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Research article

In-shoe multi-segment foot kinematics measurement during the stance phase of running using a stretch strain sensor

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A R T I C L E I N F O

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A B S T R A C T

Multi-segment foot kinematics during shod running are difficult to investigate in clinical settings. Stretch strain sensors can measure foot kinematics; however, whether they can evaluate foot kinematics during shod running or at the midfoot kinematics remains unclear. The aim of this study was to investigate the stretch strain sensor could reveal differences between shod and barefoot conditions and midfoot kinematics during running.

Eighteen healthy adults were included in the study. A stretch strain sensor and three-dimensional motion capture system were used to measure foot kinematics during barefoot and shod running with a rearfoot strike pattern. The correlation between the amplitudes of the two signals during barefoot running was investigated, and the similarity between the two signals was evaluated using the cross-correlation coefficient. Statistical parametric mapping was used to compare shod and barefoot conditions.

Shod running had significantly lower sensor strain from 30 % to 100 % stance compared to barefoot running ($p < 0.05$). The sensor amplitude was significantly correlated with the shank–rearfoot frontal ($r = 0.668$, $p = 0.002$), the rearfoot–midfoot transverse ($r = 0.546$, $p = 0.02$), and the midfoot–forefoot sagittal planes ($r = 0.563$, $p = 0.01$). A high cross-correlation was observed between the sensor signal and the shank–rearfoot sagittal, frontal, and transverse planes and the midfoot–forefoot sagittal plane.

This sensor can be used to investigate foot kinematics during shod running. The sensor signal mainly reflects the shank–rearfoot frontal and midfoot–forefoot sagittal planes, as well as the maximum kinematic range of the rearfoot-midfoot transverse plane.

1. Introduction

Running disorders have become relatively common, with an increasing number of individuals preferring running to maintain a healthy lifestyle. The foot is one of the most common sites that develop running disorders. Using a multi-segment foot model, excessive

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rearfoot and midfoot eversions are involved in running disorders [1–3]. Thus, it is necessary to evaluate multi-segment foot kinematics during running in clinical settings. Multi-segment foot kinematics are generally measured using a three-dimensional motion capture system. However, this system has difficulty in evaluating kinematics when the participants is wearing shoes because the reflective markers should be applied to the skin [4,5]. As footwear is worn in daily life and sports activities, it is necessary to evaluate foot kinematics while wearing shoes.

Previous studies have evaluated foot kinematics while wearing modified shoes (i.e., making holes) [6–8] or sandals [9] using a three-dimensional motion capture system or wearing complete shoes using high-speed dual fluoroscopic imaging systems [10]. Based on these analyses, footwear reportedly reduces the magnitude of medial longitudinal arch compression [10–12] and greatly restricts forefoot and midfoot motions during running [6]. Detecting differences in intra-foot kinematics between barefoot and shoe conditions requires high-spec equipment. However, it is not simple to perform in a clinical setting. It has been suggested that a stretch strain sensor (STR) could be used to investigate foot kinematics during walking and running with barefoot and elastic foot orthosis [13,14]. The STR might evaluate foot kinematics while wearing footwear; however, it remains unclear whether the STR can actually evaluate differences in foot kinematic with or without shoes during running.

Additionally, the STR has been validated with the Oxford foot model [13] and is capable of evaluating the forefoot with respect to the rearfoot angle during running; however, this foot model alone cannot be used to evaluate midfoot joint motion. Therefore, it is unclear whether STR signals includes data for the midfoot relative to the rearfoot. A study using the Rizzoli foot model revealed that during running without footwear, the movement of the midfoot relative to the rearfoot showed an angular amplitude comparable to that of the rearfoot relative to the shank [15]. Thus, the usefulness of the STR should also be evaluated by comparing it with the Rizzoli foot model.

This study aimed to 1) investigate whether it is possible to detect differences between foot kinematics during barefoot and shod running and 2) determine the STR can reliably measure midfoot kinematics. We hypothesized that 1) shod running would decrease the sensor strain compared to barefoot running, and 2) increased sensor strain would be associated with increased midfoot movement relative to rearfoot dorsiflexion, eversion, and abduction.

