Presentation of Hitting Sensation to the Racket by a Single DC motor Embedded in a Handle

Michiru SOBUE, Soma KATO, Izumi MIZOGUCHI, and Hiroyuki KAJIMOTO

Abstract— **This paper proposes a method of integrating a DC motor into a handle to provide the sensation of impact in racket sports. The tactile sensation from the vibration of a DC motor has a wide frequency bandwidth, and the cylindrical shape of the DC motor is suitable to be embedded in the handle. On the other hand, due to the nature of the tactile presentation by rotational torque, there is a possibility that the direction of motor rotation may be perceived. We considered that by rotating the motor in one direction for a short period and then in the opposite direction, the rotational direction would be indistinguishable. In this research, as a fundamental study in the presentation of the sensation of hitting using a motor, we clarify the conditions under which the torque direction is not perceived.**

I. INTRODUCTION

The proliferation of low-cost head-mounted displays (HMDs) has led to the widespread adoption of virtual reality (VR) across various fields, including gaming, education, communication, and so on. Within this context, VR sports emerges as a highly promising domain. It supports skill improvement by realistically reproducing the field and enables in-depth analysis of gameplay and strategies by reproducing video footage of games [1][2].

Among these VR technologies for sports, this study focuses on racket sports. Racket sports, including tennis, table tennis, and badminton, have a large population, and there are also many reproductions of racket games on TV games. Nevertheless, current commercial VR technologies for racket sports focus mainly on visual reproduction, with limited efforts to reproduce tactile sensations. Most controllers bundled with current HMDs provide tactile feedback through vibrators, but there are limitations in the tactile information that can be presented.

We propose using a single DC motor in a handheld device to provide a high-quality tactile presentation for racket sports with a simple device. When a DC motor is used as a transducer by inputting a vibration waveform, it can present both low and high frequencies, making it suitable for applications such as racket sports, where both low-frequency repulsion and high-frequency impact sensations are presented. In addition, owing to the typical cylindrical configuration of DC motors, they can be easily integrated into a handle-shaped housing that can be gripped by the hand.

On the other hand, the following issue can be considered: the sensory presentation of the DC motor is not a linear vibration presentation like a common transducer, but a rotational torque presentation. If only a single direction of rotational acceleration is presented, the user perceives the direction of rotational torque. This would be suitable for presenting the sensation that the hit was 'off' the center to either side of the racket, but not for presenting the sensation that the hit was at the center (of inertia) of the racket. Our solution to this problem was to rotate the motor in one direction for a short time and then in the opposite direction, making the direction of rotation indistinguishable.

The purpose of this study is to clarify the following two points as fundamental research for reproducing the feeling of hitting the racket by integrating a single motor within the handle part.

- What are the conditions for the pulse waveform to make the torque direction indistinguishable?
- What are the conditions for generating a stronger sense of repulsion?

II. RELATED WORK

A. Reproduction of the feeling of impact

The sensation of hitting a racket involves a wide range of haptic sensations, including a sense of repulsion mainly due to the low-frequency component, and a sense of impact mainly due to the high-frequency component.

Early attempts to reproduce the sensation of hitting an object were made using a ground-fixed haptic display. On the other hand, the commonly available haptic display is generally not good at presenting high-frequency components of several hundred Hz, because the feedback control period sets the upper limit of the frequency at which the force can be presented. For this reason, it has been proposed to mount additional vibrator to the device or to add vibration waveforms to the control signal, making it possible to represent the sensation of tapping on rubber, wood, and metal [3][4]. Efforts have also been made to reproduce the sensation of contact with a hard object by speeding up the control cycle up to 10 kHz [5]. On the other hand, these methods require desktop devices, and the workspace is limited.

There have been numerous researches into the development of handheld devices that reproduce the sensation of hitting with a racket, and most of them mounted vibrators on the racket [6][7][8][9][10]. However, due to the size limitations of the vibrators, they mainly focused on the representation of the high-frequency component. To create a sense of repulsion through the low-frequency component, it was necessary to mount a large and heavy transducer or to

---

* Research supported by JSPS KAKENHI Grant Number JP20H05957, and SCAT foundation.

Michiru Sobue, Soma Kato, Izumi Mizoguchi, and Hiroyuki Kajimoto are with The University of Electro-Communications, Chofu-city, Tokyo, (phone: +81-42-443-5445; fax: +81-42-443-5445; email: sobue@kaji-lab.jp, kato@kaji-lab.jp, mizoguchi@kaji-lab.jp, and kajimoto@kaji-lab.jp).

construct a portable force-sensing presentation device using the gyroscopic effect [11][12][13][14][15][16]. Consequently, it is difficult to reproduce from low-frequency repulsion to high-frequency impact, with a single driving source, and methods that combine multiple haptic devices have been proposed [17][18][19].

