

IMPACT OF VISUAL AIDS ON POSTURE AND MUSCULOSKELETAL RISK AMONG DENTAL PRACTITIONERS: A HUMAN FACTORS APPROACH

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Work-related musculoskeletal disorders are highly prevalent among dental practitioners due to sustained static postures and limited visual accessibility. This study examined the effects of three visual aid conditions: naked eye, magnification loupes, and dental operating microscope on operator posture and musculoskeletal risk using a human-factors approach. Ninety practitioners (n = 30 per group) performed standardized clinical tasks, with posture captured using multi-angle high-resolution photography. Ergonomic risk was assessed using the Rapid Upper Limb Assessment, Rapid Entire Body Assessment, and Branson's Posture Assessment Instrument, and analyzed using one-way analysis of variance with post hoc comparisons. Significant differences were observed across all measures: RULA ($F(2,87)=49.14$, $p<0.001$), REBA ($F(2,87)=51.97$, $p<0.001$), and PAI ($F(2,87)=37.20$, $p<0.001$). The microscope condition showed the lowest ergonomic risk scores (3.10, 2.80, and 3.23, respectively) compared with the naked-eye and loupes conditions. These findings suggest that visual magnification may contribute to improved ergonomic posture, particularly in the neck and trunk regions, and may help reduce musculoskeletal risk during dental procedures.

Keywords: Visual aids; Ergonomics; Musculoskeletal Disorders; Dentistry; Human Factors

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1. INTRODUCTION AND LITERATURE REVIEW

Work-related musculoskeletal disorders (WMSDs) continue to be one of the most significant occupational health challenges in dentistry, with recent studies confirming a high prevalence linked to prolonged static postures, repetitive fine-motor tasks, and restricted visual accessibility during clinical procedures. Research published between 2020 and 2025 consistently demonstrates that dental practitioners remain vulnerable to neck, shoulder, and upper back strain due to sustained forward head posture and trunk flexion while working in confined intraoral spaces (Chauhan *et al.*, 2025; Çınar *et al.*, 2025). Previous studies have reported that approximately 64%–93% of dental practitioners experience work-related musculoskeletal disorders (WMSDs), particularly affecting the neck, shoulders, and lower back. These disorders contribute not only to physical discomfort but also to reduced productivity, fatigue, absenteeism, and, in severe cases, early retirement from clinical practice. Consequently, WMSDs remain a major occupational health concern that affects both practitioner well-being and the sustainability of dental healthcare services.

Visual accessibility has been increasingly recognized as a primary determinant of ergonomic posture in modern dental practice (Bud *et al.*, 2021). Pîrvu *et al.* (2014) reported that when clinicians lack clear visibility, whether due to insufficient magnification, improper working distance, or low illumination, they instinctively compensate by leaning forward, elevating the shoulders, or rotating the trunk to improve their field of view. Ergonomic factors have been shown to significantly influence worker performance and cognitive workload in industrial environments, highlighting the importance of human-centered workstation design (Murugesan, 2021). These compensatory behaviors have been directly correlated with increased musculoskeletal load and elevated ergonomic risk scores (Ludwig *et al.*, 2017; Pazos *et al.*, 2022). However, visual accessibility represents only one component of the broader dental work system. Ergonomic posture during dental procedures is also influenced by workstation configuration, patient positioning, operator seating, instrument placement, task duration,

and repetitive fine-motor activities. From a human-factors engineering perspective, these interacting elements collectively determine biomechanical loading and postural compensation. Therefore, the ergonomic effectiveness of visual aids should be considered within the context of the entire clinical work system rather than as an isolated intervention.

To address these limitations, visual aids such as magnification loupes and dental operating microscopes have gained increased attention in both clinical practice and research. Recent findings highlight that properly adjusted loupes can promote a more upright cervical posture, reduce neck flexion, and improve operator comfort, although the ergonomic benefits vary widely depending on device weight, declination angle, and user-specific fit (Pazos *et al.*, 2022; Hugues, 2023). In contrast, dental operating microscopes appear to offer more consistent ergonomic advantages. Controlled laboratory and clinical studies conducted between 2023 and 2024 showed significant reductions in cervical and shoulder muscle workload when operators used microscopes compared with loupes or naked-eye vision (Ludwig *et al.*, 2017). Although previous studies have demonstrated ergonomic benefits associated with magnification systems, several methodological limitations remain. Pispero *et al.* (2021) primarily focused on kinematic posture analysis and did not integrate multiple validated ergonomic assessment tools. Ludwig *et al.* (2017) evaluated muscle workload but provided limited assessment of cumulative whole-body posture risk. Similarly, Pazos *et al.* (2022) investigated the influence of loupe magnification on posture but did not directly compare loupes and microscopes within a single standardized framework. Consequently, a comprehensive understanding of how different visual aids influence overall musculoskeletal risk remains incomplete.