2. Methods

2.1. Participants

Eighteen healthy adults (9 men and 9 women, age: 21.6 [1.7] years, height: 166.2 [5.5] cm, weight: 57.9 [6.9] kg) participated in this study (Table 1). The sample size of this study was calculated from the results of the relationship between the amplitude of the STR and the forefoot eversion (power = 0.95, $\alpha = 0.05$, effect size = 0.63) [13] using G*Power 3.1 program (Universität Düsseldorf, Düsseldorf, Germany). Foot alignment was measured using the foot posture index 6-item version [16]. The inclusion criteria were healthy adults without orthopedic or neurological diseases. All participants provided written informed consent before participation, and the study was approved by the ethics committee of our institution (No. 2023-028).

2.2. Experimental protocol

STR (C-STRETCH®, Bando Chemical Industries, Ltd., Kobe, Japan) was used to measure foot kinematics. The STR system consisted of a stretch strain sensor, transmitter, input cable, output cable, pressure sensor (FlexiForce, Tekscan, Massachusetts, USA), and an inertial measurement unit. The STR measures 10–50 mm. The STR was applied based on the spring ligament (SL) method, which was shown to be reproducible in a previous study [13]. The STR was stretched from 50 mm to 70 mm and applied to the talus and navicular bones in which the subtalar joint was at a position neutral (where the talus could be palpated equally on the medial and lateral sides) (Fig. 1) [14]. The pressure sensor was attached 2 cm anterior to the heel and used to identify initial contact. The sampling frequency of all sensors was 100 Hz.

For analysis using a three-dimensional motion capture system, the reflective marker was set based on a previous study that employed the Rizzoli foot model [4]. Thus, reflective markers measuring 9.5 mm in diameter were fixed to the right shank and foot at the tibial tuberosity, fibular head, medial malleolus, lateral malleolus, calcaneus, sustentaculum tail, peroneal tubercle, navicular bone, first metatarsal base, first metatarsal head, second metatarsal base, second metatarsal head, fifth metatarsal base, fifth metatarsal head, and head of the proximal phalanx of the hallux using a double-sided adhesive tape. Reflective markers were attached to the midpoint of the right and left posterior superior iliac spines (PSIS).

Table 1
Participants characteristics and foot posture index 6 score.

Variables	Mean (SD)
Number of participants	18
Age (years)	21.6 (1.7)
Height (cm)	166.2 (5.5)
Weight (kg)	57.9 (6.9)
Foot posture index-6	2.8 (3.0)

Abbreviations: SD, standard deviation.

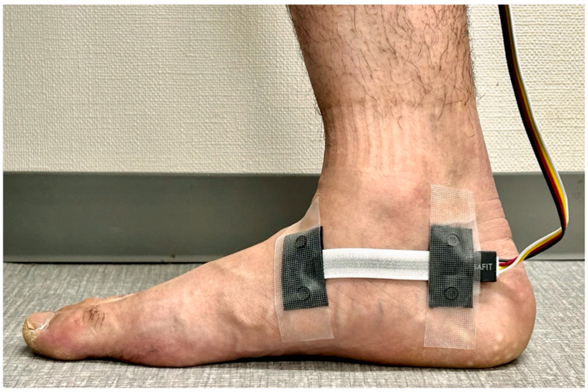

Fig. 1. Placement of the stretch strain sensor with spring ligament method.

Before measuring the running data, static data were collected from the anatomical position. The data were used to calculate the offset values for all joint angles and STR signals. After static data measurement, the participants perform barefoot and shod overground running at their preferred speed on force plates (Advanced Mechanical Technology Incorporation, USA) at sampling rate of 1000 Hz. The runway was approximately 15 m long with two force plates (width 40 cm $\times$ length 80 cm per force plate). Multi-segment foot kinematics are reportedly not affected by running speed [17] but are influenced by the foot strike pattern [18,19]. The difference in foot strike pattern between barefoot and shod conditions may affect the arch strain. Overall, 77.3 % of the participants exhibited a rearfoot strike pattern during barefoot overground running [20]. Therefore, in this study, the participants performed barefoot and shod running with a rearfoot strike pattern at their preferred speeds. We instructed the participants to perform running with rearfoot strike. Shoes were common to all participants (WAVE REVOLT, Mizuno, Osaka, Japan) and fitted to each participant's size. Participants were allowed to practice at least 10 times to ensure that they were comfortable with each running condition and with the force plate touching their right foot, after which running data were measured. After the participants confirmed that they were already accustomed to the barefoot and shod running and to the force plate touching their right foot, running data were measured. After the participants confirmed that they were already accustomed to the barefoot and shod running and to the force plate touching their right foot, barefoot running was measured first, followed by shoe. The static and barefoot running data were measured using a three-dimensional motion analysis system (Vicon, Oxford, UK) that included 9 infrared cameras at a sampling rate of 100 Hz. Shod running and barefoot running were each measured for 5 trials. After barefoot running, the shod running data were measured using a STR. Because STR data are affected by changes in STR length, the STR voltage during static was checked between each condition.