B. *Tactile presentation using a DC motor as a vibrator*

One of the factors for the limitations of conventional transducers in presenting low-frequency components is the principle of reciprocating motion of weight inside the transducer. To fit a reciprocating weight into an enclosure of a certain size, the amplitude must be limited. To limit the amplitude, a mechanism utilizing a spring component is employed to reset the weight to its initial position, resulting in the occurrence of resonance. The resonance is a significant weakness in presenting a wide frequency bandwidth.

A solution to this issue has been proposed through the use of DC motors for vibration representation [20][21][22]. When a vibration waveform is applied to a DC motor and utilized as a transducer, there is no amplitude limitation because it is a rotational vibration (i.e., it does not hit the housing). Consequently, this approach allows for the presentation of both low and high frequencies using a single unit, making it suitable for applications such as racket sports, where a range of sensations from repulsion to impact can be presented. Another type of vibrator that employs an eccentric weight (ERM: Eccentric Rotating Mass) along with a DC motor is common, but it has several issues such as the impossibility of adjusting the vibration frequency and amplitude independently and slow response.

III. DEVICE

A handheld device was created as shown in Fig. 1. A DC motor (RE25, 10W, 118746, Maxon) is mounted inside, and weights (85g × 2, diameter 15.8mm) are attached to the rotating shaft of the DC motor for torque enhancement. As the hand feels the reaction force generated by the motor when rotating the weight, the heavier weight gives more stable sensation. An accelerometer (KXR94-2050, Kionix) is attached at the bottom of the device.

Fig. 1: The proposed device (left), with an internal motor with weights embedded (right).

The handle is made of ABS and is held in the same way as a racket. By swinging the device forward in a smash-like motion, the device presents the sensation of a stroke at the appropriate time. At present, the center of mass and weight are not matched to the actual racket.

The DC motor is controlled by a microcontroller (Raspberry Pi Pico) using PWM control. The microcontroller is connected to a PC and can receive data via USB serial communication. The microcontroller receives the acceleration data at a sampling frequency of 1 kHz, and the DC motor is driven when the acceleration values of both the x-axis and z-axis start to decrease, as shown in Fig. 2. This matches the timing of hitting the shuttle. This algorithm is one that we have experimentally confirmed to synchronize the actual stroke timing.

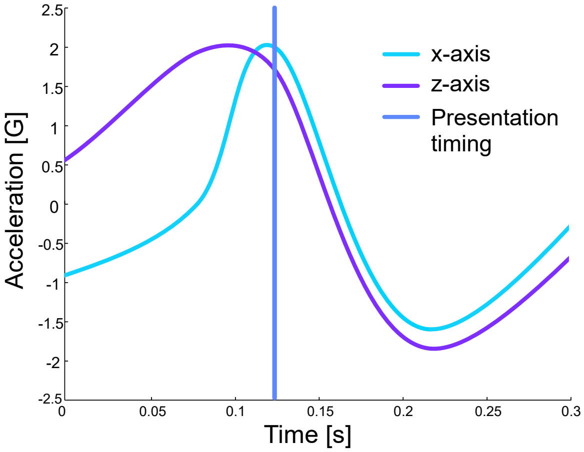

Fig. 2: Example of presentation start timing.

IV. EXPERIMENT

A. *Experiment 1*

Our proposal is to rotate the DC motor in one direction for a short period, and then rotate in the opposite direction, to make the direction of rotation imperceptible. Experiment 1 investigated the effectiveness of this technique.

We prepared the following five stimulus waveforms.

1. Clockwise with 10 ms pulse width (CWP)
2. Counter-clockwise with 10 ms pulse width (CCWP)
3. 10 ms clockwise followed by 10 ms counter-clockwise (CW&CCW)
4. Clockwise only (CW)
5. Counter-clockwise only (CCW)

Fig. 3 shows a schematic input voltage waveform for each condition and the actual angular velocity. An angular velocity sensor (MPU-6050, InvenSense) was used for the measurements, mounted at the end of the handle, and gripped by one of the authors with approximately the same force as holding a racket. A 10 ms pulse was used because in a preliminary study, two 10 ms pulses as in CW&CCW condition were not perceived as two vibrations, and the direction of rotation was not perceived.

