Hardware-in-the-Loop simulation algorithm for helicopter rotor time-varying echo signals

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ABSTRACT

The inherent micro-Doppler (m-D) feature of helicopter rotor echoes has been widely used in signal detection and identification. To meet the high accuracy and real-time performance requirements of the hardware-in-the-loop (HIL) simulation, this paper proposes a real-time simulation algorithm for the echo signals of helicopter rotor blades. The proposed algorithm can not only simulate the echo signals of different helicopter rotors but can also reflect the m-D characteristics of the helicopter rotor echo signals accurately. Compared to other methods, the simulation algorithm exhibits both high accuracy and superior real-time performance. The experimental results prove the feasibility and effectiveness of this method. The results of this study can have various industrial applications, such as helicopter detection and helicopter identification. This method can ensure the reliability of radar echo characteristics research, while effectively reducing the volume and weight of the system; thus, it can effectively reduce costs.

1. Introduction

Helicopters have garnered considerable interest for military and civil applications, because of their advantages and suitability in searching, detecting, monitoring, identifying, and locating targets (Mu et al., 2014). The echo of the rotor blades of a helicopter features micro-Doppler (m-D) characteristics (Clemente & Soraghan, 2014; Garry & Smith, 2019; Tahmoush, 2015), which are generally inherent for a radar target; the m-D characteristics exhibit less manual controllability (Guo & Sheng, 2010). Therefore, this feature has been widely studied for the classification and recognition of helicopters (Wu et al., 2018; Zuo et al., 2013). However, to study the m-D characteristics of helicopter rotor echoes, it is necessary to conduct a comprehensive study of the echoes of helicopter rotor blades. Owing to the difficulty in obtaining field experimental data, hardware-in-the-loop (HIL) simulations have become necessary for the echo simulations of helicopter rotor blades.

HIL simulations are one of the most effective methods for verifying the performance and reliability of echo simulations (Li et al., 2006). In general, the HIL simulation is a real-time simulation method, as the platform reacts in approximately the same manner as a real experiment (Cai et al., 2008; Corpino & Stesina, 2014; Olivier et al., 2011). Griffith and Gupta (Griffith & Gupta, 2011) proposed an approach called ‘approximate simulator’, which was suitable for implementation in HIL testing as it did not involve significant costs. However, for elucidating the in-situ time-domain response of an antenna over the frequency band of interest, either measurements at discrete frequencies or numerical analyses are required, which can be significantly time-consuming. Moreover, previous research indicates that this method cannot accurately reflect the m-D characteristics of the echo signal of a helicopter rotor blade, making it unsuitable for the detection and identification of helicopters (Singh et al., 2019; Vorobev, 2018; Vorobev et al., 2018; Wang et al., 2018). Guo et al. (Guo et al., 2019) proposed a novel technology for the electromagnetic characteristic simulation of helicopter blades. However, owing to the limitations of the actual manufacturing process, the consistencies of the amplitude and phase responses of each scattering source could not be guaranteed, which could reduce the efficiency of synthesis.

Many studies have also focused on analysing the scattering characteristics of helicopter rotor blades, which are generally obtained through numerical methods and high-frequency progressive methods. Xiang et al. (Xiang, 2010; Xiang et al., 2010) proposed a multi-level fast multipole algorithm to simulate the echo signal of a helicopter rotor blade.
rotor. However, because of the limitations in terms of calculation resources and calculation time, the numerical method could only be used to simulate radar echo signals in the lower frequency bands. Jiang (Jiang & Zhao, 2016) and Wang (Wang et al., 2015) both designed CAD models of the rotor blade of a helicopter and obtained the radar cross section (RCS) of a target by using physical optics (PO) and equivalent current methods. Li et al. (Li et al., 2019) used the secondary development function provided by the software NX10.0 to realize independent control and analysis, and they used the PO method to obtain the scattering characteristics of the helicopter rotor blades.

For the echo analysis of a certain helicopter target, most conventional methods require the re-modelling of the target, which can take several months. Moreover, researchers must model the helicopter accurately and divide the density and scale of the electromagnetic grid reasonably. Otherwise, the obtained scattering characteristics of the helicopter will be inaccurate, leading to the waste of a significant amount of labour and material resources. Therefore, in HIL simulations, if the physical modelling of a certain helicopter target can be avoided, we can directly obtain an accurate echo of the helicopter rotor in real time based on a mathematical model of the echo, which can not only reduce resource consumption but also provide economic benefits. In addition, the mathematical model of the echo signal can be considered to be composed of a series of related parameters of the helicopter. Compared with the aforementioned method of CAD modelling, its parameter expression is more straightforward and concise, which is convenient for data analysis and optimization applications.

