Int. j. racket sports sci. vol. 6(1), 2024, 9-20. eISSN: 2695-4508
Original Investigation
DOI: 10.30827/---

The Influence of Tennis Serve Kinematics on Ball Impact Sound and Post Impact Ball Speed and Spin

Influencia de la cinemática del servicio de tenis en el sonido del impacto de la pelota y en la velocidad y el efecto de la pelota tras el impacto

Naoyuki Takeda[1]*, Osamu Terashima[1], Fumiya Kinoshita[1], Hideaki Touyama[1] & Shuho Yamada[1]

1 Toyama Prefectural University, Kurokawa, Imizu, Toyama, Japan.

Received: 11-08-2024

Accepted: 29-10-2024

Abstract

In this study, we examined the pressure levels of ball impact sounds during serving in tennis. Ten participants were recruited and instructed to serve from the Deuce and Advantage Courts in the Center and Wide directions. The sound pressure levels were measured and analyzed on the receiver side. High-speed cameras, motion capture, and racket excitation experiments were also conducted to assess the spin amount, initial velocity of the ball, and impact position of the racket during service. The results indicated that the ball impact sound during service is influenced by the racket's impact position, initial velocity of the ball, and spin amount of the ball. Furthermore, it was found that when the spin amount of the ball was high, the racket's impact position tended to deviate from the center, leading to a decrease in the ball impact sound. However, there was little difference in the tendencies observed in participants based on handedness or sex. These findings suggest that receivers can improve their accuracy in play by predicting the spin amount and velocity of the ball based on the ball impact sound. Additionally, servers can strive to strike the ball at the center of the racket and maintain the initial velocity of the ball, even when applying spin, to make their serves more difficult for receivers to predict. The p-value in the present experimental results is less than 0.47, and the discussion is based on results with certain significant differences.

Keywords: *tennis, serve, impact sound, ball spin, ball speed, modal analysis, motion capturing.*

Resumen

En este estudio se examinaron los niveles de presión de los sonidos del impacto de la pelota durante el servicio en tenis. Se seleccionaron diez participantes y se les indicó que sirvieran desde las canchas de deuce y advantage en las direcciones abierto y al cuerpo. Se midieron y analizaron los niveles de presión sonora en el lado del receptor. También se realizaron experimentos con cámaras de alta velocidad, captura del movimiento y excitación de la raqueta para evaluar la cantidad de efecto, la velocidad inicial de la pelota y la posición del impacto de la raqueta durante el servicio. Los resultados indicaron que el sonido del impacto de la pelota durante el servicio está influenciado por la posición del impacto de la raqueta, la velocidad inicial de la pelota y la cantidad de efecto de la pelota. Además, se observó que cuando el efecto de la pelota era alto, la posición del impacto de la raqueta tendía a desviarse del centro, lo que provocaba una disminución del sonido del impacto de la pelota. Sin embargo, no hubo grandes diferencias en las tendencias observadas en los participantes en función de su lateralidad o sexo. Estos resultados sugieren que los receptores pueden mejorar su precisión en el juego prediciendo la cantidad de efecto y la velocidad de la pelota basándose en el sonido del impacto. Adicionalmente, los servidores pueden esforzarse por golpear la pelota en el centro de la raqueta y mantener la velocidad inicial de la pelota, incluso cuando aplican efectos, para que sus servicios sean más difíciles de predecir para los receptores. El valor p en los resultados experimentales es inferior a 0,47 y la discusión se basa en resultados con ciertas diferencias significativas.

Palabras clave: *tenis, servicio, sonido de impacto, efecto de la pelota, velocidad de la pelota, análisis modal, captura de movimiento.*

Corresponding author: Naoyuki Takeda, naoyukisoccer4113@gmail.com

---

Cite this article as:
Takeda, N., Terashima, O., Kinoshita, F., Touyama, H., & Yamada, S. (2024). The Influence of Tennis Serve Kinematics on Ball Impact Sound and Post Impact Ball Speed and Spin. *International Journal of Racket Sports Science, 5*(2), 9-20.

INTRODUCTION

The study of the sound produced during ball impacts in various ball sports has a lengthy history, with numerous investigations leveraging the modal analysis of vibrations and assessments of auditory impressions. Key contributions to this field include the investigations by Roberts et al (2001, 2006). on golf clubs, research by D. A. Russell (2017) on bats used in baseball and softball, and detailed studies on tennis rackets by G.H. Banwell et al. (2012, 2014). These studies span a range of sports and equipment employed within each domain, marking a robust domain of inquiry. More recent studies have focused intensively on the specific sounds produced in these contexts, with research covering table tennis (Klein et al, 2021), soccer, and volleyball (Sors et al., 2017; Camponogara et al., 2024); the distinctive sounds of golf shots (Roberts et al., 2005) and badminton (Zhu, 2013; Arianto et al., 2017); and further investigations into tennis (Bower & Cross, 2003; Cañal-Bruland et al., 2018). These research efforts have examined the various ways athletes utilize sound information, the psychological benefits of auditory feedback, and the impact of sound on the accuracy and quality of play. Particularly in tennis, studies have shown that the intensity of a racket-ball impact sound can influence players' predictions of ball trajectory, revealing a significant correlation between auditory cues and precision of play (Cañal-Bruland et al., 2018).

In this study, we extend previous research by empirically investigating the relationship between the sounds produced during tennis serves and players' performance accuracy, with a special focus on the sounds emitted during the service. Our initial experiments aimed to identify any correlation between the sound produced at the moment of service and the subsequent direction of the service. We then investigated the reasons for the variations in these sounds depending on the direction of the service. The study involved ten participants, each asked to perform multiple serves directed towards both wide and central court positions, while the resulting sounds were recorded and analyzed from the perspective of the serve's receiver. Further analytical efforts included vibrational testing of the tennis rackets and examination of their modal vibrations and natural frequencies to explore the potential causes of the observed acoustic phenomena. To enhance our understanding of how the direction of the serve influences the resulting sound, we employed high-speed cameras and motion-capture systems to analyze the trajectories of the rackets. This comprehensive approach not only deepens our understanding of acoustic effects in tennis serves but also provides insights into how auditory information can be strategically utilized to enhance athletic performance.

Our study complements and extends the existing research on visual anticipation and auditory information by focusing specifically on the acoustic properties of ball-impact noise during tennis serves. Our findings provide a new perspective on how differences in sound pressure levels influence visual anticipation, and contribute to the development of specific training methods aimed at improving sports performance.