2.3. Data analysis

Each five successive trial (i.e., the participant's right foot was in a rearfoot strike pattern with a force plate) were performed and analyzed. Raw signals from the STR were filtered using a 10 Hz Butterworth low-pass filter. The raw marker trajectory and ground reaction force data during running were obtained using a Butterworth low-pass filter at 10 Hz and 50 Hz, respectively. In this study, segments were defined as the shank (tibia and fibula), rearfoot (talus and calcaneus), midfoot (navicular, cuneiform, and cuboid), and forefoot (first–fifth metatarsals) are created from reflective markers attached to bony landmarks according to the Rizzoli foot model [4]. Three-dimensional joint angles were calculated at the distal joint segment and expressed relative to the adjacent proximal segment using a right-handed orthogonal Cardan Zxy rotation [4] (sequence of plantar flexion/dorsiflexion, eversion/inversion, and abduction/adduction). Joint angles were calculated using Visual 3D (C-Motion, Germantown, MD, USA) for the rearfoot with respect to the shank (sha–rear), the midfoot with respect to the rearfoot (rear–mid), and the forefoot with respect to the midfoot (mid–fore).

The stance phase was identified based on the ground reaction force data. Initial contact was defined as an increase in the vertical ground reaction force data of $>$20 N, and toe-off was defined as the return of the ground reaction force value to $<$20 N after initial contact. For the STR system, the timing of the maximum value obtained by the pressure sensor was defined as the initial contact. The number of frames in the stance phase, which was calculated from the ground reaction force and toe-off, was defined as the maximum value of the pressure sensor and number of frames in the stance phase. The running stance phase was then time-normalized to 101 points. The running speed was calculated from the anteroposterior component of the reflective marker trajectory affixed to the midpoint of the left and right PSIS.

In this study, the validity of the stretch sensor was evaluated based on excursion and signal similarity. Angular excursion was calculated as the difference in peak dorsiflexion, eversion, and abduction from initial contact. The difference in strain between the initial contact and maximum strains was calculated as the loading arch strain multiplied by 100 [13]. The cross-correlation coefficient was used to evaluate the similarity between the angular and STR signals. Correlation coefficients $>$0.7 (or $<$0.7) indicated strong correlation, coefficients of between 0.3 and 0.69 and 0.3 0.69 represented a moderate correlation, and coefficients between 0.3 and 0.3 suggested a weak or no correlation [17].

2.4. Statistics

Statistical analyses were performed using the R software (version 4.0.4; R Foundation for Statistical Computing, Vienna, Austria). For comparison between barefoot and shod running, the Shapiro–Wilk test was performed on the STR amplitudes for each condition to confirm normality followed by the paired *t*-test. Moreover, the paired-samples *t*-test of statistical parametric mapping (SPM) was performed to evaluate differences between barefoot and shod running. SPM analysis was performed using the open-source SPM code (www.spm1d.org) in MATLAB (R2018b; MathWorks Inc.). Additionally, the Shapiro–Wilk test was used to evaluate the normal distribution of the angular excursion and arch strain. Pearson and Spearman correlation analyses were used to assess the relationship between arch strain and angular excursion in the sha–rear, rear–mid, and mid–fore. Statistical significance was set at $p < 0.05$.

3. Results

3.1. Comparison of barefoot and shod running

Running speed was significantly higher in the shod condition than barefoot (barefoot: 2.86 [0.44] m/s, shod: 3.02 [0.50] m/s, $p = 0.008$). Shod running had significantly lower STR strain from the 30%–100 % stance compared to barefoot running ($p < 0.05$) (Fig. 2).