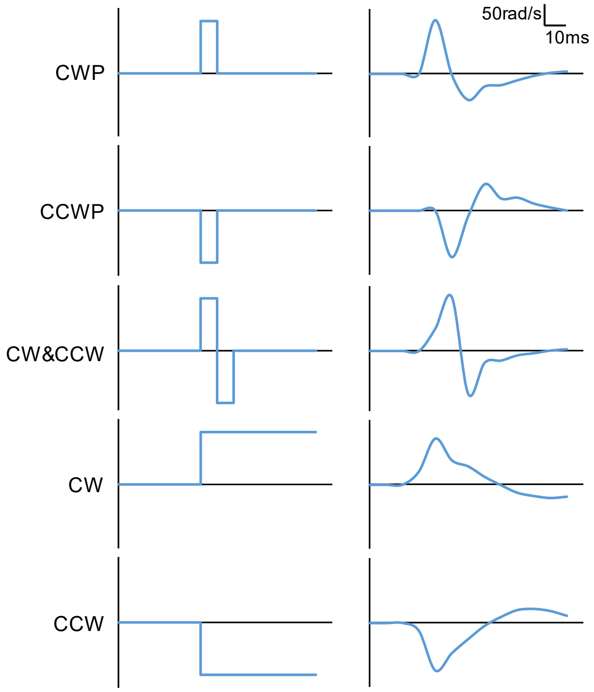

Fig. 3: Schematic diagram of input voltage waveform (left) and measured angular velocity of the device (right).

Thirteen male participants (aged 21-27, all right-handed) took part in the experiment. Participants were instructed to wear a headphone (QuietComfort 35, Bose). During the presentation, white noise was presented through the headphones to eliminate auditory cues, and they were instructed to close their eyes to eliminate visual cues. The experiment was conducted in a seated position with their right arms extended to the front.

Participants held the device in their right hand with no movement while the sensation was presented every 1.0 seconds. There was no limit to the number of times the sensation was presented. The intensity of the presented sensation was rated on a 7-point Likert scale, ranging from 1 (weakest) to 7 (strongest). Additionally, the clarity of the torque direction was rated on a 7-point Likert scale, ranging from -3 (strongly felt left rotation) to 3 (strongly felt right rotation). Subsequently, participants repeated the same procedure while holding the device in their left hand. Following the experiment, participants freely commented on the experiment. The order of the stimulus waveform conditions was randomized, with each condition presented once.

1) *Experimental results*

Fig. 4 shows the intensity of the sensation presented to the right hand, rated on a 7-point Likert scale. A Friedman test was performed on these data, and no significant differences were found.

Fig. 5 shows the clarity of the torque direction of the presented sensation when presented to the right hand, rated on a 7-point Likert scale. A Friedman test was performed on these data ($p<0.01$), and multiple comparisons using the Bonferroni method resulted in CWP - CW, CWP - CCW, CCWP - CW, CW&CCW - CW, CW&CCW - CCW, CW - CCW ($p<0.01$), and CCWP - CCW ($p<0.05$) showed significant differences.

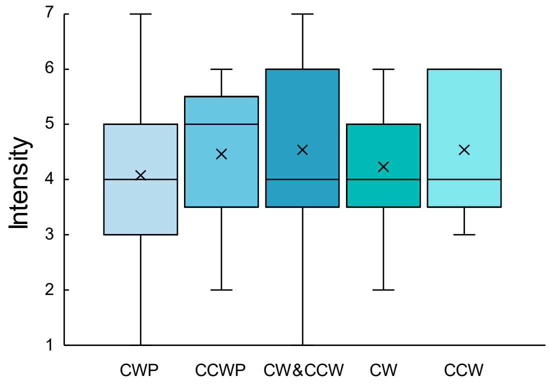

Fig. 4: Subjective sensory intensity (right hand).

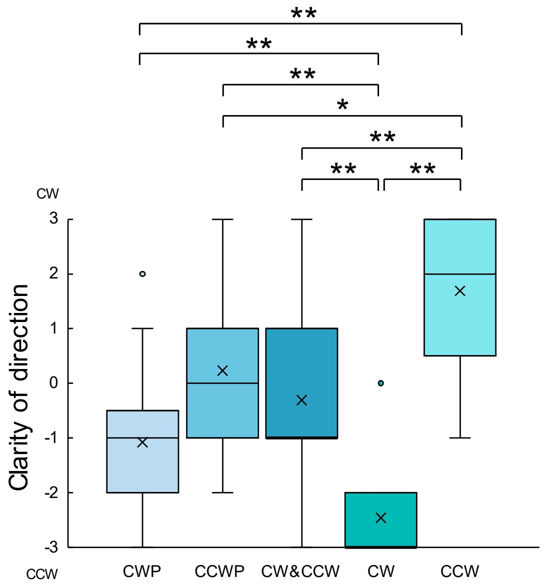

Fig. 5: Clarity of torque direction and its orientation (right hand).