From a human-factors engineering perspective, visual accessibility strongly influences operator posture and biomechanical loading. When visual targets are difficult to observe, practitioners often compensate by leaning forward, increasing cervical flexion and trunk bending. Visual magnification systems may therefore influence ergonomic behavior by modifying visual accessibility and operator interaction with the dental workstation. Understanding how different magnification systems influence operator posture is therefore essential for developing evidence-based ergonomic strategies to reduce work-related musculoskeletal disorders in dental practice. This perspective aligns with Industrial Engineering principles of human-system integration, workstation design, and operator-equipment compatibility

1.1. Research Gap and Contribution

Despite increasing research on ergonomic magnification systems in dentistry, limited studies have directly compared naked-eye vision, magnification loupes, and dental operating microscopes within a single standardized human-factors framework. Furthermore, previous studies frequently relied on isolated posture measurements, muscle activity analysis, or single ergonomic assessment tools, limiting comprehensive evaluation of cumulative musculoskeletal risk. Unlike Pispero *et al.* (2021), Hong *et al.* (2024), and Pazos *et al.* (2022), the present study integrates RULA, REBA, and Branson's PAI to simultaneously assess upper-limb posture, whole-body posture, and cumulative ergonomic risk across three visual aid conditions. This integrated approach provides a more comprehensive understanding of how visual accessibility influences biomechanical loading and ergonomic performance in dental practice.

Therefore, this study aimed to evaluate the effects of naked-eye vision, magnification loupes, and dental operating microscopes on posture and musculoskeletal risk among dental practitioners using RULA, REBA, and Branson's PAI. Specifically, the study sought to determine whether significant differences existed among visual aid conditions in:

- (i) overall ergonomic posture risk,
- (ii) neck and trunk posture alignment,
- (iii) upper-limb loading involving the shoulder, arm, and wrist segments,
- and (iv) self-reported musculoskeletal discomfort patterns.

2. METHODOLOGY

This study used a human-factors approach that combined standardized posture observations, validated ergonomic assessment tools, and statistical analyses to evaluate the effects of different visual aids on posture and musculoskeletal risk among dental practitioners. A total of 90 participants were recruited, with 30 practitioners assigned to each visual aid condition (naked eye, magnification loupes, and dental operating microscope), consistent with sample sizes commonly used in recent ergonomic posture studies to allow reliable group-level comparison. The selected sample size was also considered adequate for detecting medium-to-large effect sizes in one-way ANOVA comparisons among three groups. Participants represented a range of dental specialties and clinical experience levels to enhance the generalizability of the findings. Prior to participation, all individuals received written information about the study procedures and provided informed consent, including consent for posture photography. Participation was voluntary, and participants could withdraw at any time without penalty. Individuals reporting current neck, back, or shoulder pain were excluded to minimize bias in posture evaluation, in line with standard exclusion criteria used in dental ergonomics research (Çınar *et al.*, 2025). Ethical approval for this study was obtained from the

University of Malaya Research Ethics Committee (UMREC) (Approval No. UMREC_4990, approved on 6 August 2025). All participants provided written informed consent before participation. Posture photographs were coded using participant identification numbers and stored on password-protected devices accessible only to the research team. Any identifying information was removed before analysis and reporting. Figure 1 summarizes the overall methodology flow.

