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Authors
Doud, Winston
Habib, Ali
Gehrig, Jill
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Carpal Tunnel Syndrome and Dental Ergonomics: How Hand Health Shapes Clinical Instrumentation

Winston Doud[1], Ali Habib[2], Jill Gehrig[3], Jerica Block[4], Thair Takesh[1] and Petra Wilder-Smith[1*]

[1]Beckman Laser Institute, University of California Irvine School of Medicine, Irvine CA 92697

[2]Department of Neurology, University of California Irvine School of Medicine, Orange CA 92868

[3]Asheville-Buncombe Technical Community College, Asheville, NC 28804

[4]San Joaquin Valley College School of Dental Hygiene, Ontario, CA 91764

[*]**Corresponding author:** Petra Wilder-Smith, Professor, Director of Dentistry; Beckman Laser Institute, University of California, Irvine; 1002 Health Sciences Rd East, Irvine, CA 92617, USA

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Abstract

Objectives: Musculoskeletal disorders (MSDs) affect most dental hygienists, causing pain, fatigue, and reduced career longevity. Goal was to examine the effect of carpal tunnel syndrome (CTS) on muscle work, grip force and distribution, fatigue, discomfort, and tactile feedback during instrumentation with four curettes featuring differing ergonomic designs.

Methods: Forty hygienists - 20 without MSDs and 20 with physician-diagnosed CTS - participated in this study. Clinicians removed a standardized load of artificial calculus from 4 typodont models using four curettes (rigid stainless steel, rigid resin, rigid silicone, and adaptive silicone-overlaid stainless steel). Surface electromyography (sEMG) mapped activity in hand/forearm muscles; ultrathin pressure sensors measured thumb and forefinger grip force. Visual analogue scales recorded discomfort, fatigue, and tactile feedback. Deposit removal was assessed with Image J software.

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Results: Participants with CTS expended significantly more muscle work than healthy hygienists. Grip force and thumb: forefinger grip force ratios were greater in participants with CTS, who also reported significantly greater discomfort and fatigue. An adaptive curette design significantly improved outcomes in both groups. For all instruments, tactile feedback was significantly reduced in individuals with CTS, and the adaptive curette performed best in both groups.

Conclusions: CTS alters instrumentation biomechanics, increasing muscle work and grip force, disrupting grip balance, increasing discomfort, and accelerating fatigue. Instrument design parameters significantly affected ergonomic outcomes in all testers. Adaptive handles mitigated some of the adverse effects of MSDs, supporting their role in ergonomic instrument design and demonstrating their potential for preventing and mitigating MSD-related symptoms in dental hygienists.

Keywords
Ergonomics; Musculoskeletal disorders; Curette design; Muscle work; Grip force; Tactile feedback.

Introduction
Musculoskeletal disorders (MSDs) affect most dental clinicians, with dental hygienists experiencing the highest level of risk [1-4]. These conditions are commonly the result of repetitive strain and cumulative trauma from instrumentation that requires precise, forceful, repetitive motions, as well as awkward and static postures [2,4-15]. MSDs encompass a wide range of injuries affecting both hard and soft tissues, including carpal tunnel syndrome, tension neck syndrome, tendonitis, trapezius myalgia, and vibration-induced neuropathy [2,3,5]. The consequences of these injuries include reduced daily working hours, longer treatment durations or suboptimal outcomes, poor work satisfaction, debilitation, pain and suffering, as well as reduced career longevity.

A more comprehensive understanding of the musculoskeletal processes engaged during instrumentation by healthy clinicians, as well as the compensatory adjustments made by hygienists with MSDs, may help to identify and optimize novel preventive and coping strategies. Individual and combined variables that bear closer examination include instrument design features and technique modifications aimed at reducing muscle work; redistributing forces away from the small muscles of the fingers; reducing grip force; balancing force distribution between the thumb and forefinger; and facilitating intra-oral access by the instrument during use. Moreover, enhancing tactile feedback to ensure accurate endpoint detection during instrumentation may reduce redundant effort while improving the patient experience and outcomes.