3.2. Validity of stretch strain sensor measurement

The multi-segment foot joint angles and STR signals are shown in Fig. 3, and the results of the correlation between the amplitudes are listed in Table 2. Arch strain was significantly associated with the angles of the sha–rear frontal plane ($r = 0.668$, $p = 0.002$), rear–mid transverse plane ($r = 0.546$, $p = 0.02$), and mid–fore sagittal plane ($r = 0.563$, $p = 0.01$). The cross-correlation coefficients between the STR signals and multi-segment foot angles are shown in Table 2. The STR signal and sha–rear sagittal, frontal, and transverse planes ($r = 0.77$, -0.70, and -0.74, respectively) and mid–fore sagittal planes showed a strong cross-correlation ($r = 0.75$) (Table 2).

4. Discussion

In this study, we investigated 1) whether it is possible to assess foot kinematics during shod running and 2) whether the STR signal is related to the rear–mid angles as quantified by the Rizzoli foot model. The results showed that the STR signal was significantly lower during shod running than barefoot running during from the 30%–100 % stance. Arch strain was significantly associated with the amplitudes of the sha–rear frontal, rear–mid transverse, and mid–fore sagittal planes. Among the correlations with the STR, high cross-correlations were observed in the sha–rear frontal and mid–fore sagittal planes.

The present study showed that the STR can evaluate the differences in foot motion between barefoot and shoe conditions. Previous studies have evaluated foot kinematics while wearing modified shoes (i.e., holes) [6–8] or sandals [9] using a three-dimensional

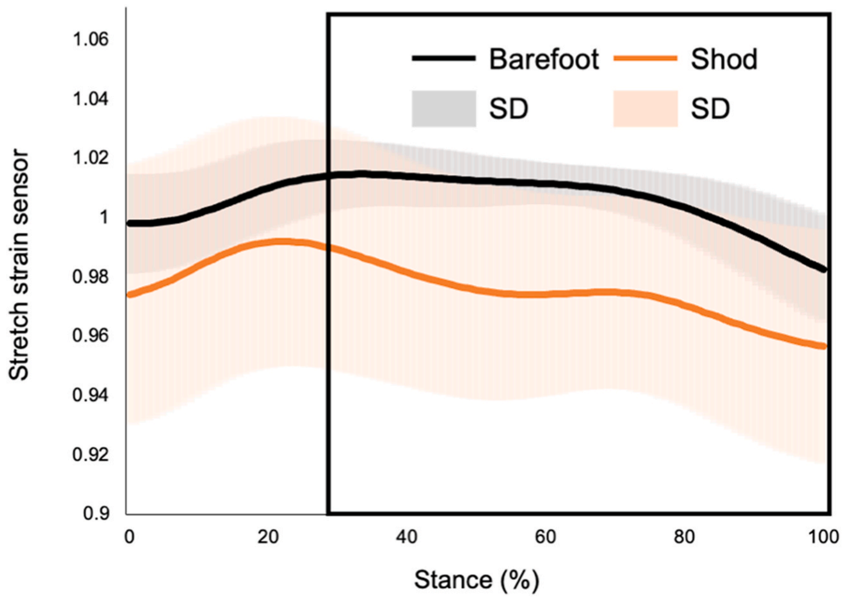

Fig. 2. Time series data from the stretch strain sensor for barefoot and shod conditions during stance phase of running. Boxes indicate statistical significance from statistical parametric mapping. Abbreviations: SD; standard deviation.