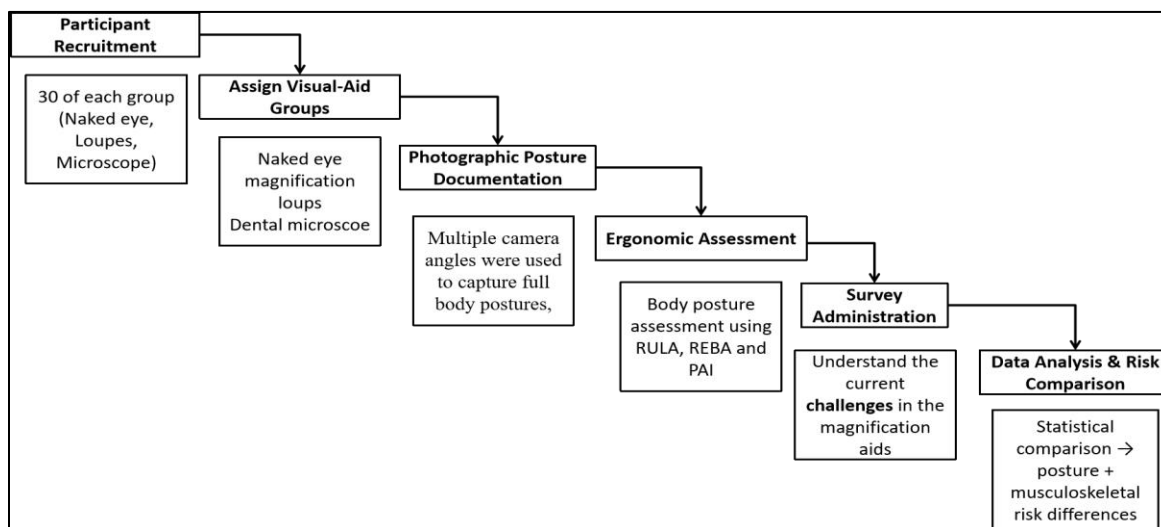


Figure 1. Methodology flowchart

Participant Allocation and Task Duration: Ninety dental practitioners were allocated into three visual aid groups ($n = 30$ per group): naked-eye vision, magnification loupes, and dental operating microscope. Participants represented a range of clinical experience levels and dental specialties. Participants were allocated to visual aid groups according to the visual aid routinely used in their clinical practice, while maintaining approximately equal group sizes ($n = 30$ per group) to facilitate comparison. Formal matching based on anthropometric characteristics, handedness, previous magnification experience, or years of clinical experience was not performed. Prior to data collection, participants assigned to loupe and microscope conditions received a familiarization session to ensure comfortable use of the equipment and reduce potential learning effects. Each participant subsequently completed the standardized clinical task under the assigned visual aid condition. Task duration was limited to 30–40 minutes per participant to reflect common periods of sustained working posture in clinical practice while ensuring consistency across all groups.

Standardized Clinical Task Protocol: All participants performed routine clinical dental procedures under real patient treatment conditions. The procedures required sustained visual focus, fine motor control, and prolonged static working postures typical of everyday dental practice. Although the specific treatment performed varied according to patient needs, all observations were conducted under normal clinical operating conditions using standard dental instruments and equipment. The procedure sequence generally involved patient positioning, clinical examination or treatment, instrumentation, visual inspection, and treatment completion. This approach was adopted to capture realistic operator posture during routine dental practice.

Workstation Setup: To maintain consistency across participants, the patient chair was positioned in a standardized treatment configuration and adjusted to provide appropriate access to the treatment area. Participants were seated on adjustable operator stools and instructed to perform the procedure using their usual working posture. Ambient lighting and dental operating light intensity were maintained consistently throughout all observations to minimize variation in visual conditions.

Visual Aid Specifications: Participants in the loupe group used commercially available dental magnification loupes routinely employed in clinical practice. Participants in the microscope group used standard dental operating microscopes available within their clinical settings. As the study aimed to evaluate posture under typical clinical working conditions, individual device specifications such as magnification level, working distance, and brand varied according to the equipment routinely used by the participating practitioners. All visual aids were used according to normal clinical practice during data collection. Typical loupe magnification ranged from $2.5\times$ to $3.5\times$, while microscope magnification ranged from approximately $4\times$ to $12\times$ depending on routine clinical settings. This approach was selected to reflect real-world clinical practice; however, variability in device specifications may have contributed to differences in ergonomic outcomes.

Standardized Posture Image Capture: To ensure consistency across participants and visual aid conditions, posture was documented using a standardized photographic protocol. High-resolution images were captured at two predefined procedural moments (initial and mid-procedure) to represent typical working posture during task performance. Photographs were obtained from sagittal, frontal, and over-the-shoulder views using a fixed tripod, with camera height, distance, and angle kept constant for all participants. This standardized setup minimized measurement variability and enabled reliable comparison of posture across visual aid conditions, as illustrated in Figure 2.



