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Research article

Kinematic analysis of countermovement jump performance in response to immediate neuromuscular electrical stimulation

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Abstract: The purpose of this study was to examine the effect of neuromuscular electrical stimulation (NMES) immediate intervention training on the countermovement jump (CMJ) height and to explore kinematic differences in the CMJ at each instant. A total of 15 male students who had never received electrical stimulation were randomly selected as the research participants. In the first test, the CMJ performance was completed with an all-out effort. The second experiment was best performed immediately to complete the CMJ operation after NMES for 30 min. Both experiments used a high-speed camera optical capture system to collect kinematic data. The results of this experiment revealed that after im-mediate NMES training, neuromuscular activation causes post-activation potentiation, which increases the height of the center of gravity of the CMJ and affects the angular velocity of the hip joint, the velocity and acceleration of the thigh and the shank and the velocity of the soles of the feet. The use of NMES interventional training based on the improvement of technical movements and physical exercises is recommended in the future.

Keywords: sports performance; exercise; strength; conditioning; biomechanics

1. Introduction

Jump height is commonly employed to evaluate athletic performance, whereas the countermovement jump (CMJ) movement model is usually utilized to monitor an athlete's lower body athletic ability for jumping and explosive power [1–3]. The significance of jump height is evident across various sports and athletic domains, including basketball, volleyball, track and field and other sports that require leaping and reaching skills. In basketball and volleyball, for example, jump height is a critical factor in scoring, blocking and overall performance. The main mechanism behind a CMJ occurs through stretch-shortening cycles (SSCs), and the action mode includes concentric contraction (CON) and eccentric contraction (ECC) modes [4–6]. However, lower body muscle strength is a very crucial characteristic for athletes. The main muscle control mechanism behind the CMJ occurs through the muscle-tendon unit (MTU), which is rapidly and forcibly stretched. Commonly, this is followed by an elastic response that immediately shortens muscles, so the muscles are prestretched and then accompanied by CON CMJ performance. This mode of movement helps to improve sports performance [7–10]. Previous investigations have shown that the use of SSC elastic energy mechanisms is able to enhance the strength, velocity, and activation of the CMJ muscles and increase the height of the CMJ [11–13]. Therefore, the CMJ can be analyzed to effectively evaluate lower limb muscle strength and explosive power, and these parameters can be implemented as indicators of progress in lower limb muscle strength training [1,14–16].

Neuromuscular electrical stimulation (NMES) is a method of electrical stimulation that directs current through the entire peripheral nervous system to induce muscle contraction. It causes muscle contraction and stimulates post activation potentiation (PAP). When the rate of development of muscle strength increases, NMES leads to the static maximum voluntary muscle contraction, which increases the sensitivity of muscle fibers to calcium ions, stimulates the nervous system to produce excitation, recruits more muscle fibers into motor units, and increases the activity of the cross-bridges of thick and thin muscle fibers, causing muscle contraction. The result leads to an increase in force and velocity, and, thereby the induction of the PAP phenomenon [7,11,13,17,18]. Former explorations have revealed that adults experience an assisted lifting effect during NMES strength training for 10 to 30 min [19–23].

Therefore, the purpose of this study was to examine the effect of NMES immediate intervention training on the CMJ height and to explore kinematic differences in the CMJ at each instant. The study measured the CMJ height with and without NMES intervention to assess its impact on performance. Additionally, the researchers analyzed the dynamic characteristics of the CMJ, including the kinematic variables, to understand the differences in movement patterns and biomechanics between an NMES-assisted CMJ and a regular CMJ. The research was aimed to provide insights into the practical application and value of NMES in terms of enhancing CMJ performance, thereby contributing valuable information to the field of sports science.

2. Materials and methods

2.1. Participants

A total of 15 male students who had never received electrical stimulation were randomly selected as the research participants. Individuals with any sports injuries or health issues were excluded to ensure the reliability and accuracy of the research results. (height 179.10 ± 4.33 cm; weight 72.29 ± 6.56 kg; age 21.14 ± 1.03 years old). Before the experiment started, the participants were informed of the purpose of the study and asked to sign a consent form. The study complied with the Declaration of Helsinki, which was approved by the local university [No. 22040851].