Fig. 6 shows the intensity of the sensation presented to the left hand, rated on a 7-point Likert scale. A Friedman test was performed on these data, and no significant differences were found.

Fig. 7 shows the clarity of the torque direction of the presented sensation when presented to the left hand, rated on a 7-point Likert scale. A Friedman test was performed on these data ($p<0.01$), and multiple comparisons using the Bonferroni method revealed that CWP - CCWP, CWP - CCW, CCWP - CW&CCW, CCWP - CW, CW&CCW - CW, CW&CCW - CCW, CW - CCW ($p<0.01$) showed significant differences.

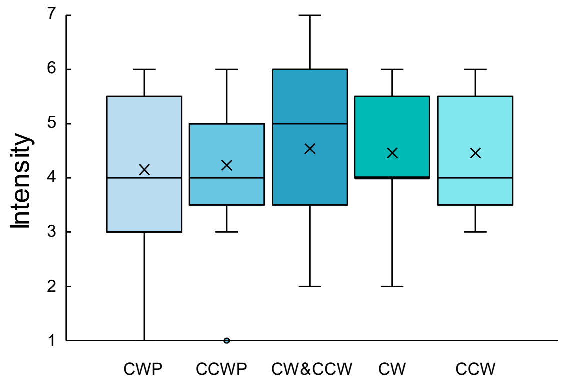

Fig. 6: Subjective sensory intensity (left hand).

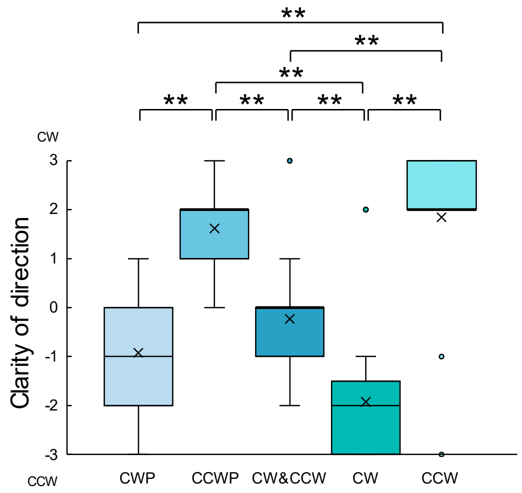

Fig. 7: Clarity of torque direction and its orientation (left hand).

B. *Experiment 2*

In Experiment 2, we investigated the boundary between whether the presented sensation is perceived as one event or two events regarding the interval between forward and backward rotation. We also examined the interval at which the presented sensation is strongly felt but perceived as a single event. If the interval between forward and backward rotation is large, it is expected that each rotation would be perceived as a separate rotational torque. On the other hand, if these intervals were smaller, we expected them to be perceived as a single sensation, but if the intervals were too small, we expected the presented sensation to be perceived as weak.

The schematic diagram of the stimulus waveform is the same as in the CW&CCW condition of Experiment 1. We prepared ten conditions for the interval between forward and backward rotation (= pulse width), ranging from 5 ms to 50 ms, interleaved every 5 ms.

Thirteen male participants (aged 21-27, all right-handed), who were also participants in Experiment 1, took part in the experiment. The visual and auditory conditions were the same as in Experiment 1. The overview of the experiment is shown in Fig. 8.

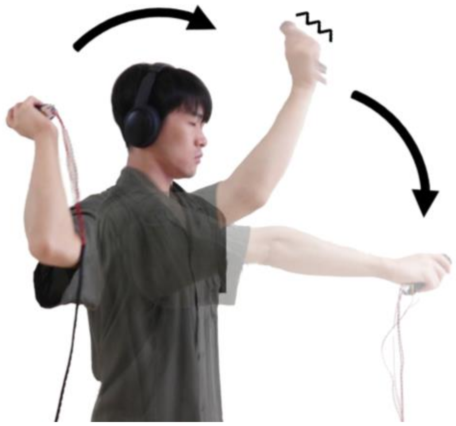

Fig. 8: Overview of Experiment 2.

In this experiment, the tactile presentation was performed under actual racket-playing conditions, with participants in a swinging motion. To reduce the variability of the swing, the participant practiced swinging the device beforehand.

