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ORIGINAL RESEARCH

The Effect of Mattress Firmness on Sleep Architecture and PSG Characteristics

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Background: The influence of sleep environments on sleep quality is well-established; however, the specific role of mattress design remains underexplored. Existing studies focus primarily on ergonomic aspects, such as pressure relief and spinal support, yet lack conclusive evidence linking these features to improved sleep quality.

Objective and Methods: This study aimed to evaluate the effects of mattress firmness on sleep quality. Twelve participants with a moderate body mass index (BMI) were tested across three levels of mattress firmness: soft (32.6 HA), medium (64.6 HA), and firm (83.8 HA). Sleep architecture and neurophysiological activity were assessed using polysomnography (PSG), with EEG-derived features, including power spectral characteristics, sleep spindle activity, and slow-wave parameters, further analyzed.

Results: Our findings indicate that a medium-firm mattress provides better sleep quality, reflected in a narrower range (Range=xmax-xmin) of sleep duration, efficiency, and sleep latency, as well as increased sleep spindle activity. A repeated-measures ANOVA revealed a significant effect of mattress type on sleep latency ($p < 0.05$, partial η^2=0.26), with sleep latency being longer on the soft mattress (12.42 ± 1.94 min) than the medium mattress (7.71 ± 1.31 min, $p < 0.05$). Another repeated-measures ANOVA showed significant differences in stage transitions ($p < 0.05$, partial η^2=0.32), with more transitions on the soft mattress (29.17 ± 2.35) compared to the firm mattress (21.75 ± 2.13, $p < 0.05$). The firm mattress yielded mixed results, suggesting suitability for some individuals but not universally. Post-sleep vigilance differences were not statistically significant.

Conclusion: This study provides evidence that mattress firmness significantly influences sleep quality, with medium firmness offering optimal outcomes for individuals with a moderate BMI. The findings contribute to the development of scientifically informed mattress designs, including smart mattresses aimed at improving sleep quality.

Keywords: mattress firmness, sleep quality, sleep architecture, EEG characters, PVT

Introduction

With changes in the environment, stress, and lifestyle, modern individuals are experiencing more fragile sleep quality, and the frequency of sleep problems is on the rise.[1,2] As sleep disturbances become more prevalent, understanding the various factors that influence sleep quality has become increasingly important. Previous studies have shown that many external factors, such as light, noise, temperature, and room decor, influence sleep quality.[3–5] However, although the mattress, as a core component of the sleep micro-environment, plays a crucial role in providing support and comfort to the body, its impact remains underexplored, especially in terms of objective physiological data.

Most existing studies have primarily focused on the ergonomic design of mattresses, examining how different material types, thicknesses, and layers contribute to pressure relief and spinal support.[6–8] Although these features are correlated with subjective comfort ratings,[7] their direct impact on long-term sleep quality remains uncertain. Many studies use short experimental durations (5 to 30 minutes), raising concerns about whether short-term comfort can effectively predict long-term sleep outcomes. Consequently, the need for long-term, objective evaluations remains pressing. Some studies have also focused on the impact of the thermal environment of bedding systems on sleep quality.[9–12] However, research on the direct impact of mattress design on sleep remains limited.

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Previous long-term studies with larger sample sizes have identified mattress firmness as a potentially key factor affecting sleep quality.[13,14] For example, Kovacs et al[15] conducted a double-blind trial involving 313 adults with chronic non-specific low back pain, demonstrating that medium-firm mattresses improved pain and functional disability. However, such studies predominantly focus on individuals with back pain,[16] leaving a gap in understanding how mattress firmness influences sleep quality in the general population. Additionally, most research relies on subjective surveys and fails to directly measure the physiological impact of mattress choice on sleep.[14,17,18]

Objective assessments of how mattress comfort affects sleep have produced mixed results. While studies suggest that peak mattress pressure should remain below 30 mmHg to reduce discomfort from localized skin hypoxia,[19] the direct link between pressure relief and sleep quality remains unclear. Vaughn McCall et al[20] tested a pressure-relieving mattress designed to limit contact points exceeding 30 mmHg, yet neither polysomnography nor subjective sleep evaluations revealed significant differences between this mattress and participants' original mattresses. Similarly, studies on mattress firmness and sleep quality found no significant differences,[21] implying that individual preferences may play a more critical role in sleep quality and mattress selection. Conversely, study by Chen et al[22] found that the intermediate pressure distribution mattress increased the duration and proportion of NREM sleep stages 3 and 4, reduced micro-arousals, and resulted in higher self-reported sleep quality compared to mattresses with over-even or over-concentrated pressure distributions. A study by Hyunja Lee and Sejin Park[23] found that participants using a comfortable mattress had higher sleep efficiency, a greater percentage of deep sleep, and lower percentages of WASO (Wake After Sleep Onset) and stage 1 sleep compared to those using an uncomfortable mattress. Nevertheless, further research is needed to clarify the relationship between mattress design, individual preferences, and sleep quality.

This study aims to address a critical gap in sleep medicine by systematically examining the effects of mattress firmness on sleep quality using objective polysomnography (PSG) and electroencephalography (EEG) assessments. While the influence of sleep environments on sleep quality is well-documented, the specific role of mattress design remains insufficiently explored. Existing research has primarily focused on ergonomic aspects such as pressure distribution and spinal alignment, yet direct evidence linking these features to physiological improvements in sleep quality remains limited.

To bridge this gap, this study investigates the impact of three mattress firmness levels—soft (32.6 HA), medium (64.6 HA), and firm (83.8 HA)—on sleep architecture and neurophysiological activity in 12 participants with a moderate body mass index (BMI). Additionally, this research explores whether mattress firmness affects not only nocturnal sleep parameters but also post-wake cognitive performance, including reaction time and alertness. By elucidating the relationship between sleep surface characteristics and waking function, this study aims to provide scientific evidence to inform mattress design and contribute to the development of novel strategies for optimizing sleep quality and overall well-being.

Materials and Methods

Participants

Participants for this study were recruited from Beijing Forestry University. Inclusion criteria required participants to be right-handed, healthy adults aged 18 to 25, with at least a bachelor's degree and a body mass index (BMI) within the normal range (18.5–24.9). Exclusion criteria included a history of musculoskeletal disorders, spinal surgery, insomnia, sleep apnea, or other sleep, psychiatric, or neurodevelopmental conditions. Participants with a State-Trait Anxiety Inventory (STAI) score over 40 or a Pittsburgh Sleep Quality Index (PSQI)[24] score above 5 were also excluded.