Recent research in hygienists without MSDs has demonstrated that weight, shape, diameter, and surface properties of instruments can be optimized to reduce strain and improve comfort [16-26]. For example, a softer, thermally insulating silicone handle beneficially reduces vibrations and protects the hand from cold [27]. However, silicone can also dampen tactile feedback [28,29]. To address this limitation, some silicone-overlaid instruments now incorporate tactile sensors to enhance the clinician's ability to "feel" the tooth surface during instrumentation [28]. On another front, adaptive handle designs can reduce muscle work and fatigue while improving comfort [23,28,30]. Blade sharpness is also critical: sharper blades are more efficient at removing deposits and therefore are considered ergonomically more favorable [31-33]. Grip force is used as one measure of work during instrumentation, yet the significance of grip force distribution between the thumb and forefinger, the overall inter-relationship between grip force and MSDs, and options for potential optimization of grip-related variables remain underexplored [34-36]. In clinicians with MSDs, ergonomic designs may provide even greater benefits than in their healthy counterparts [36, 37].

Clinician posture also influences musculoskeletal health [38-40]. Suboptimal positioning of the torso, shoulders, arms, and neck - often to improve intraoral access - remains widespread and clinician posture affects musculoskeletal health [38-40]. The goal of this study was to map instrumentation-related myodynamics, fatigue and discomfort in dental hygienists with and without MSDs, and to compare outcomes from the use of 4 dental curettes with different design features in these 2 groups of clinicians. Our long-term goal is to develop a comprehensive approach to understanding the multivariate musculoskeletal kinetics that determine the ergonomic performance of dental instruments, and to translate this knowledge into better instrument design and usage. Our hope is that this knowledge will provide a sound basis for developing better approaches to protecting and maintaining the musculoskeletal health of dental clinicians.

Study Population and Methodology

Clinicians

Forty hygienists who met study inclusion/exclusion criteria participated in this study. They were recruited by word of mouth and received a $25 incentive after study completion. Twenty individuals who reported neither injuries, symptoms nor disorders of their fingers, hands, or wrists within 6 months prior to this study, nor any symptoms or diagnosis of upper-extremity MSDs constituted the healthy group (Group 1). Group 2 consisted of twenty individuals who had been diagnosed by their physician at least 1 year previously with active and ongoing carpal tunnel syndrome (CTS). These individuals reported ongoing symptoms but had not received any surgery for the condition to date.

Study inclusion criteria:

- Female
- Right-handed
- Small-to medium clinical glove size
- Practicing as a dental hygienist for at least 5 years, minimum 3 days/week

Study Protocol

This study received exempt status by the University of California Irvine IRB, as only de-identified, coded data were recorded during testing in typodont models. Because the variables that are inevitably associated with prophylaxis in live patients would introduce a considerable number of confounding factors into the study - ranging from the patient's anatomy to the level of oral deposits - this study was performed in typodont models with standardized quantities and locations of deposits. While the researchers are convinced of the need for this decision to ensure experimental rigor, they also recognize its disadvantages, and follow-up studies in live patients are under way.

Instruments Tested

Four curettes were selected:

- **Curette A:** rigid stainless-steel handle (Hu-Friedy® Nevi, USA)

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- **Curette B:** rigid resin handle (American Eagle BlackJack®, USA)
- **Curette C:** rigid silicone handle (LM ErgoSense®, Finland)
- **Curette D:** adaptive silicone-over-stainless-steel handle (ErgoFlex Elite®, USA)

Instrument properties are summarized in (**Table 1).**

Instrument	Trade name	Handle material	Handle length	Handle diameter (pen grip)	Weight
Curette A	Hu-Friedy Nevi	Stainless steel	108.7mm	9.4mm	21.1g
Curette B	American Eagle BlackJack	Resin	108.6mm	10.2mm	11.7g
Curette C	LM ErgoSense	Silicone	108.8mm	13.4mm	17.7g
Curette D	ErgoFlex Elite	Silicone-overlaid stainless steel	110.6mm	11.5mm	19.4g

Table 1: Properties of the four test instruments used in this study.

Testing setup

Each hygienist was provided with a full set of artificial teeth in a typodont model, which in turn was attached to a manikin (Acadental, Overland Park, KS, USA) mounted onto a clinical dental chair. Artificial calculus (Dental Calculus Set, Kilgore International Inc., Coldwater, MI, USA) had previously been applied by the same researcher to the 12 anterior typodont teeth using a template, to ensure identical amounts of deposits on each model. The calculus was applied 18 h before study begin, to ensure comparable levels of "set" of the artificial deposits, as the hardness of artificial calculus increases over time. All curettes were newly sharpened by the same investigator before each study arm for consistent instrument performance. Because not all testers were familiar with the adaptive curette D, a 1-minute instructional video was shown to all testers, and clinicians were given a five-minute acclimation period before study begin.

