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A biomechanical analysis of applied pinch force during periodontal scaling

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Abstract

One of the factors associated with the high prevalence of upper extremity musculoskeletal disorders, such as carpal tunnel syndrome, among dental practitioners is the repeated high pinch force applied during periodontal scaling. The goal of this study was to determine the relationship between the pinch force applied during periodontal scaling and the forces generated at the tip of the tool. A linear biomechanical model that incorporated tool reaction forces and a calculated safety margin was created to predict the pinch force applied by experienced and inexperienced dentists during periodontal scaling.

Six dentists and six dental students used an instrumented scaling tool while performing periodontal scaling on patients. Thumb pinch force was measured by a pressure sensor, while the forces developed at the instrument tip were measured by a six-axis load cell. A biomechanical model was used to calculate a safety factor and to predict the applied pinch force.

For experienced dentists, the model was moderately successful in predicting pinch force ($R^2 = 0.59$). For inexperienced dentists, the model failed to predict peak pinch force ($R^2 = 0.01$). The mean safety margin was higher for inexperienced (4.88 ± 1.58) than experienced (3.35 ± 0.55) dentists, suggesting that students apply excessive force during scaling.

Keywords: Pinch force; Grip force; Tool; Design; Dental

1. Introduction

Dental practitioners are at an elevated risk of developing work-related musculoskeletal disorders (MSD) because their work requires repetitive hand motions, high pinch force and sustained awkward hand postures (such as radial/ulnar deviation or flexion/extension of the wrist from its neutral position) (Lalumandier and McPhee, 2001; American Dental Association, 1997; American Academy of Orthopaedic Surgeons, 1965). A 1997 survey by the American Dental Association reported that an estimated 9% of dentists had been diagnosed with an MSD, with carpal tunnel syndrome (CTS) being the most common diagnosis (American Dental Association, 1997). The Bureau of Labor Statistics reported in 1998 that dental hygiene ranked first among all occupations in the United States in the number of CTS cases per 1000 employees (Bureau of Labor Statistics, 1998). The high pinch force applied during scaling appears to be a critical risk factor responsible for injury (Roquelaure et al., 1997). Estimates of the average pinch force exerted during periodontal scaling were between 11% and 20% of maximum pinch strength (Bramson et al., 1998). In addition, high pinch force is an important factor for localized muscle fatigue.

Periodontal scaling is a procedure used to remove deposits on teeth such as plaque and calculus. Periodontal tools typically have a stainless-steel handle approximately 100 mm in length, 7–8 mm in diameter, and at either end a 4–5 mm stainless-steel blade that is set perpendicular to the long axis of the handle. The tool is usually gripped with a chuck pinch (pad of the thumb in opposition to the pads of both the index and middle fingers) and the handle rests on the radial side of the dentist's metacarpophalangeal joint.

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Scaling is performed by pulling the tool, with the fingers, wrist or forearm or a combination of these, along the long axis of the tool handle while the blade scrapes the plaque on the surface of the tooth (see Fig. 1) (LaRoche et al., 2006). The tool blade is held parallel to the tooth surface during scraping and different surfaces of the same tooth are accessed by changing the dentist's wrist or torso posture or by changing the tool to one with a different tip.

Previous studies have estimated pinch forces required to perform hand intensive tasks, but none have created a biomechanical model to predict peak pinch force (Frederick and Armstrong, 1995; Buchholz et al., 1988; Radwin et al., 1992). Developing a model that predicts pinch force may be useful in identifying jobs that pose high risks of injury and assisting in the design of safer tools.

The purpose of this study was to determine the relationship between pinch force and tool tip force during scaling and to compare that relationship for experienced dentists and inexperienced dental students. The hypothesis was that the force at the tip of the tool is linearly related to the applied pinch force.

2. Materials and methods

2.1. Subject recruitment

Twelve dental providers (six dentists and six senior-year dental students) and 12 patients were recruited from two community clinics. Based on radiographic and clinical examinations, all patients had moderate to heavy calculus buildup.