The remainder of this paper is organized as follows. Section 2 describes the materials and methods used. Section 2.1 describes a high-precision mathematical model of the time-varying echoes of helicopter rotor blades. As HIL simulations need to meet the high accuracy and real-time performance requirements, based on Section 2.1, Section 2.2 proposes a real-time simulation algorithm for the echo signals of helicopter rotor blades. Section 2.3 presents the simulation analysis of the real-time algorithm and aims to prove that the time-varying echo signal simulated by the real-time simulation algorithm proposed herein, which is the same as the mathematical model, can accurately reflect complex m-D characteristics. Section 3 presents the results. Section 4 states the discussion; Section 4.1 provides an error analysis of the real-time simulation algorithm, while Section 4.2 discusses the calculation and analysis involved in the real-time simulation algorithm. Finally, the conclusions of the study are presented in Section 5.

For the HIL simulation, high-precision and real-time echo simulations of the helicopter rotor blades are required. High precision implies that the simulated time-varying echo signal should accurately reflect the complex m-D characteristics. Without reducing the precision of the true time-varying echo signal, real-time implementation requires the consumption of fewer multiplier resources (also termed as digital signal processing (DSP) in the hardware platform), along with easier hardware implementation. To address these requirements, the authors first use a high-precision mathematical model of the time-varying echo signals of helicopter rotor blades to ensure high-accuracy echo signals. Second, based on the mathematical model, this paper proposes a real-time simulation algorithm to ensure the real-time performance of echo simulation. To the best of the author’s knowledge, such a solution in HIL from this perspective has not been reported thus far.

2. Materials and methods

2.1. Signal model

By using Dr. Chen’s integral model (Chen, 2001), the echo model of a single blade of a helicopter rotor can be expressed as follows:

\[
s(t) = \sum_{i=1}^{K} s_{pi}(t) = \exp\left(-j \frac{4\pi R_0}{\lambda} \right) \sum_{i=1}^{K} \sigma_{pi} \exp\left(-j \frac{4\pi}{\lambda} \right) \times x_i \cos(\theta_1 + 2\pi f_{rot} t) \cos \beta
\]

where \( K \) is the number of strong scattering centres, \( P \) is a certain strong scattering point on the blade, \( R_0 \) is the distance between the radar and rotor centre \( O' \), \( i \) is the \( i^{th} \) scattering centre, \( f_{rot} \) is the rotation frequency of the rotor, and \( x_i \) and \( \theta_1 \) are the distance and initial rotation angle between the scattering point \( P_i \) and the rotor centre, respectively. \( \lambda \) is the wavelength of the transmitted signal, \( \beta \) is the pitch angle, and \( \sigma_{pi} \) is the backscattering coefficient (Chen, 2001). The geometric relationship between the radar and rotor blade scattering points is shown in Figure 1 (Xia et al., 2019).

This study mainly analyses the situation wherein the scattering coefficients are consistent and the scattering points are distributed at equal intervals. According to (Chen et al., 2016), the echo model of the helicopter rotor
multi-blade is given by

\[
S_\Sigma(t) = \sum_{n=1}^{N} s_n(t) = \sigma \exp(-j\frac{4\pi R_0}{\lambda}) \sum_{n=1}^{N} \sum_{i=1}^{K} \exp(-j\frac{4\pi}{\lambda}(i-1)d) \times \cos(\theta_i + 2\pi(n-1)/N + 2\pi f_{rot}t) \cos \beta) 
\]

where \(N\) is the number of helicopter rotor blades, \(\sigma\) is the backscattering coefficient, and \(d\) is the interval between adjacent scattering points.

### 2.2. Real-time simulation algorithm of helicopter rotor echo signal

The real-time simulation algorithm mainly adopts amplitude characteristic modulation, the in-phase and quadrature (IQ) control algorithm, and accumulation processes to perform real-time reconstruction of the helicopter rotor multi-blade echo. Figure 2 shows a data-flow diagram of the target echo reconstruction process.

