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Design and Performance Assessment of a Time-Based Non-Optical Dual-Axis Solar Tracking System

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Abstract

This paper aims to maximize photovoltaic (PV) energy yield by using time based non optical a dual-axis solar PV tracking system. System's design, simulation, prototype implementation, and performance evaluation will be presented. The dual-axis system under investigation, in contrast to fixed or single-axis tracking systems, allows for optimal solar incidence throughout the day and throughout the seasons by adjusting the orientation of the solar panels along the east-west and north-south axes of the sun azimuth and tilt angles. The time based non optical tracker is used to avoid using sensors in the system to reduce the cost and maintenance of PV system. PVsyst software is used to execute a simulation for 10KW PV system to evaluate performance and demonstrate system efficiency. A prototype is built for 15W PV module with microcontroller that has been programmed using the Arduino IDE to make real-time angle adjustments. The results validate the potential of non-optical dual axis tracking systems for broad renewable energy applications by demonstrating a significant boost in energy generation efficiency

تصميم وتقييم أداء نظام تتبع شمسي ثنائي المحور لا يعتمد على المستشعرات البصرية

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الملخص: تهدف هذه الورقة البحثية إلى تعظيم إنتاج الطاقة من الخلايا الكهروضوئية (PV) باستخدام نظام تتبع شمسي ثنائي المحور يعتمد على الزمن وغير بصري. يتم عرض تصميم النظام، ومحاكاته، وتنفيذ نموذج أولي له، بالإضافة إلى تقييم أدائه. وعلى عكس الأنظمة الثابتة أو أنظمة التتبع أحادية المحور، يتيح نظام التتبع ثنائي المحور المدروس تحقيق أفضل استقبال ممكن للإشعاع الشمسي طوال اليوم وعلى مدار فصول السنة، وذلك من خلال ضبط اتجاه الألواح الشمسية وفقًا لمحوري الشرق–الغرب والشمال–الجنوب بما يتوافق مع زاويتي السمت والميل للشمس. يُستخدم نظام التتبع المعتمد على الزمن وغير البصري لتجنب استخدام الحساسات في النظام، مما يسهم في خفض تكلفة نظام الخلايا الكهروضوئية وتقليل متطلبات الصيانة. وقد تم استخدام برنامج PVsyst لإجراء محاكاة لنظام كهروضوئي بقدرة 10 كيلوواط بهدف تقييم الأداء وإظهار كفاءة النظام. كما تم بناء نموذج أولي لوحدة كهروضوئية بقدرة 15 واط مزودة بمتحكم دقيق تمت برمجته باستخدام بيئة Arduino IDE لإجراء تعديلات آنية على زوايا التتبع. وقد أثبتت النتائج الإمكانات الكبيرة لأنظمة التتبع ثنائية المحور غير البصرية في تطبيقات الطاقة المتجددة واسعة النطاق، حيث أظهرت زيادة ملحوظة في كفاءة توليد الطاقة..

الكلمات المفتاحية: التتبع الذي لا يعتمد على المستشعرات البصرية؛ الكهروضوئية؛ تتبع ثنائي المحور؛ Arduino IDE؛

1. Introduction

Photovoltaic (PV) technology has become one of the fastest-growing renewable energy technologies worldwide due to its declining installation costs, environmental benefits, and ability to support sustainable energy development. As the deployment of PV systems continues to increase in residential, commercial, and utility-scale applications, improving the energy yield and overall efficiency of solar installations has become an important research objective. One of the most effective approaches for enhancing PV energy production is solar tracking, which enables photovoltaic modules to maintain a more favorable orientation toward the sun throughout the day. By reducing the angle of incidence between incoming solar radiation and the PV surface, solar tracking systems can significantly increase the amount of solar energy captured compared with conventional fixed-tilt installations [1]. Jordan's energy sector has made significant progress toward energy independence and sustainability, with renewable energy becoming an increasingly important component of the national energy mix [2]. Among the available renewable energy resources, solar energy represents one of the most promising options due to the country's high solar irradiance levels and favorable climatic conditions. As photovoltaic technology continues to advance and installation costs decline, the adoption of PV systems has expanded considerably in both residential and commercial sectors [3]. Photovoltaic technology has progressed significantly over the past few years. These technologies convert sunlight directly into electricity through the photovoltaic effect, the conversion depends on semiconductor materials such as silicon to generate electric currents when the panel is exposed to light [4].