Research on the impact of auditory information on visual anticipation in tennis suggests that the intensity of racket-ball-contact sounds systematically biases the estimation of ball speed, thereby influencing anticipatory judgment. Here, we examined whether the effect of auditory information on visual anticipation is dependent on sport-specific context in two separate experiments. In Experiment 1, participants watched short videos of tennis rallies occluded at the moment of racket-ball contact. The racket-ball contact sounds of the final shot were either present or absent. Participants performed different tasks in two counterbalanced blocks: in one block, they estimated the ball's speed, and in the other block, they indicated the ball's landing location. The results showed that Participants estimated longer ball flight trajectories and higher ball speeds in the sound-present condition than in the sound-absent condition. To probe whether this effect was dependent on sport-specific context, Experiment 2 introduced an abstract (i.e., context-free) version of the previous stimuli. Based on the ball locations in the original videos used in Experiment 1, we rendered new videos that displayed only circular movements against a blank background. The sine tones replaced the original racket-ball contact sounds. The results indicated that sound presence had no impact on location anticipation judgments. However, similar to the results of Experiment 1, the object speed was judged to be higher when the final sound was present. Together, these findings suggest that the impact of auditory information on anticipation does not seem to be driven by sound alone but is moderated by contextual information (Murphy et al., 2016).

The impact of auditory information on visual anticipation has been a subject of significant research. For instance, arguments in favor of context dependency are based on recent research on visual anticipation (e.g., Murphy et al., 2016) and anticipatory gaze behaviors (e.g., Goettker et al., 2021), indicating that contextual information can be used to successfully predict the future location of a ball in tennis or a puck in hockey. Conversely, arguments in favor of context independence stem from research showing that the synchronous presentation of audiovisual stimuli, without any additional context information, may cause an illusory increase in perceived object speed (Meyerhoff et al., 2022), which in turn may account for the reported effects of auditory information on anticipatory judgments in sports (for example, Cañal-Bruland et al., 2018; Müller et al., 2019).

To test competing hypotheses, participants watched tennis rally videos where racket-ball contact sounds were either present or absent (Experiment 1) or context-free videos with only circular movements and sine tones (Experiment 2). The results from Experiment 1 showed that racket-ball contact sounds influenced judgments of ball flight trajectory and speed. In contrast, Experiment 2 showed that sound presence did not affect location anticipation but influenced speed perception. These findings emphasize the role of context in sports anticipation.

Research shows that racket-ball contact sound intensity influences ball speed estimation and anticipation judgments. Two experiments tested the effect of auditory information on visual anticipation. In Experiment 1, the participants estimated longer flight trajectories and higher ball speeds when sound was present. Experiment 2 used context-free videos and showed that sound had no effect on location judgments but did influence speed perception. These findings suggest that the role of sound in anticipation is moderated by the context.

Together, the results of previous studies and our current study provide evidence against the purely context-independent effect of auditory information on location anticipation. Instead, they support a context-dependent effect, aligning with findings on the impact of contextual information on visual anticipation (Murphy et al., 2016; Goettker et al., 2021; Cañal-Bruland et al., 2022). The aim of this study is to investigate how auditory cues during tennis serves influence players' anticipation of ball trajectory and speed, depending on the context. We hypothesize that auditory cues will have a significant effect on speed estimation, but this effect will be moderated by the presence or absence of contextual information. These findings have practical implications for training protocols in sports, emphasizing the importance of multisensory integration and context-specific training in enhancing anticipatory skills.

EXPERIMENTAL SETUP AND PROCEDURE

Participants

The measurements were conducted in the outdoor tennis courts of the university to which the authors belong. A total of ten participants, comprising nine male and one female individuals were included in this study. Participants were selected from the University's students with tennis experience. One male participant was left-handed. Their ages ranged from 20 to 24 years, heights from 160 to 178 cm, weights from 50 to 70 kg, and years of tennis experience from 1 to 10 years. These individuals will be referred to as Participants A through J, with Participant I being left-handed and Participant J being female. The experiments in the study were conducted in accordance with ethical guidelines. Prior to the commencement of the experiment, approval was obtained from the Ethics Review Subcommittee of the "Research for Human Subjects" section at author's University. Informed consent was obtained from all participants prior to their involvement in the study.

Ball Impact sounds

The primary focus of this study was the sounds produced during service. The impact sounds were measured using a microphone (PCB Inc., 130F20) and data logger (Keyence Corp., NR-500/-CA04). The direction of the stroke, the impact position of the racket, and the landing spot of the ball were recorded using a high-speed camera (CASIO Corp., EX-100F). The balls utilized were AUSTRALIAN OPEN (DUNLOP Corp.), and the rackets were VCORE100 (Yonex Corp.) with standard gut tension (52.5 pounds).

The arrangement of the participants and equipment in the tennis court is shown in Figure 1. Microphones were placed on both sides of each participant, and high-speed cameras were positioned in front of and behind them. The data logger and other equipment were strategically placed behind the participants to prevent any interference with their services.

Participants initially served two balls from the deuce court (indicated by the black dashed line in Figure 1) to the center of the court, and the impact sounds were measured. They then served two balls, each from the ad court to the center, the deuce court to near the edge of the court (hereinafter referred to as "wide"), and the ad court to wide. Similar measurements were performed for each condition. Any service that did not land within the designated area was considered invalid and was not included in the analysis. The sampling time for the measurements was approximately 30 s with a sampling rate of 100 kHz. The impact sounds were analyzed using a frequency analysis. In this study, high-speed cameras were used to measure the amount of spin and speed of the ball. Measurements were taken using a Photron Nova S9 high-speed camera paired with a Nikon AF-S NIKKOR 50 mm f/1.8G lens. The frame rate was set to 1000 fps, and the pixel resolution of the captured images was 1024×1024 pixels. Measurements of the impact position and trajectory of the ball were conducted using a high-speed camera, and the impact position, spin amount, and speed were calculated from these images.

It is important to note that in Figure 1, when participants served from the Advantage Court, the position of the receiver was mirrored to reflect this change. However, the position of camera 1 remained unchanged. This ensured consistency in capturing the serve dynamics, while accurately representing the adjusted position of the receiver.

