly activated. Forehand topspin with more power or spin produced significantly higher muscle activation for the biceps femoris and gluteus maximus muscles compared to other maneuvers, including backhand top, forehand smash, and flick.

4.3. Lower limb biomechanics

Different footwork targeting side versus cross-step [9], long versus short chasse step [35], stepping directions and friction [36], and squatting [13], were investigated, while one study compared players of different levels performing a cross-step [17].

Both side-step and cross-step footwork produced significantly higher ground reaction force, knee flexion angle, knee moment, ankle inversion and moment compared with one-step footwork, in addition to a significantly higher peak pressure on the total foot, toe, first, second and fifth metatarsal regions [9]. On the other hand, long and short chasse steps during a forehand topspin stroke were compared [35]. Long chasse steps produced an earlier muscle activation for the vastus medialis, quicker angular velocity, and larger ankle and hip transverse RoM, whereas larger ankle coronal RoM and hip sagittal RoM compared with the short chasse steps [35]. A stable lower limb support base is another important attribute to tackle serve.

Compared to a stand serve, a squat serve produced larger angles and velocities of hip flexion, adduction, knee flexion, and external rotation as well as ankle dorsiflexion, whereas standing serve produced a higher force-time integral in the rearfoot region [13]. Different stepping angle and footwear friction could also influence the center of mass and knee kinematics, respectively [36]. Different footwork imposed distinct lower limb kinematics required for tablekinematics; kinetics; table tennis; ping pong; racket tennis players.

5. Summary and Perspective

This scoping review [37] was conducted on 13 July 2020, covering electronic databases including ISI Web of Science (excluding patents, from 1970), Scopus (from 1960), and PubMed (from 1975) using the search terms “table tennis” AND the terms “biomechan*” or “kinematics” or “kinetics” in the topic field. This review summarize information from 29 eligible studies which were original research articles either case-control or longitudinal studies investigating playing levels or differences in maneuvers published in English peer-reviewed journals.

Higher-level players may not necessarily produce higher ball or racket speed. Shoulder joint seems to play an important role to coordinate an effective stroke, as indicated by the effective use of elbow flexion torque, while the power of the wrist joint is important during a drop shot or long shot service. On the other hand, lower extremities facilitated momentum generation for increased racket velocity. In fact, leg-hip-trunk kinetics is accounted for more than half of the energy and muscle force generation in racket sports [11]. Apart from shorter swinging time, the increase in hip flexion and knee external rotations for higher-level players would potentially facilitate a more efficient muscle output to generate racket velocity through the kinetic chain [11][12], in addition to larger hip and ankle angular velocities [11] which could be correlated with an increased ball speed after ball impact [38]. It should be noted that body coordination movement varies between individuals and trials but players attempted to reproduce movement during critical instants [16]. This was known as functional variability such that players could adapt to the conditions and requirements of the tasks and compensated for the changes with other tested parameters [39]. An optimal training model of body movement could be different among athletes.

Techniques in footwork could play an important role in compromising between dynamic stability and agility to recover back to the ready position for the next move/stroke. Less experienced players tended to have a larger peak ankle dorsiflexion and anterior center of pressure but lesser contact area, which indicated a weaker support base and stability [8][11]. Additionally, shorter center of pressure in the anterior-posterior direction in the higher level players facilitate quicker responses to resume to a neutral position for the next move [8][11]. However, it should be noted that higher level players exhibited larger ankle RoM during the match which may inherit the risk of ankle sprain [11][12].

Majority of the existing studies did not report clearly the source of the population and sampling method. There was also a lack of blinding. Although blinding the maneuver conditions seemed to be impossible since the participants needed to be acknowledged for the tasks they performed, it could be accomplished by counting successive returns from delivering random serves by the coaches or serving robots [13][27]. Furthermore, implementation of randomized cross-over design across various interventions, such as different maneuvers, is necessary to avoid carry-over effects. Future studies can investigate how technologies can improve the training outcome. For instance, augmented reality (AR) technology with different filmed footages of different balls and gaze information can be modulated with artificial intelligence program to simulate the opponent with similar playing levels. Such simulations would provide a stepping stone towards individualized training solutions. On the other hand, several studies investigated a large number of outcome variables which were not well justified. While a full biomechanical profile with a large number of outcome variables were endeavored, statistical analyses were performed without corrections for multiple or multivariate comparisons. This may fall into the trap of data dredging or p-hacking [40] and those research may confine to exploratory studies [41].

In summary, we found that most investigations focused on upper and lower limb biomechanics of table-tennis players performing different maneuvers, fewer studies looked into trunk kinematics and EMG among. In addition, our study identified research gaps in backspin maneuvers and longline maneuvers, strikes against sidespin, and pen-hold players that warrant future investigations. Computation simulations could also be implemented to investigate the internal stress and strain of the foot and ankle complex upon impact in different footwork and the implications of footwear [42][43].

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