2.2. Equipment and data collection

Before the experiment, the venue was arranged. Two high-speed cameras (sampling rate = 120 Hz, shutter speed = 1/1000 s, Sony, PXW-FS7H, tokyo, Japan) were set at the center of the three-dimensional coordinate frame at an angle of 90 degrees and extended 12 meters to the side; an LED light was applied as a camera synchronization signal. With the center of the CMJ as the origin, we set a three-dimensional coordinate system with dimensions of 2.0 m × 1.5 m × 2.0 m (length × width × height) and 12 markers. The optical axis of the lens was pointed to the center of the coordinate system setting, and its shooting range was able cover the coordinate system.

In this experiment, each participant performed a total of two tests. Before each test, a warm-up (800-meter running) was required; then, we attached 21 optical capture reflective ball marking points to the participant's head, left and right ears, middle fingertips, shoulder joints, elbow joints, wrist joints, hip joints, knee joints, ankle joints, heels and toes. In the first test (T1), the CMJ performance was requested to be completed with an all-out effort. The second experiment (T2) was best performed immediately to complete the CMJ operation after the participant underwent NMES for 30 min. To ensure PAP-induced production of learning and energizing effects, the interval between T1 and T2 was set to be at least 7 days. Previous explorations indicate that the main muscles exerted by the CMJ are the vastus medialis and gastrocnemius muscles. Hence, regarding the NMES experiment, T2 involved the use of a frequency-modulated pulsed neuromuscular electrotherapy device to stimulate the participant's vastus medialis and gastrocnemius muscles to produce neuromuscular stimulation (Figure 1) [2,5,6,24]. The process of using the frequency-modulated pulsed neuromuscular electrotherapy device, as well as its frequency were as follows. First, the automatic mode of the frequency-modulated pulsed electrotherapy device was selected and the frequency range to start the stimulation was set as 1000 Hz. The intensity was adjusted to the participant's maximum tolerance range. The average vastus medialis power was 31.30 ± 3.06 VA and the gastrocnemius muscle power was 31.48 ± 2.48 VA.

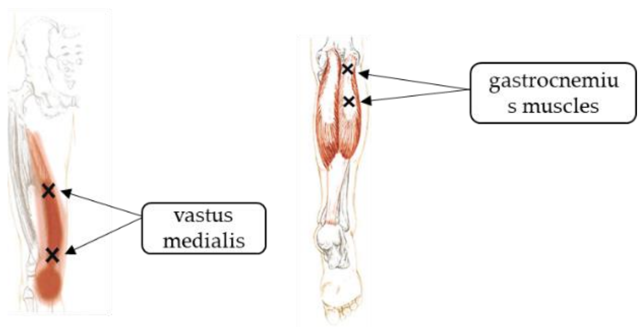

Figure 1. Schematic diagram of neuromuscular electrode placement.

Note: In a Biel (Ed.) Trail guide to the body's quick reference to trigger points, 2019, pp.6, 56, 71, 93.

2.3. Data processing

The captured images were processed using the Kwon3D (Visol, Inc., Gwangmyeongsi, Kyonggido, South Korea) motion analysis suite, and an optical auto-capture system digitized the markers attached to the imaged joints. The X, Y and Z axes of the global coordinate system represent the (horizontal) left-right, front-back, and (vertical) up-down directions of space, respectively. We referred to the existing literature to establish the parameters for human limbs [25]. The 3D space original data of this study were smoothed by using a 4th order Butterworth low pass filter to filter the noise, where the cutoff frequency was 6 Hz, and the 3D space reconstruction error was 0.508 cm.

We divided the CMJ movement into four instantaneous moments (hereafter referred to as instants) for analysis. (1) The lowest point of the center of gravity: the instant defined by the vertical distance between the center of gravity and the ground when the center of gravity is at the lowest point. This instant captures the moment when the athlete reaches the bottom-most position during the CMJ. Analyzing this point helps one to understand the initial phase of the jump and the amount of potential energy stored before the upward propulsion begins; (2) The feet leave the ground: the instant when the toes leave the ground. This instant marks the start of the actual jumping motion, where the toes lose contact with the ground. Examining this moment is essential to understanding the take-off phase and the initiation of the jump; (3) The highest point of the center of gravity: the instant defined by the vertical distance between the center of gravity and the ground when the center of gravity is at the highest point. At this instant, the athlete reaches the peak height of the jump. Analyzing this point allows for the assessment of the jumper's performance and the amount of vertical displacement achieved; (4) The feet contact the ground: the instant when the toes contact the ground, exploring the kinematic parameters at the four instants. This instant represents the landing phase when the toes make contact with the ground again. Analyzing this point is crucial for understanding the landing technique and the forces exerted upon impact (Figure 2) [9,10,16,26].