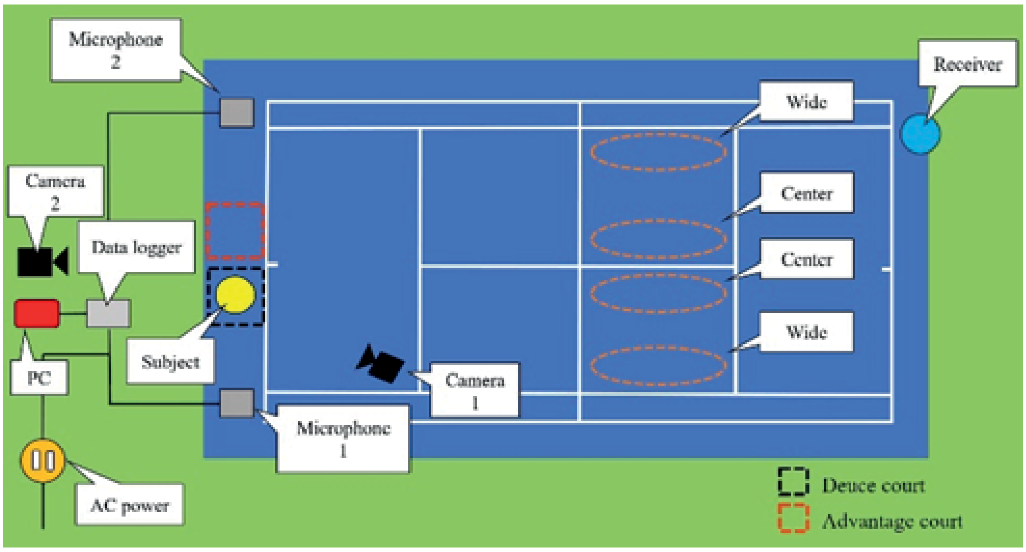

Figure 1. Experiment setup in the tennis court, showing the arrangement when participants serve from the advantage court. The receiver's position is mirrored, while Camera 1 remains unchanged.

Racket Vibration Modes

An impact hammer (PCB Inc., 086C03) was used to excite the rackets. As shown in Figure 2(a), a vibration accelerometer (PCB Inc., 352C41, 2.8 g) was affixed to the frame of the racket to quantify the vibration acceleration generated during excitation. Ten sensors were deployed and positioned at locations 1-10 on the frame, as illustrated in the figure. The positions of excitation by the hammer, as depicted in Figure 2(b), were the center of the racket face (1), right edge (2), intermediate position at 45 ° (3), end position at 45 ° (4), intermediate position at -45 ° (5), and end position at -45 ° (6). A data logger (Keyence Corp., NR-500/-CA04) was employed to capture the signals from the vibration accelerometers with a sampling time of approximately 10 s and a sampling rate of 100 kHz. The acquired vibration acceleration data and CAD data of the tennis racket, generated through shape measurement, were imported into the operational modal analysis software (Vibrant Technology Inc., ME'scopeVES) for vibration mode analysis. The acquisition of the racket shape data essential for vibration mode analysis was performed using a 3D texturing system (Steinbichler, COMET L3D 8M). The racket was mounted on a turntable and a white spray was applied to enhance the reflectivity of the laser for measurement. Based on the measured data, a 3D CAD model was created in STL format. Because of the limited scanning area accessible to the camera's light, the racket was scanned in sections, strings, and other parts separately and then merged to produce a comprehensive CAD model of the entire racket. The CAD data contained minor imperfections that were smoothed using software. Moreover, owing to the considerable number of contact points in the STL, the contact points from the measurement data were compressed and thinned to approximately 10%, resulting in approximately 314,376 contact points for the entire racket.

Racket Trajectory

Measurements for this study were conducted with a single participant, referred to as Man A participated in the experiment. The research utilized four OptiTrack Flex3 motion capture cameras and OptiTrack Motive control software to track the participants' movements during the service and create accompanying videos. The sampling frequency for this motion capture is 100 Hz. Data measured with OptiTrack Motive control software is smoothed or low pass filtered. Motion capture was not done with other experiments. The x-axis was defined as the forward and backward directions, the y-axis as the vertical direction, and the z-axis as the left-right direction. The trajectory of the tennis racket during serve was measured by tracking the movement of the reflective markers attached to the racket with the cameras.

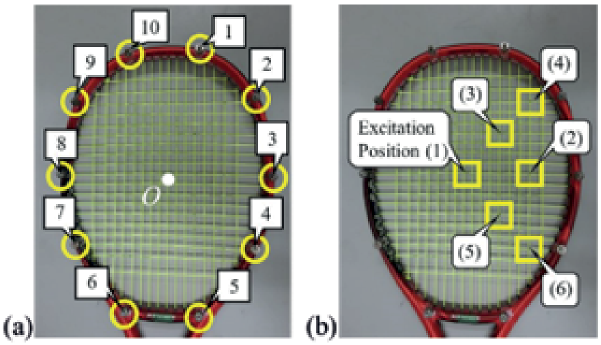

Figure 2. Photographs of (a) measurement positions and (b) excitation positions

RESULTS

Ball Impact Sounds

Figures 3 and 4 present the frequency analysis results for the ball-impact sounds measured for participant A. The horizontal axis represents the frequency in Hz, while the vertical axis represents the sound pressure in dB, with values normalized to the minimum audible sound pressure of 2×10^{-5} Pa. Figure 3 depicts the results from the Deuce Court, and Figure 4 represents the Advantage Court. Each figure also includes photographs illustrating the ball impact positions, specifically during serves directed towards the center. The results are presented as representative examples of the findings observed across all participants. Detailed discussions of the measurement results for individual participants are provided in Section 3.4.

From both figures, particularly Figure 3 from the Deuce court, a difference in sound pressure between serves to the Center and Wide is observed, particularly at approximately 1000 Hz. However, this trend is less pronounced in the Advantage Court, where the sound pressure near 1000 Hz tends to be higher for the service-directed Wide. Furthermore, the serve speeds were approximately 120 km/h to the center and approximately 100 km/h to the Wide on the Deuce court, and approximately 105 km/h to the center and 115 km/h to the Wide on the Advantage court. The spin rates were approximately 1500 rpm to the center and 3000 rpm to the Wide on the Deuce court, and approximately 2000 rpm to the center and 2500 rpm to the Wide on the Advantage court. Additionally, from Figure 3, it can be observed that serves towards the center direction on the Deuce court are struck at the central position of the racket, whereas from Figure 4, it is evident that serves towards the center direction on the Advantage court are struck at the upper right position of the racket.