Among the participating dentists, there were five female and one male, while there were three male and three female participants among the dental students. The average age of the dentists was 40.5 ($\pm$7.7) years and each had two or more years experience, while the dental students were 29.8 ($\pm$3.3) years old and had less than 2 years experience with periodontal scaling. The study was approved by the UCSF Committee of Human Research. Informed consent from both the dental providers and patients was obtained prior to data collection.

Fig. 1. Typical tool and hand posture during periodontal scaling.

2.2. Periodontal scaling task

All dental practitioners were asked to use a modified scaling tool (Fig. 2) to perform routine scaling of calculus buildup. The instrumented tool was composed of stainless-steel and had a grip surface machined with a diamond pattern (21 teeth per inch) texture. The tool weighed 100 g, while a typical scaling tool weighs 20–30 g. All subjects wore latex gloves and were asked to hold the tool with their usual hand posture while maintaining thumb contact with a custom-designed pressure sensor on the handle barrel (ConTacts Pressure Profile Systems, Inc., Los Angeles, CA, USA). The modified scaling tool was fitted with Gracey number 11 curette tips (Hu-Friedy, Inc., USA). Dental providers were instructed to perform scaling in their usual manner in eight areas of dentition: both the distal-lingual and mesial-facial surfaces of teeth 3, 14, 19 and 30. Typically, the tool blade edge is pulled along the axis of the tooth.

2.3. Force measurements and data collection

A six-axis load cell ($\pm$0.1 N; ATT Industrial Automaton, Apex, North Carolina, USA) recorded the forces and moments applied at the tool tip. Because we did not know whether the load cell assigned the normal contact force to F_x or F_y, we resolved the forces into a resultant total perpendicular tip force, F_t, (the tip force perpendicular to the handle of the tool) and used that value for all analyses. The force along the axis of the tool, F_z, represents the pulling (positive F_z) and pushing (negative F_z) force at the tooth–curette interface. The absolute value of F_z was used for analyses. The recorded moments were not of primary importance, but were used to verify the accuracy of forces recorded at the tip of the device.

Thumb pinch forces were measured using a pressure sensor mounted on the handle. The sensor, measuring 0.58 mm in thickness, covered approximately $\frac{1}{4}$ of the diameter of the tool and was secured in place with a thin latex sleeve. To evaluate regional sensitivity of the sensor, we applied a 2.289 kg load to the distal, middle and proximal surfaces of the sensor. The interface was a rubber tip with a shape similar to a thumb. The estimated pinch force error due to regional sensitivity of the sensor was 4.9%. The estimated mean error due to time drift, measured with the same rubber tip in the middle of the sensor, was 3.5% per 30 s.

Force–time series data were recorded separately for each of the eight areas of dentition. Before scaling each area, the user was instructed to find the most comfortable position to hold the handle of the instrument. The sensor pad was adjusted so that the pulp of the thumb was placed in the middle of the sensor pad. Baseline force measures were recorded before scaling while the thumb rested lightly on the sensor pad. The subject was then instructed to begin scaling, and approximately 1 min of the scaling process was recorded. When scaling was completed, the subject was instructed again to lightly hold the instrument while the baseline force measures were recorded once again.

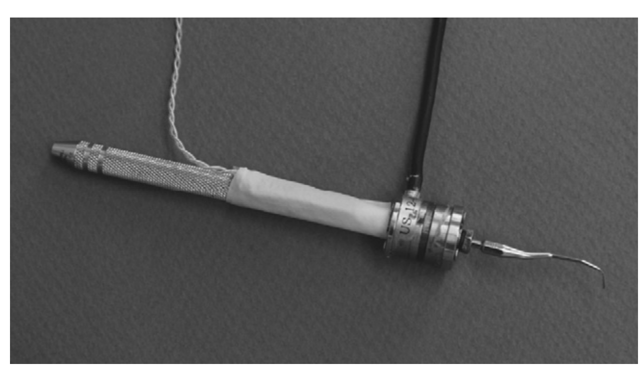


Fig. 2. Modified periodontal scaling tool. The pressure sensor is located under the thin latex sleeve and the six-axis load cell is between the handle and the tip. The cables were of sufficient length to not interfere with scaling.

