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Comparative Assessment of Cardiac Strain Across Different Carpentry Activities

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Abstract

Introduction: Carpentry is a crucial, widespread trade within India's construction industry, employing a large informal workforce across rural and urban regions. Although the trade is slowly adopting machinery, carpentry remains a highly labor-intensive profession requiring significant hands-on work. This cross-sectional observational study evaluated and classified the physiological workload of six common manual carpentry activities, using three standardized cardiac strain indices.

Methods: Thirty-three male carpenters from furniture-making units participated in multiple tasks, generating 218 worker-activity combinations. Working heart rates were recorded under actual field conditions, and a linear mixed-effects model with restricted maximum likelihood (REML) was employed.

Results: The study demonstrated a consistent activity gradient across all three indices. Sawing imposed the highest cardiac demand, placing it in the 'action required' category. Planing and sanding constituted a moderate intermediate tier, while hammering, chiseling, and varnishing formed the lowest-demand group.

Conclusion: The individual worker characteristics substantially contributed to cardiac response, beyond task type alone. A three-tier action-level classification for net cardiac cost (NCC) is proposed to guide ergonomic interventions in the informal carpentry sector. Findings underscore the importance of distribution shape, in designing work-rest schedules and targeted ergonomic controls for at-risk workers.

Keywords: Cardiac strain, carpentry, ergonomic, linear mixed-effects model, net cardiac cost, occupational physiology, relative cardiac cost, working heart rate

1. Introduction

Carpentry is a widely practiced occupation and an integral component of the construction industry across both rural and urban sectors in India, engaging a large informal workforce. Despite gradual mechanization, carpentry continues to involve a considerable amount of manual effort. Previous studies have identified carpentry as a high-risk occupation with significant ergonomic stress involving repetitive movements and sustained awkward postures that expose workers to musculoskeletal disorders and work-related fatigue[1,2].

While musculoskeletal outcomes among carpenters are relatively well documented, quantitative evaluation of physiological workload in specific carpentry tasks remains limited. Carpentry encompasses a variety of heterogeneous tasks that differ in terms of energy expenditure and cardiovascular strain. Systematic studies comparing these tasks

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using standardized indices are scarce. Objective indices such as working heart rate (WHR), net cardiac cost (NCC), and relative cardiac cost (RCC) are widely accepted in occupational physiology for quantifying cardiovascular demand and classifying workload intensity[3-7]. Such quantifications are especially critical in the unorganized sector, where working conditions often remain unregulated and ergonomic interventions are minimal.

Therefore, the present study aims to evaluate and classify the physical workload associated with selected carpentry activities using WHR, NCC, and RCC, with the goal of providing a scientific basis for ergonomic interventions.

2. Methods

2.1. Study design and participants

A cross-sectional observational study was conducted to evaluate the physical strain involved in six common manual carpentry activities: chiseling, planing, sawing, hammering, sanding, and varnishing. Carpenters employed in randomly selected furniture-making units constituted the sampling frame, which was used to select participants based on predefined inclusion and exclusion criteria. The inclusion criteria included (i) minimum two years of work experience, (ii) continuous engagement in work for at least two weeks prior to the study, and (iii) absence of any self-reported illness at the time of data collection. Exclusion criteria included part-time workers, individuals with known cardiorespiratory disorders, and those who had experienced any acute illness within two weeks preceding the study. Prior to data collection, subjects were explained about the study objectives and the extent of their involvement. Written informed consent was obtained from all eligible and willing participants. Ethical approval was obtained from the Institutional Ethics Committee of Himachal Dental College, Sundernagar, Himachal Pradesh (Letter No. HDC/IEC/2026/29/037), dated December 20, 2025.

2.2. Description of carpentry activities

Six common carpentry activities were identified based on the nature of work and tool usage:

- Chiseling: Manual shaping, carving, or grooving of wooden surfaces using a chisel.
- Planing: Smoothing and leveling wooden surfaces using a hand planer.
- Sawing: Cutting wooden planks and plyboards into desired dimensions using a hand saw.
- Hammering: Driving nails into wooden components using a hammer for the purpose of fixing or joining parts.
- Sanding: Rubbing the wooden surface with sandpaper to reduce roughness.
- Varnishing: Applying layers of varnish onto sanded wooden surfaces manually.

Cardiovascular strain parameters were assessed and compared across these six activities.