Figure 2. Multiple Angles of Full-Body Postures During Dental Procedures

A standardized scoring protocol was applied to ensure consistent and objective evaluation of all posture images. Posture assessment was conducted by the researcher using RULA, REBA, and Branson's PAI scoring procedures. Prior to formal assessment, the scoring guidelines for each instrument were reviewed and applied consistently across all posture images. Images were evaluated using the same assessment criteria and scoring procedures throughout the study to minimize scoring variability. This standardized approach was implemented to enhance consistency and reduce potential observer bias during posture evaluation.

Comparative analysis was conducted by examining differences in mean posture scores and discomfort ratings across the three groups. Higher REBA, RULA, or PAI values indicated increased musculoskeletal risk, allowing direct comparison of ergonomic burden between visual aids. Subjective discomfort responses were summarized by frequency of reported symptoms (e.g., neck, shoulder, back, eye strain), and common pain combinations were compared across groups to identify visual aids associated with greater self-reported discomfort. Findings were interpreted by mapping RULA, REBA, and PAI scores to their respective validated risk categories, allowing classification of posture risk levels and clearer comparison of ergonomic burden across visual aid conditions. In addition, statistical analysis was performed using one-way ANOVA to compare posture scores (RULA, REBA, PAI) across the three visual aid groups. Descriptive statistics (mean $\pm$ SD) were calculated for all ergonomic outcomes, and the significance level was set at $p < 0.05$. Prior to conducting ANOVA, assumptions of normality, homogeneity of variance, and independence of observations were assessed. Homogeneity of variance was evaluated using Levene's test. No substantial violations of normality, homogeneity of variance, or independence assumptions were detected. Significant ANOVA results were followed by Tukey's HSD post hoc comparisons to determine pairwise group differences. Statistical significance was established at $p < 0.05$.

3. RESULTS

Table 1 summarizes the descriptive statistics for RULA, REBA, and PAI across the three visual aid conditions.

Table 1. Descriptive statistics for RULA, REBA, and PAI across the three visual aid conditions

Outcome Measure	Naked Eye (n = 30)	Loupes (n = 30)	Microscope (n = 30)
RULA Final Score (Mean $\pm$ SD)	4.70 $\pm$ 1.00	3.98 $\pm$ 0.87	3.10 $\pm$ 0.89
REBA Final Score (Mean $\pm$ SD)	4.87 $\pm$ 1.17	3.72 $\pm$ 0.84	2.80 $\pm$ 0.45
PAI Score (Mean $\pm$ SD)	6.13 $\pm$ 1.37	4.40 $\pm$ 1.10	3.23 $\pm$ 0.77

A consistent reduction in scores was observed, where the naked-eye condition was associated with the highest ergonomic risk scores, with intermediate values observed in the loupes group and the lowest scores in the microscope group. RULA values decreased from 4.70 (SD = 1.00) using the naked eye to 3.98 (SD = 0.87) with loupes and 3.10 (SD = 0.89) with the microscope. REBA scores showed a similar pattern, declining from 4.87 (SD = 1.17) to 3.72 (SD = 0.84) and 2.80 (SD = 0.45), respectively. PAI demonstrated the steepest decline, decreasing from 6.13 (SD = 1.37) in the naked-eye condition to 4.40 (SD = 1.10) with loupes and 3.23 (SD = 0.77) with the microscope. The mean RULA score observed in the naked-eye condition (4.70) approached the action threshold where further ergonomic investigation and workplace modification are recommended. In contrast, the loupe and microscope conditions demonstrated lower risk classifications, indicating reduced ergonomic concern. Figure 3 presents the mean RULA, REBA, and PAI scores across the three visual aid conditions.