Data was collected at a frequency of 100 Hz through a National Instruments data acquisition card and processed using LabView software (National Instruments Corp., Austin, TX, USA). To convert the sensor output (Volts) to force (Newtons), we calibrated the sensor by supporting the scaling tool on a load cell and pushed down with the pulp of the thumb on the pressure sensor. The pressure sensor registered the voltage while the load cell registered the corresponding force. A regression analysis was used to develop the calibration equation to convert sensor voltage to Newtons.

2.4. Biomechanical model

A biomechanical model was developed based on the typical pinch posture applied to the tool and the orientation of the tool tip relative to the tooth and fingers. Fig. 3 shows a free body diagram of the loads applied to the tool. The free body diagram is simplified to a two-dimensional model by lumping the force from the index finger (D2) and the middle finger (D3). Using the free-body diagram, we derived a relationship for the minimum pinch force required to counteract the forces created by gravity, F_t and F_z:

$$F\text{pinch min} = \left(\frac{w}{2\mu} + \frac{F_z}{2\mu} + 2F_t\right). \tag{1}$$

The first term of the equation, $w/2\mu$, is derived from the minimum pinch force required to resist the force of gravity, where w is the tool mass and μ is the coefficient of friction between the gloved fingers and the tool (Frederick and Armstrong, 1995). The second term, $F_z/2\mu$, acts along the axis of the tool and is the pinch force required to resist the force of pulling or pushing. F_z, in our case, acts in the same direction as w. The third term in the equation was derived from the free-body diagram (see Fig. 3). As the user applied pressure at the tip of the tool, F_t, a force (equal in magnitude and direction to the tip force) was generated at the metacarpophalangeal (MCP) joint. The tool, in this case, can be modeled as a lever with the forces at the opposing ends of the tool, each F_t in magnitude, and the fulcrum being the point where the pinch force is applied. Because the applied pinch force must be enough to counteract the forces applied at both the tip and the MCP joint, we get the relationship $F_{\text{pinch}} \geqslant 2F_t$. Taking all these contributions into account, we arrive at Eq. (1).

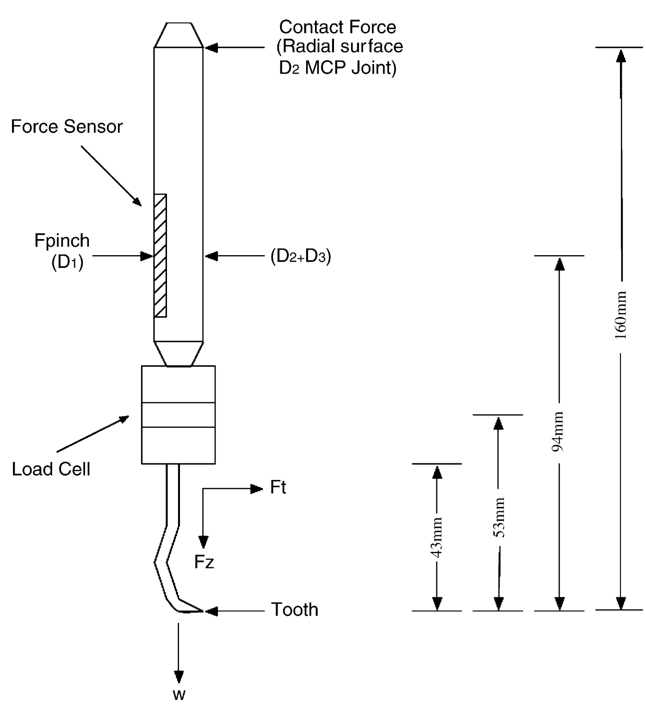


Fig. 3. Periodontal scaling tool free-body diagram with the six-axis load cell and all applicable forces. Dimensions are to scale. The forces D_1, D_2 and D_3 (thumb, first and second digit, respectively) denote the location where the user applies the pinch grip. The contact force at the MCP joint is where the end of the tool rests against the user's hand.