After practice, the participant swung the device forward about five times in a smash-like motion. In this case, as described in III. A, the accelerometer built into the device triggered the stimulation when the arm passed the highest point. Participants responded using a two-alternatives forced choice as to whether they felt the presented repulsion sensation once or twice and rated its intensity on a 9-point Likert scale, ranging from 1 (weakest) to 9 (strongest). After the experiment, participants commented freely on the experiment. The order of the stimulus conditions was randomized, with each condition presented once.

1) *Experimental results*

Fig. 9 shows the probability of feeling the repulsion sensation twice. The probability is 16% or less when the interval between forward and backward rotation is less than 30 ms, but almost 50% at 35 ms and exceeding 80% at 50 ms.

Fig. 10 shows the intensity of the presented sensations rated on a 9-point Likert scale, ranging from 1 (weakest) to 9 (strongest). A Friedman test was performed on these data ($p<0.01$), and multiple comparisons using the Bonferroni method found significant differences between the following conditions: 5-30, 15-45, 20-45, 25-45, 30-35, 30-45, 30-50 ($p<0.01$), 10-30, 15-50, 25- 50, 30-40 ($p<0.05$).

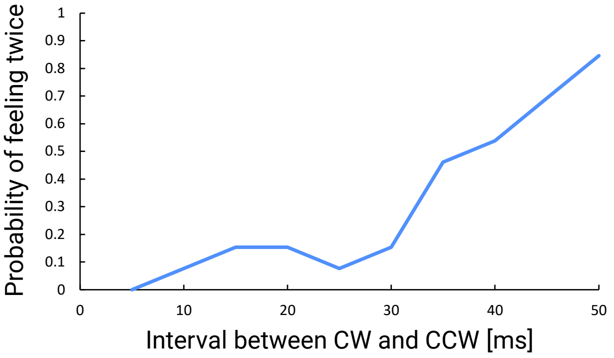

Fig. 9: Probability of feeling the repulsion sensation twice.

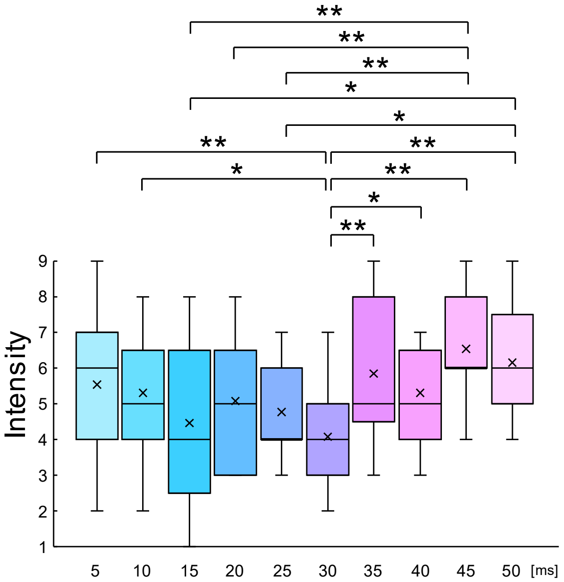

Fig. 10: Assessment of the intensity of the presented sensations.

V. DISCUSSION

A. Presentation of forward and backward rotation in a short time (Experiment 1)

In this study, voltage pulses were given as shown in Fig. 3. When single pulses were presented (CWP and CCWP conditions), the braking function of the motor driver (a function to stop the motor abruptly by short-circuiting the two output terminals) was used after the pulse. As a result, the motor rotated in one direction and the angular velocity decreased rapidly when the pulse ended. As observed in the actual measurement results presented in Fig. 3, the angular acceleration takes a large positive value when the pulse is turned on and a relatively small negative value when the pulse is turned off. This suggests that people are likely to perceive the change in angular velocity mainly at the time of the onset. In contrast, when both positive and negative pulses were given continuously as seen in the proposed method (CW&CCW condition), the angular velocity waveform displayed a close to positive-negative symmetry pattern, as shown in the actual measurement results on the right side of Fig. 3. This made it difficult to perceive the direction of the torque. When positive or negative step waveforms were given (CW and CCW conditions), the angular velocity of the grasp tended to gently approach zero following the initial increase, as shown in the actual measurement results. Consequently, participants predominantly perceived the initial rise in angular velocity.