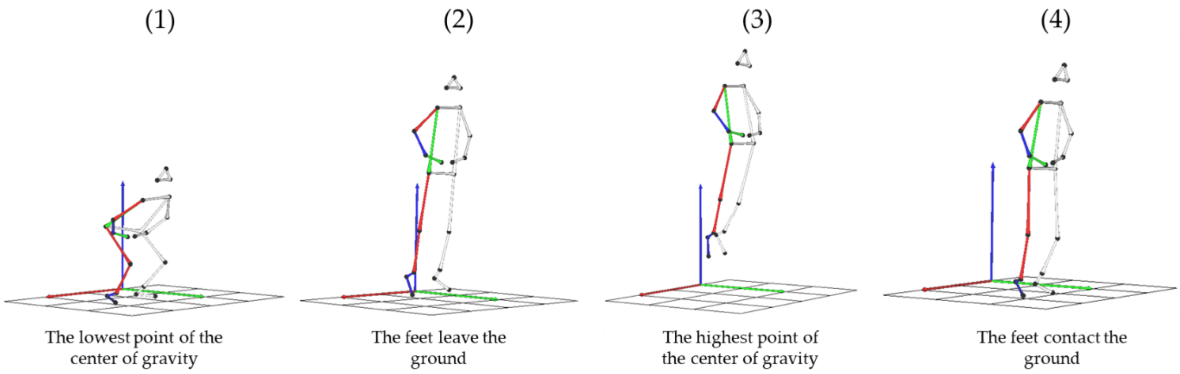

Figure 2. Schematic diagram of each instant.

The definitions of various kinematic parameters are as follows. The hip joint angle is the angle formed by the three points of the shoulder joint, hip joint and knee joint. The knee joint angle is the angle formed by the three points of the hip joint, knee joint and ankle joint. The ankle joint angle is the angle formed by the three points of the knee joint, ankle joint and toe. The velocities of the thigh, shank and sole of the foot are represented by the resultant velocities ($\overrightarrow{Rv}$) of the thigh, shank and sole of feet in the (horizontal) left–right direction ($\vec{V}_x$), the forward–backward direction ($\vec{V}_y$) and the (vertical) upward–downward direction ($\vec{V}_z$), respectively. The acceleration of the thigh, shank and sole of each foot is the resultant acceleration ($\overrightarrow{Ra}$) of the thigh, shank and sole of each foot in the left–right direction ($\vec{a}_x$), the forward–backward direction ($\vec{a}_y$) and the vertical upward–downward direction ($\vec{a}_z$), respectively [26–29] (Figure 3).

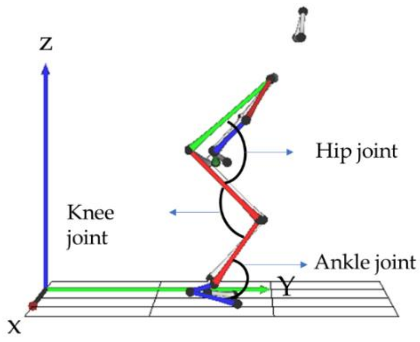

Figure 3. Schematic diagram of each joint angle.

2.4. Statistical analysis

SPSS 26 was used to represent the mean and standard deviation of each kinematic parameter with descriptive statistics, and then the Wilcoxon Signed Rank Test was used to test the T1 and T2 CMJ performance in each instant in terms of the kinematic differences ; the significance level was set as $\alpha = 0.5$. The effect size of each parameter between T1 and T2 was calculated by using Cohen's D as an evaluation of the practical applicability of the quantitative results (d value ≤ 0.2 is a small effect size, $0.2 < d < 0.8$ is a medium effect size, and $d \geq 0.8$ is a large effect size) [30]. G*Power computer software (G*Power 3.1, Dusseldorf, Germany) was used to calculate the statistical power of each parameter in T1 and T2, and the statistically significant level was set as power = 0.8. [30].