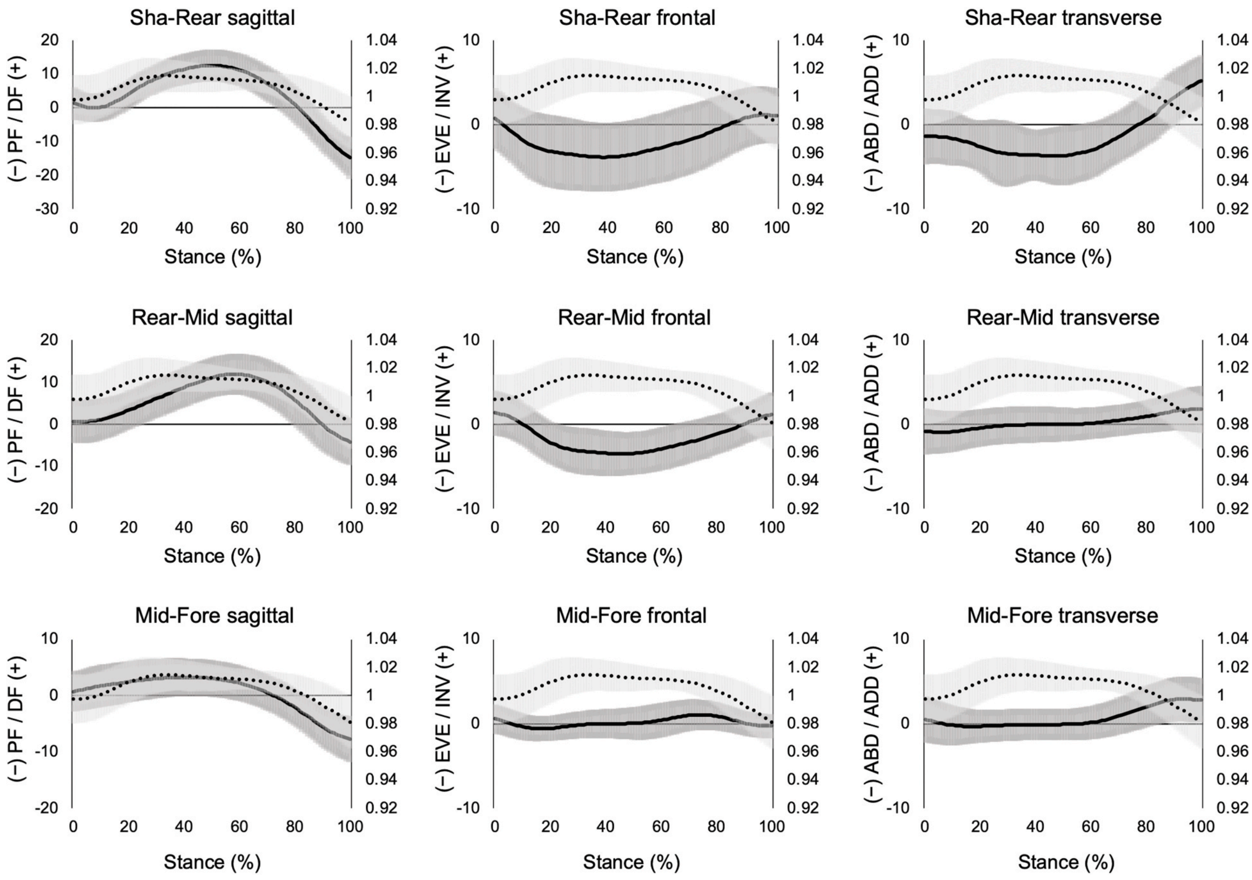

Fig. 3. Time series data from multi-segment foot kinematics (solid) and stretch strain sensor signal (dot) during stance phase of running. The first axis shows the respective multi-segment foot kinematics, and the second axis shows the stretch strain sensor signal. Abbreviations: Sha; shank, Rear; rearfoot, Mid; midfoot, Fore; forefoot, DF; dorsiflexion, PF; plantarflexion, INV; inversion, EVE; eversion, ADD; adduction, ABD; abduction.

Table 2
Correlation and cross-correlation coefficients between amplitude of multi-segment foot kinematics and stretch strain sensor signal.

	Sagittal	Frontal	Transverse
Coefficient			
Shank-Rearfoot	−0.004	0.668[b]	0.07
Rearfoot-Midfoot	0.305	0.186	0.546[a]
Midfoot-Forefoot	0.563[a]	0.146	−0.253
Cross-correlation coefficient			
Shank-Rearfoot	0.77 (0.22)	−0.70 (0.22)	−0.74 (0.20)
Rearfoot-Midfoot	0.59 (0.31)	−0.66 (0.24)	−0.35 (0.47)
Midfoot-Forefoot	0.75 (0.14)	0.12 (0.47)	−0.53 (0.22)

Data are presented as mean (standard deviation).
[a] : $p < 0.050$.
[b] : $p = 0.002$.

motion capture system. However, these experimental designs may not fully reproduce foot motion during shod running because the integrity of the shoe is compromised. In contrast, measurement with high-speed dual fluoroscopic imaging systems allows for the investigation of foot motion with a complete shoe [10]. However, these methods are not simple and difficult to use in a clinical setting. STR are thin and light, the STR may be useful for assessing foot motion in shoes in a clinical setting.