All participants were required to maintain a regular sleep-wake schedule, ensuring at least 7 hours of sleep each night for three days before each experimental session. Compliance was monitored using sleep diaries. Participants were also instructed to avoid medications, alcohol, and caffeine for 24 hours before the study. The research protocol was approved by the Ethics Committee of Beijing Forestry University, and all participants provided written informed consent. Upon completing the experiment, participants received a remuneration of 150 RMB.

Initially, 15 participants were recruited; however, two were excluded for failing to sleep during the adaptation night, and one was excluded for being unable to sleep on the soft mattress. Consequently, the final analysis included 12 participants (6 males and 6 females) with a mean age of 23.33 ± 1.50 years, a height of 1.73 ± 0.09 meters, a weight of 61.75 ± 8.72 kilograms, and a BMI of 20.52 ± 1.79.

Mattress and Experiment Environment

The experimental setup involved three polyurethane foam mattresses (manufactured by Xianghe Wantai Foam Factory, Langfang, Hebei, China), each with a thickness of 10 cm and differing in firmness. These mattresses were made of general-purpose polyether-based polyurethane foam. Mattress hardness was measured using a Shore A durometer (HANDPI LX-F, Shenzhen, China). To ensure measurement accuracy, five points were assessed on each mattress, with at least a 25 mm interval between measurements, and the average of these readings was recorded as the mattress's hardness value. Mattress 1 (soft) had a hardness of 32.6 HA, Mattress 2 (medium) had a hardness of 64.6 HA, and Mattress 3 (firm) had a hardness of 83.8 HA. All mattresses have the same bottom structure to ensure comparability.

We also conducted compression performance tests on the three mattresses using a universal testing machine (MWD-20, Jinan, China) with a force accuracy of 1% of the load value and a displacement accuracy of 0.5% of the measured value. The tests were conducted in accordance with ISO 2439-2008 standards. Prior to testing, the samples were conditioned in a constant temperature and humidity chamber for 16 hours at 27°C and 65% RH. The testing setup included a compression head with a diameter of 100 mm, a support plate measuring 380×420 mm with a hole spacing of 20 mm, and a hole diameter of 5 mm. The loading speed was set to 100 mm/min. The resulting force-displacement curves of the soft, medium and firm mattresses are shown in Figure 1.

The laboratory environment was controlled to maintain an indoor temperature of 21 ± 2°C, relative humidity of 45 ± 5%, and a noise level of ≦ 50 db. The laboratory was kept dark using blackout curtains.

Procedure

As shown in Figure 2, all participants were required to visit the laboratory for an adaptation nap five days before the formal experiment. Participants with sleep disorders, such as sleep apnea, or those whose nap duration was less than one hour were excluded from the study.

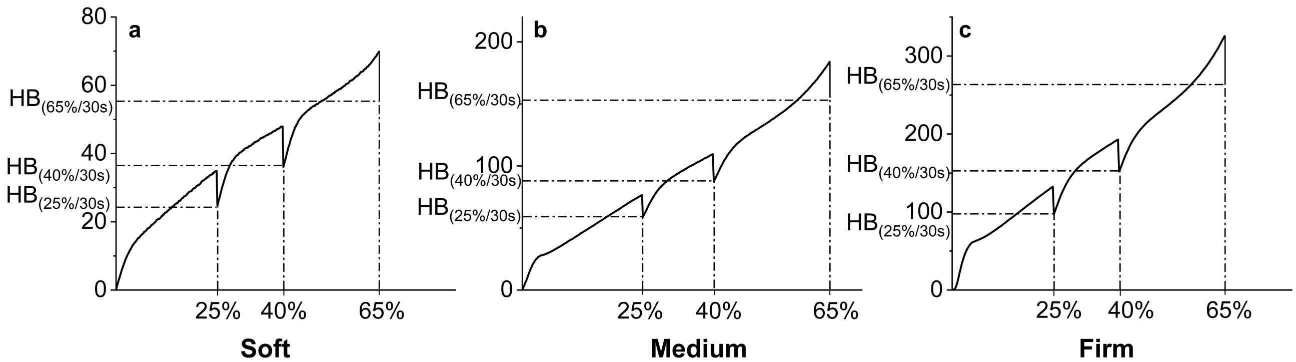

Figure 1 Force-displacement curves of the three mattresses with different firmness levels. (**a**) Force-displacement curve of the soft mattress. (**b**) Force-displacement curve of the medium mattress. (**c**) Force-displacement curve of the firm mattress.
Notes: The percentages (25%, 40%, and 65%) represent the mattress compression to 25%, 40%, and 65% of their original thickness, respectively. The Y-axis represents force (N), and HB indicates hardness at each compression stage.

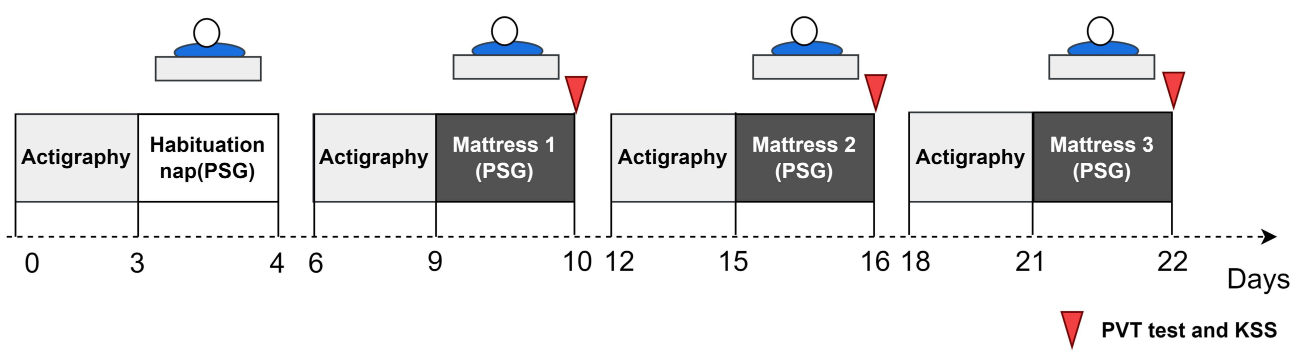

Figure 2 Experimental Setup.