2.3. Sample size estimation

As each participant performed two to three of the six designated activities, the study employed a partially repeated measures design and appropriate formula for sample size estimation was applied as follows: $n=(Z\alpha+Z\beta)^2 \times 2(1-\rho)/f^2\cdot k$, where, $Z\alpha$ is the critical value of the chosen significance level, $Z\beta$ is the critical value of the desired statistical power, ρ is the assumed within-subject correlation across conditions, f is the effect size, and k denotes the number of repeated conditions. The following parametric assumptions were adopted: a moderate effect size (f=0.25)[8], six occupational task conditions (k=6), a within-subject correlation of ρ=0.50, a two-tailed significance level of α=0.05 ($Z\alpha$=1.96), and a statistical power of 1-β=0.80 ($Z\beta$=0.84). Substituting these values: $n=((1.96+0.84)^2 \times 2(1-0.5))/(0.25)^2\cdot 6\approx 21$. The estimation indicated that a minimum of 21 participants were required to achieve 80% statistical power at the 5% significance level for detecting a moderate effect across six repeated conditions. In practice, a total of 33 male carpenters volunteered in the study, providing adequate statistical power to detect meaningful differences in physiological strain across the designated carpentry activities.

2.4. Work sampling procedure

Not all workers participated in every activity. Of the 33 carpenters, 31 contributed to two or more activities. Multiple work samples representing 3-4 WHR per worker per activity were collected, resulting in a total of 218 worker-activity combinations. Each work sample represented a brief period of activity (3-5 minutes) and were collected during actual working conditions on different working days to capture natural variability in workload and performance.

2.5. Physical and physiological measurements

Height, weight, body mass index (BMI), and work experience were the basic parameters collected. Resting heart rate (RHR) was considered as the lowest value of three HR recordings measured by auscultation, after an initial rest of 15 minutes. Maximum heart rate (MHR) was estimated using the following age-predicted equation[9]: MHR=208-0.7×(age in years). Heart rate reserve (HRR) was calculated as the difference between MHR and RHR. The WHR was recorded by auscultating the apex beat and counting the time of 10 cardiac cycles with a stopwatch. Next, the time recorded was converted into HR using the formula: WHR (beats/min)=600/time (seconds) for 10 cardiac cycles. The NCC was used as an index of cardiac strain and calculated as the difference between the WHR and RHR: NCC=WHR-RHR. The RCC was also used as a cardiac strain index and expressed as the percentage of HRR utilized during work. It is calculated as: RCC (%)=NCC/HRR×100.

2.6. Statistical analysis

The statistical analysis was conducted with three connected aims. First, to produce the descriptive summary of WHR, NCC and RCC by activity. Second, to test the global hypothesis that activity has no effect on cardiac strain after accounting for between-worker heterogeneity. Third, to produce a gradation of the six activities from most to least strenuous, supported by pairwise contrasts. The preferred choice of statistical model was a linear mixed model, used for repeated-measures structure, since the same individuals appeared in more than one activity. The model was fitted using restricted maximum likelihood (REML), with activity treated as a fixed effect and individual workers as a random intercept. The most strenuous activity was set as the reference level so that the fixed-effect coefficients could be read directly as the deviation in beats per minute (bpm) or %, of each activity from the most strenuous one. Normality was assessed with the Shapiro-Wilk test and homogeneity was tested with Levene's test using deviations from the median (data not shown).

3. Results

3.1. Participant characteristics

The 33 male carpenters had a mean age of 44±11.3 years, with the majority (57.5%) aged between 40-59 years. Mean BMI was 22.8±2.0 kg/m², with 90.9% falling within the healthy range. Mean occupational experience was 25.2±11.8 years, with over half (51.5%) having more than 25 years of experience.

3.2. Physiological strain

The box plots of parameters illustrate the distribution of all three cardiac strain indices (WHR, NCC, RCC) across the six carpentry activities, revealing a descending gradient from sawing to varnishing. Sawing imposed the highest cardiac demand across all indices, with a mean WHR of 113 bpm (median: 111.0; IQR: 100-123), mean NCC of 34.9 bpm (IQR: 28-44), and mean RCC of 35.9% (IQR: 26.8-45.8%). Planing and sanding formed a clearly distinguishable intermediate tier, with mean WHR values of 103.5 and 100.9 bpm, and mean RCC values of 27.1% and 24.0%, respectively. Hammering, chiseling, and varnishing collectively constituted the lowest-demand group, with mean WHR values ranging from 94.1 to 96.7 bpm and mean RCC values between 16.8% and 18.6%, with comparatively compressed distributions (Figure 1).