In Experiment 1, no significant difference in intensity perception was observed between the right and left-hand conditions. It is somewhat surprising that no difference in intensity was perceived between the CWP, CCWP, and CW&CCW conditions, despite the difference in pulse number. However, the effect of averaging stimulus intensity by stimulus duration might have worked. On the other hand, previous studies have shown that subjective intensity varies with the duration of the vibratory stimulus [23][24][25], and we should investigate the intensity perception in detail in the future.

Significant differences were found between CW&CCW - CW and CW&CCW - CCW for both the right and left hand. This suggests that the proposed method has the effect of making it difficult to perceive the direction of torque due to rotational acceleration, as we have expected. On the other hand, no significant differences were found between CW&CCW - CWP and CW&CCW - CCWP when presented to the right hand and between CW&CCW - CWP when presented to the left hand. A reason could be the reverse torque generated when rotation slows down: as mentioned above, the braking function of the motor driver was used in this experimental setup, and it is assumed that the torque in the opposite direction is generated at the end of the pulse, so it is possible that the situation was similar to the proposed method of "presenting torque in one direction and torque in the opposite direction in a short period" to some extent, even with a single pulse.

Significant differences were found between CWP - CCWP and CCWP - CW&CCW in the left hand. This suggests that people perceive the direction of the force of the earlier sensation more strongly than the later sensations presented within a short period. One reason for this is that the later sensation is masked by the earlier one. Since there were no differences in pulse amplitude across these conditions, it is conceivable that the later sensation was canceled out by the strength of the earlier sensation.

Additionally, notable differences were observed between CWP - CW and CCWP - CCW in the right hand and between CWP - CCWP in the left hand. This suggests that when presenting the sensation of hitting with the racket, it is possible to adjust the left-right deviation in the hitting position by using different pulse widths and rotations, such as "presentation by CW or CCW rotation when the hitting position deviates greatly to the left or right" and "presentation by CWP or CCWP when the hitting position deviates slightly to the left or right". We received many comments that the direction of the torque was easier to understand in the CW and CCW conditions than in the CWP and CCWP conditions, suggesting that this is an effective method of presenting the impact position.

Comparing Fig. 5 and Fig. 7, there seems to be a slight difference between right-hand and left-hand conditions, suggesting that there is a direction of torque that is easier to perceive for the right or left hand. Specifically, the right hand tends to perceive the torque direction of counter-clockwise rotation (CCW) and the left hand tends to perceive the torque direction of clockwise rotation (CW). This is considered to be the direction in which the wrist is easily rotated. In this study, all participants were right-handed, and it remains to be seen whether similar results can be obtained for left-handed people.

B. Interval of repulsion (Experiment 2)

In Experiment 2, the probability of perceiving the presented sensation as two distinct sensations was at or lower than 16% when the interval between forward and backward rotation was less than 30 ms, but it was almost 50% when the interval was 35 ms. This suggests that the threshold in the present system is in the range of 30~35 ms. The temporal resolution of tactile stimuli (the threshold at which two sequential stimuli are perceived as two stimuli) has been reported in many classical literatures [26] and is generally in the range of 10 ms to 50 ms, which agrees with our result. However, it is interesting to note that in our case, there is a noticeable shift between 30 ms and 35 ms. This may be because the participants in this study were a relatively homogeneous population (all males in their 20s). This point also needs to be discussed in our future study.

In Fig. 10, when we focus on the 5 ms to 30 ms periods in which the sensation was perceived as a single stimulus, we can see that the strength of the sensation monotonically decreases as the presentation time increases and is the weakest at 30 ms. This cannot be explained by the strength of the physically presented torque. One plausible explanation is that the perceived intensity could be the result of an "average" intensity, divided by the duration of the presentation. This is similar to the phenomenon in Experiment 1, where the subjective intensity of a single pulse did not differ from that of two pulses. Alternatively, the perception may have been weakened by the characteristics of human mechanoreceptors, especially as the pulse width increases, lower-frequency components prevail over higher-frequency components. If the latter is correct, the quality of the sensation would have changed from a hard to a soft repulsive sensation, suggesting that the feel of the hitting can be altered by varying the time interval between the forward and backward rotations.

When the time width was 35 ms, the participant began to perceive the presented sensation as two stimuli and reported a stronger perception of the stimuli in comparison to the 30 ms time width. This is supported by the participant's comment: "I felt the force stronger with two pulses than with one pulse". This may be due to the effect of masking: when the participant perceived the pulses as one stimulus, the sensation of the second pulse was masked by the first pulse. However, when they perceived them as two distinct stimuli, the participants perceived them as stronger.