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In the formal experiment, each participant took three 90-minute naps on Mattresses 1, 2, and 3. The order of mattresses was randomized and counterbalanced among participants, with at least five days between each nap to prevent carry-over effects. All experiments were completed within two months to minimize seasonal influences. On the day of the experiment, participants arrived at the laboratory at 12:00 PM. After fitting the equipment, lights-out was at 12:30 PM, and lights-on was at 2:00 PM. Sleep was monitored using polysomnography (PSG). After the nap, participants completed the Karolinska Sleepiness Scale (KSS) and gave subjective evaluations of mattress comfort. Twenty minutes after waking, they performed a 10-minute Psychomotor Vigilance Task (PVT).

PSG was recorded using a portable multichannel sleep monitoring device from Compumedics (Somté PSG, North Carolina, USA). Standard polysomnography (PSG) captured physiological signals including electroencephalography (EEG), electrocardiography (ECG), electromyography (EMG), electrooculography (EOG), respiratory effort (measured with thoracic and abdominal belts), body position and movement, and blood oxygen saturation. EEG electrodes were placed according to the international 10–20 system at six sites (C4-M1, F4-M1, O2-M1; C3-M2, F3-M2, O1-M2) with a sampling rate of 256 hz. Sleep structure was analyzed using ProFusion sleep 4.

Measurements

Polysomnography Analysis

Polysomnography (PSG) data were analyzed and scored by a certified sleep technician in accordance with AASM (The American Academy of Sleep Medicine) standards. The technician was fully blinded to the study's objectives and design. Sleep stages were scored in 30-second epochs, with sleep onset defined as the first instance of two consecutive epochs of a specific stage following lights out. The Total Sleep Period (TSP) was the overall time from sleep onset to final awakening, while Total Sleep Time (TST) represented the total duration of sleep, excluding any wakefulness during the sleep period. Time In Bed (TIB) was the overall time spent in bed which is 90 minutes for all participants. Sleep efficiency was calculated as TST/TIB *100. We separately calculated the total duration and percentage of N1, N2, N3, and REM sleep stages (TSP%).

We also calculated the number of sleep stage shifts and shifts to lighter sleep stages as described in.[25,26] Shifts to lighter sleep stages are defined as the number of shifts from rapid eye movement (REM) sleep to wakefulness, as well as shifts from NREM stages to lighter NREM stages or wakefulness.

The EEG data were preprocessed using MATLAB 2022b (MATLAB 2022b, Natick, USA) and EEGLAB (EEGLAB v2023.1, University of California San Diego, USA) toolbox. Initially, data in EDF format were converted to the EEGLAB-compatible SET format. The electrode layout followed the international 10–20 system, and only the F3, F4, C3, C4, O1, and O2 electrodes were retained for analysis. The data were then filtered with a high-pass filter at 0.1 hz and a low-pass filter at 45 hz to remove noise. Next, the data were segmented into 4-second epochs. EEG channels and segments containing motion artifacts were identified through visual inspection and removed. The removed channels were interpolated using the Spherical Spline Interpolation method. The data were then re-referenced to the average reference across all channels.

For power calculation, we focused on N2 stage sleep, following the methodology outlined by Laurence Bayer et al[27] Artifact-free data from the C4 channel during the N2 stage were selected. The data were concatenated and segmented into 20-second epochs. A Fast Fourier Transform (FFT) with a Hanning window and an FFT length of 8192 was applied to each segment. Power within each frequency band was computed by summing the spectral power across frequencies within the band. Relative power was calculated as the ratio of the power in each frequency band to the total power within the 1–45 hz range. Power spectral analysis was conducted for the following frequency bands: delta (1–4 hz), theta (4–8 hz), alpha (8–13 hz), beta (13–30 hz), low gamma (30–45 hz), and the total frequency range (1–45 hz).

For sleep spindle analysis, continuous NREM data (N1, N2, N3 stages combined) were downsampled to 128 hz and band-pass filtered between 12–15 hz using the C4 channel. Spindles were detected using the a2 automatic detection algorithm, with amplitude thresholds set at 2 and 6 times the average amplitude of the entire time series, and a duration threshold of 0.5 to 3 seconds. Several spindle characteristics were extracted, including spindle density (number of spindles per 20s), spindle frequency (peak frequency within 12–15 hz), spindle amplitude (maximum amplitude in μV),

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spindle duration (average spindle length), integrated absolute amplitude, and spindle activity (integrated amplitude per total recording time in minutes).

For slow oscillation analysis, NREM data were downsampled to 128 hz and band-pass filtered between 0.4 and 2.4 hz using the C4 channel. Slow oscillations were identified based on a 25 μV amplitude threshold between consecutive zero-crossings. Characteristics of slow oscillations, including frequency, maximum amplitude, duration, and density (number of half-waves per 20s), were computed.

Finally, delta activity in the first 20 minutes of sleep was analyzed by calculating delta power in the 0.75–4.5 hz range. The slope of the delta power build-up was calculated as the change in delta power over the first 20 minutes of sleep.

Subjective Ratings

The Borg CR10 scale[28] was used to assess the comfort level of mattresses. Discomfort levels were rated on a scale from 0 to 10 (0 indicating no discomfort at all, and 10 indicating absolute maximum discomfort) upon waking.

The Karolinska Sleepiness Scale (KSS)[29] was used to assess participants' levels of sleepiness and alertness. Participants rated their current level of alertness on a scale from 1 (extremely alert) to 10 (extremely sleepy). This standardized scale was employed to systematically evaluate participants' subjective experiences upon waking.

PVT

The Psychomotor Vigilance Task (PVT) is a widely used method for assessing alertness by measuring response speed to visual stimuli. Shorter response times indicate higher alertness. The PVT was programmed using E-Prime 3.0 software, where a red stopwatch appeared at the center of the screen, and participants were instructed to press the space bar as quickly as possible after its appearance. Stimulus presentation intervals varied randomly between 3500 ms and 8500 ms, with a total of 80 trials. The stopwatch stimulus size was 480×162 pixels, and the entire task lasted 10 minutes.