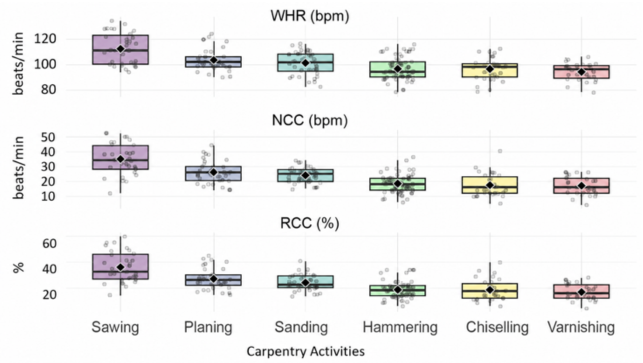

Figure 1: Box plots of cardiac strain across six carpentry activities
Boxes show the inter-quartile range (IQR) and median; whiskers extend to 1.5 IQR; jittered points are individual observations; black diamonds mark the activity mean. Activities are ordered by descending overall mean WHR

3.3. Physiological strain in different activities

The box plot of different parameters across activities demonstrates the strain levels in different tasks. The half-violin plot demonstrates the RCC distribution across different activities. There is a clear gradation of activities based on workload. Sawing has the highest mean RCC, followed by planing and sanding, and least for hammering, chiseling and varnishing (Figure 2).

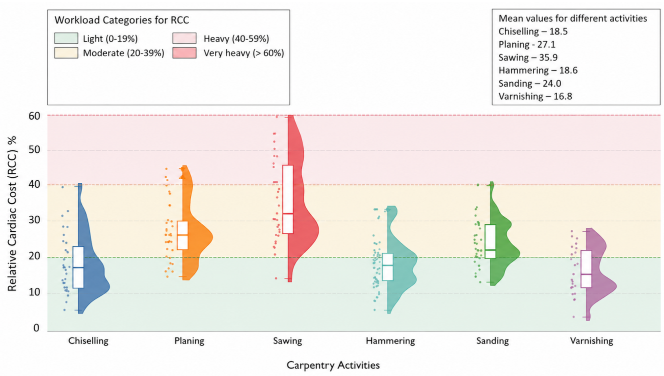

Figure 2: Half-violin, box plots and jittered points for RCC by activity
RCC: relative cardiac cost; horizontal reference bands denote workload categories

The activities exhibit rightward (positive) skew in their distribution curves, confirming that while most workers had moderate cardiovascular responses, a smaller group experienced notably higher cardiovascular strain, pulling the distribution toward higher values away from the modal cluster. Varnishing is the sole exception, showing a near-symmetric distribution (skew≈0.09) tightly confined within the light workload category (Table 1). The NCC distributions reinforce the RCC picture. Sawing is the only activity whose group mean (34.9 bpm) falls squarely in the 'action required' zone (30-39 bpm), while the others fall under the 'no action required' category (Table 2).

3.4. Linear mixed-effects model

The mixed-effects model is fitted with REML, keeping activity as a fixed factor and a random intercept for worker. The intra-class correlation ranged between 0.30-0.60 (0.30 for NCC, 0.36 for RCC and 0.60 for WHR), confirming that worker-level differences are substantial. A Type-III ANOVA on the mixed model (using Satterthwaite degrees of freedom) was used to test whether cardiac strain differs significantly across activities after accounting for worker-to-worker differences. All three strain indices show highly significant activity effects ($p<0.001$). The variance was further explained through the Nakagawa-Schielzeth marginal and conditional R^2, that provide evidence on how well the model explains the variance in cardiac strain. While the R^2 marginal variance was explained by activity (fixed effects) alone, the R^2 conditional variance was explained by activity plus worker differences (fixed + random effects combined). The gap between marginal and conditional R^2 was large (0.28 *vs* 0.71 for WHR, 0.39 *vs* 0.58 for NCC, and 0.37 *vs* 0.59 for RCC), which confirmed that although activity alone has a real, meaningful effect (explaining 28-40% of variation), worker identity explained a substantial portion of cardiac response. For example, in terms of HR variations, the effect of activity jumped from 28% to 71% when the worker effect was added. Therefore, while activity alone had a real, meaningful effect (explaining roughly 28-40% of variation), the full picture requires individual variations.