Testing procedure

Clinicians were set the task of removing supra-gingival deposits from the 12 anterior teeth using traditional scaling technique. Each participant instrumented four typodonts, one with each curette type, in randomized order (Research Randomizer, https://www.randomizer.org, accessed April–August 2025). Each instrument test consisted of four 2-minute scaling intervals separated by 30-second breaks, followed by a 30-minute rest period before the next instrument test. Deposit removal was photographed and quantified as percentage area cleaned using image analysis standard techniques and the ImageJ software (https://imagej.net/ij/, accessed April–August 2025). The instrumentation sequence with each instrument was structured as follows:

1. **Two minutes:** facial surfaces lower anteriors toward
   30s rest
2. **Two minutes:** facial surfaces lower anteriors away
   30s rest
3. **Two minutes:** lingual surfaces lower anteriors toward
   30s rest
4. **Two minutes:** lingual surfaces lower anteriors away

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30 minutes rest

During “towards” instrumentation, testers sat in the 7-9 o’clock seated position. During “away” instrumentation, testers sat in the 12 o'clock seated position.

Testers could not be blinded during the study because of the very different appearance and functionality of the curettes, but all data extraction and evaluation were performed by the same blinded, experienced, pre-standardized investigator (TT).

Surface electromyographic (sEMG) mapping of muscle work (Figure 1)

Real-time, continuous sEMG was used to measure muscle activity throughout instrumentation in four key muscles involved in dental prophylaxis:

- The Abductor Pollicis Brevis abducts the thumb and plays a crucial role in opposing the thumb, which is essential for gripping and grasping objects
- The First Dorsal Interosseous abducts the index finger from the middle finger, assists in flexing the index finger at the metacarpophalangeal joint as well as extending it at the interphalangeal joints, and contributes to thumb-index finger pinch grip and stability
- The Flexor Pollicis Longus flexes the thumb
- The Extensor Digitorum Communis straightens the fingers, allowing for motions like gripping tools and assisting in various hand and wrist movements.

The sEMG data collection process proceeded according to a standardized regimen [20,23,28,34,37]. Electric action potential signals propagated in each muscle during instrumentation were detected by strategically affixed surface electrodes. These were transmitted wirelessly via a USB-port dongle to a dedicated Dell laptop computer, on which proprietary FREEEMG® software ((FREEEMG, ©BTS Engineering, Quincy, MA, USA) had previously been installed. The placement of the sEMG electrodes on each of the 4 muscles was guided and confirmed by live muscle function tests. Next, the testers performed a 15 s maximum voluntary isometric contraction (MVC) for each muscle, and this value was used as the 100% activity threshold for that muscle to permit subsequent normalization of the test data. Finally, sEMG signals were recorded from all 4 muscles throughout instrumentation. Total muscle work was calculated from the integrated sEMG curve after the stored raw sEMG signals had been rectified and filtered using a second-order Butterworth filter with a 10 Hz high-pass cutoff frequency.

Figure 1: Tester arm with surface Electromyography (sEMG) electrodes in place.

Real-time grip force mapping (Figure 2)

Two ultra-thin-film mini-force sensors (Rp-CMk01-1, Hilitand, Wuhan City, CN) linked to a U4 microcontroller (Arduino, Monza, IT) were mounted using a thin sheath (Handix, Oslo, NO) on each hand instrument in the locations where it is gripped by the thumb and forefinger. The force sensors emitted real-time digital signals that continuously measured thumb and index finger grip force during instrumentation. Correct placement of the sensors was confirmed prior to data collection and the participants verified verbally that the equipment did not interfere with the scaling tasks.