Eq. (1) yields the minimum pinch force required to perform the task, given the forces applied. To capture the excess force above and beyond the minimum force applied by subjects to perform this task, we introduced a safety factor, S. The expression for the pinch force now becomes:

$$F\text{pinch} = \left(\frac{w}{2\mu} + \frac{F_z}{2\mu} + 2F_t\right)S, \tag{2}$$

where $w = 0.1$ kg and $\mu = 0.5$ (LaRoche et al., 2006).

2.5. Data analysis

Mean and peak forces were estimated using amplitude probability distribution functions at the 50th (APDF50) and 90th (APDF90) percentiles, respectively (Jonsson, 1982). APDF90 estimates the force where 90% of the forces are below this value, while APDF50 estimates the median. APDF90 was used to estimate the peak force to avoid biasing these estimates by force spikes. The recorded force–time series of some tooth areas (10 of 48 for the experienced and 16 of 48 for the inexperienced) were eliminated because either the thumb was not in contact with the pressure sensor or the load cell was contacted by a tooth or the user's finger. All subjects had at least five recorded series used for analysis. Fig. 4 depicts a typical force–time series for a given subject.

Summary measures of F_{pinch}, F_z, and F_t were calculated from the force–time series for each tooth and subject using APDF90 values. The APDF90 measures for F_{pinch}, F_z, and F_t were substituted into the biomechanical model and the safety factor was calculated for each subject.

2.6. Statistical analysis

Linear regression analysis was used to determine how well the biomechanical model predicted the applied pinch force as well as evaluated the relationship between F_z and F_t. A group mean safety factor was calculated and used in subsequent models. To determine if there were any differences in the model between the two groups of subjects (experienced and inexperienced) for variables F_{pinch}, F_z, F_t and S, we used a two-tailed paired t-test with a significance level of $\alpha < 0.05$.

3. Results

3.1. Force summary measures

The experienced group applied a significantly lower peak pinch and median pinch force compared to the inexperienced group (Table 1). Peak perpendicular tip forces (F_t) were similar in magnitude to the peak axial tip forces (F_z). Surprisingly, the tip forces, F_t and F_z, did not differ between groups; therefore, the estimated safety factor for applied pinch force was greater for the inexperienced group (4.88 ± 1.58) than the experienced group (3.35 ± 0.55).

3.2. Relationship of F_t to F_z

Although the perpendicular (F_t) and axial (F_z) tip forces occur at the same point and as a result of the same action, linear regression analysis demonstrated that peak values for F_t and F_z were independent of one another for all subjects and across all teeth ($R^2 = 0.06$).

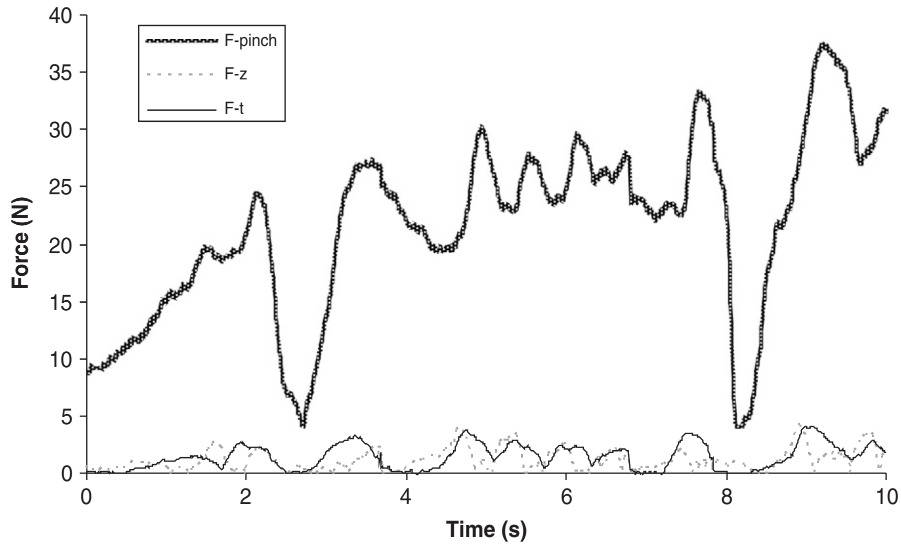


Fig. 4. Typical time-plot of force–time series during the scaling task.