This review [5] focused on achieving the maximum energy output of solar systems. This review compared various types of solar tracking systems based on their axis rotation and drive types to receive the maximum radiation from the sun all day. The output of this literature is that the highest efficiency can be obtained by using Dual tracking system. This research [6] focused on how they can maximize the power output, due to the population growth and increase in demand. They found out to maximize the power output from solar panels; they need to keep the panels aligned with the sun using microcontroller. After simulation, using dual axis solar tracker system produced 40% more energy than the fixed solar system. The study [7] demonstrated that dual axis tracking solar panels are more efficient and produce higher power output than fixed panels, especially during morning and evening times, making them a valuable solution for maximizing solar energy utilization. This study [8] demonstrated that dual-axis sun-tracking PV systems are significantly more efficient than fixed PV systems, making them a more effective solution for maximizing solar energy output. The aim of the project [9] was to design, develop, and implement a dual-axis solar tracking system using Arduino, Light Dependent Resistors (LDRs), and stepper motors. The dual-axis solar tracking system proved to be an efficient and cost-effective solution for maximizing solar energy capture, demonstrating significant improvements over fixed and single-axis systems.

Although numerous studies have investigated dual-axis photovoltaic tracking systems, many existing designs rely on optical sensors such as Light Dependent Resistors (LDRs) to determine the position of the sun. While these sensors can provide accurate tracking, their performance may be affected by dust accumulation, partial shading, sensor aging, and additional maintenance requirements. Furthermore, several previously published studies focused either on simulation-based evaluations or hardware implementation without providing an integrated assessment that combines mathematical modeling, simulation, prototype development, and economic evaluation.

To address these limitations, this study presents a non-optical dual-axis solar tracking system based on solar position calculations and real-time clock (RTC) synchronization. The proposed approach eliminates the need for optical sensing devices while maintaining accurate panel orientation throughout the day. The main contributions of this work can be summarized as follows:

- Development of a time-based non-optical dual-axis tracking algorithm using solar position calculations.
- Design and implementation of a low-cost Arduino-based prototype incorporating RTC-controlled tracking.
- Performance evaluation through PVsyst simulation and experimental prototype testing.
- Preliminary techno-economic assessment including energy yield, levelized cost of electricity (LCOE), payback period, and long-term savings.

The proposed system demonstrates a practical and cost-effective alternative to sensor-based solar tracking systems, particularly for educational, small-scale, and distributed photovoltaic applications.

2. Methodology

2.1 System Architecture

The proposed system is a non-optical dual-axis photovoltaic (PV) tracking system designed to continuously orient a PV module toward the sun without the use of optical sensors. Unlike conventional tracking systems that rely on Light Dependent Resistors (LDRs) or other optical sensing devices, the proposed approach utilizes astronomical solar position calculations and real-time clock (RTC) synchronization to determine the required tracking angles.

The system consists of four main components: an Arduino Uno microcontroller, an RTC module, two servo motors, and a photovoltaic module mounted on a dual-axis mechanical structure. The RTC module continuously provides date and time information to the Arduino controller. Based on the geographical coordinates of the installation site and the current date and time, the controller calculates the solar position parameters and generates the required commands for the azimuth and tilt servo motors.

The overall operational sequence of the system can be summarized as follows:

RTC Module → Arduino Controller → Solar Position Algorithm → Azimuth Servo Motor & Tilt Servo Motor → PV Module Orientation

This architecture eliminates the need for optical sensors, thereby reducing system complexity, maintenance requirements, and susceptibility to environmental factors such as dust accumulation, sensor degradation, and partial shading.

2.2 Solar Position Calculation

The proposed tracking system determines the position of the sun using astronomical equations rather than optical sensing devices. The tracking algorithm utilizes the geographical coordinates of the installation site together with real-time date and time information obtained from the RTC module to calculate the solar position throughout the day. Based on these calculations, the photovoltaic module is continuously oriented to maximize the incident solar radiation and improve energy harvesting efficiency.