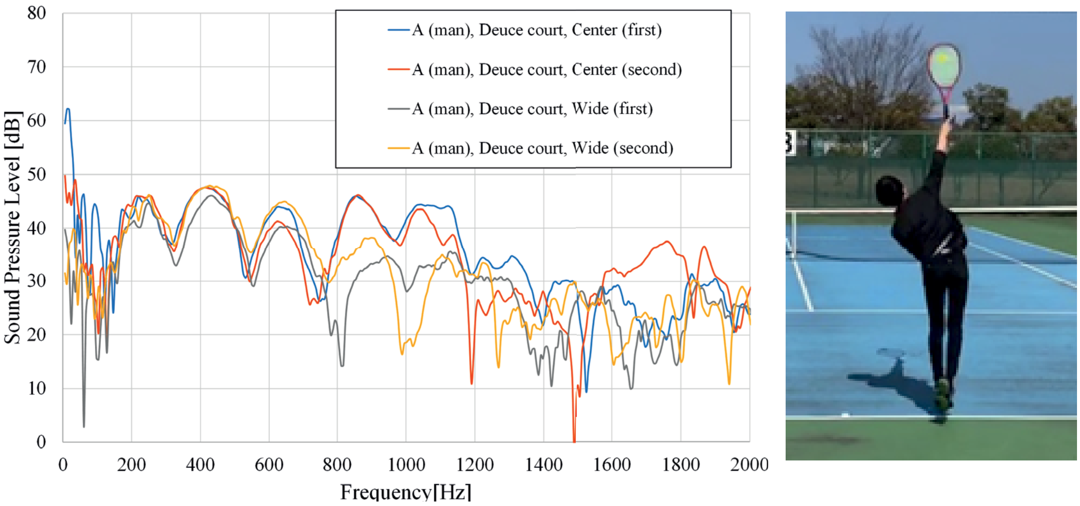

Figure 3. Measured sound pressure and ball impact position when the ball direction was center (Participant A, Deuce court).

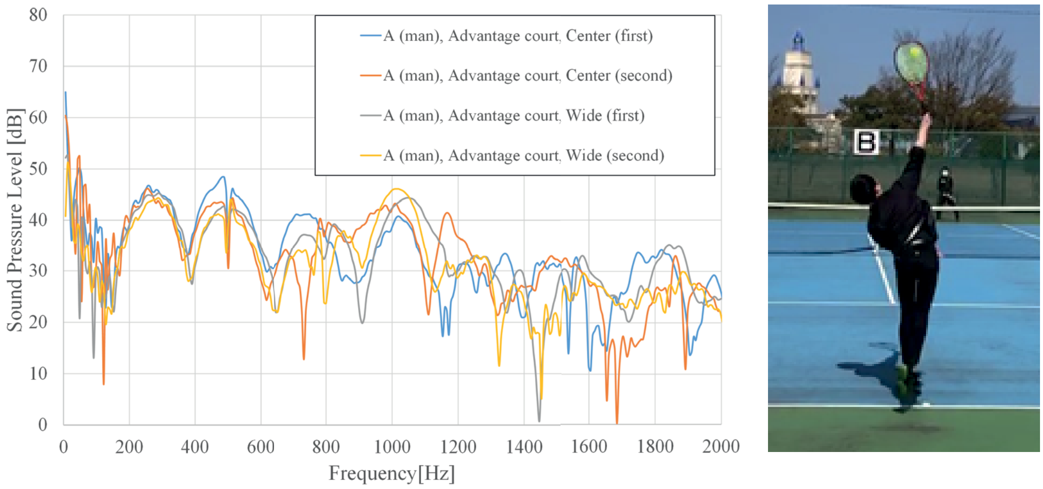

Figure 4. Measured sound pressure level and ball impact position when the ball direction was center (Participant A, Advantage court).

Racket Vibration Modes

Figure 5 presents the findings of the frequency analysis of the vibration acceleration at various measurement points when the racket was excited at positions (1) and (3). Figure 5(a) and 5(b) correspond to the excitation positions (1) and (3), respectively. With reference to Figure 5, it is essential to acknowledge that the sensor numbers depicted in the legend denote the specific measurement positions shown in Figure 2(b). As observed in Figure 5, a significant vibration acceleration was detected at 1130 Hz in both Figure 5(a) and (b) at a frequency of approximately 1000 Hz, where differences were observed in Figures 3 and 4. Additionally, in Figure 5(a), a notable vibration acceleration was seen at 1020 Hz, and in Figure 5(b), a notable vibration acceleration was seen at 1040 Hz.

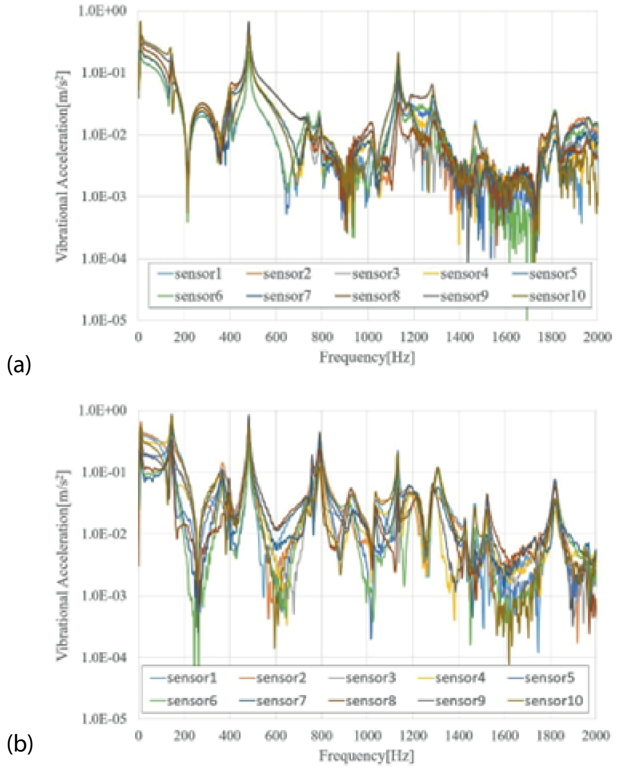

Figure 5. Frequency analysis results of vibration acceleration at each measurement location during racket excitation: (a) Excitation position (1) and (b) excitation position (3).

Figure 6 shows the results of visualizing the vibration of the racket at these frequencies. Figure 6(a) depicts the vibration at 1020 Hz for excitation position (1), and Figure 6(b) depicts the vibration at 1040 Hz for excitation position (3). As depicted in Figure 6, it is evident that for the excitation position (1), the vibration acceleration was higher on the frame on either side of the excitation point (measurement positions 3 and 8). Conversely, for excitation position (3), the frame at the upper position (measurement position 10) exhibited increased vibration acceleration. Therefore, it became apparent that differences in the excitation positions resulted in variations in the frame vibration frequencies and locations. Furthermore, the excitation of the racket at other positions demonstrated peaks in the vibration acceleration near 1000 and 1130 Hz. The aforementioned findings indicate that the vibration acceleration per unit excitation force (1 N) per frame is lower when vibrating position (3) is stimulated in comparison to vibrating position (1). Consequently, it is inferred that vibration acceleration at 1130 Hz occurs regardless of the excitation position. Additionally, the vibration at a frequency of 1000 Hz varies depending on the excitation position, exhibiting similar trends between positions (1) and (2), whereas positions (3), (4), (5), and (6) display an increased vibration acceleration at measurement positions 3 and 9 in a specific vibration mode.