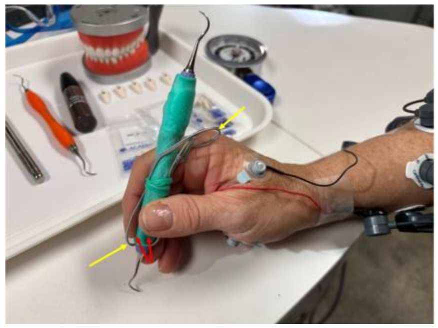

Figure 2: Tester holding test instrument with ultrathin, flexible force sensors affixed to thumb and forefinger grip zones using a thin green sheath. Sensors are not visible, but their location underneath the green sheath is indicated by red arrows. The sensors are connected by fine wires (yellow arrows) to the microcontroller. Some surface Electromyography (sEMG) electrodes and leads are visible.

Discomfort, Fatigue and Tactile Feedback

Immediately following each trial, participants completed 3 visual analogue scale (VAS) surveys. Scores were recorded separately on a paper chart. Each chart featured a line 10 cm in length, representing either discomfort, fatigue, or tactile feedback, with 0 representing the best outcome (no pain, no fatigue, optimal tactile feedback) and 10 the worst outcome. The VAS scoring process was calibrated and completed in accordance with best practices [41]. Using a clear, conversational tone the scale was explained individually to each patient by the same investigator, who used the same language from a written text before commencement of the scoring process. First, each scoring tool was introduced briefly and separately: "We're going to use a Visual Analog Scale to help you rate your discomfort/fatigue/tactile feedback."

Next, the scale anchors were defined: "You'll see a straight line on this paper. One end of the line says, 'no discomfort/no fatigue/perfect tactile feedback,' and the other end says, 'the worst discomfort/fatigue/tactile feedback imaginable. 'This line represents the entire range of possible discomfort/fatigue/tactile feedback". Next, the investigator explained the marking process: "I'd like you to place a single mark on the line at the point that best represents your current discomfort/fatigue/tactile feedback level. You can place the mark anywhere on the line, not just at the endpoints". The investigator emphasized the holistic nature of the rating: "To place your mark accurately, try to think about the full range of discomfort/fatigue/tactile feedback you've ever experienced, from none/best tactile feedback to the worst you can imagine". Once the verbal explanation was complete, the tester was guided through the physical process of using the scale. Each hygienist was given a fresh, clean copy of the VAS and a writing utensil for each scoring event. This was done to avoid visual bias from previous marks or stray

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lines. Finally, after the tester had marked the line, the distance from the "zero" end to their mark was measured in centimeters to provide a VAS score from 0 to 10. VAS instruments have longstanding validity in clinical research for quantifying subjective symptoms [42-44].

Data analysis

Data were analyzed using standard SPSS 19 software (IBM®, Armonk, NY, USA). A general linear model with pairwise comparisons assessed differences between instruments, followed by Tukey's post hoc testing. Significance was set at $p < 0.05$.

Results

All 40 participants completed the study in full compliance with the protocol. Demographic characteristics are presented in (Table 2).

Variable	Group 1 (No MSDs)	Group 2 (Carpal Tunnel Syndrome)
Gender	20 female, 0 male	20 female, 0 male
Mean age (range)	32.7 (28.1–43.8) years	39.7 (29.8–45.2) years
Race/ethnicity	1 African American, 7 Asian, 1 Hawaiian/Pacific Islander, 2 Multiracial, 9 White (4 Hispanic)	8 Asian, 3 Multiracial, 9 White (3 Hispanic)
Mean years in practice (≥3 days/week)	7 years	12 years

Table 2: Demographic characteristics of participating dental hygienists.

Deposit Removal

The area of deposit removal did not differ significantly across instruments (p>0.61), averaging 92.4% (SD 3.6%) in testers with CTS and 94.4% (S.D. 2.7%) in healthy testers. Slightly more deposits were removed by healthy testers than those with CTS (p<0.04).

Muscle work (Figure 3)

Participants with CTS required significantly (p<0.0001) more muscle work than healthy hygienists to complete each test arm. Compared to healthy controls, CTS participants expended approximately double the muscle work, regardless which curette was used.

Comprehensive results are shown in Figure 3. Testers with CTS expended significantly more muscle work when instrumenting with the rigid stainless-steel curette than the 3 other curettes (p<0.0001). Using the rigid silicone curette required significantly more work than the rigid resin (p=0.0118) and the adaptive curette (p<0.0001), and working with the rigid resin instrument was significantly more strenuous than utilizing the adaptive curette (p<0.0001). In testers with no MSDs, the amount of work expended during instrumentation did not differ significantly between the 3 rigid curettes (p>0.2596), while significantly less effort was required using the adaptive curette (p<0.0001).