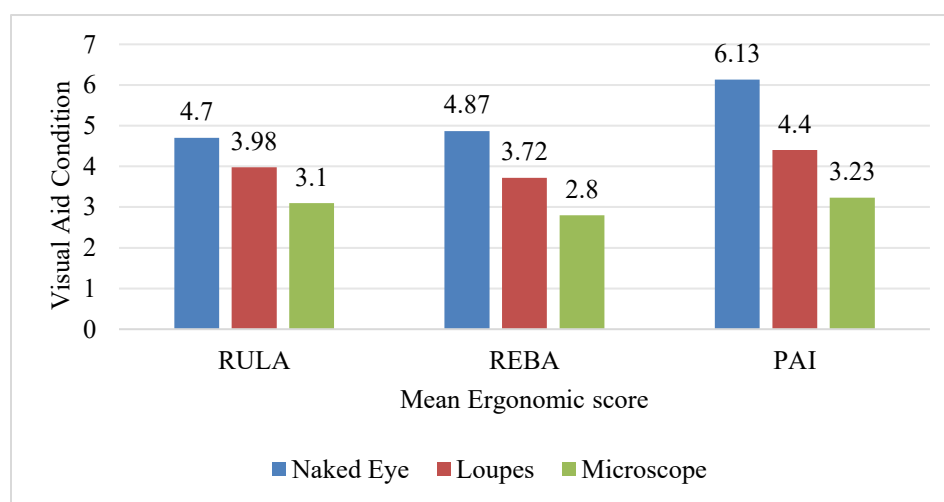


Figure 3. Comparison of Mean RULA, REBA, and PAI Scores Across Visual Aid Conditions

To further examine the biomechanical mechanisms underlying the observed reduction in aggregate RULA and REBA scores, individual joint components were analyzed separately. This joint-level evaluation provides deeper insight into which specific body segments contributed most to the overall ergonomic improvement observed with increasing magnification, as presented in Table 2.

Joint-level findings demonstrate that the reduction in global posture scores was primarily driven by substantial improvements in cervical and trunk alignment. Neck scores decreased markedly from 2.60 (naked eye) to 1.47 (microscope) in RULA, while trunk scores showed a similar reduction. REBA findings confirmed this trend, with both neck and trunk segments reaching the lowest values in the microscope group. However, improvements were not uniform across all segments. Upper arm and wrist scores demonstrated minimal reduction across visual aid conditions, suggesting persistent upper limb loading despite improved spinal posture. These findings indicate that aggregate posture scores may conceal localized biomechanical strain, particularly within upper limb segments.

The statistical outcomes presented in Table 3 indicate that posture scores differed significantly across the three visual aid conditions for all ergonomic measures. RULA scores showed a significant effect of visual aid condition, $F(2,87)=49.14$, $p<0.001$. REBA scores also differed significantly between groups, $F(2,87)=51.97$, $p<0.001$. Similarly, PAI scores varied significantly across visual aid conditions, $F(2,87)=37.20$, $p<0.001$. These findings confirm that visual aid condition was

significantly associated with ergonomic posture outcomes within the study sample. The observed effect sizes ($\eta^2 = 0.46\text{--}0.54$) indicate that the visual aid condition accounted for a substantial proportion of variance in ergonomic posture outcomes within the study sample. These effect sizes should be interpreted as measures of variance explained within the study sample and not as evidence of direct causality.

Table 2. Mean Joint-Level RULA and REBA Component Scores Across Visual Aid Conditions

Assessment Tool	Body Region	Naked Eye	Loupes	Microscope
RULA	Neck	2.60	2.00	1.47
RULA	Trunk	2.60	2.37	1.47
RULA	Upper Arm	2.60	2.40	2.00
RULA	Lower Arm	1.60	1.00	1.00
RULA	Wrist	2.00	2.00	2.00
REBA	Neck	2.00	2.00	1.47
REBA	Trunk	2.07	2.40	1.47
REBA	Legs	1.00	1.00	1.00
REBA	Upper Arm	2.07	2.40	2.00
REBA	Lower Arm	1.53	2.00	1.00

Table 3. One-Way ANOVA Results for RULA, REBA, and PAI Across Visual Aid Conditions

Outcome Measure	df Between	df Within	F-value	p-value	η^2
RULA	2	87	49.14	<0.001	0.53
REBA	2	87	51.97	<0.001	0.54
PAI Total Score	2	87	37.20	<0.001	0.46

Note: All analyses were conducted using complete data from 90 participants (n = 30 per group). No missing outcome data were observed.

Post hoc comparisons (Table 4) further clarified the relationship between the visual aid conditions. Significant differences were found in all pairwise comparisons for RULA, REBA, and PAI. The naked-eye condition consistently scored significantly higher than both loupes and the microscope, confirming the ergonomic disadvantage of unaided visual work. The largest mean differences occurred between the naked-eye and microscope groups, highlighting the considerable ergonomic benefit provided by the microscope. Furthermore, significant differences between loupes and microscope usage indicate that higher magnification yields additional ergonomic improvement beyond the benefit of loupes alone. This stepwise progression, naked eye → loupes → microscope, suggests a magnification-dependent reduction in posture-related risk.