Table 1: RCC across workload categories for different activities

Activity (n)	Mean ± SD	Skewness	Overall Workload	Distribution of observations across workload categories % (n)			
				L (0-19%)	M (20-39%)	H (40-59%)	VH (≥60%)
Chiseling (31)	18.5 ± 8.0	+0.82	L	67.7 (21)	32.3 (10)	0 (0)	0 (0)
Planing (35)	27.1 ± 8.0	+0.61	M	20.0 (7)	68.6 (24)	11.4 (4)	0 (0)
Sawing (31)	35.9 ± 11.7	+0.36	M	3.2 (1)	61.3 (19)	35.5 (11)	0 (0)
Hammering (58)	18.6 ± 6.7	+0.67	L	62.1 (36)	37.9 (22)	0 (0)	0 (0)
Sanding (36)	24.0 ± 6.2	+0.49	M	22.2 (8)	75.0 (27)	2.8 (1)	0 (0)
Varnishing (27)	16.8 ± 6.3	+0.09	L	63.0 (17)	37.0 (10)	0 (0)	0 (0)
All (218)	23.1 ± 10	+ 0.99	M	41.3 (90)	51.4 (112)	7.3 (16)	0 (0)

RCC: relative cardiac cost; L: light; M: moderate; H: heavy; VH: very heavy

Table 2: NCC across workload categories for different activities

Activity	n	Mean (bpm)	SD	Skewness	Action Category
Chiseling	31	17.3	7.4	+1.02	No action required
Planing	35	26.1	7.6	+0.43	No action required
Sawing	31	34.9	10.6	−0.07	Action Required
Hammering	58	18.5	6.3	+0.42	No action required
Sanding	36	24.0	4.9	+0.01	No action required
Varnishing	27	17.1	6.1	−0.10	No action required

NCC: net cardiac cost

3.5. Estimated marginal means and activity rankings

Estimated marginal means (EMM) are the model-predicted average strain values for each activity, adjusted for imbalance in sample sizes and for between-worker differences. They form the basis for fair activity comparisons. Sawing is set as the reference level so that the fixed-effect coefficients can be read directly as the deviation, in bpm or %, of each activity from the most strenuous one. Pairwise contrasts across all activity pairs were adjusted using Tukey's honestly significant difference (HSD) test ($\alpha=0.05$) through compact letter display (CLD). Activities sharing a letter do not differ significantly. Across all three strain indices, the mixed-model EMMs yielded a consistent and defensible activity gradation: sawing was unambiguously the most demanding, planing and sanding formed a clear intermediate tier, and hammering, chiseling, and varnishing constituted the lowest tier, sharing Tukey group 'a' with no significant mutual differences (Table 3).

4. Discussion

Comparing the field values of WHR, NCC, and RCC obtained in different carpentry activities with published literature reveals broadly consistent trends. The reported mean WHRs of lathe machine workers (99-105 bpm)[6] aligns well with most of the mid-range activities of the present carpenters, like sanding and planing. A study on confectionery workers exposed to heat during summer[4], documented WHRs around 107 bpm and RCC values near 30%, a workload closely comparable to the planing but less than sawing task in the current cohort. An inland fishing study recorded NCC values of approximately 20-30 bpm, a range that overlaps with the sanding (23.97 bpm) and planing (26.14 bpm) activities observed in the present study[10]. A higher degree of workload exceeding 33% of RCC was reported for male construction workers[5] as compared to the strain recorded for most of the present carpentry activities. Cardiovascular loads in bulk waste workers[11] with a mean HR of 102 bpm and corresponding RCC of 36%, also exceeded the work demand for majority of the carpentry tasks, except sawing. In another study among old age subjects engaged in physically demanding occupations[7] the documented mean RCC was 24.9%, which was consistent with the WHR range of the carpenters engaged in planing, sawing, and sanding tasks. Well documented studies have reported RCC values of 20-40% for Greek steelworkers[12] that encompassed most carpentry activities and 28-36% in coal mine drillers[3] representing a range that mirrored the higher-demand carpentry tasks. A RCC of 36% was reported among logging choker setters[13], which was comparable only to sawing. A French study found marked inter-individual differences in workload, which was categorized as 'heavy' or 'very heavy' for more than one-third of the workers engaged in vineyard tasks. This was consistent with carpentry tasks[14].