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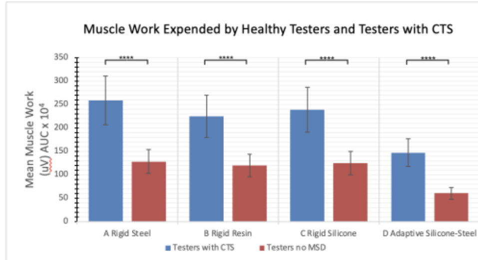

Figure 3a

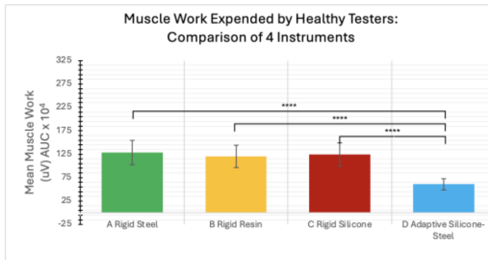

Figure 3b

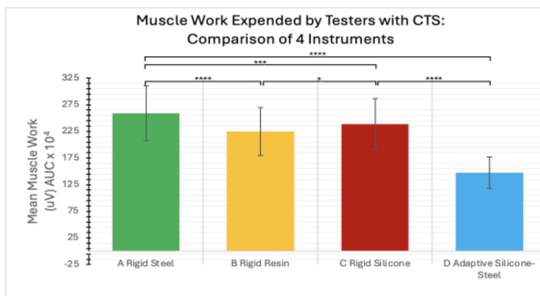

Figure 3c

Figure 3: Total muscle work expended during instrumentation. **Figure 3a** compares muscle work between testers with and without Carpal Tunnel Syndrom (CTS). **Figure 3b** compares muscle work expended in the 4 test instruments by testers with no Musculoskeletal disorders (MSDs), while **Figure 3c** compares muscle work expended in the 4 test instruments by testers with CTS. *$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$; ****$p \leq 0.0001$.

Grip Force (Figure 4 and Figure 5)

Hygienists with CTS used significantly ($p<0.0001$) stronger mean thumb and forefinger grip forces than their healthy colleagues. Thumb:forefinger grip force ratios also differed between the 2 tester groups, although they did not quite attain significance ($p=0.05842$). Healthy hygienists maintained a thumb: forefinger grip force ratio of approximately 3:1, whereas participants with CTS demonstrated a ratio of 3.4:1.

Comprehensive results are shown in (Figure 4 and 5). Testers with CTS used significantly greater thumb grip force when instrumenting with the rigid stainless-steel curette vs. the rigid resin ($p=0.0133$), the rigid silicone ($p<0.0001$) and the adaptive curette ($p<0.0001$). Moreover, thumb grip force was significantly greater when using the rigid silicone and the rigid resin vs. the adaptive curette ($p<0.0001$). Testers with no MSDs used significantly greater thumb grip force when instrumenting with the rigid stainless-steel curette than the rigid resin and the adaptive curette ($p<0.0001$). Moreover, thumb grip force was

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significantly greater using the rigid silicone vs. the rigid resin (p=0.002), and the adaptive curette (p<0.0001). Finally, a significantly greater thumb grip force was employed when working with the rigid resin instrument vs. the adaptive curette (p<0.0001). In both tester groups, forefinger grip force was greatest using the rigid stainless-steel curette (p<0.0006) and lowest using the adaptive curette (p<0.001).