Shod running showed significantly a lower STR signal compared to barefoot running at 30%–100 % stance. In a previous study reported that shod running reduces the magnitude of medial longitudinal arch compression during from 0% to 70 % stance [10]. According to this result, the STR does not reflect differences from 0% to 20 % stance phase. These discrepancies are thought to occur because the foot motion assessed by STR reflects three-dimensional foot motion. A study [6] evaluated foot motion in children wearing shoes and reported that wearing shoes greatly limited the movement of the midfoot sagittal, frontal, and transverse planes during the propulsion phase (period when the anterior-posterior component of GRF is positive). In this study, the STR was associated with multiple joint movements, including rear-, mid-, and forefoot. Therefore, the STR may be evaluated as a limitation of the intra-foot complex joints due to wearing shoes only during the propulsion phase.

In a previous study, the STR was shown to reflect on the motion of the forefoot relative to the rearfoot as analyzed by the Oxford foot model [13]. However, the motion of the forefoot relative to the rearfoot comprises motions of the talonavicular, calcaneocuboid, cuneonavicular, and tarsometatarsal joints [5]. In this study, the Rizzoli foot model was used, and it was found that the signal of STR reflected rear-mid transverse movement. Therefore, this study suggests that STR signals can reflect more multi-segmental foot motions than previously thought. However, the STR was affixed to spring ligaments; thus, the STR signal may include multiple components of joint movements. Sha–rear sagittal, frontal, transverse, and mid–fore sagittal ranges of motion are greater than midfoot kinematics [21]. Therefore, rear–mid kinematics may be masked in the sha–rear and mid–fore kinematics. Future research should consider sensor attachment methods that focus more on rear-mid kinematics.

This study had several limitations. First, there is a possibility of noise in the obtained data because of the pressure of the shoes on the STR. As the STR is stretched and pressed, the area of the sensing portion increases, while the distance between the electrodes decreases, increasing the capacitance [22]. Especially during the first half of the running stance phase, the multi-segment foot kinematics demonstrate eversion [23], which may cause pressure from the shoes. Second, this study was conducted on healthy adults; it may not be suitable for assessing foot motion in children. The STR may underestimate arch strain if the initial length is excessively short. Therefore, when measuring foot motion in children with the STR, it is necessary to use a shorter sensor. Third, foot kinematics during shod running were not evaluated using a three-dimensional motion capture system. In future studies, it will be necessary to investigate in greater detail whether the STR signal reflects foot kinematics during shod running by using a three-dimensional motion capture system. Fourth, this study did not examine the sensitivity or reliability of each foot alignment. Therefore, it is not clear whether participants with all foot alignments would show similar results. Future studies should examine whether sensor sensitivity differs among different foot alignments.

5. Conclusion

In this study, we examined the validity of STR and compared the differences in foot kinematics between barefoot and shod running, revealing that STR can detect differences between these two conditions. Furthermore, the sensor signal mainly reflects the sha–rear frontal and mid–fore sagittal planes as well as the maximum kinematic range of the rear–mid transverse plane. These results may be applied to the assessment of foot motion in clinical settings, evaluation of foot motion under foot orthoses, and footwear development. However, foot kinematics during shod running were not evaluated using a three-dimensional motion capture system, and the results obtained may differ from the actual foot kinematics owing to compression of the sensor by the shoe. Future research should investigate in greater detail the validity of foot kinematics using STR during shod wearing.

Data availability statement

Data associated with the study has not been deposited into a publicly available repository and is available from the corresponding author on reasonable request.

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Takahiro Watanabe: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Masahiro Tsutsumi:** Writing – review & editing, Methodology. **Eiichi Kuroyanagi:** Writing – review & editing, Investigation. **Hinata Furusawa:** Writing – review & editing, Investigation. **Shintarou Kudo:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors have no conflicts of interest to declare.

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