In this study, we introduced the utilization of a DC motor to present the sensation of hitting the racket. One of its main advantages was its ability to present a wide range of frequencies. On the other hand, the results of the present experiment showed that in the situation of a positive and a negative pulse stimulus, a pulse longer than 30 ms was perceived as two pulses. This suggests that the presentation of frequencies lower than 33 Hz is difficult with the present method. It should be noted, however, that this experiment was conducted with square-wave pulses, a situation in which the individual pulses were relatively easy to identify. By using waveforms whose rise and fall times are difficult to distinguish, it may be possible to use a wider range of pulses. In addition, further research is needed to explore cases involving a greater number of stimuli.

VI. CONCLUSION

We proposed the utilization of a single DC motor for the compact presentation of the impact sensation, with the goal of reproducing the sensation of hitting with a racket and conducted a fundamental consideration for this purpose.

Presenting tactile feedback by motor rotation requires that the direction of rotation is imperceptible. To achieve this, we proposed a method of "rotating the motor in one direction and then in the opposite direction" and conducted two experiments. The results indicated the effectiveness of the proposed method and suggested a way to change the hitting location and perception.

Many research questions remain, however. For instance, the right and left hands tend to perceive the presented rotational vibration differently, and it needs to be verified whether the same results can be obtained with a wide range of stimulus parameters. In the proposed method, the positive and negative pulses were presented one after the other, but it is necessary to verify the change in perception and quality of sensation when the number of pulses is increased. In particular, it is well known that it is possible to express the sensation of the material property of the target object by giving a decaying sinusoidal wave [3][4], but such a wave can be considered as a continuous and damped presentation of positive and negative pulses, as used in this study. In the future, we would like to improve the presentation of hitting sensation in racket sports by investigating these factors.

REFERENCES

[1] H. Liu, Z. Wang, C. Mousas, and D. Kao, 'Virtual Reality Racket Sports: Virtual Drills for Exercise and Training', in 2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), Jan. 2020, pp. 566–576.

[2] Y. Huang, L. Churches, and B. Reilly, 'A Case Study on Virtual Reality American Football Training', in Proceedings of the 2015 Virtual Reality International Conference, in VRIC '15. New York, NY, USA: Association for Computing Machinery, Apr. 2015, pp. 1–5.

[3] P. Wellman and R. D. Howe, 'Towards realistic vibrotactile display in virtual environments', in Proceedings of the ASME dynamic systems and control division, Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems, 1995, pp. 713–718.

[4] A. M. Okamura, M. R. Cutkosky, and J. T. Dennerlein, 'Reality-based models for vibration feedback in virtual environments', IEEE/ASME Transactions on Mechatronics, vol. 6, no. 3, pp. 245–252, Sep. 2001.

[5] K. Akahane, T. Hamada, T. Yamaguchi, and M. Sato, 'Development of a High Definition Haptic Rendering for Stability and Fidelity', in Human-Computer Interaction. Interaction Techniques and Environments, J. A. Jacko, Ed., in Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, 2011, pp. 3–12.

[6] T. Amemiya and T. Maeda, 'Asymmetric Oscillation Distorts the Perceived Heaviness of Handheld Objects', IEEE Transactions on Haptics, vol. 1, no. 1, pp. 9–18, Jan. 2008.

[7] I. Choi, E. Ofek, H. Benko, M. Sinclair, and C. Holz, 'CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality', in Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, in CHI '18. New York, NY, USA: Association for Computing Machinery, Apr. 2018, pp. 1–13.

[8] I. Choi, H. Culbertson, M. R. Miller, A. Olwal, and S. Follmer, 'Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality', in Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology, in UIST '17. New York, NY, USA: Association for Computing Machinery, Oct. 2017, pp. 119–130.

[9] H. Benko, C. Holz, M. Sinclair, and E. Ofek, ‘NormalTouch and TextureTouch: High-fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers’, in Proceedings of the 29th Annual Symposium on User Interface Software and Technology, in UIST ’16. New York, NY, USA: Association for Computing Machinery, Oct. 2016, pp. 717–728.

[10] F. W. Teck, C. C. Ling, F. Farbiz, and H. Zhiyong, ‘Ungrounded haptic rendering device for torque simulation in virtual tennis’, in ACM SIGGRAPH 2012 Emerging Technologies, in SIGGRAPH ’12. New York, NY, USA: Association for Computing Machinery, Aug. 2012, p. 1.

[11] M. Sakai, Y. Fukui, and N. Nakamura, ‘Effective Output Patterns for Torque Display’, presented at the International Symposium on Information, Communication and Automation Technologies, 2003. Accessed: Oct. 24, 2023.