3. Results

The results of this study revealed that the CMJ performance in T2 was significantly higher than that in T1 (z = –3.059, P = 0.002, d = 0.88, power = 0.99) (Figure 4).

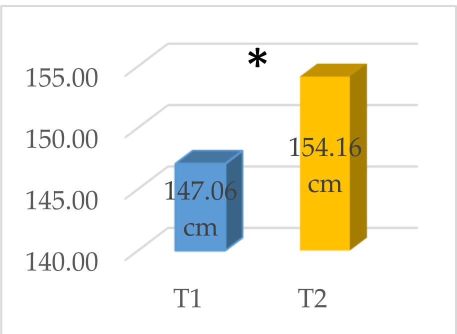

Figure 4. CMJ performance before and after NMES intervention.

Note: CMJ performance was the vertical distance between the center of gravity and the ground when the center of gravity at the highest point.

At the lowest point of the CMJ center of gravity, the shank velocity in T2 was significantly faster than that in T1 (z = –2.197, P =0.028, d = 0.87, Power = 0.61) (Table 1).

Table 1. Kinematic parameters at the lowest point of the CMJ center of gravity. (N = 15).

	T1		T2		z		d	Effect Size	Power
Angle (°)									
Hip joint	101.06	± 13.62	93.31	± 14.70	–1.245		0.55	medium	0.29
Knee joint	94.90	± 10.75	92.32	± 10.71	–1.412		0.24	medium	0.09
Ankle joint	84.34	± 17.87	84.55	± 13.54	–0.157		0.01	small	0.05
Angular Velocity (°/s)									
Hip joint	54.70	± 37.27	65.20	± 40.04	–0.706		0.27	medium	0.26
Knee joint	52.19	± 46.09	70.18	± 36.09	–1.334		0.43	medium	0.56
Ankle joint	62.64	± 40.65	98.28	± 83.14	–1.177		0.54	medium	0.75
Velocity (m/s)									
Thigh	0.28	± 0.17	0.33	± 0.17	–0.706		0.29	medium	0.12
Shank	0.18	± 0.12	0.28	± 0.11	–2.197	*	0.87	large	0.61
Soles of feet	0.13	± 0.07	0.17	± 0.08	–1.334		0.53	medium	0.28
Acceleration (m/s^2)									
Thigh	7.08	± 4.49	8.71	± 5.45	–0.628		0.33	medium	0.14
Shank	5.02	± 2.14	5.54	± 2.87	–0.628		0.21	medium	0.08
Soles of feet	3.40	± 2.19	4.03	± 1.22	–0.863		0.36	medium	0.15

*$p < .05$

Regarding the results for the CMJ at the instant at which the feet leave the ground, the shank velocity in T2 was significantly faster than that in T1 (z = –2.118, P =0.034, d = 0.55, Power = 0.30); the shank acceleration in T2 was significantly faster than that in T1 (z = –2.118, P =0.034, d = 1.15, Power = 0.84) (Table 2).

Table 2. Kinematic parameters for the CMJ instant at which the feet leave the ground. (N = 15).

	T1		T2		z	d	Effect Size	Power
Angle (°)								
Hip joint	167.74	± 5.97	169.31	± 4.11	–0.941	0.31	medium	0.12
Knee joint	165.69	± 6.42	165.48	± 5.02	–0.784	0.04	small	0.05
Ankle joint	137.84	± 12.07	137.64	± 9.58	–0.235	0.02	small	0.05
Angular Velocity (°/s)								
Hip joint	220.53	± 138.23	248.59	± 129.79	–1.177	0.21	medium	0.17
Knee joint	377.60	± 123.30	338.84	± 135.49	–0.417	0.30	medium	0.30

	T1		T2		z		d	Effect Size	Power
Ankle joint	416.40	± 198.44	372.39	± 196.07	–0.863		0.22	medium	0.19
Velocity (m/s)									
Thigh	2.56	± 0.34	2.71	± 0.28	–1.255		0.48	medium	0.24
Shank	2.34	± 0.38	2.55	± 0.38	–2.118	*	0.55	medium	0.30
Soles of feet	1.79	± 0.37	1.94	± 0.39	–1.020		0.40	medium	0.17
Acceleration (m/s^2)									
Thigh	8.80	± 3.49	11.02	± 5.44	–1.020		0.49	medium	0.24
Shank	13.56	± 4.99	18.86	± 4.17	–2.118	*	1.15	large	0.84
Soles of feet	27.35	± 9.06	28.48	± 7.11	–0.392		0.14	small	0.06