According to Equation (2), the echo model of a single blade of a helicopter rotor can be modified to the following form:

\[
s_n(t) = \sum_{i=1}^{K} \exp(-j\frac{4\pi}{\lambda}(i-1)d) \times \cos(\theta_i + 2\pi(n-1)/N + 2\pi f_{rot}t) \cos \beta)\sigma \exp(-j\frac{4\pi R_0}{\lambda}) 
\]

If \(A = \sigma \exp(-j\frac{4\pi R_0}{\lambda})\), const \(= 2\pi \cos \beta/\lambda\), const1 \(= 2\pi d/\lambda\), \(\Psi_n(t) = \text{const} \times \cos(\theta_n + 2\pi f_{rot}t)\), \(\Theta_n(t) = \text{const} \times \cos(\theta_n + 2\pi f_{rot}t)\), and \(\theta_n = \theta_1 + 2\pi(n-1)/N\), the echo model of a single blade of a helicopter rotor can be transformed into the following I and Q signal forms:

\[
s_n(t) = \begin{cases} 
A \times (l_n(t) + j \times Q_n(t)) & \text{if } \sin[\Theta_n(t)] \neq 0 \\
A \times K & \text{if } \sin[\Theta_n(t)] = 0 
\end{cases} 
\]

where \(l_n(t) = \cos[\Psi_n(t)] \times \frac{\sin[\Psi_n(t)] \cos[\Theta_n(t)] + \sin[\Theta_n(t)] \cos[\Psi_n(t)]}{\sin[\Theta_n(t)] \cos[\Theta_n(t)] + \sin[\Theta_n(t)] \cos[\Psi_n(t)]}\) is a real signal, and \(Q_n(t) = -\sin[\Psi_n(t)] \times \frac{\sin[\Psi_n(t)] \cos[\Theta_n(t)] + \sin[\Theta_n(t)] \cos[\Psi_n(t)]}{\sin[\Theta_n(t)] \cos[\Theta_n(t)] + \sin[\Theta_n(t)] \cos[\Psi_n(t)]}\) is an imaginary signal. The phases \(\Psi_n(t)\) and \(\Theta_n(t)\) can be expressed in the following forms:

\[
\Psi_n(t) = INT[\Psi_n(t)] + \Delta \Psi_n(t) \\
\Theta_n(t) = INT[\Theta_n(t)] + \Delta \Theta_n(t) 
\]

where \(\text{INT}[\cdot]\) is the integer part, and \(\Delta\) is the fractional part with range of \(\Delta \in [0, 1)\).

Here, we only need to substitute the relevant parameters of the echo signal of the helicopter rotor in this algorithm to obtain an accurate single-blade echo signal \(s_n(t)\) of the helicopter rotor.

Finally, we calculate the cumulative sum of all helicopter rotor blade echo signals to obtain the echo of the helicopter rotor multi-blade, as follows:

\[
S_\Sigma(t) = \sum_{n=1}^{N} s_n(t) 
\]

where \(n = 1, 2, \ldots, N\).

### 2.3. Effectiveness analysis of real-time algorithm

To verify whether the real-time simulation algorithm described above correctly generates echo signals similar to the actual echo signals, we conducted a simulation experiment. The parameters were set as follows: the wavelength \(\lambda\) was 0.3 m; the distance between the radar and rotor centre \(R_0\) was 50,000 m; the length of the blade was 6 m; the interval between adjacent scattering points, \(d\), was 0.04 m; the pulse repetition frequency (PRF) was 4000 Hz; the rotation frequency of the rotor, \(f_{rot}\), was 5 Hz; and \(\theta_1 = \beta = 0\). The amplitudes involved in this work were all normalized, and when not specified, they were unitless. We used the short-time Fourier transform (STFT) of a Gaussian window to analyse the time–frequency characteristics of the helicopter rotor blades.

We compared and analysed the actual echo signal and the echo of the helicopter rotor blade obtained via the real-time simulation algorithm, as described in
Figure 3. Actual echo signal \((N = 2)\): (a) time-domain signal and (b) time-frequency domain signal.