Table 1
Summary measures of peak (APDF 90) and median (APDF 50) pinch and tip forces and safety margin by experience

	Experienced ($n = 6$)		Inexperienced ($n = 6$)		p-value
	Mean	SD	Mean	SD	
Peak F_{pinch}	28.28 N	4.08 N	37.22 N	5.61 N	0.01
Mean F_{pinch}	18.31 N	2.56 N	26.27 N	2.61 N	0.00
F_z	2.65 N	1.32 N	2.96 N	1.92 N	0.66
F_t	2.76 N	0.82 N	2.59 N	1.32 N	0.80
S (safety factor)	3.35	0.55	4.88	1.58	0.04

3.3. Biomechanical model accuracy

The relationship of predicted peak pinch force to actual peak pinch force is plotted in Fig. 5a and b. The model, using APDF90 values for F_z and F_t as inputs, predicted the peak pinch force moderately well for the experienced dentists ($R^2 = 0.59$), suggesting a linear relationship between the tip forces, F_z and F_t, and the applied pinch force, F_{pinch}. The model failed to predict the pinch forces for the inexperienced group ($R^2 = 0.01$).

Fig. 6a and b show the actual and predicted grip force, using the actual values of F_z and F_t from the first 10 s of the subjects' force–time series, for both an experienced and inexperienced subject. Overall, the model shows a reasonable approximation of the maximum and minimum pinch forces exerted during the task for an experienced dentist, but has difficulty predicting the pinch force for the inexperienced dental students.

4. Discussion

The study demonstrates that a linear model developed from biomechanical principles can predict pinch forces during tooth scaling for experienced dentists, but not for