Performance metrics included average Reaction Time (RT), the number of errors (trials with RT > 500 ms), the average of the fastest 10% response times (10% Fastest Response Time, 10% FRT), and the average of the slowest 10% response times (10% Slowest Response Time, 10% LRT). These metrics were used to systematically and quantitatively evaluate participants' alertness levels.

Data Processing

A priori power analysis was conducted using G*Powerr software 3.1.9.7 (Franz Faul, Universitat Kiel, Germany) to determine the minimum required sample size for this study. A repeated measures ANOVA was selected with a within-subject factor (three mattress conditions). The analysis assumed a large effect size ($f = 0.40$), an α level of 0.05, a power of 0.80, and a correlation among repeated measures of 0.5. Based on these parameters, the calculated minimum required sample size was 12 participants. Therefore, the current sample size is adequate to detect significant differences between the conditions.

The data analysis was performed using IBM SPSS Statistics (version 27, IBM Corp., USA). Repeated measures ANOVA was selected to analyze the sleep parameters, considering the within-subject factor of mattress condition. When Mauchly's test indicated a violation of sphericity ($p < 0.05$), multivariate methods, specifically Pillai's Trace, were used to determine the effects, which is more robust under the violation of sphericity. For significant main effects, pairwise post-hoc comparisons were conducted with Bonferroni correction applied to account for multiple comparisons. The significance level was set at $p < 0.05$. Effect sizes of significant effects were reported using partial eta squared (partial η^2). The interpretation of partial η^2 follows established guidelines, with small, medium, and large effect sizes corresponding to η^2 values of 0.01, 0.06, and 0.14, respectively.[30]

The range, defined as the difference between the maximum and minimum values within each condition, was utilized to assess the consistency of participants' sleep responses to different mattresses.

Additionally, the gray relational analysis was employed to evaluate the similarity of sleep characteristics under different mattress conditions, allowing us to quantify the impact of mattress firmness on sleep and rank the influence on various sleep parameters. This method was chosen for its ability to analyze complex relationships and quantify the impact of mattress firmness on sleep. GRA is especially useful for comparing parameters when data is non-normally distributed or relationships are nonlinear. In this study, data from the medium mattress were used as the reference sequence, while data from the soft and firm mattresses were used as comparison sequences. The gray relational degree of the soft and firm mattresses relative to the medium mattress was calculated, and the average value was taken as the final relational degree. Theoretically, sleep parameters for the same participant should remain relatively stable, which would be reflected in a higher gray relational degree. Mattress firmness, however, is considered the primary factor contributing to a decrease in this degree, meaning that the lower the gray relational degree, the greater the influence of firmness. Therefore, we used gray relational analysis to rank the impact of mattress firmness on sleep structure parameters.

Results

Effect of Mattress Firmness on Sleep Architecture

Table 1 and Figure 3 compares the sleep parameters across different mattress firmness levels, including sleep stages (N1, N2, N3), total sleep period (TSP), total sleep time (TST), sleep efficiency, sleep latency, and sleep stage transitions. As shown Figure 3a and b, the repeated measures ANOVA results indicate no significant differences in total sleep period (TSP) across the three mattress types ($F(2,22) = 2.26$; $p = 0.13$). Similarly, the results for total sleep time (TST) show no significant differences between the three mattress types ($F(2,22) = 1.37$; $p = 0.28$). However, the average TSP values and TST values are higher for Mattress 2 (medium firmness) compared to the other two mattresses.

Table 1 Comparison of Sleep Architecture on Each Mattress

	Soft	Medium	Firm	F	P
TSP	75.42±2.94	81.33±1.64	75.96±2.66	2.26	0.13
TST	68.83±3.22	75.92±2.12	69.54±4.15	1.37	0.28
Sleep efficiency (%TIB)					
	76.48±3.58	83.57±2.86	77.27±4.61	0.99	0.39
Sleep Stages (min)					
N1	9.75±1.39	8.83±1.08	8.83±1.17	0.24	0.79
N2	37.50±3.10	38.71±3.10	38.21±2.77	0.11	0.90
N3	13.71±3.71	17.42±4.22	14.25±4.22	0.55	0.59
REM	7.88±2.60	10.96±2.34	8.25±2.71	0.42	0.66
WASO	8.79±2.61	6.33±2.17	8.96±3.71	0.21	0.81
(% TSP)					
N1%	12.89±2.20	11.23±1.26	11.81±1.64	0.46	0.64
N2%	52.26±4.24	46.22±4.30	51.03±4.13	2.52	0.10
N3%	15.32±3.80	23.67±5.37	18.18±5.15	1.67	0.21
REM%	11.71±3.58	11.43±2.45	10.24±3.36	0.06	0.94
Stage shifts(n)					
	29.17±2.35^{a}	23.33±2.58	21.75±2.13^{b}	5.17	0.01
Shifts to lighter stages(n)					
	12.25±1.21	9.08±1.26	9.17±1.10	3.64	0.04
Sleep latencies (min)					
To N1	12.42±1.94^{a}	7.71±1.31^{b}	11.50±2.30	3.80	0.04
To N2	13.75±2.02	11.63±1.97	16.00±2.86	2.05	0.15

Notes: All measurement are reported as mean ± SEM; n= 12; Values with different superscripts (^{a,b}) indicate significant differences between conditions ($p < 0.05$, repeated measures ANOVA with Bonferroni correction); Total Sleep Time and Period are calculated from sleep onset; Sleep efficiency: TST/TIB*100%; Shifts to lighter sleep stages are defined as the number of shifts from rapid eye movement (REM) sleep to wakefulness, as well as shifts from NREM stages to lighter NREM stages or wakefulness.

Abbreviations: TSP, Total sleep period; TST, total sleep time; TIB, Total time in bed; Sleep efficiency, TST/TIB*100%; N1, NREM stage 1; N2, NREM stage 2; N3, NREM stage 3; REM, rapid eye movement sleep stage; WASO, wake after sleep onset.