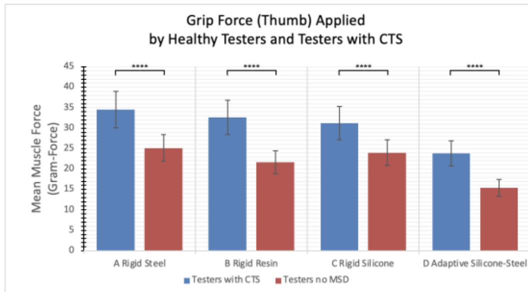

Figure 4a

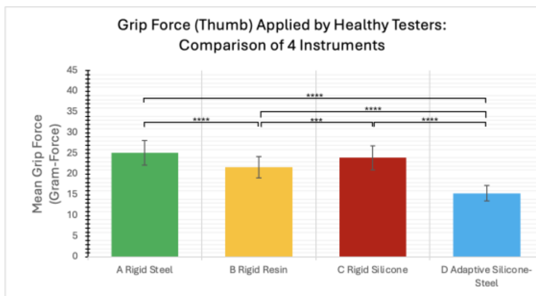

Figure 4b

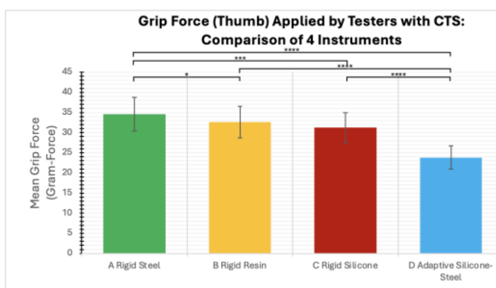

Figure 4c

Figure 4: Grip Force applied by thumb during instrumentation. Figure 4a compares thumb grip force between testers with and without Carpal Tunnel Syndrome (CTS). **Figure 4b** compares thumb grip force applied to the 4 test instruments by testers with no Musculoskeletal Disorders (MSDs), while **Figure 4c** compares thumb grip force applied to the 4 test instruments by testers with CTS. *p$\leq$0.05; **p$\leq$0.01; ***p$\leq$0.001; ****p$\leq$0.0001.

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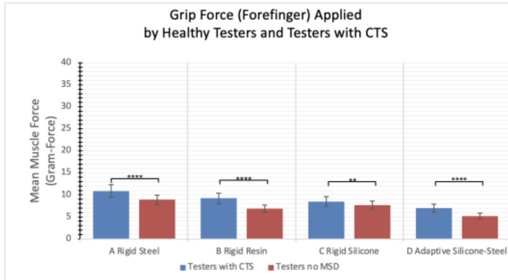

Figure 5a

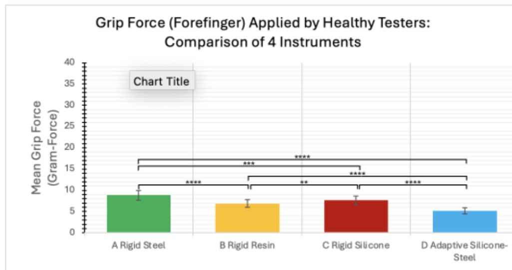

Figure 5b

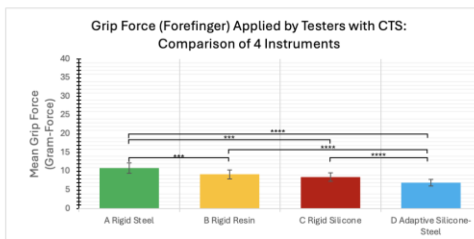

Figure 5c

Figure 5: Grip Force applied by forefinger during instrumentation. Figure 5a compares forefinger grip force between testers with and without Carpal Tunnel Syndrome (CTS). **Figure 5b** compares forefinger grip force applied to the 4 test instruments by testers with no Musculoskeletal Disorders (MSDs), while **Figure 5c** compares forefinger grip force applied to the 4 test instruments by testers with CTS. $*p \leq 0.05$; $**p \leq 0.01$; $***p \leq 0.001$; $****p \leq 0.0001$.

Discomfort, fatigue and tactile feedback (Figure 6 and 7)

Self-reported outcomes mirrored objective findings. CTS participants reported significantly greater discomfort and fatigue compared to healthy colleagues (p< 0.05). Across both groups, adaptive curettes were associated with significantly lower discomfort and fatigue than rigid curettes (p<0.05). In both groups of testers, tactile feedback was rated best for the rigid stainless steel and the adaptive curette (p<0.04).