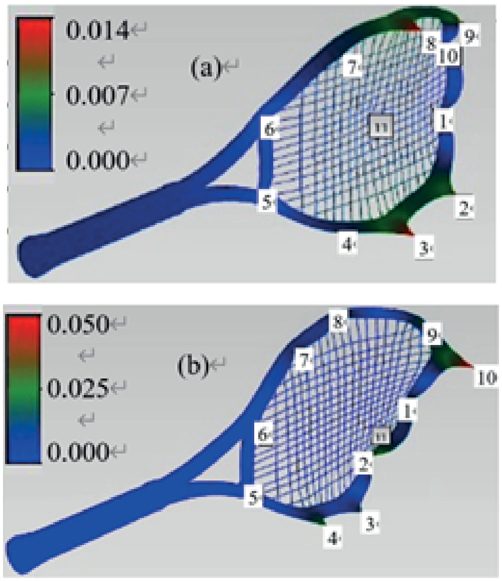

Figure 6. Results of modal analysis in (a) excitation position (1) at 1,020 Hz and (b) excitation position (3) at 1,040Hz. The red arrows in the diagram indicate the excitation positions.

Racket Trajectory

Figure 7 displays the results of measuring the trajectory of the racket while serving, using Participant A's data as a representative example. As shown in Figure 7(a), when the ball is struck at the center position of the racket (as indicated by (1) in Figure 2(b)), and in Figure 7(b), when the ball is struck 45 °upward and to the right of the center of the racket (as indicated by (3) in Figure 2(b)), the trajectories represent the tip of the racket (red), center (green), base (cyan), left end (yellow), and right end (pink), respectively. A comparison of the two trajectories indicates that there is greater variation in the forward-backward and left-right directions when the ball is struck 45 °upward and to the right from the center of the racket. This suggests that the striking surface of the racket (the side with the strings) rotates around the grip of the racket as its central axis.

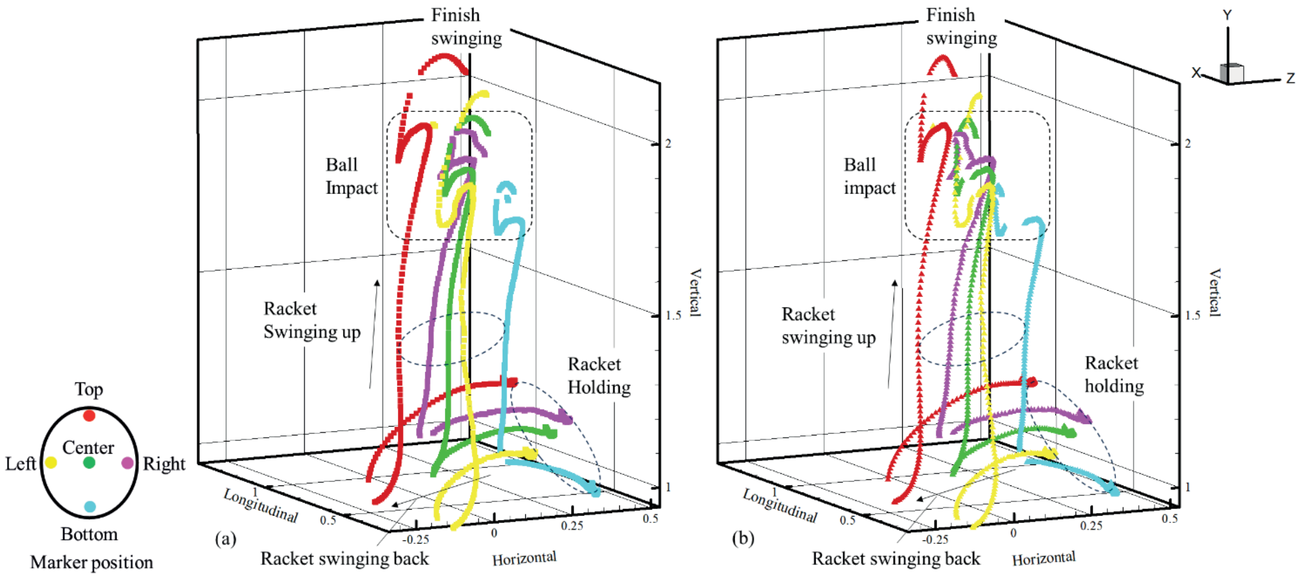

Figure 7. Results of racket trajectory in (a) ball impact position is center of the racket (impact position (1) in Fig. 2) and (b) 45 degrees upward and to the right from the center of the racket (impact position (3) in Fig. 2).

Relationship between tennis serve kinematics on ball impact sound

Based on the findings in Sections 3.1–3.3, it was observed that an increase in the spin amount of the ball during a player's serve was accompanied by a decrease in ball speed and a shift in the impact position of the racket away from its center. Additionally, changes in the sound pressure and frequency at approximately 1000 Hz were noted. To further validate these observations, data from additional participants were used as a reference.

The connection between the ball's spin amount and the impact position during each subject's serve is shown in Figure 8. Table 1 shows the average values and standard deviations of the ball spin rate and impact position for each player. This figure encompasses all measurement data from 10 participants who served twice each from the Deuce and Advantage courts in both the Wide and Center directions, resulting in 80 data points for the analysis. The horizontal axis of Figure 8 represents the amount of spin, while the vertical axis indicates the distance from the origin O, which is the center of the racket, to the impact position. The blue circles in the figure represent the outcomes when serving from the Deuce court in the center direction, the orange circles indicate the results when serving from the Deuce court in the wide direction, the gray circles show the outcomes when serving from the Advantage court in the center direction, and the yellow circles represent the results when serving from the Advantage court in the wide direction. Figure 8 shows that for the majority of the subjects, there was a tendency for the impact position to move away from the center of the racket as the spin amount on the ball increased. Note that since there is only one left-handed player and one female player, no conclusions can be drawn regarding the relationship between handedness or gender and these results.