Table 4. Post hoc pairwise comparisons for RULA, REBA, and PAI across visual aid groups

Outcome Measure	Comparison	Mean Difference	t-value	p-value	Significance
RULA	Naked vs Loupes	+0.72	2.65	0.0097	Significant
	Naked vs Microscope	+1.60	5.12	1.3×10^{-6}	Highly significant
	Loupes vs Microscope	+0.88	2.41	0.018	Significant
REBA	Naked vs Loupes	+1.06	2.96	0.0042	Significant
	Naked vs Microscope	+2.07	5.89	3.4×10^{-8}	Highly significant
	Loupes vs Microscope	+1.01	2.82	0.0060	Significant
PAI	Naked vs Loupes	+1.23	2.97	0.0043	Significant
	Naked vs Microscope	+2.40	6.15	7.6×10^{-8}	Highly significant
	Loupes vs Microscope	+1.17	4.75	1.4×10^{-5}	Highly significant

In addition to the objective posture findings, subjective discomfort patterns were also evaluated to provide complementary insight into practitioners' musculoskeletal experiences under each visual aid condition, as shown in Table 5 below.

Table 5. Distribution of self-reported discomfort by visual aid condition

Discomfort Area	Naked Eye (n=30)	Loupes (n=30)	Microscope (n=30)
Neck pain	20	22	15
Shoulder pain	10	15	18
Back pain	5	7	12
Eye strain	12	5	3

The subjective discomfort findings revealed a mixed pattern across visual aid conditions. The microscope group reported lower neck discomfort than the naked-eye and loupes groups, consistent with improved cervical posture. However, shoulder and back discomfort remained evident and were reported more frequently in the microscope group. These findings suggest that while magnification systems improve neck and trunk posture, they may not completely eliminate upper-limb and postural loading associated with prolonged clinical work. As the discomfort data were collected descriptively and were not subjected to inferential statistical testing, these findings should be interpreted with caution.

Similarly, persistent upper arm scores across all visual aid conditions corresponded with reported shoulder discomfort, indicating that magnification improves spinal posture but does not completely eliminate upper limb loading. The wrist scores remained unchanged across groups, which aligns with the relatively stable reports of wrist discomfort. This objective–subjective consistency strengthens the internal validity of the study by demonstrating that ergonomic scoring tools accurately reflect practitioners’ musculoskeletal experiences. However, it also highlights that even in the microscope condition, residual upper limb strain may remain despite improved overall posture scores.

4. DISCUSSION

The biomechanical interpretation of these findings aligns with established ergonomic theory. Working without magnification often forces clinicians to lean forward or increase cervical flexion to achieve adequate visual detail, resulting in elevated posture scores (Branson *et al.*, 2002). Magnification loupes increase the working distance and permit operators to maintain a more upright head and trunk posture. The microscope’s fixed focal distance and binocular design may encourage a more upright working posture by reducing the need for forward head displacement and excessive trunk flexion (Hong *et al.*, 2024). These mechanisms explain why PAI, which captures cumulative postural deviation across multiple segments, produces the largest effect size.

The findings support a conceptual human-factors mechanism linking visual accessibility to ergonomic risk. When visual targets are difficult to observe under naked-eye conditions, practitioners compensate by reducing their viewing distance through increased cervical flexion, trunk inclination, and forward head posture. These compensatory adjustments increase biomechanical loading on the neck and trunk, leading to higher ergonomic risk scores. Magnification systems improve visual accessibility by enlarging the visual field and increasing effective working distance, thereby reducing the need for compensatory postural adjustments. Consequently, biomechanical loading is reduced in the cervical and trunk regions, resulting in lower RULA, REBA, and PAI scores. Figure 4 illustrates the proposed human-factors mechanism underlying the relationship between visual accessibility and ergonomic risk.