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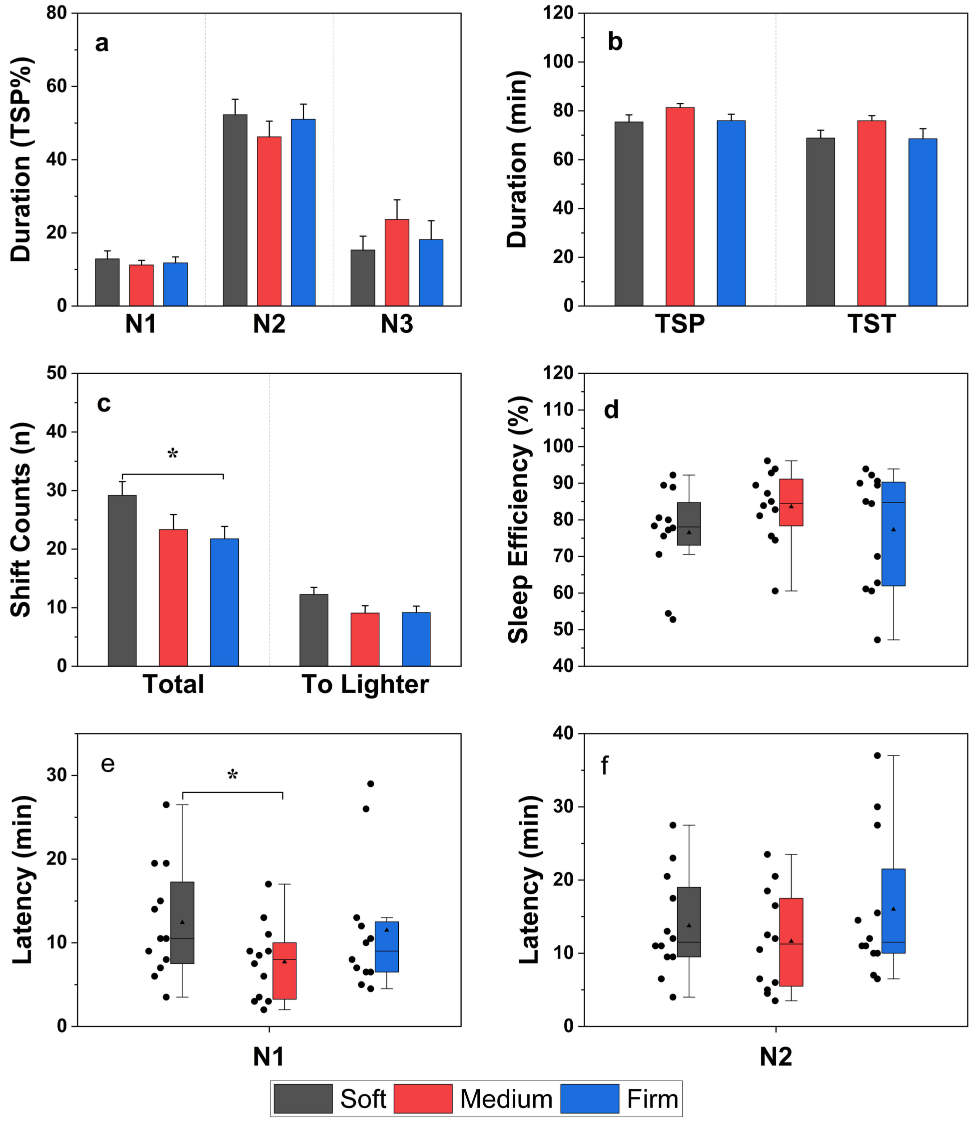

Figure 3 Comparison of sleep parameters on each mattress. (**a**) Effect of mattress firmness on sleep duration of N1, N2, N3. (TST). (**b**) Effect of mattress firmness on total sleep period (TSP) and total sleep time (TST). (**c**) Sleep stage shifts and stage shifts to lighter stages (REM to wake, NREM stages to lighter NREM stages or wakefulness) on each mattress. (**d**) Effect of mattress firmness on sleep efficiency. (**e**) Effect of mattress firmness on sleep latency to N1. (**f**) Effect of mattress firmness on sleep latency to N2. One star (*) indicates $p < 0.05$.

Regarding specific sleep stages, The medium firm mattress resulted in shorter durations in the N1 and N2 stages but a longer duration in the N3 stage, suggesting it may promote more deep sleep (N3 stage). However, these differences were not statistically significant.

In the scatter plot of sleep efficiency (Figure 3d), data show that participants using the medium firm mattress (95% CI [77.26, 89.87]) exhibit higher and more consistent sleep efficiency, indicating that most participants adapt well to medium firmness, leading to more stable sleep efficiency. In contrast, the sleep efficiency data for the firm mattress (95% CI [67.12, 87.41]) show marked polarization, with participants' sleep efficiency clustered in the upper and lower quartiles. This suggests significant variability in adaptation: those who adapt to the firm mattress achieve higher sleep efficiency, while those who do not exhibit lower sleep efficiency, indicating greater individual variability in response to the firm mattress.

Analysis of sleep latency and sleep stage shift counts (Figure 3c, e and f) reveals that the soft mattress (Mattress 1) is associated with longer sleep latency and higher shift counts. N1 sleep latency on Mattress 1 is significantly longer than on the medium firmness mattress ($F(2,22) = 3.795$; $p < 0.05$), indicating that the soft mattress is less conducive to rapid sleep onset. Further box plot analysis shows differences in sleep latency distribution among the three mattresses.

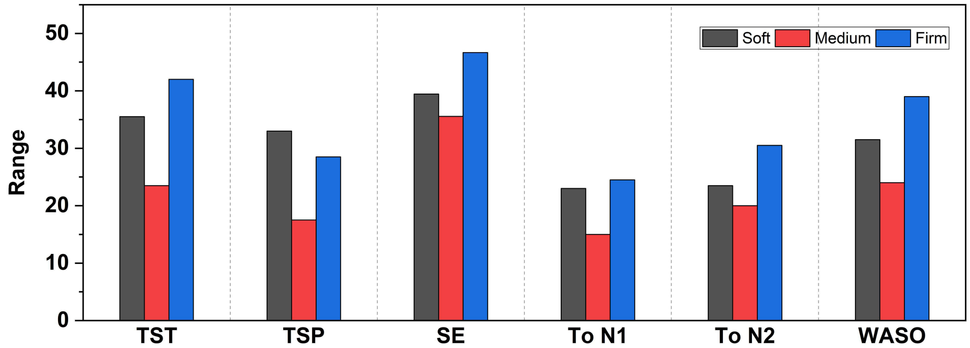

Figure 4 Comparison of range of sleep parameters on each mattress.
Note: Range = xmax − xmin.
Abbreviations: TST, total sleep time; TSP, total sleep period; SE, sleep efficiency; To N1, sleep latency to N1; To N2, sleep latency to N2; WASO, wake after sleep onset.