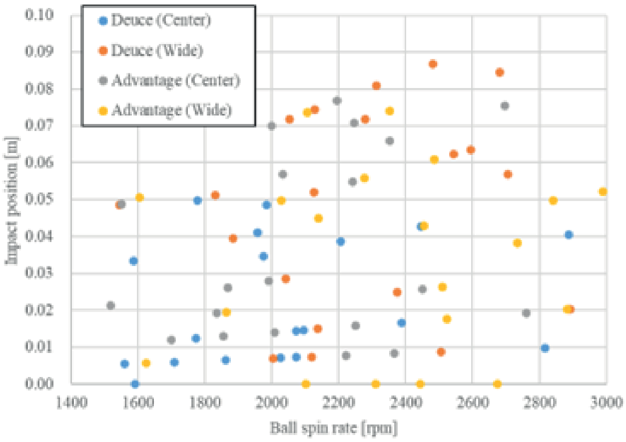

Figure 8. Relationship between ball spin rate and ball's impact position

Using all the data shown in Figure 8, the correlation between the ball spin rate and the distance of the ball impact position was found to be 0.21, indicating a slightly positive correlation, although not a strong one. Additionally, when calculating the correlation coefficients using the data from Deuce (Center), Deuce (Wide), Advantage (Center), and Advantage (Wide) Serve, the results were 0.047, 0.151, 0.222, and 0.035, respectively. This indicates that when serving from the Advantage Court, an increase in spin rate resulted in the ball impact position deviating more from the center of the racket. Finally, Table 2 shows the correlation coefficients between ball spin rate and ball impact position for each participant. As can be seen from Table 2, the correlation coefficients for Participant F and Participant H are low or negative, indicating a different trend from the other participants. However, for the other eight participants, a consistent positive correlation was observed between ball spin rate and ball impact position.

Table 1.
Average values and standard deviations of the ball spin rate and impact position for each player.

	Ball spin rate (rpm)		**Impact position (m)**	
	Average	**Deviation**	**Average**	**Deviation**
Participant A	2079	252	0.0465	0.0238
Participant B	2024	303	0.0225	0.0143
Participant C	2311	346	0.0332	0.0279
Participant D	2605	279	0.0447	0.0250
Participant E	2116	351	0.0296	0.0201
Participant F	1940	331	0.0349	0.0391
Participant G	1995	125	0.0267	0.0183
Participant H	2356	428	0.0418	0.0269
Participant I (Left-handed)	2428	259	0.0538	0.0298
Participant J (Female)	2020	282	0.0326	0.0201

Table 2.
Correlations between ball spin rate and impact position for each player

Participant A	0.56
Participant B	0.59
Participant C	0.60
Participant D	0.82
Participant E	0.70
Participant F	-0.14
Participant G	0.62
Participant H	0.12
Participant I (Left-handed)	0.64
Participant J (Female)	0.58

Figure 9 depicts the relationship between the spin amount of the ball and the initial velocity of the ball during service. Table 3 shows the average values and standard deviations of the ball spin rate and impact position for each player. The meaning of each symbol's color is the same as that shown in Figure 8. In addition, the total number of plots was the same as that shown in Figure 8. From this figure, it can be observed that as the spin amount of the ball increases, there is a tendency for the initial velocity of the ball at the time of serving to decrease for most participants. The correlation between the ball spin rate and initial velocity was found to be -0.90. Although this result pertains only to the ten participants in this study, it suggests that an increase in the ball spin rate may lead to a decrease in the initial velocity of the serve.

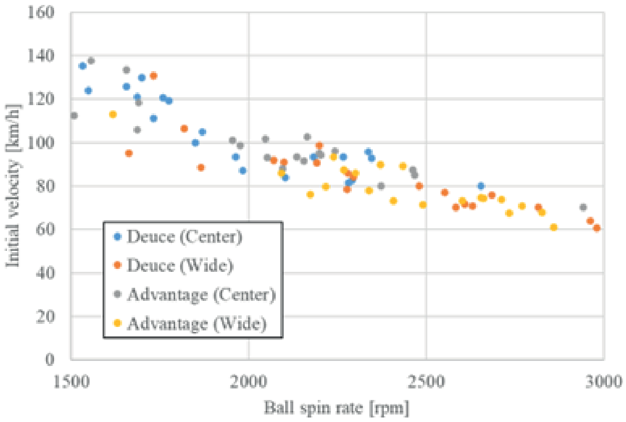

Figure 9. Relationship between ball spin rate and initial velocity

Table 3.
Average values and standard deviations of the initial velocity for each player

	Initial velocity (km/h)	
	Average	**Deviation**
Participant A	91.0	18.2
Participant B	89.4	25.3
Participant C	85.6	15.4
Participant D	89.3	14.5
Participant E	94.2	15.3
Participant F	96.2	24.2
Participant G	89.3	12.8
Participant H	87.6	18.6
Participant I (Left-handed)	97.4	17.9
Participant J (Female)	96.0	13.6

Figure 10 illustrates the relationship between the ball spin amount and sound pressure of the ball impact sound. Table 4 shows the average values and standard deviations of sound pressure level for each player. The colors of the symbols and the total number of plots are the same as those in Figure 8. Additionally, the ball impact sound was represented by the partial O.A. value of the sound corrected with the A-characteristic in the range of 1000-1200 Hz. From this figure, it can be observed that as the spin amount of the ball increased, the ball impact sound tended to decrease. The correlation between the ball spin rate and sound pressure level was – -0.88, suggesting that an increase in the ball spin rate may lead to a decrease in the sound pressure level.

Based on these findings, it is clear that the sound produced during a serving while impact the ball varies depending on the position of the racket, initial velocity of the ball, and amount of spin on the ball. Furthermore, it was observed that when the spin on the ball was high, the impact position of the racket tended to deviate from the center of the racket, resulting in a decrease in the ball impact sound. Moreover, these trends were observed to be independent of handedness or sex differences, as all participants demonstrated similar tendencies.

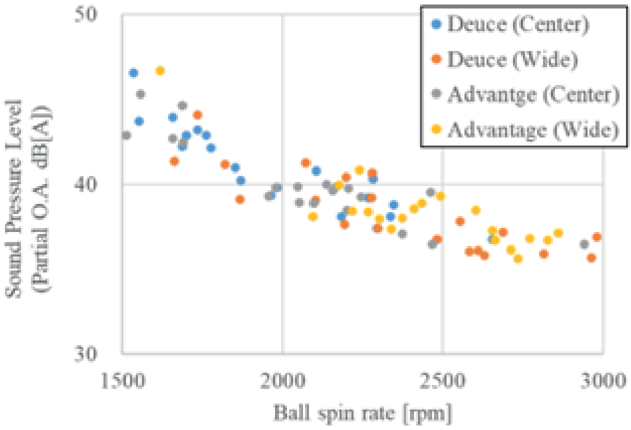

Figure 10. Relationship between the ball spin rate and the sound pressure level.