Table 3: EMM for WHR, NCC and RCC from mixed-effects model

Parameter	Activity	EMM (bpm)	SE	95% CI Lower-Upper	Tukey Group
WHR	Sawing	113.0	1.86	109.3 - 116.7	c
	Planing	104.6	1.83	100.9 - 108.2	b
	Sanding	102.4	1.75	98.9 - 105.9	b
	Chiseling	97.3	1.87	93.6 - 101.0	a
	Varnishing	95.8	1.88	92.1 - 99.5	a
	Hammering	95.4	1.60	92.2 - 98.6	a
NCC	Sawing	35.1	1.47	32.2 -38.0	c
	Planing	26.5	1.43	23.7 - 29.3	b
	Sanding	24.4	1.36	21.7 - 27.1	b
	Chiseling	18.8	1.48	15.8 - 21.7	a
	Hammering	17.7	1.16	15.4 - 20.0	a
	Varnishing	17.6	1.51	14.6 - 20.6	a
RCC	Sawing	36.1	1.61	32.9 - 39.3	c
	Planing	27.3	1.57	24.2 - 30.4	b
	Sanding	25.0	1.49	22.1 - 28.0	b
	Chiseling	19.5	1.63	16.3 - 22.8	a
	Varnishing	18.2	1.65	14.9 - 21.4	a
	Hammering	18.0	1.29	15.4 - 20.5	a

Tukey's compact letter display (CLD) interpretation: a: least strenuous cluster, b: intermediate strenuous cluster, c: most strenuous cluster; activities sharing a letter do not differ at α=0.05; EMM: estimated marginal means; WHR: working heart rate; NCC: net cardiac cost; RCC: relative cardiac cost

This comparative picture gains further clarity when considered alongside the physiological basis of the indices employed. The WHR is the simplest index of cardiovascular load, but is confounded by the workers' RHR, which differs markedly with age, fitness, and health status[15]. Although a number of studies have reported a linear relationship between HR and oxygen consumption, this relationship may not be valid in all working conditions, particularly during more static work, when HR increases without a corresponding increase in oxygen uptake[16,17]. This makes HR the preferred parameter in field studies involving more static muscular efforts with simultaneous exposure to ergonomic stressors[18]. The choice of HR as the principal measure in the present study was motivated by these facts.

The WHR remains relatively stable across carpentry tasks. The relatively low variability of HR in different activities despite inter-individual differences, prompted the use of derived indices. The derived indices NCC and RCC exhibited substantial variability, highlighting the influence of individual physiological differences and task-specific work patterns. The NCC removes the resting baseline, and emerged as a useful index of strain, connected more with the activity and thus highly sensitive to individual efficiency, skill level, and work technique[19]. The variability of carpentry activities was also reflected in the mixed-model analysis, accounting for 28% of variation. It has been previously proposed that a NCC of 30-35 bpm can be considered as the limit for continuous work[17]. Based on the mixed-model analysis that reflected a meaningful contribution of both activity and individual, the authors propose a three-tier action level classification of NCC to be applicable for ergonomic intervention in carpentry tasks; 'no action required' for light category (NCC: 0-19 bpm), 'action required' for moderate to heavy category (NCC: 0-39 bpm), 'immediate action required' for very heavy category (NCC: ≥40 bpm). The authors opined that the selection of this criteria was conservative and allowed more physiological safety margin for the workers. RCC takes into account the MHR of the subject and is affected by differences in fitness levels and variation in cardiac reserve utilization. It is a more subjective index that reflects relative physiological strain[19]. The variability in RCC in different carpentry tasks places even more importance in workers' fitness level, as confirmed by the large gap in marginal and conditional R^2 obtained in mixed-model analysis. With respect to the relative oxygen consumption, researchers have recommended values ranging from 33%[20] to 45%[21] being the limits beyond which workers may find the task physically demanding. The authors opted a range of 20-39% of RCC as moderate demand, which was felt as a conservative criterion to allow more physiological safety margin for the workers.

Informed by both the literature comparisons and the interpretive framework of these indices, the characterization of physiological strain across individual carpentry activities becomes more meaningful. In the mixed-model analysis, all three strain indices showed highly significant activity effects confirming that the choice of carpentry task materially affects cardiac demand, independent of who performs it. The task variability appeared from irregular force application and variable posture. Across both metrics, sawing emerged as the most physiologically demanding carpentry task, with mean values of NCC within the 'action-required' thresholds and with upper-tail individuals approaching the heavy/'immediate-action' boundaries. The high cardiovascular demand in this job is consistent with the biomechanical demands of the task, i.e., sustained upper-body force production against resistance, combined with awkward postures. These could result in higher cumulative cardiac cost during a prolonged work duration. Based on the criteria for NCC and RCC established above, sawing appeared in the 'action required' category, with moderate physiological demand.