$*p < .05$

At the highest point of the CMJ center of gravity, the hip joint angular velocity in T2 was significantly faster than that in T1 (z = –2.589, P =0.01, d = 0.93, power = 0.99); the thigh velocity in T2 was significantly faster than that in T1 (z = –2.353, P =0.019, d = 0.99, power = 0.73) (Table 3).

Table 3. Kinematic parameters at the highest point of the CMJ center of gravity. (N = 15).

	T1		**T2**		**z**		**d**	**Effect Size**	**Power**
Angle (º)									
Hip joint	173.88	± 2.76	172.94	± 5.23	–0.780		0.22	medium	0.09
Knee joint	169.13	± 5.42	168.37	± 8.27	–0.157		0.11	small	0.06
Ankle joint	142.31	± 8.61	143.19	± 10.82	–0.157		0.09	small	0.06
Angular Velocity (º/s)									
Hip joint	15.92	± 11.23	47.08	± 46.14	–2.589	*	0.93	large	0.99
Knee joint	19.57	± 10.42	39.99	± 46.10	–1.098		0.61	medium	0.84
Ankle joint	62.90	± 40.07	72.31	± 67.77	–0.000		0.17	small	0.13
Velocity (m/s)									
Thigh	0.13	± 0.07	0.21	± 0.09	–2.353	*	0.99	large	0.73
Shank	0.24	± 0.10	0.30	± 0.16	–1.177		0.45	medium	0.21
Soles of feet	0.30	± 0.12	0.33	± 0.15	–0.628		0.22	medium	0.08
Acceleration (m/s^2)									
Thigh	9.90	± 2.91	11.78	± 3.62	–1.490		0.57	medium	0.31
Shank	11.36	± 3.59	10.24	± 4.11	–0.863		0.29	medium	0.12
Soles of feet	12.45	± 3.73	11.05	± 3.94	–0.078		0.36	medium	0.16

$*p < .05$

Regarding the results for the CMJ instant at which the feet contact the ground, the velocity of the soles of the feet in T2 was significantly slower than that in T1 (z = –2.197, P =0.028, d = 1.06, power = 0.78); the thigh acceleration in T2 was significantly faster than that in T1 (z = –2.118, P =0.034, d = 0.90, power = 0.64); the shank acceleration in T2 was significantly faster than that in T1 (z = –2.353, P =0.019, d = 1.09, power = 0.81) (Table 4).

Table 4. Kinematic parameters of the CMJ at the feet contact the ground. (N = 15).

	T1			T2			z		d	Effect Size	Power
Angle (º)											
Hip joint	172.01	±	3.60	169.84	±	6.89	–1.177		0.39	medium	0.17
Knee joint	160.66	±	5.88	158.43	±	8.39	–0.628		0.31	medium	0.12
Ankle joint	129.46	±	10.44	124.32	±	14.30	–0.628		0.41	medium	0.19
Angular Velocity (º/s)											
Hip joint	111.64	±	85.78	148.73	±	84.21	0.239		0.44	medium	0.56
Knee joint	316.79	±	130.34	366.66	±	139.81	0.480		0.37	medium	0.43
Ankle joint	442.48	±	163.64	400.72	±	163.82	0.638		0.26	medium	0.23
Velocity (m/s)											
Thigh	2.53	±	0.33	2.64	±	0.26	–0.628		0.37	medium	0.16
Shank	2.10	±	0.40	2.07	±	0.30	–0.863		0.08	small	0.06
Soles of feet	1.50	±	0.27	1.22	±	0.26	–2.197	*	1.06	large	0.78
Acceleration (m/s^2)											
Thigh	6.38	±	4.14	13.57	±	10.47	–2.118	*	0.90	large	0.64
Shank	14.07	±	8.05	26.76	±	14.30	–2.353	*	1.09	large	0.81
Soles of feet	23.63	±	8.00	28.36	±	7.44	–1.334		0.61	medium	0.35