The medium firm mattress (95% CI [4.82, 10.59]) displays a more concentrated distribution with fewer outliers, while the soft (95% CI [8.15, 16.69]) and firm mattresses (95% CI [6.45, 16.55]) show greater variability and more outliers, indicating inconsistent effects on sleep latency and greater individual differences.

Additionally, the soft mattress has significantly higher sleep stage shift counts (Figure 3c) compared to the medium mattress ($F(2,22) = 5.165$; $p < 0.05$). Overall, Mattress 2 (medium) shows better generalizability, while the firm mattress is suitable for participants who can adapt to its firmness. The soft mattress, however, is associated with notable deficiencies in sleep quality.

The analysis of the range in sleep parameters under different mattress conditions further supports the advantage of the medium mattress in participant adaptability. As shown in Figure 4, the medium firm mattress exhibits the smallest range across TST, TSP, sleep efficiency, sleep latency, and WASO, indicating more consistent results. Mattress 1 follows, while the firm mattress shows the largest range across all sleep parameters, suggesting the greatest variability in participant responses.

Table 2 shows the average gray relational degree of sleep parameters across the three mattresses, ranked in ascending order. The results indicate that TST, REM, and N2 duration percentage, the sleep efficiency, sleep latency are more

Table 2 Gray Relational Analysis of the Impact of Mattress Firmness on Various Sleep Parameters

	Medium-Soft	Medium-Firm	Average
TST	0.69	0.57	0.63
REM (%TSP)	0.61	0.66	0.64
N2 (%TSP)	0.60	0.74	0.67
Sleep efficiency (TIB%)	0.73	0.61	0.67
Sleep latencies to N1	0.69	0.67	0.68
Sleep latencies to N2	0.68	0.68	0.68
TSP	0.72	0.71	0.71
Stage shifts(n)	0.71	0.72	0.71
WASO	0.76	0.68	0.72
N1 (%TSP)	0.72	0.75	0.73
N3 (%TSP)	0.81	0.72	0.77
Shifts to lighter stages(n)	0.77	0.80	0.79

Notes: REM%, N1%, N2%, and N3% are calculated as stage duration/TSP × 100%; Sleep efficiency, TST/TIB*100%; Shifts to lighter sleep stages are defined as the number of shifts from rapid eye movement (REM) sleep to wakefulness, as well as shifts from NREM stages to lighter NREM stages or wakefulness.
Abbreviations: TST, total sleep time; REM, rapid eye movement sleep stage; N1, NREM stage 1; N2, NREM stage 2; N3, NREM stage 3; REM, rapid eye movement sleep stage; TSP, total sleep period; WASO, wake after sleep onset.

significantly affected by mattress firmness. In contrast, TSP, the number of sleep stage transitions, and percentage of N1 and N 3 are less influenced by mattress firmness.

Effect of Mattress Firmness on Slow Waves and Spindle Characteristics

Figure 5 illustrates the comparison of slow wave and spindle characteristics across different mattress firmness levels, including delta power buildup, spectral power during N2, and the maximum and integrated absolute amplitude of sleep spindles. As shown in Figure 5a and b, there were no significant differences in power across frequency bands during the N2 stage among the three mattress conditions. Similarly, there were no significant differences in the delta power build-up rate during the first 20 minutes after sleep onset.

Repeated measures ANOVA of slow oscillation metrics revealed no significant differences in the frequency, duration, amplitude, or density of slow waves, indicating that mattress firmness does not significantly affect these characteristics of slow oscillations.

However, as shown in Figure 5c and d, certain spindle characteristics exhibited significant differences. Specifically, the maximum amplitude ($F(2,22) = 6.219$; $p < 0.01$) and integrated absolute amplitude ($F(2,22) = 8.034$; $p < 0.01$) of spindles were significantly higher with the medium mattress compared to the soft and hard mattresses. This suggests that mattress firmness influences neural activity during sleep, with the medium mattress potentially providing optimal support that enhances neural activity and improves sleep processes.

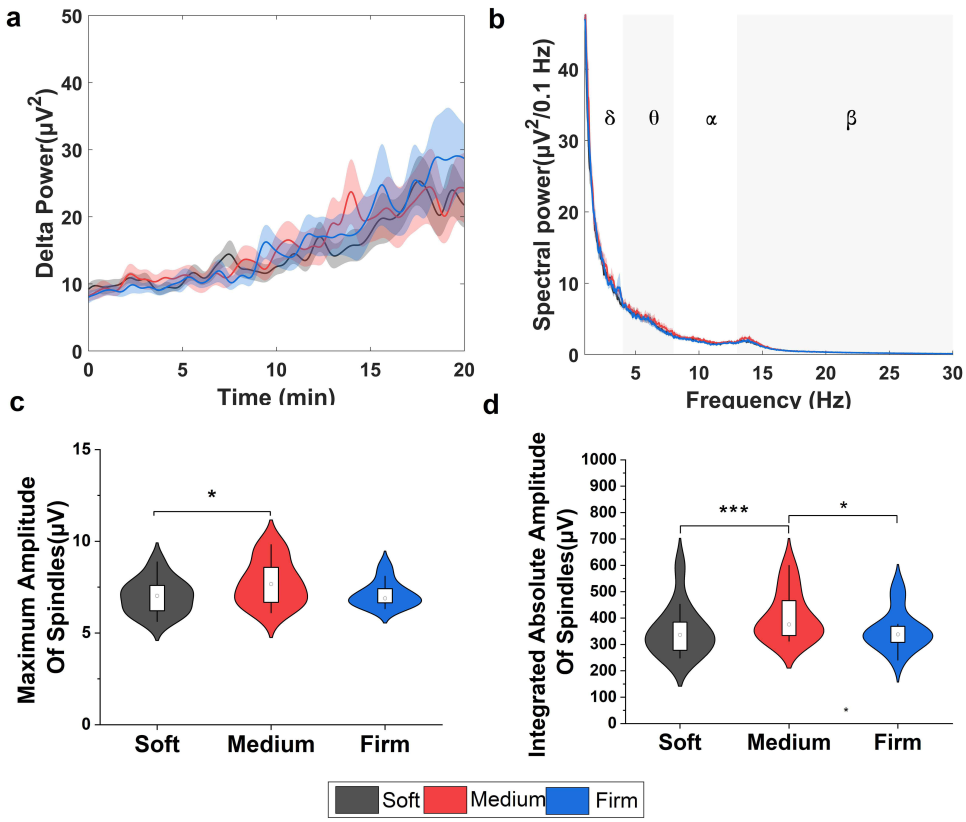

Figure 5 Comparison of slow waves and spindle characteristics on each mattress. (**a**) Buildup of delta power (0.75–4.5Hz) after sleep onset. (**b**) Spectra power of channel C4- M1 during stage N2. (**c**) Effect of mattress firmness on the maximum amplitude of sleep spindles. (**d**) Effect of mattress firmness on the integrated absolute amplitude of sleep spindles.