Planing and sanding occupy an intermediate position. Planing involved rhythmic effort mostly standing with bent back and intermittent action and sanding is characterized by less forceful but comparatively long cycle time of repetitive task. The moderate means and modest positive skew of these activities suggest that while most carpenters manage these tasks within safe limits, the occasional elevations in heart rate require ergonomic control (task rotation, rest scheduling) to prevent cumulative strain over extended shifts. Hammering, chiseling, and varnishing formed the lowest tier. Hammering and chiseling, both are intermittent percussive tasks that despite their muscular intensity, irregular force application and variable posture, allow brief recoveries that limit cardiovascular accumulation. The strong positive NCC skew in chiseling signaled that a subset of workers, likely those with higher RHR, lower fitness, or more strenuous execution style, merit individual-level surveillance. Varnishing involved wide variation in posture and interrupted work with pauses, making it low-strain high-variable work. Among sanding and varnishing, the latter appeared to be a relatively lighter finishing task. The minor reordering of hammering and varnishing between NCC and RCC within the same Tukey group reflected activity-specific sensitivity.

The consistent rightward skew across most activities underlines a key occupational health principle, i.e., group means alone are an insufficient basis for risk management. Distribution shape, particularly the extent and weight of the upper tail, should guide intervention thresholds and work-rest ratio design.

5. Limitations of the Study

Several limitations should be acknowledged. The activity factor is treated as fixed, but several activities are heterogeneous. For example, hammering varied substantially in workpiece, hammer mass and stroke rate, contributing to the wider hammering distribution. Future work could enrich the model with task-level covariates (e.g., workpiece dimensions, tool mass) and a random slope for activity within worker, the latter requiring a denser observational schedule than the present design. Wet-bulb globe temperature as direct indices of heat stress measure is not recorded, despite its recognized influence on thermoregulatory efficiency and cardiovascular strain.

6. Conclusion

The findings of this study demonstrate that carpentry activities impose meaningfully distinct levels of cardiovascular demand, with sawing as the only task reaching the ‘action required’ zone of the proposed three-tier classification framework. This finding is biomechanically consistent with the sustained upper-body force production and awkward trunk postures. The substantial between-worker variability captured by intra-class correlation coefficients and the gap between marginal and conditional R^2 values underscores that aggregate measures alone are insufficient for risk characterization, and the skewed strain distributions further reinforce that individual-level monitoring is essential to avoid masking elevated cardiac loads in vulnerable workers. Taken together, these results support the adoption of a three-tier action-level framework with a conservative NCC threshold as a practical ergonomic decision-making tool for the informal carpentry sector, where occupational health surveillance is largely absent. Ergonomic interventions for sawing should be prioritized and may include mechanized or power saws to reduce isometric upper-body load, structured work-rest scheduling for workers approaching the heavy-work threshold (≥40%), and adjustable workbenches to minimize trunk flexion and shoulder elevation. Future replication with a larger, more geographically diverse sample encompassing a wider age range is recommended to evaluate the generalizability of the three-tier NCC classification across regions, workshop types, work practices, and in relation to heat load.

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Conflict of Interest

AC is a Vice President of SAAP from India.

Disclosure of AI Use

The AI tool Claude (Sonnet 4.6), was used during the preparation of this manuscript for the following: (i) proofreading the manuscript for grammatical and typographical errors; (ii) assisting in formulating R commands for statistical analysis, regarding model specification, fixed and random effects, checking assumptions, extracting output and post-hoc tests with pairwise comparisons. (iii) rephrasing and refining sections related to statistical inference. Other scientific content, including discussion and conclusions remain solely the work of the authors.

Authors’ Contributions

RB conceived and designed the study, RB, VS, DW, AGC and AC were responsible for data collection. RB, LC and DW were responsible for analysis, and obtaining study results. VS, LC, AGC, and AC contributed to drafting the manuscript. RB provided critical revisions to the paper. All authors contributed valuable feedback and thoroughly reviewed and approved the final manuscript version.

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