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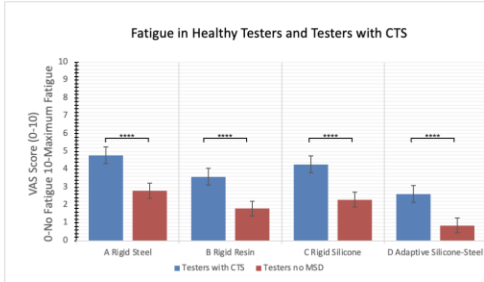

Figure 6a

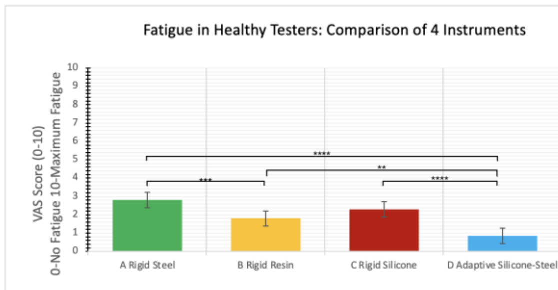

Figure 6b

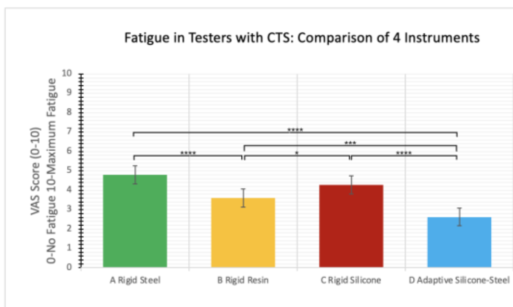

Figure 6c

Figure 6: VAS scores for instrumentation-related fatigue. Figure 6a compares fatigue between testers with and without Carpal Tunnel Syndrome (CTS). **Figure 6b** compares fatigue related to using the 4 test instruments by testers with no Musculoskeletal Disorders (MSDs), while **Figure 6c** compares fatigue related to using 4 test instruments by testers with CTS. *p<u><</u>0.05; **p<u><</u>0.01; ***p<u><</u>0.001; ****p<u><</u>0.0001.

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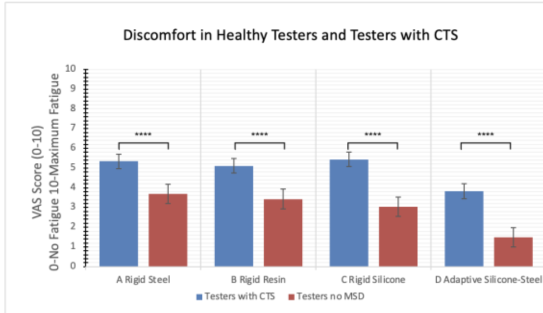

Figure 7a

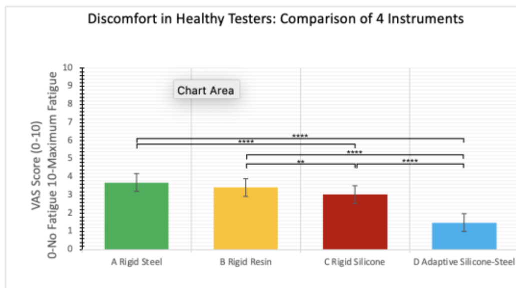

Figure 7b

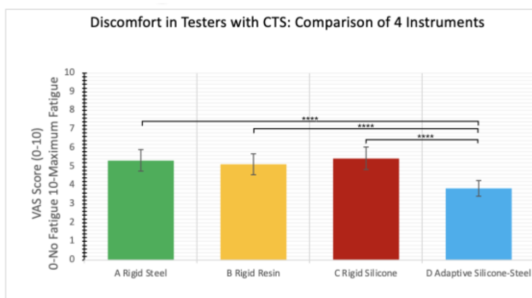

Figure 7c

Figure 7: VAS Scores for instrumentation-related discomfort. Figure 7a compares discomfort between testers with and without Carpal Tunnel Syndrome (CTS). **Figure 7b** compares discomfort related to using the 4 test instruments by testers with no Musculoskeletal Disorders (MSDs), while **Figure 7c** compares discomfort related to using 4 test instruments by testers with CTS. *$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$; ****$p \leq 0.0001$.

Discussion

This study demonstrated that carpal tunnel syndrome (CTS) significantly affects nearly every aspect of dental instrumentation. Compared with healthy hygienists, those with CTS expended greater muscle work, fatigued more severely, reported higher discomfort, and exhibited altered grip force trajectories. Although slightly less mean deposit removal was achieved in the CTS group, participants in the CTS group worked harder and experienced more discomfort and fatigue than their healthy counterparts during instrumentation.