*$p < .05$

4. Discussion

This study examined the effect of immediate NMES training on the CMJ performance. To ensure the learning effect and PAP-enhancing effect, T2 should be performed at a time interval of more than 7 days after T1. The results of this experiment revealed that after immediate NMES training, neuromuscular activation causes PAP, which increases the height of the center of gravity of the CMJ and affects the angular velocity of the hip joint, the velocity and acceleration of the thigh, the velocity and acceleration of the shank and the velocity of the soles of the feet. The main CMJ muscles are the vastus medialis and gastrocnemius. In order to improve the performance of CMJ movements, in this research, immediate NMES was employed for electrical stimulation of the vastus medialis and gastrocnemius; particularly, the muscles were activated to achieve the PAP effect and increase muscle strength [2,3,5,6,31]. The CMJ starts from a standing position (hands on the waist), and then the body's center of gravity begins to drop until it reaches the lowest point of the body's center of gravity, causing the hip, knee and ankle joints to produce squat-type flexion characteristics. Then, the lower limbs continue to push upward, causing the hip, knee and ankle joints to flex to extend the body upward. When the velocity of the upward movement increases to the fastest state, the whole body leaves the ground from the initial standing position, resulting in a vacant stage to the highest point of the center of gravity and finally to the contact of the feet with the ground [9,10,16]. The main feature of this jump is the creation of a natural mechanism through the SSC, which is usually accompanied by a reverse movement, during which the muscles work in the form of CON and ECC immediately afterward [4,5,9,13,16].

The results of this study revealed that the shank velocity in T2 was significantly faster than that in T1 at the lowest point of the CMJ center of gravity. Additionally, the shank velocity and acceleration in T2 was significantly faster than that in T1 at the instant at which the feet left the ground; the hip joint angular velocity and the thigh velocity in T2 were significantly faster than that in T1 at the highest point of the CMJ center of gravity; the velocity of the soles of the feet in T2 was significantly slower than that in T1, and the thigh and shank acceleration in T2 was significantly faster than that in T1 at the instant at which the feet made contact with the ground. The results of former research works have revealed that after NMES training, muscle strength and jumping ability increased significantly compared to people who did not receive NMES [19,20,32]. CMJ movement research also confirmed that the reverse movement increased the velocity of the feet leaving the ground during the take-off phase, thereby increasing the maximum height of the center of gravity [9,10,14,16]. Higher angular velocity performance at the highest point of the center of gravity is mainly related to greater trajectory due to applied force and acceleration [1,9,15,16]. In addition, SSC can generate more power output and improve ground reaction force [12,33]. Jumping ability is very important in many sports such as track and field, volleyball, basketball and badminton. The key to jumping ability is that the lower body muscles can exert maximum force output. The CMJ is commonly used to assess the ability of the lower extremity muscles at the maximal output to achieve the highest aerial height [8,9,16,34]. However, once NMES is appropriately applied, it can regulate the function of the neuromuscular system and improve the body's ability to move. It can stimulate neuromuscular fibers and cause muscle contraction, thereby producing a strengthening effect after muscle activation. PAP after NMES application is a new approach to neuro-muscular activation that can better enhance the body's muscle activation level so that the body can perform well during CMJ-related movements [18,21–23].

This study had certain limitations since it mainly examined the effect of a short-term 30-min NMES session on CMJ performance, and it did not evaluate the influence of long-term NMES training on the CMJ. Additionally, the results of this experiment only apply to males. In the future, it will be possible to further investigate whether long-term NMES affects female and male CMJs.

5. Conclusions

Immediate NMES can activate the muscles, increase muscle contraction force, and have a substantial effect on improving exercise ability and CMJ performance; particularly, this entails increasing the height of the center of gravity of the CMJ and changing the angular velocity of the hip joint, the velocity and acceleration of the thigh, the velocity and acceleration of the shank and the velocity of the soles of the feet. The incorporation of NMES interventional training to enhance technical movements and physical exercises is recommended for future studies. In particular, it would be beneficial to investigate the long-term effects of NMES training on CMJ performance. Additionally, exploring potential differences in responses to NMES training among different sex and age groups could provide valuable insights into its applicability across diverse populations.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare that there is no conflict of interest.

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