Table 4.
Average values and standard deviations of sound pressure level for each player.

	Sound Pressure Level (Partial O.A. [dB])	
	Average	**Deviation**
Participant A	39.0	2.2
Participant B	39.5	2.9
Participant C	38.6	2.0
Participant D	38.8	1.5
Participant E	39.9	2.7
Participant F	39.9	3.2
Participant G	39.2	2.3
Participant H	38.7	2.5
Participant I (Left-handed)	40.1	3.4
Participant J (Female)	40.5	1.5

These findings suggest that receivers can enhance the accuracy of their play during a serve by predicting the spin amount and velocity of the ball based on the ball impact sound. Furthermore, servers can increase the difficulty of their servers for receivers to predict by aiming for the center of the racket and maintaining the initial velocity of the ball, even when applying a spin. These results indicate that the relationship between the sound of impact and the accuracy of predicting a player's movements, as demonstrated in other studies [7, 8], also exists during tennis serves, indicating the possibility of predicting the characteristics of serves based on impact sound.

While it is generally known that increasing the initial speed of a serve can be achieved by impacting the ball towards the upper part of the racket (closer to the tip), our findings suggest that if players can increase the initial speed of the serve while impacting the ball at the center of the racket, it would be an effective technique. This approach could provide an additional advantage by making the serve more difficult for the receiver to predict based on the sound alone.

The study also found that the trends observed remained consistent when the tension of the strings was set at 60 pounds and 42.5 pounds; however, there was a slight difference of approximately 100 Hz in the frequency of the generated sound. This suggests that the quality of the striking sound may vary based on string tension. The examination of 64 serves performed by right-handed male participants revealed that the average spin rates for serves from the Deuce court to the Center direction were 1917 rpm, from the Deuce court to the Wide direction were 2482 rpm, from the Advantage court to the Center direction were 2074 rpm, and from the Advantage court to the Wide direction were 2532 rpm. The results indicate that the spin rate tends to decrease when serving in the central direction and increases when serving in a wide direction.

DISCUSSION

The findings of this study provide new insights into the acoustic properties of tennis serves and their effects on player performance. Specifically, we observed that an increase in the spin amount of the ball during serve is associated with a decrease in ball speed and a shift in the racket's impact position away from its center. Additionally, changes in sound pressure and frequency at approximately 1000 Hz were noted. These observations align with existing research on the role of auditory information in visual anticipation, particularly studies by Cañal-Bruland et al. [20], Murphy et al. [14], and Goettker et al. [15], which highlight the importance of sound in predicting the trajectory and speed of a ball.

Comparison with previous research

Previous research has demonstrated that auditory cues, such as the sound of racket-ball contact, can significantly influence players' ball trajectory and speed predictions. For instance, Cañal-Bruland et al. [20] showed that the intensity of racket-ball-contact sounds systematically biases estimates of ball speed, thereby affecting anticipatory judgment. Similarly, Meyerhoff et al. [15] found that the synchronous presentation of audiovisual stimuli could cause an illusory increase in perceived object speed, thereby influencing players' anticipatory judgments. Our study extends these findings by showing that the specific acoustic properties of serves, such as sound pressure and frequency changes associated with increased ball spin, can further refine players' anticipatory skills. The observation that higher spin rates are linked to lower sound pressure and frequency supports the notion that auditory information is a critical component of effective visual anticipation in tennis.

In recent years, several studies have investigated the role of auditory information in sports performance, particularly in relation to how sound impacts athletes' anticipatory skills. For example, study by Cañal-Bruland et al. (2018) demonstrated how auditory cues, such as the sound of ball impact, can significantly enhance visual anticipation in fast-paced sports. This finding complements the work of Goettker et al. (2021), who showed that contextual factors, like ball trajectory and speed, play a critical role in how auditory and visual cues are integrated during high-speed movements. Similarly, Murphy et al. (2016) emphasized the importance of contextual auditory information in perceptual-cognitive tasks, suggesting that auditory cues, when combined with temporal constraints, can improve an athlete's ability to predict and respond quickly. Also, studies by Murphy et al. (2019) and Goettker et al. (2021) found that auditory cues, such as the sound of ball impact, can significantly influence a player's ability to predict ball trajectory and speed. These findings align with our results, which suggest that the intensity of racket-ball impact sounds affects both speed estimation and anticipatory judgment. However, while previous studies primarily focused on the general influence of sound, our research adds nuance by exploring how contextual factors, such as spin and ball trajectory, moderate these auditory effects.

Consideration of context-dependency

Murphy et al. (2016, 2018) and Goettker et al. (2021) argued that the impact of auditory information on visual anticipation is context-dependent. They suggested that contextual information, such as the visual and auditory environment of a tennis match, enhances players' ability to accurately predict ball trajectories. Our study supports this view, showing that the changes in sound properties related to ball spin and speed are crucial for making accurate predictions during serve. However, our findings also indicate that these auditory cues are effective regardless of the player's handedness or gender, suggesting that fundamental auditory processing mechanisms are robust across different player demographics. This aligns with previous research indicating that the integration of the auditory system with visual cues is a generalizable phenomenon in sports anticipation.

Limitations

While our study offers new findings, it is not without limitations. The sample size was relatively small compared to other studies in human sciences. Future research should aim to include a larger and more diverse participant pool to enhance the generalizability of the findings. Additionally, investigating the impact of various playing surfaces and environmental conditions on the acoustic properties of serves could provide a more comprehensive understanding of the role of auditory information in tennis. The p-value in the present experimental results is less than 0.47, and the discussion is based on results with certain significant differences.

CONCLUSIONS

In this study, we explored the acoustic properties of ball impact sounds in tennis by focusing on the serves. Our findings indicate that the direction of the serve, deviation of the racket from the center of the court, spin amount, and initial velocity of the ball all influence the differences in sound pressure levels. Some of the measured data showed consistency and coherence, suggesting that these findings may be applicable to a broader population. Additionally, it was demonstrated that a high spin amount on the ball tends to cause the racket to diverge from the center, leading to a reduction in ball impact sound. This implies that receivers can potentially improve the precision of their returns by estimating the spin and velocity of the ball based on ball impact sound. While it is generally recommended that servers impact the ball slightly above the center of the racket to increase the initial velocity, our study suggests that impact the ball at the center without reducing its initial velocity can make it more difficult for receivers to predict the serve.