The installation site considered in this study is located in Amman, Jordan, with a latitude of approximately 32°N. The solar position is determined through a sequence of calculations involving the solar declination angle, hour angle, solar altitude angle, solar azimuth angle, and zenith angle. These parameters collectively define the instantaneous position of the sun relative to the PV module and provide the required tracking angles for the dual-axis mechanism.

Table 1 summarizes the mathematical relationships used to calculate the solar position parameters required by the tracking algorithm.

Table (1). Solar position equations used in the proposed tracking algorithm.

φ (latitude)	32°.
δ (Declination angle)	$\delta=23.45\sin(360(n-81) \backslash 365)$
ω (hour angle)	$\omega = 15*$ (local solar time -12)
αs (Solar Altitude Angle)	$Sin\ (\propto s) = Sin\ (\emptyset)\ Sin(\delta) + \cos\ (\emptyset) \cos(\delta) \cos(\omega)$

γs (Solar Azimuth Angle)	For $w < 0$ $\gamma s = -\cos^{-1}(\frac{\cos \Theta z \times \sin \phi - \sin \delta}{\sin \Theta z \times \cos \phi})$ For $w > 0$ $\gamma s = \cos^{-1}(\frac{\cos \Theta z \times \sin \phi - \sin \delta}{\sin \Theta z \times \cos \phi})$
γ (Surface Azimuth Angle)	with zero due to south, east negative, and west positive (-180° ≥ γ ≥180°)
θz (Zenith Angle)	$\theta z = (90° - \alpha)$
β (Surface Tilt Angle)	Solar Altitude Angle to maximize solar energy.
θ (Incidence Angle)	equal to zero so radiation is perpendicular to the panel.

The calculated solar altitude and azimuth angles are subsequently used by the control algorithm to determine the required positions of the azimuth and tilt servo motors. The azimuth motor controls the east-west movement of the PV module, while the tilt motor adjusts the north-south inclination to maintain near-perpendicular incidence of solar radiation throughout daylight hours.

2.3 Tracking Algorithm

The proposed tracking algorithm utilizes the RTC module to obtain real-time date and time information. Based on these inputs, the Arduino controller calculates the required solar position angles and adjusts the orientation of the PV module accordingly.

The algorithm operates according to the following sequence:

- Read current date and time from the RTC module.
- Determine the day number of the year.
- Calculate the solar declination angle.
- Calculate the solar hour angle.
- Determine solar altitude and solar azimuth angles.
- Convert calculated angles into servo motor positions.
- Rotate the azimuth and tilt motors to the required positions.
- Maintain the new orientation until the next update cycle.
- Repeat the procedure continuously throughout daylight hours.

The tracking logic ensures that the photovoltaic module remains as close as possible to perpendicular incidence with the incoming solar radiation, maximizing the energy harvested during the day.

2.4 Simulation Methodology

Prior to hardware implementation, the proposed tracking system was evaluated using PVsyst software. A 10 kWp photovoltaic system located in Jordan was modeled under three different operating configurations:

- Fixed-tilt PV system.
- Single-axis tracking PV system.
- Dual-axis tracking PV system.

The objective of the simulation was to quantify the potential energy gain achieved through dual-axis tracking and verify the effectiveness of the proposed control strategy. The annual energy production obtained from each configuration was subsequently compared to assess system performance.

2.5 Simulation Results

In this project PVSYST is used for simulation [10]. The simulation was for fixed solar system, Single axis tracking solar system and dual axis tracking solar system. The results proved that dual axis tracking solar systems produce 30% more energy compared to fixed solar systems.

- For fixed solar system, the obtained results were around 17760 kWh/year.
- For single axis tracking solar system, the results obtained were around 20552 kWh/year.
- For dual axis tracking solar system, the obtained results were around 24624 kWh/year.

The simulation shows the normalizing product for dual axis demonstrated in figure (1).

2.6 Simulation Validation

Figure (2) depicts the monthly average energy yield production for the 10kwp system at the specified location using an online website which represents real time data. The figure shows that in July a maximum energy yield was produced. While comparing the results and the real time data obtained using this website, the total energy yield achieved over one year was about 24600 kWh/year, which is approximately equivalent to the simulated data using PVsyst [11].