Although the dental operating microscope demonstrated the lowest aggregate ergonomic risk scores, deeper analysis suggests that the observed improvements are primarily segment-specific rather than universally corrective. Joint-level findings indicate that cervical and trunk alignment improved substantially, whereas upper limb loading, particularly at the shoulder and wrist, persisted across all visual aid conditions. The findings suggest that magnification systems may reduce forward head posture and improve cervical and trunk alignment under the observed clinical conditions. These findings highlight the importance of deeper ergonomic analysis beyond overall posture scores. Although aggregate RULA and REBA scores suggest that microscope use substantially reduces ergonomic risk, joint-level evaluation reveals that certain biomechanical loads, particularly in the upper limbs, remain present. Without examining individual joint components and subjective discomfort patterns, these localized risks could remain undetected. Therefore, combining multiple ergonomic assessment methods provides a more comprehensive understanding of occupational strain in dental practice. Importantly, the findings also demonstrate that ergonomic improvements are segment-specific rather than uniform across the entire body. While visual magnification substantially reduced loading in the cervical and trunk regions, shoulder, arm, and wrist scores showed smaller improvements. This suggests that visual accessibility primarily influences posture compensation mechanisms associated with viewing behavior, whereas upper-limb loading remains strongly influenced by instrument handling, static arm positioning, and task-related requirements. These findings suggest that ergonomic improvements are not uniform across all body regions and highlight the importance of assessing individual body segments alongside overall posture scores.

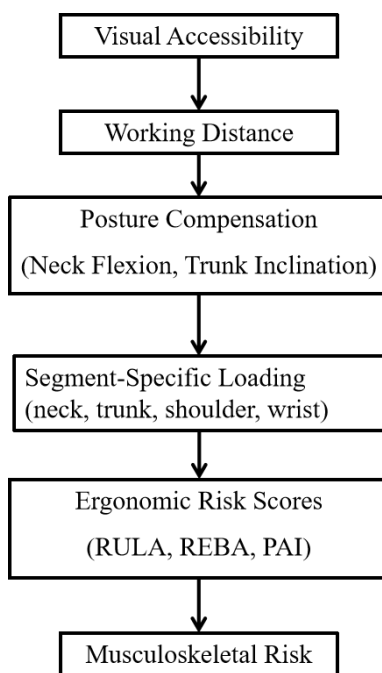


Figure 4. Proposed Human-Factors Mechanism Linking Visual Accessibility and Ergonomic Risk

While the microscope condition demonstrated the lowest overall ergonomic risk scores, it is important to consider the potential influence of operator anthropometry on postural outcomes. Variations in body height, upper limb length, and seated elbow height may potentially influence ergonomic outcomes; however, these variables were not measured in the present study and should be investigated in future research, as the ergonomic recommendations should consider anthropometric compatibility between the operator and visual aid system to ensure that magnification benefits are achieved without introducing secondary postural compensations.

The joint-level findings of this study showed that although cervical and trunk posture improved substantially with magnification, upper arm scores remained moderately elevated across all visual aid conditions. This pattern may partly reflect anthropometric mismatch between the operator and the fixed focal distance or positioning requirements of magnification devices. For example, shorter practitioners may elevate their shoulders to maintain appropriate instrument positioning, whereas taller practitioners may adjust trunk inclination depending on chair and patient positioning.

These considerations suggest that magnification alone does not guarantee optimal ergonomic alignment for all users. Instead, the ergonomic effectiveness of visual aids may depend on their compatibility with individual anthropometric characteristics. Future research should examine the interaction between operator height, working distance, and joint-level posture scores to better understand how magnification systems can be tailored to support diverse practitioner profiles. Understanding these biomechanical effects is essential for translating the findings into practical ergonomic guidance for clinical dentistry. Clinically, these results highlight the substantial ergonomic benefits of incorporating magnification, especially the dental operating microscope, into routine practice. As musculoskeletal disorders remain among the most common occupational hazards in dentistry (Aboalshamat *et al.*, 2020), adopting magnification devices may contribute to reducing long-term musculoskeletal risk when combined with appropriate ergonomic practices. The findings suggest that magnification training may be beneficial within dental education and highlight the potential value of ergonomically informed workstation design. Despite the overall ergonomic advantages observed with microscope use, the findings indicate that magnification alone does not completely eliminate musculoskeletal risk. Joint-level analysis and subjective discomfort reports revealed persistent loading in the upper limbs, particularly in the shoulder and wrist regions. Therefore, optimal ergonomic outcomes require a comprehensive approach that combines visual magnification with appropriate workstation design, adjustable seating, patient positioning, instrument organization, and ergonomic work practices.