[12] K. N. Winfree, J. Gewirtz, T. Mather, J. Fiene, and K. J. Kuchenbecker, ‘A high fidelity ungrounded torque feedback device: The iTorqU 2.0’, in World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Mar. 2009, pp. 261–266.

[13] J. M. Walker, M. Raitor, A. Mallery, H. Culbertson, P. Stolka, and A. M. Okamura, ‘A dual-flywheel ungrounded haptic feedback system provides single-axis moment pulses for clear direction signals’, in 2016 IEEE Haptics Symposium (HAPTICS), Apr. 2016, pp. 7–13.

[14] T. Hashimoto, S. Yoshida, and T. Narumi, ‘MetamorphX: An Ungrounded 3-DoF Moment Display that Changes its Physical Properties through Rotational Impedance Control’, in Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology, in UIST ’22. New York, NY, USA: Association for Computing Machinery, Oct. 2022, pp. 1–14.

[15] T. Tanabe, H. Yano, and H. Iwata, ‘Temporal characteristics of non-grounded translational force and torque display using asymmetric vibrations’, in 2017 IEEE World Haptics Conference (WHC), Jun. 2017, pp. 310–315.

[16] T. Tanabe, H. Yano, H. Endo, S. Ino, and H. Iwata, ‘Motion Guidance Using Translational Force and Torque Feedback by Induced Pulling Illusion’, in Haptics: Science, Technology, Applications, I. Nisky, J. Hartcher-O’Brien, M. Wiertlewski, and J. Smeets, Eds., in Lecture Notes in Computer Science. Cham: Springer International Publishing, 2020, pp. 471–479.

[17] D.-G. Kim, J. Lee, and S. Choi, ‘MMGrip: A Handheld Multimodal Haptic Device Combining Vibration, Impact, and Shear for Realistic Expression of Contact’, in SIGGRAPH Asia 2022 Posters, in SA ’22. New York, NY, USA: Association for Computing Machinery, Dec. 2022, pp. 1–2.

[18] Y. Tanaka, A. Horie, and X. ‘Anthony’ Chen, ‘DualVib: Simulating Haptic Sensation of Dynamic Mass by Combining Pseudo-Force and Texture Feedback’, in Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology, in VRST ’20. New York, NY, USA: Association for Computing Machinery, Nov. 2020, pp. 1–10.

[19] C. Park, J. Park, S. Oh, and S. Choi, ‘Realistic Haptic Rendering of Collision Effects Using Multimodal Vibrotactile and Impact Feedback’, in 2019 IEEE World Haptics Conference (WHC), Jul. 2019, pp. 449–454.

[20] V. Yem, R. Okazaki, and H. Kajimoto, ‘Vibrotactile and pseudo force presentation using motor rotational acceleration’, in 2016 IEEE Haptics Symposium (HAPTICS), Apr. 2016, pp. 47–51.

[21] M. Manabe, K. Ushiyama, A. Takahashi, and H. Kajimoto, ‘Vibrotactile Presentation using a Motor within a Housing and Rotor Fixed to the Skin’, in 2021 IEEE World Haptics Conference (WHC), Jul. 2021, pp. 906–911.

[22] R. Gourishetti and K. J. Kuchenbecker, ‘Evaluation of Vibrotactile Output From a Rotating Motor Actuator’, IEEE Transactions on Haptics, vol. 15, no. 1, pp. 39–44, Jan. 2022.

[23] S. Bochereau, A. Terekhov, and V. Hayward, ‘Amplitude and Duration Interdependence in the Perceived Intensity of Complex Tactile Signals’, in Haptics: Neuroscience, Devices, Modeling, and Applications, M. Auvray and C. Duriez, Eds., in Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, 2014, pp. 93–100.

[24] F. Tang and R. P. McMahan, ‘The Syncopated Energy Algorithm for Rendering Real-Time Tactile Interactions’, Frontiers in ICT, vol. 6, 2019, Accessed: Oct. 24, 2023.

[25] M.-H. Choi, K.-B. Kim, Y.-J. Kim, J.-S. Kim, H.-S. Kim, and S.-C. Chung, ‘Study on the Cognitive Characteristics Induced by Changes in the Intensity, Frequency and Duration of Vibratory Stimuli’, Behav Sci (Basel), vol. 13, no. 5, p. 350, Apr. 2023.

[26] L. Petrosino and D. Fucci, ‘Temporal Resolution of the Aging Tactile Sensory System’, Percept Mot Skills, vol. 68, no. 1, pp. 288–290, Feb. 1989.