Figure 4. Real-time simulation algorithm \((N = 2)\): (a) time-domain signal (b) time-frequency domain signal.

d this section. The number of blades was set as \(N = 2\). Figure 3 (a) and (b) show the time-domain signal and time-frequency domain signal obtained from the actual echo signal, respectively. Figure 4 (a) and (b) show the time-domain echo signal and time-frequency domain signal obtained using the real-time simulation algorithm, respectively. Through an analysis of Figure 3 (a) and (b) and Figure 4 (a) and (b) by using the real-time simulation algorithm, it is evident that the actual echo signal and the echo result of the helicopter rotor blade simulation are consistent. Therefore, based on above-discussed simulation, we conclude that the echo signal simulated by the real-time simulation algorithm proposed herein can accurately reflect the m-D characteristics of the helicopter rotor blade.

3. Results

We conducted several simulation experiments in order to verify that the real-time simulation algorithm described above correctly generates echo signals for different parameters. In cases where the new parameters are not specified, the same parameters mentioned in Section 2.3 were used.

3.1. Analysis of different blade numbers

We compared and analysed the echoes obtained by different numbers of helicopter rotor blades by using the real-time simulation algorithm. We set the number of blades as \(N = 3\) and \(N = 4\). Figure 5 (a) and (b) show the time-domain echo signal and time-frequency domain signal obtained by the real-time simulation algorithm, respectively, when \(N = 3\). Figure 6 (a) and (b) show the time-domain echo signal and time-frequency domain signal obtained by the real-time simulation algorithm, respectively, when \(N = 4\).

Through an analysis of Figure 5 (a) and (b) and Figure 6 (a) and (b), it is evident that, by using the real-time simulation algorithm, we can obtain different stable echo signals for different numbers of helicopter rotor blades. Furthermore, it is also clear that the parities of the helicopter blades, which are determined by the characteristics of the helicopter rotor, cannot be distinguished through time-domain analyses of Figure 5 (a) and Figure 6 (a) alone. This is because odd-numbered blades are not strictly symmetrical in the time domain, whereas even-numbered blades are strictly symmetrical; this will inevitably cause an overlapping of the time-domain signals.
3.2. Analysis of different scattering point intervals

Different scattering point intervals will have different effects on the m-D characteristics of the helicopter rotor echo signals; therefore, we studied the effects of scattering point intervals, as explained in this section. To facilitate the observation of the m-D characteristics of the helicopter rotor blades, we set the number of blades as \( N = 1 \); the scattering point intervals are 0.3 and 1. Figure 7 (a) and (b) show the time-domain echo signal and time–frequency domain signal obtained by the real-time simulation algorithm, respectively, when \( d = 0.3 \). Figure 8 (a) and (b) show the time-domain echo signal and time–frequency domain signal obtained by the real-time simulation algorithm, respectively, when \( d = 1 \).

Figure 5. Real-time simulation algorithm \((N = 3)\): (a) time-domain signal (b) time-frequency domain signal.

Figure 6. Real-time simulation algorithm \((N = 4)\): (a) time-domain signal (b) time-frequency domain signal.

Through an analysis of Figure 7 (a) and (b) and Figure 8 (a) and (b), it is evident that, by using the real-time simulation algorithm, we can obtain different echoes for helicopter rotor blades at different scattering point intervals with high precision. Moreover, the time domain analysis of the echo signal can accurately reflect the phenomenon of multiple peaks; the time–frequency domain analysis of the echo signal can accurately reflect the phenomenon of multiple sinusoids. The simulation results further show that the m-D characteristics of the helicopter rotor echo are complex and that the echo signal obtained by the real-time simulation algorithm proposed herein can be the basis for the target identification of helicopters.

3.3. Analysis of different rotor rotation frequencies

Because different rotor rotation frequencies will have different effects on the m-D characteristics of helicopter rotor echo signals, we analysed the effects of rotor rotation frequencies, as described in this section. According to previous studies (Cheng, 1999; Jiang & Zhao, 2014), the rotation frequency of a helicopter rotor lies between 3 and 7 Hz. To facilitate the observation of the m-D characteristics of the helicopter rotor blades and simulate more realistic experimental situations, we set the number of blades as \( N = 1 \), observation time as 0.35 s, and rotation frequency of the helicopter rotor as 3 and 6 Hz. Figure 9 (a) and (b) show the time-domain echo signal and time–frequency domain signal obtained by the real-time simulation algorithm, respectively, when \( f_{\text{rot}} = 3 \) Hz. Figure 10 (a) and (b) show the time-domain echo signal and time–frequency domain signal obtained by the real-time simulation algorithm, respectively, when \( f_{\text{rot}} = 6 \) Hz.