3. Experimental Results

A prototype of the dual axis solar tracking system was accomplished using the following materials:

- Arduino UNO
- RTC module
- 2 Servo motors
- Breadboard

- Solar panel
- Structure
- DC Bulb
- Digital Multimeter (DMM)

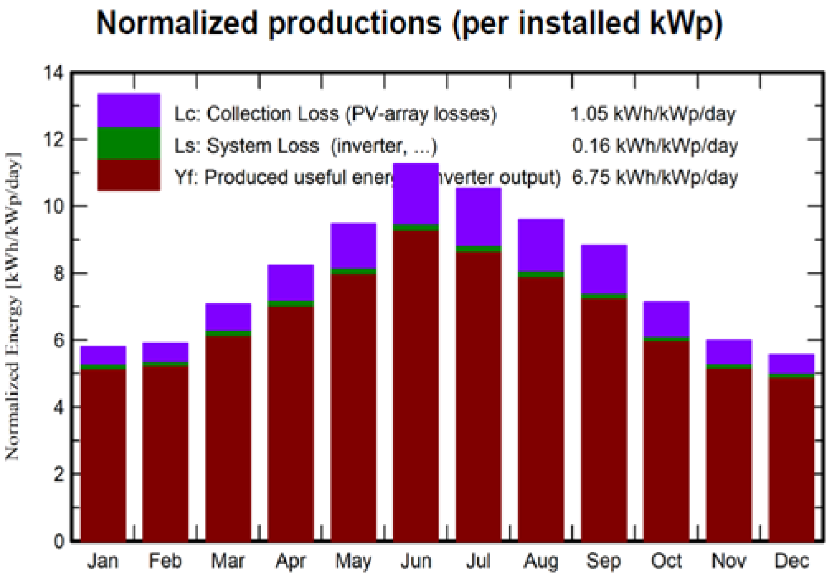

Figure 1. Dual axis solar tracking system normalized production results.

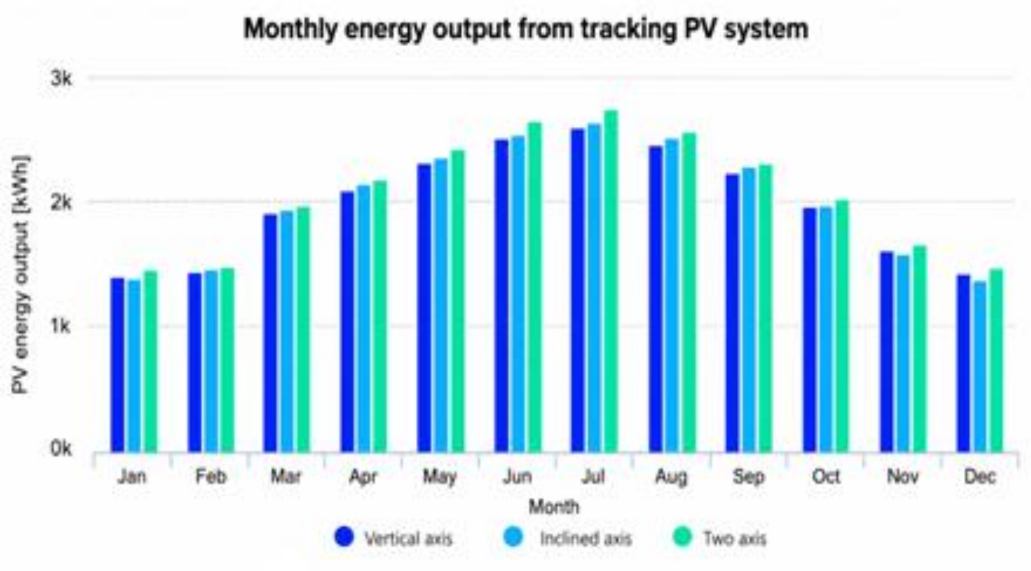

Figure 2. The energy yield produced [11].

3.1 Arduino uno code

The following flow chart shown in figure (3) represents the operating procedure of the code. The connection of the control system shown in figure (4) was simulated using Tinkercad software [12].