Notes: The lines represent the average power, the shaded areas represent the standard error of the mean (SEM) of power, and the stars indicate the statistical significance (p) of conditions as determined by a repeated measures ANOVA. One star (*) indicates $p < 0.05$, and three stars (***) indicate $p < 0.001$.

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Table 3 Comparison of State Upon Waking up After Sleep on Each Mattress

	Soft	Medium	Firm	F	P
KSS	5.17±0.35	5.33±0.28	4.75±0.45	3.67	0.42
Discomfort	2.33 ± 2.19	1.75 ±1.36	3.33 ± 2.15	3.03	0.07
PVT					
RT	281.96±12.60	274.57±8.36	273.34±7.99	0.75	0.49
10%FRT	215.12±7.87	208.76±7.18	213.37±6.13	0.70	0.51
10%LRT	386.17±16.72	381.50±14.99	381.89±12.51	0.09	0.89
Lapses	1.67±0.78	1.17±0.53	1.67±0.57	0.31	0.73

Notes: All measurement are reported as mean ± SEM; n= 12; *p < 0.05.
Abbreviations: KSS, the Karolinska Sleepiness Scale; PVT, Psychomotor Vigilance Test; RT, Reaction Time; 10%FRT, the average of the fastest 10% response times; 10%LRT, the average of the slowest 10% response times; Lapses, the number of errors (trials with RT > 500 ms).

Effect of Mattress Firmness on PVT, KSS and Comfort Ratings After Sleep

Table 3 shows the comparison of participants' state upon waking up after sleep on each mattress, including sleepiness (KSS), discomfort, and performance in the Psychomotor Vigilance Test (PVT) across different mattresses (soft, medium, and firm). A repeated measures ANOVA of the Psychomotor Vigilance Task (PVT) results under the three mattress conditions revealed no significant differences in average reaction times (RT), the number of lapses (RT > 500 ms), 10% fastest response times (10% FRT), or 10% slowest response times (10% LRT) among the conditions (see Table 3). Similarly, analysis of the Karolinska Sleepiness Scale (KSS) showed no significant differences in subjective sleepiness ratings across the three mattress conditions.

The discomfort ratings for the soft, medium, and firm mattresses were 2.33 ± 2.19, 1.75 ± 1.36, and 3.33 ± 2.15, respectively. There was no significant difference in discomfort ratings among the three mattresses. The firm mattress was rated has the highest average uncomfortable rating, followed by the soft mattress, while the medium mattress was rated as the most comfortable.

Discussion

Sleep quality is essential for both physiological and psychological health,[31–33] and identifying the type of mattress that enhances sleep remains a key focus of research. Mattress firmness is considered a key factor influencing sleep quality.[15,21] This study examined the impact of mattress firmness on sleep architecture and brain activities by collecting data from subjects with a medium BMI using three types of mattresses (soft, medium, and firm). Polysomnography (PSG) was employed to explore how mattress firmness affects sleep architecture, underlying EEG mechanisms, as well as its impact on alertness and reaction time upon waking. These findings provide valuable insights into how mattress firmness affects sleep quality, sleep EEG, and related mechanisms, and may inform improvements in sleep environments and targeted sleep interventions.

The results indicated that for individuals with a medium BMI, the medium mattress (Mattress 2) demonstrated the best overall performance. Although there were no significant differences in total sleep period (TSP) and total sleep time (TST) among the three mattress types, the medium mattress had higher average values compared to the others. A detailed analysis of sleep architecture showed that subjects on the medium mattress spent less time in N1 and N2 light sleep stages, and more time in N3 deep sleep, crucial for physical recovery and cognitive function.[31,34] While these differences were not statistically significant, the trend suggests that a medium mattress may improve deep sleep duration and overall sleep quality.

Gray relational analysis provides new insights, indicating that total sleep time (TST), sleep efficiency, and sleep latencies are more significantly influenced by mattress firmness. This finding aligns with sleep architecture research, which shows that the medium mattress is associated with shorter sleep latency, longer average TST, and higher average sleep efficiency.

Further analysis of data range and distribution highlighted the meidum firm mattress' advantages in subject universality. The medium firm mattress showed the smallest range across TST, TSP, sleep efficiency, sleep latency, and WASO, indicating more stable sleep and reduced adaptability demands on subjects. Sleep efficiency data indicated that the medium mattress had higher and more consistent average sleep efficiency than the soft and firm mattresses. This suggests better adaptation and more stable sleep quality for most subjects.

These findings align with previous research indicating that medium mattresses improve subjective sleep quality.[35–37] Jacobson et al[13] used Visual Analog Scales (VAS) to compare sleep on participants' own beds versus new medium mattresses and found that medium mattresses significantly enhanced subjective sleep quality. While fewer studies have used objective methods like polysomnography (PSG) to evaluate different mattresses, some research highlights the importance of proper support. D. Van Deun et al[38] assessed an actively adjusting sleep system designed to provide appropriate support, finding it significantly improved subjective sleep quality and showed a trend toward increased slow-wave sleep. Chen et al[22] investigated different pressure distributions and found that mattresses with intermediate pressure distribution increased the duration and proportion of N3 sleep and reduced micro-arousal. However, these studies primarily focused on mattress effects on sleep architecture.

To gain a deeper understanding of how mattress firmness affects sleep and its underlying neural mechanisms, we analyzed EEG characteristics under three mattress conditions. The results indicated no significant differences in power across frequency bands during N2 sleep or in the delta wave accumulation rate within the first 20 minutes after sleep onset. Further analysis of slow-wave oscillations, including frequency, duration, amplitude, and density, revealed no significant differences.