Direct mapping of muscle work during instrumentation using sEMG techniques revealed that hygienists with CTS expended 1.4–1.6 times more muscle work than healthy hygienists when completing the same

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instrumentation task. This aligns with prior studies reporting increased muscular demand and altered muscle recruitment patterns in clinicians with MSDs [37,45].

Grip dynamics also diverged markedly between the 2 groups of testers. Healthy hygienists consistently demonstrated a thumb:forefinger grip force ratio of approximately 3:1, reflecting stable reliance on the thumb when the instrument is gripped. Surprisingly, participants with CTS manifested an increased thumb:forefinger grip force ratio of approximately [3.4:1] which seems counterintuitive. This force redistribution might perhaps represent an attempted compensatory mechanism for thumb weakness or discomfort, but may itself accelerate fatigue and pain in the muscles of the thumb. More research is needed to clarify this finding. Optimizing handle design to distribute grip force more evenly may provide benefits for mitigating this maladaptive pattern.

Previous studies have determined that many of the variables evaluated in this study are affected by the level of the clinician's experience [35,46]. For this reason, only clinicians with more than 5 years of clinical experience were included in the study. Moreover, this study included only female clinicians with small to medium glove sizes, a deliberate choice to control for variables such as gender and hand size [47,48]. Future studies should be expanded to include all hand sizes and genders.

Because muscle work and grip force can be affected by the type of scaling technique used, testers were instructed to use traditional scaling technique in this study. Again, future studies should evaluate a range of the most commonly used scaling techniques.

In this study, not all instruments had the same shape and weight, and this may have affected study outcomes [17,27,49]. A previous study reported that a round, tapered instrument handle shape evokes the smallest grip force [17], and another associated a lightweight instrument handle with the lowest grip force [49]. Moreover, handle material can affect hand comfort and strength. One study reported overall better performance by silicone handles vs. stainless steel handles in this regard [27]. However, the results of our study underline the multifactorial nature of ergonomic outcomes, with each design feature and material providing different advantages and disadvantages.

Semi-quantitatve outcomes paralleled quantifiable findings throughout the study. Participants with CTS reported significantly greater instrumentation-related discomfort and fatigue than their healthy colleagues, particularly with rigid curettes. Adaptive curettes were associated with lower discomfort and fatigue vs. rigid instruments in both groups of clinicians, supporting the results of previous studies that reported ergonomic benefits of an adaptive handle design [28,50-52]. In both groups of testers, tactile feedback was rated best for the adaptive curette, with the rigid stainless-steel instrument performing at [37,53] a similar level. Prior work suggests that silicone dampens vibrational feedback [37,53]. and indeed, in this study, testers scored tactile feedback less favorably in the solid silicone instrument than in any other curette. However, findings from this study confirm that the integration of tactile sensor technology into the adaptive curette, which features a silicone overlay over a stainless-steel core, can counter this disadvantage of silicone and enhance tactile feedback during instrumentation. Effective tactile feedback is important to avoid the clinical outcome hazards of over- or under-instrumentation, as well as unnecessary musculoskeletal work by the clinician.

This study confirmed that the ergonomic performance of dental instruments reflects a complex interplay of muscle activity, grip dynamics, tactile perception, and user comfort. The findings demonstrate that the MSD status of a clinician influences every aspect of instrumentation-related ergonomic outcomes. Because this study only investigated individuals with CTS, future investigations should address the specific effects of different MSDs in dental clinicians. Moreover, larger studies in well-controlled clinical settings using a wider range of instruments are needed.

Conclusion

Dental hygienists with carpal tunnel syndrome (CTS) exhibited altered instrumentation biomechanics and symptoms. Compared to their healthy counterparts, they expended greater muscular effort and grip force to achieve a specific clinical outcome. They also demonstrated an altered grip profile, increased discomfort, heightened fatigue, and diminished tactile sensitivity. Although these trends were consistently observed across all four curettes evaluated in this study, each instrument's unique design features influenced the extent of ergonomic stress, as reflected by specific biomechanical and symptomatic variables. Healthy testers identified similar strengths and weaknesses in each instrument as those with CTS. Adaptive handles provided some distinct ergonomic advantages over rigid designs, underscoring their role in instrument development and their potential to support the prevention and mitigation of musculoskeletal disorders.

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