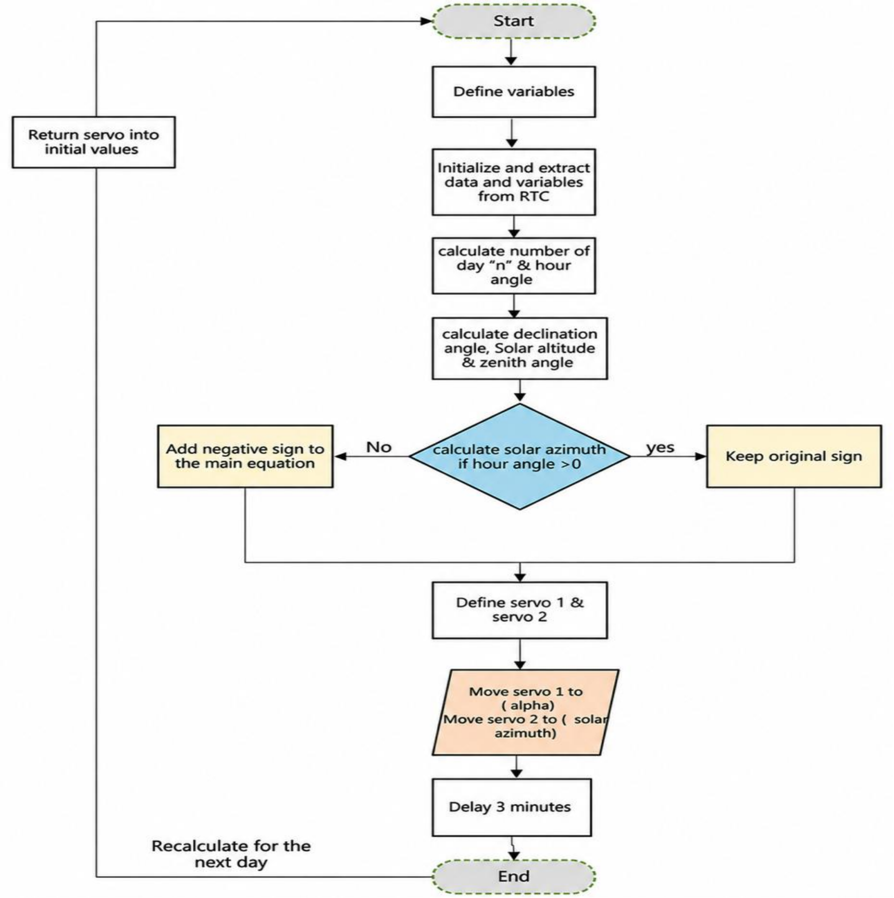

Figure 3. Flow chart of Arduino uno code.

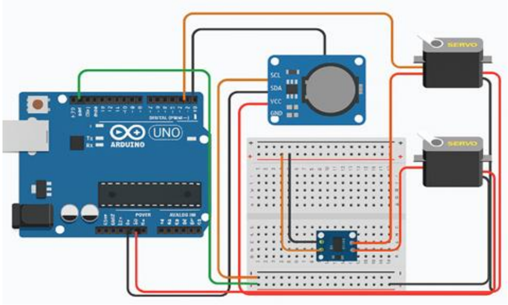

Figure 4. Prototype wiring using Tinkercad

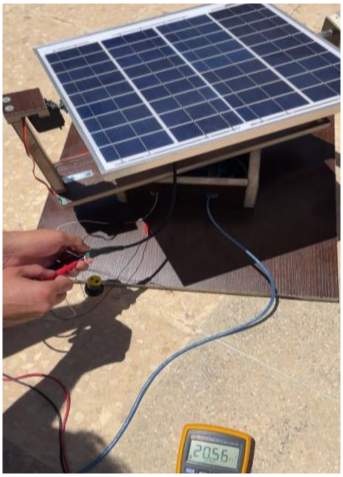

Figure 5. Actual prototype

A structural model was designed using SketchUp software to provide an accurate 3D representation of the proposed system & as shown in figure (5) the actual prototype was constructed [13].

Results are obtained on June 21, 2025, are represented below at table 2.

Table (2). Experimental rsults of the prototype.