Through an analysis of Figure 9 (a) and (b) and Figure 10 (a) and (b), it is evident that, by using the real-time simulation algorithm, we can obtain different echoes for helicopter rotor blades at different rotation frequencies with high precision. From the time–frequency domain analysis of the echo signal, the m-D characteristics of the helicopter can be reflected with high accuracy. This is because, theoretically, at the same observation period, the rotation frequency of the rotor is proportional to
Figure 7. Real-time simulation algorithm ($d = 0.3$): (a) time-domain signal (b) time-frequency domain signal.

Figure 8. Real-time simulation algorithm ($d = 1$): (a) time-domain signal (b) time-frequency domain signal.

Figure 9. Real-time simulation algorithm ($f_{\text{rot}} = 3 \text{ Hz}$): (a) time-domain signal (b) time-frequency domain signal.

Figure 10. Real-time simulation algorithm ($f_{\text{rot}} = 6 \text{ Hz}$): (a) time-domain signal (b) time-frequency domain signal.
the number of times the time–frequency characteristics occur; therefore, it will be proportional to the maximum value of the m-D frequency. The greater the rotation frequency of the rotor, the more frequently the time–frequency characteristics appear. The greater the rotation frequency, the greater the maximum value of the m-D frequency.

3.4. Analysis of different lengths of blades

Because different lengths of blades have different effects on the m-D characteristics of helicopter rotor echo signals, we analysed the effects of different lengths of blades, as described in this section. According to previous studies (Cheng, 1999; Jiang & Zhao, 2014), the lengths of helicopter rotor blades range from 5 to 12 m. To facilitate the observation of the m-D characteristics of the helicopter rotor blades and simulate more realistic experimental situations, we set the number of blades as $N = 1$ and the lengths of the blades as 5 and 8 m. Figure 11 (a) and (b) show the time-domain echo signal and time–frequency domain signal obtained by the real-time simulation algorithm, respectively, when the length is 5 m. Figure 12 (a) and (b) show the time-domain echo signal and time–frequency domain signal obtained by the real-time simulation algorithm, respectively, when the length is 8 m.

Through an analysis of Figure 11 (a) and (b) and Figure 12 (a) and (b), it is evident that, by using the real-time simulation algorithm, we can obtain different echoes for the helicopter rotor blades of different lengths with high precision. The time–frequency domain analysis of the echo signal reflects the m-D characteristics of the helicopter accurately. This is because, theoretically, at the same observation time, different helicopter rotor blade lengths will not affect the number of time–frequency domain features; however, the length of helicopter rotor blade is proportional to the maximum value of the m-D frequency. The longer the helicopter rotor blade, the greater is the maximum value of the m-D frequency. Therefore, these simulation results further illustrate that, by using the real-time simulation algorithm presented herein, we can simulate a considerably close approximation of the real echo signals of helicopter rotors.

4. Discussion

4.1. Error analysis of real-time simulation algorithm

To ensure the accuracy and real-time performance of the algorithm, without adding additional spurious components, it is necessary to perform an error analysis for the selection of phases $\Psi_n(t)$ and $\Theta_n(t)$. As the calculation of the single-blade echo signal of the helicopter rotor
involves the analysis of the signal \( \sin[\cdot] \) and \( \cos[\cdot] \), we analysed the error according to the following mathematical formula:

\[
\sin(\vartheta + \Delta \vartheta) = \sin(\vartheta) \cos(\Delta \vartheta) + \cos(\vartheta) \sin(\Delta \vartheta) \\
\approx \sin(\vartheta) + \cos(\vartheta) \Delta \vartheta
\]

(8)

According to Equation (8), the error term is \( d_e = \cos(\vartheta) \Delta \vartheta \in [-\Delta \vartheta, \Delta \vartheta] \), where \( \vartheta \) represents the actual angle, and \( \Delta \vartheta \) represents the error angle. Therefore, as long as the resolution of the phase \( \Psi_n(t) \) and \( \Theta_n(t) \) is not less than 0.01°, the theoretical error rate of 1% can be guaranteed.