However, specific spindle characteristics showed significant differences. Under the medium mattress condition, the maximum amplitude and integral absolute amplitude of sleep spindles were significantly higher compared to the soft and firm mattresses. Given that sleep spindles are EEG markers of N2 sleep associated with memory consolidation and learning, increased spindle amplitude and integral absolute amplitude suggest enhanced neural activity during sleep,[39,40] potentially improving memory processing and learning efficiency.[41] Thus, a medium mattress may offer optimal support, enhancing neural activity and overall sleep quality.

In contrast, the soft mattress exhibited notable shortcomings in overall sleep quality. Sleep latency studies revealed that the soft mattress resulted in significantly longer sleep latency compared to the medium mattress. Additionally, sleep stage shifts analyses showed that the soft mattress led to more frequent transitions and shifts to lighter sleep stages compared to the firm mattress. This indicates that the soft mattress may impair rapid sleep onset and stable sleep maintenance, potentially due to inadequate support and poor spinal alignment.[42,43] In mattress research, proper support is considered crucial for comfort. It refers to the mattress's ability to evenly distribute the body's weight, maintaining the spine's natural curvature, similar to its alignment in a standing position.[6,43] Insufficient support may cause areas such as the hips to sink, leading to increased internal pressure on the spine, resulting in discomfort or even long-term pain.[16,42] Additionally, localized skin pressure may rise, exacerbating discomfort and potentially disrupting sleep maintenance. Vincent Verhaert et al[44] found that a sinking sleep system negatively impacted sleep quality for individuals who sleep in lateral or prone positions, reducing REM sleep time. Therefore, ensuring proper spinal alignment is essential for enhancing sleep quality and maintaining overall musculoskeletal health.

Compared to others, the firm Mattress required greater adaptability and was suitable only for specific groups. The sleep efficiency data for the firm mattress showed significant polarization, with participants' sleep efficiency concentrated in the upper and lower quartiles, reflecting considerable individual differences in adaptability. A study of data ranges further highlighted Mattress 3's disadvantages in terms of adaptability; among the three mattress groups, Mattress 3 had the largest range in TST, TSP, sleep efficiency, sleep latency, and WASO. This indicates significant variation in sleep time, efficiency, and latency among participants using Mattress 3. Participants who adapted well to Mattress 3 exhibited higher sleep efficiency, longer sleep duration, and shorter sleep latency, while those who did not adapt showed lower sleep efficiency, shorter sleep duration, and longer sleep latency. The firm mattress also exhibited more outliers in sleep latency during N1 and N2 stages, indicating poorer overall applicability.

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On one hand, this variation in adaptability may be due to individual anthropometric differences. Research by Shore et al[45] on spinal alignment across different mattress firmness levels (soft, medium, and firm) found that, in addition to BMI, factors such as body weight, hip circumference, and height affect how well individuals adapt to different mattresses. For example, heavier individuals tend to have better spinal alignment on firmer mattresses, while those with larger hip circumferences experience greater misalignment on softer mattresses. Similarly, Gaby G Bader et al[21] studied on sleep quality with various mattress firmness levels suggests that heavier individuals may benefit more from firmer mattresses for improved spinal support and better sleep quality. In line with these findings, our previous study, which primarily focused on surface electromyography (sEMG) activity on soft, medium, and firm mattresses,[46] showed that firmer mattresses may be better suited for individuals with higher BMI and larger waist circumference, as these factors were linked to lower sEMG activity on firm mattresses. The current study builds on this by examining the impact of mattress firmness on sleep, focusing on sleep architecture and PSG characteristics under the same experimental conditions.

On the other hand, differences in adaptability may also be related to personal preferences and sleep habits.[47] Research indicated that sinking sleep systems negatively affect those who sleep in lateral or prone positions but do not have the same negative impact on individuals who sleep supine.[44]

However, the generalizability of these findings is limited by the study's restricted participant age range (18–25 years) and specific BMI criteria. Sleep patterns, mattress preferences, and comfort perceptions may differ across other age groups or BMI ranges. For example, older adults may face unique musculoskeletal challenges or sleep needs, and individuals with higher or lower BMI may perceive comfort and sleep quality differently. Additionally, this study focused on 90-minute naps rather than full nocturnal sleep, which may limit its relevance to overnight sleep. Naps often exhibit different sleep architectures, including REM duration and stage transitions, compared to uninterrupted overnight sleep. Moreover, testing at a fixed time point (12:30 PM) may limit the generalizability of the findings, as circadian rhythms could influence sleep parameters at different times of the day. Future research should include a more diverse population and investigate the effects of mattress firmness on overnight sleep to better understand its broader implications for sleep architecture and quality.

Conclusion

This study directly examines the effects of mattress firmness on sleep by utilizing long-term PSG and EEG data for a more objective and comprehensive evaluation. We found the medium mattress (64.6HA) emerged as the most effective, optimizing sleep architecture, and reducing sleep onset latency. EEG analysis further revealed that medium mattresses enhance spindle wave activity. These findings highlighting the importance of designing mattresses that balance comfort and support while accommodating individual variations.

Data Sharing Statement

The datasets generated during the current study are available from the corresponding author on reasonable request at luobincl@bjfu.edu.cn.

Ethics Statement

The human study protocol was reviewed and approved by the Human Study Ethics Committee of Beijing Forestry University (Approval No: BJFUPSY-2024-032), and all participants provided written informed consent.The study was conducted in accordance with the principles outlined in the Declaration of Helsinki.

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The Pittsburgh Sleep Quality Index (PSQI) was utilized in this study as a validated, publicly available tool for assessing sleep quality. The Karolinska Sleepiness Scale (KSS) was referenced according to its original publication. The

State-Trait Anxiety Inventory for Adults (STAI-AD) was administered under a valid license obtained from Mind Garden, Inc., through their official website, in accordance with the purchase agreement, permitting its use in research settings.

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All authors agreed on the journal to which the article was submitted, reviewed and approved all versions of the manuscript prior to submission, during revision, and the final version accepted for publication. They also agreed to take responsibility and be accountable for the contents of the article, including any significant changes introduced during the proofing stage. All authors have drafted or written, or substantially revised or critically reviewed the article.

Disclosure

The authors declare that they have no competing interests.

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