Time	Solar Azimuth angle	Tilt angle	Output Voltage	Output Current
11:30 a.m	-39.64°	79.18°	20.6 V	0.009 A
13:00 p.m	60.91°	74.23°	21.15 V	0.009 A
14:30 p.m	85.07°	55.91°	20.6 V	0.009 A
15:00 p.m	89.44°	49.55°	19.5 V	0.009 A

The results show a clear insight into how the solar panel produces voltage and current under different conditions and different periods of time. As shown in table 2 the current remains the same for the different periods, this is because of the dc load bulb which requires a small current input.

Due to prototype size limitations, experimental validation was intended primarily to verify tracking functionality and angle calculations. The quantitative energy gain assessment was therefore performed using PVsyst simulations representing a full-scale 10 kWp installation.

4. Techno-Economic Analysis

A preliminary techno-economic analysis was conducted to evaluate the financial feasibility of the proposed non-optical dual-axis solar tracking system. The analysis considers the capital investment, annual operating expenses, energy production, levelized cost of electricity (LCOE), simple payback period, and long-term economic benefits.

The assessment was performed for a 10 kWp photovoltaic system operating under Jordanian climatic conditions. A project lifetime of 20 years was assumed, which is consistent with the typical service life of photovoltaic installations. The economic evaluation was based on an average electricity tariff of 0.10 JOD/kWh to estimate the monetary value of the generated electrical energy. Annual operation and maintenance costs were assumed to remain constant throughout the project lifetime and are included within the reported OPEX value. For simplicity, annual energy production was assumed to remain constant over the analysis period, and the effects of system degradation and discount rate were not considered in this preliminary assessment.

The estimated capital expenditure (CAPEX) of the proposed system is 5,670 JOD after subsidy, while the annual operation expenditure (OPEX) is approximately 410 JOD/year. Based on the simulated annual energy production of 24,600 kWh, the system is capable of generating substantial economic savings over its operational lifetime. The total net savings over a 20-year period are estimated at approximately 41,000 JOD.

The simple payback period was calculated to be approximately 2.8 years, indicating that the initial investment can be recovered within a relatively short period. In addition, the Levelized Cost of Electricity (LCOE), which represents the average cost of generating one kilowatt-hour of electricity over the system lifetime, was estimated to be approximately 0.02819 JOD/kWh. This relatively low LCOE highlights the economic attractiveness of the proposed tracking system compared with conventional electricity sources. A summary of the main techno-economic indicators is presented in Table 3.

Table 3. Techno-economic summary of the proposed non-optical dual-axis tracking system.

Metrics	Value
System Size	10 kWp
Inverter Size	8 kW
Net System Cost (after subsidy)	5,670 JOD
Annual Energy Output	24,600 kWh
Annual OPEX	410 JOD/year
LCOE	0.02819 JOD/kWh
Simple Payback Period	2.8 years
20-Year Net Savings	41,000 JOD

5. Conclusions

The development and implementation of a non-optical dual-axis solar tracking system have been explored in this study to enhance energy capture and efficiency. The research highlights the significant advantages of dual-axis tracking over fixed and single-axis systems, with simulation results showing a 30-40% increase in energy output. The designed system, controlled by an Arduino-based microcontroller, ensures real-time adjustments based on mathematical calculations rather than optical sensors, making it a cost-effective and reliable solution for solar energy applications.Through PVSYST simulations and prototype testing, the system demonstrated superior performance in maximizing solar exposure and energy production. The findings confirm that dual-axis tracking provides a viable method for optimizing solar panel efficiency, especially in high solar potential regions like Jordan.

Future work may focus on long-term outdoor testing, optimization of tracking intervals, and comparative evaluation against sensor-based tracking approaches under different climatic conditions.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

Authors' Contributions

Firas Obeidat initiated and supervised the research, developed the study concept and methodology, guided the system design and performance evaluation, interpreted the results, and led the writing and revision of the manuscript. Abdelhadi Sabagh, Omar Khalaf, and Tala Shabo contributed to the simulation work, prototype design and implementation, experimental testing, data collection, and preparation of the initial manuscript draft under the supervision of the first author. Ibrahim Rahoma contributed to the technical review of the methodology, analysis of the results, and manuscript revision. Mokhtar Amrani provided technical feedback and contributed to the review of the manuscript. Yara Haddad contributed to the review, editing, and final improvement of the manuscript. All authors reviewed and approved the final version of the manuscript.

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Data Availability

Data are available from the corresponding author upon reasonable request.

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