### 4.2. Calculation and analysis involved in the real-time simulation algorithm

According to the real-time simulation algorithm and the error analysis in Section 4.1, the simulation algorithm only needs basic calculations and trigonometric functions to simulate additional helicopter rotor echoes in real time. Because we calculate the echo data of each helicopter rotor (real signal), the number of operations required for multiplication is approximately three, and the number of operations for addition is approximately one. If the working frequency of the multiplier is 250 MHz, for a data rate of 500 MHz, we only need approximately six DSP units to realize the real-time calculations. As stated in Section 1, the real-time analysis is mainly evaluated through the DSP resources consumed by the system. As this study uses a Xilinx's Vortex-7 series field programmable gate array (FPGA), X7CVX415T-1FFG1157C, the number of DSP units in the chip can reach a maximum of 2,160. This implies that the DSP resources required by the proposed algorithm account for approximately 0.28% of those in Xilinx's Vortex-7 series FPGA, which is a considerably low percentage. Therefore, the proposed algorithm can be used in real time. Moreover, when engineers design a helicopter rotor blade, they need to analyse multiple aspects, such as dynamics, rotor rotation speed, and the severity of the resonance phenomenon of the rotor. Severe resonance causes significant vibrations and noise problems in the rotor system. This will have a strong impact on the helicopter’s flight performance, stability, and manoeuvrability (Yang et al., 2014). Furthermore, once the helicopter’s rotor is designed, its related parameters \( (N, \sigma, f_{rot}, \text{and} \ l) \) are determined.

When performing echo simulations for helicopter rotor blades by using the proposed real-time simulation algorithm, we only need to change the environmental parameters (such as \( \lambda \) and \( R_0 \)) required for HIL simulation. Related design parameters of the solid-state hardware need not be altered. Therefore, the real-time simulation algorithm involves low calculation burdens and costs. Even for the simulation of a new helicopter rotor blade, the system does not consume additional hardware resources; consequently, the volume and weight of the system need not be increased, which affords an effective reduction in costs.

It should be noted that the results presented herein only serve to provide a solution for the high-precision and real-time performance of the simulations of helicopter rotor blade echoes. The study focuses on meeting the requirements of high precision and real-time performance for the time-varying echo signal simulations, while the high-precision mathematical model for the time-varying echo signals of helicopter rotor blades is used in the actual HIL simulation hardware platform. The hardware platform considered in this study is shown in Figure 13. The analysis showed that the real-time algorithm proposed herein can accomplish the simulations with a considerably low consumption of the multiplier resources; thus, the algorithm could be applied in real time. In addition, it could also ensure high accuracy of the time-varying echo signals of helicopter rotor blades. In future studies, the real-time algorithm will be tested on the hardware platform.

### 5. Conclusion

This study focused on the HIL simulation of helicopter rotor echo signals. To ensure that the HIL simulations met the requirements of both real-time performance and accuracy, based on a high-precision mathematical model of the time-varying echo signals of helicopter rotor blades, a high-precision, real-time simulation algorithm for helicopter rotor echoes was proposed herein. The
algorithm was able to not only simulate the echo signals of different helicopter rotors but also reflect the complex m-D characteristics of the time-varying echo signals of the helicopter rotor blades accurately. Analyses show that the real-time simulation algorithm had high accuracy and superior real-time performance; therefore, the real-time simulation algorithm can be implemented in hardware platforms. Finally, comparisons with the theoretical results proved that the proposed algorithm could simulate the echo signals of different helicopter rotors accurately. As it is difficult to obtain field experimental data, the results of this study are expected to be beneficial for applications such as the detection and identification of helicopters and used for testing the quality of detection equipment for helicopters in order to reduce errors under actual field conditions.

The robustness of the echo simulation algorithm when the system is under abnormal or dangerous circumstances is a topic for future research. For example, when the simulation algorithm is tested on the hardware platform or in the presence of outfield background clutter, Gaussian noise will have a significant impact on the time-varying echo simulations of the helicopter rotor blades. Additional feedback modules could be designed to further enhance the robustness of the method, which is beyond the scope of this study.

**Disclosure statement**

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**Declaration of interest**

No potential competing interest is reported by the author.

**Data availability statement**

Due to the nature of this research, participants of this study did not agree for their data to be shared publicly; therefore, supporting data are not available.

**Notes on contributor**

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