These findings have practical implications for training protocols in tennis and other ball sports. Coaches can use this information to develop drills that enhance players' sensitivity to auditory cues, thereby improving anticipatory skills. For instance, training sessions could include exercises that focus on recognizing and reacting to different sound patterns associated with various service spins and speeds. Furthermore, servers can use this knowledge to make their serves less predictable by maintaining a high ball speed while applying significant spin, thus reducing the auditory cues available to the receiver. This strategic use of sound can make it more challenging for opponents to anticipate and return serves effectively.

Further research is needed to explore the impact of different court surfaces and environmental conditions on ball-impact sounds. Additionally, expanding the participant pool to include a wider range of skill levels and age groups would help to validate and generalize these findings.

CONFLICT OF INTERESTS

The authors have no conflict of interests to declare that are relevant to the content of this research.

FUNDING

No funding was received for this study.

ETHICAL APPROVAL

The experiments described above were conducted in accordance with ethical guidelines. Prior to the commencement of the experiment, approval was obtained from the Ethics Review Subcommittee of the "Research for Human Subjects" section at author's University. Informed consent was obtained from all participants prior to their involvement in the study.

CONSENT TO PARTICIPATE

Consent to participate in this study has been obtained from the participants.

CONSENT TO PUBLISH

Consent to publish has also been obtained from the participants.

DATA AVAILABILITY STATEMENTS

The author confirms that all data generated or analysed during this study are included in this published article. A portion of the data that support the findings of this study, which are not shown in this paper, are available from the author upon reasonable request.

REFERENCES

Arianto, I. S., Nuri, N., & Yulianto, A. (2017). Effect of the pull and diameter string of badminton racket based on coefficient of restitution value. Journal of Natural Sciences and Mathematics Research, 2(1), 85-90. https://doi.org/10.21580/jnsmr.2016.1.1.1639

Banwell, G. H., Roberts, J. R., Halkon, B. J., Rothberg, S. J., & Mohr, S. (2014). Understanding the dynamic behavior of a tennis racket under play conditions. Experimental Mechanics, 54, 527-537. https://doi.org/10.1007/s11340-013-9803-9

Banwell, G., Mohr, S., Rothberg, S., & Roberts, J. (2012). Using experimental modal analysis to validate a finite element model of a tennis racket. Procedia Engineering, 34, 688-693. https://doi.org/10.1016/j.proeng.2012.04.117

Bower, R., & Cross, R. (2003). Player sensitivity to changes in string tension in a tennis racket. Journal of Science and Medicine in Sport, 6(1), 120-131. https://doi.org/10.1016/S1440-2440(03)80015-4

Camponogara, I., Murgia, M., D'Orso, G., & Sors, F. (2024). Volleyball serves impact sound intensity and frequency spectrum affect the predictions of the future ball's landing point according to the level of auditory-motor experience. International Journal of Sport and Exercise Psychology, 22(2), 467-480. https://doi.org/10.1080/1612197X.2023.2284318

Cañal-Bruland, R., Meyerhoff, H. S., & Müller, F. (2022). Context modulates the impact of auditory information on visual anticipation. Cognitive Research: Principles and Implications, 7(1), 76. https://doi.org/10.1186/s41235-022-00425-2

Cañal-Bruland, R., Müller, F., Lach, B., & Spence, C. (2018). Auditory contributions to visual anticipation in tennis. Psychology of Sport and Exercise, 36, 100-103. https://doi.org/10.1016/j.psychsport.2018.02.001

Goettker, A., Pidaparthy, H., Braun, D. I., Elder, J. H., & Gegenfurtner, K. R. (2021). Ice hockey spectators use contextual cues to guide predictive eye movements. Current Biology, 31(16), R991-R992. https://doi.org/10.1016/j.cub.2021.06.087

Klein-Soetebier, T., Noël, B., & Klatt, S. (2021). Multimodal perception in table tennis: the effect of auditory and visual information on anticipation and planning of action. International Journal of Sport and Exercise Psychology, 19(5), 834-847. https://doi.org/10.1080/1612197X.2020.1819370

Meyerhoff, H. S., Gehrer, N. A., Merz, S., & Frings, C. (2022). The beep-speed illusion: Non-spatial tones increase perceived speed of visual objects in a forced-choice paradigm. Cognition, 219, 104978. https://doi.org/10.1016/j.cognition.2021.104978

Müller, F., Jauernig, L., & Cañal-Bruland, R. (2019). The sound of speed: How grunting affects opponents' anticipation in tennis. PLoS One, 14(4), e0214819. https://doi.org/10.1371/journal.pone.0214819

Murphy, C. P., Jackson, R. C., & Williams, A. M. (2018). The role of contextual information during skilled anticipation. Quarterly Journal of Experimental Psychology, 71(10), 2070-2087. https://doi.org/10.1177/1747021817739201

Murphy, C. P., Jackson, R. C., Cooke, K., Roca, A., Benguigui, N., & Williams, A. M. (2016). Contextual information and perceptual-cognitive expertise in a dynamic, temporally-constrained task. Journal of Experimental Psychology: Applied, 22(4), 455. https://doi.org/10.1037/xap0000094

Roberts, J. R., Jones, R., Mansfield, N. J., & Rothberg, S. J. (2005). Evaluation of impact sound on the 'feel'of a golf shot. Journal of sound and vibration, 287(4-5), 651-666. https://doi.org/10.1016/j.jsv.2004.11.026

Roberts, J. R., Jones, R., Rothberg, S. J., Mansfield, N. J., & Meyer, C. (2006). Influence of sound and vibration from sports impacts on players' perceptions of equipment quality. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 220(4), 215-227. https://doi.org/10.1243/14644207JMDA86

Roberts, J., Jones, R., Harwood, C., Mitchell, S., & Rothberg, S. (2001). Human perceptions of sports equipment under playing conditions. Journal of sports sciences, 19(7), 485-497. https://doi.org/10.1080/026404101750238944

Russel, D. A. (2017). Acoustics and vibration of baseball and soft ball bats. Acoustics Today, 13(4), 35-42. https://acousticstoday.org/wp-content/uploads/2017/12/Acoustics-and-Vibration-of-Baseball-and-Softball-Bats-Daniel-A.-Russell.pdf

Sors, F., Murgia, M., Santoro, I., Prpic, V., Galmonte, A., & Agostini, T. (2017). The contribution of early auditory and visual information to the discrimination of shot power in ball sports. Psychology of Sport and Exercise, 31, 44-51. https://doi.org/10.1016/j.psychsport.2017.04.005

Zhu, Q. (2013). Perceiving the affordance of string tension for power strokes in badminton: Expertise allows effective use of all string tensions. Journal of Sports Sciences, 31(11), 1187-1196. https://doi.org/10.1080/02640414.2013.771818