The findings also highlight important considerations for ergonomic design in dental workstations. While magnification systems improve cervical and trunk posture, optimal ergonomic outcomes require proper integration with adjustable patient chairs, operator seating, and instrument positioning. Designing magnification devices with adjustable declination angles, lightweight frames, and appropriate working distances may further enhance ergonomic performance and reduce upper limb loading observed in this study. From a human-factors perspective, the findings suggest that visual accessibility influences

posture through a series of biomechanical and behavioral adaptations. Previous studies primarily reported posture improvements associated with magnification devices; however, the present findings suggest a broader mechanism in which visual accessibility influences working distance, posture compensation, segment-specific loading, and ultimately ergonomic risk outcomes. The proposed framework helps explain how visual technologies may influence operator behavior and musculoskeletal loading during dental procedures.

5. STRENGTHS AND LIMITATIONS

This study has several strengths, including a robust sample size ($n = 90$) and the use of three validated ergonomic assessment tools (RULA, REBA, and PAI), allowing for a comprehensive evaluation of postural risk across different visual aid conditions. Standardized clinical tasks and balanced group allocation further enhance the internal validity of the findings. However, some limitations should be noted. Posture assessment was conducted by a single evaluator, and inter-rater reliability was therefore not assessed. Because posture scoring was performed by a single trained evaluator, inter-rater reliability statistics such as the intraclass correlation coefficient (ICC) or weighted kappa could not be calculated. Future studies should include multiple evaluators to assess scoring reliability. Although a standardized scoring protocol was applied throughout the study, some degree of observer-related bias cannot be completely excluded. Also, posture was assessed from static positions, which may not fully capture dynamic movements during real procedures. Moreover, the cross-sectional design does not allow assessment of long-term ergonomic outcomes or adaptation to magnification.

Additionally, microscope use may involve a learning curve, and muscle activity was not measured. Also, participant anthropometric characteristics, handedness, and previous experience with magnification systems were not formally recorded and therefore could not be controlled during analysis. Consequently, residual between-group differences associated with these variables cannot be completely excluded. In addition, a formal *a priori* power analysis was not conducted; however, the selected sample size was consistent with previous ergonomic posture studies and was considered adequate for detecting medium-to-large group differences. Another limitation is that detailed technical specifications of the magnification devices, including magnification level, working distance, declination angle, and device model, were not standardized across participants because the study was conducted under real clinical conditions using practitioners' routinely available equipment. Future studies should control and report these variables to enable more precise evaluation of their influence on ergonomic outcomes. These factors may influence posture outcomes and warrant consideration in interpreting the findings. These strengths and limitations outline the boundaries of the current evidence and help identify key directions for future ergonomic research.

6. FUTURE RESEARCH RECOMMENDATIONS

Future studies should incorporate dynamic posture analysis (e.g., motion capture or wearable sensors) and electromyography to better quantify biomechanical load during magnified and non-magnified work. Longitudinal designs are recommended to evaluate whether sustained use of loupes or microscopes reduces the incidence of musculoskeletal disorders over time. Research focused on optimizing magnification design parameters such as declination angle, frame ergonomics, and working distance would further refine ergonomic guidelines. Combining magnification with ergonomic training or workstation redesign may also offer synergistic benefits and should be explored in future investigations. These recommendations may help guide future research on ergonomic interventions and magnification systems in dental practice.

7. CONCLUSION

This study demonstrated significant differences in ergonomic posture outcomes among dentists using naked-eye vision, magnification loupes, and dental operating microscopes. Significant differences were observed for RULA ($F(2,87)=49.14$, $p<0.001$), REBA ($F(2,87)=51.97$, $p<0.001$), and PAI ($F(2,87)=37.20$, $p<0.001$), with the microscope condition producing the lowest overall ergonomic risk scores. Improvements were most evident in neck and trunk posture, while residual shoulder, arm, wrist, and back discomfort remained present across all visual aid conditions.

These findings suggest that visual magnification may contribute to improved ergonomic posture, particularly in the neck and trunk regions; however, it should not be considered a complete solution for preventing work-related musculoskeletal disorders. The study was conducted under real clinical conditions, and device specifications were not standardized across participants, which should be considered when interpreting the findings. Future ergonomic interventions should integrate magnification systems with optimized working distance, adjustable declination angle, appropriate chair and patient positioning, anthropometric fit, and ongoing ergonomics training to achieve more comprehensive reductions in musculoskeletal risk.

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