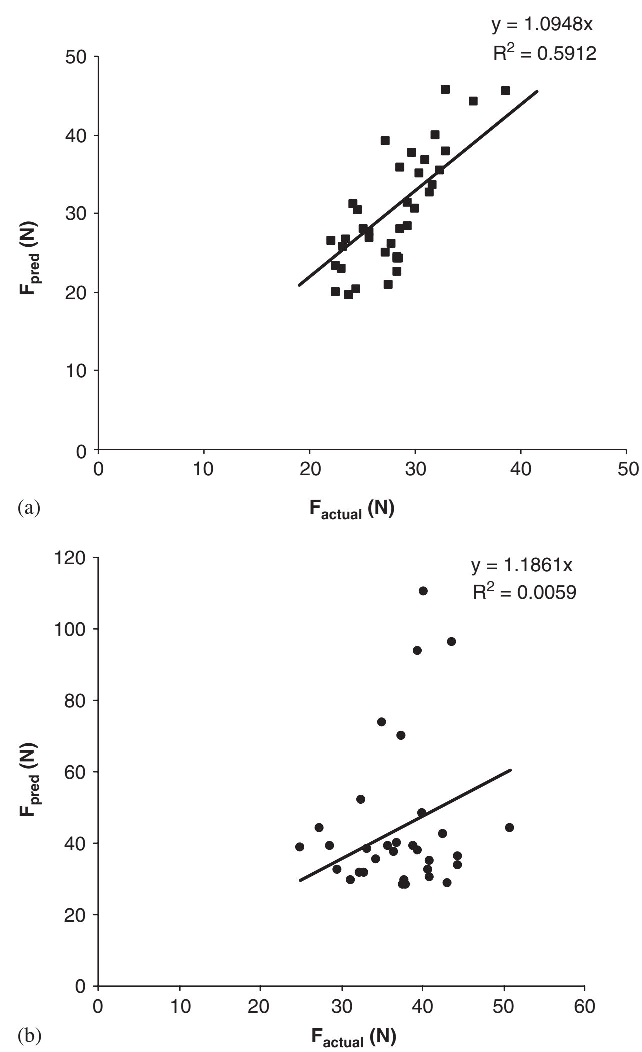
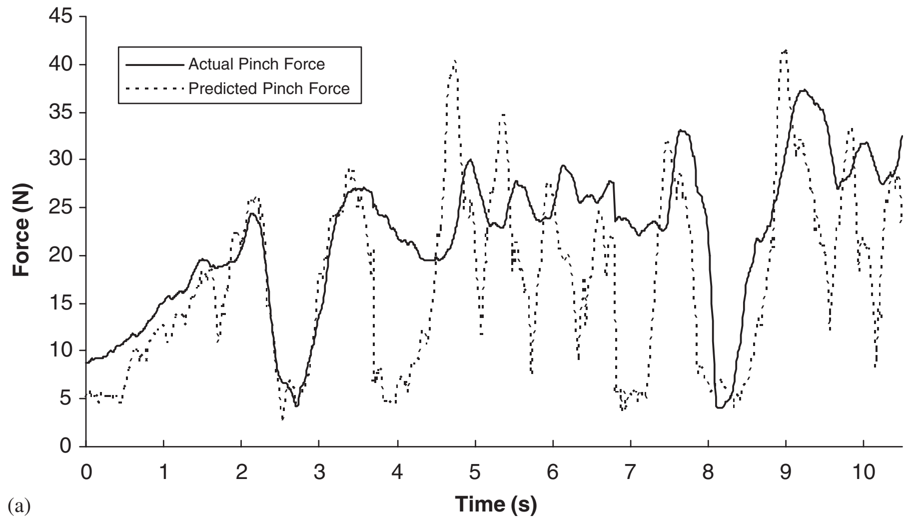
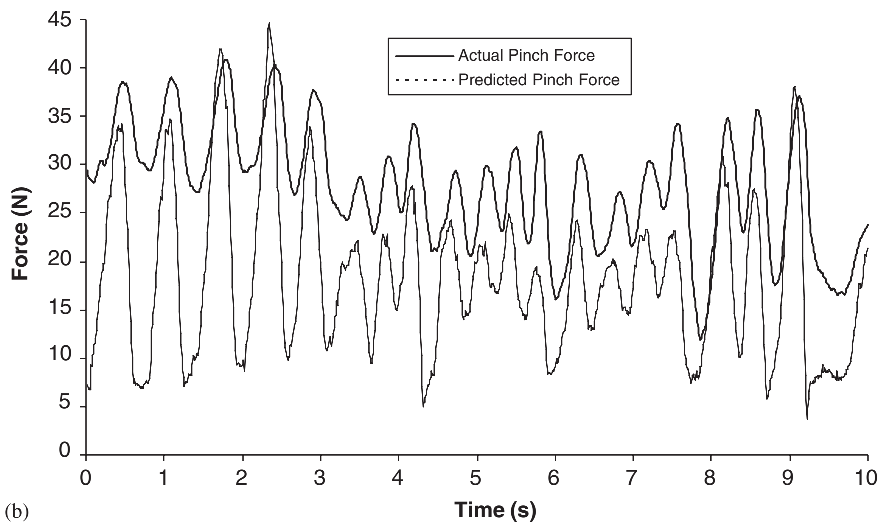


Fig. 5. Predicted vs. actual peak pinch force for experienced dentists (Fig. 5a) and inexperienced students (Fig. 5b). Predicted pinch force is based on Eq. (2), which uses APDF90 values for F_z and F_t.



(a)



(b)

Fig. 6. Predicted and actual pinch force–time series from a scaling task for an experienced (a) and an inexperienced (b) dentist. The predicted force is based on the tip forces and the model. Although there is some error in the middle portion of the sample, the model gives a reasonable approximation of the maximum and minimum pinch forces during the task for the experienced dentists, but has difficulty tracking the force changes for the inexperienced dentist.

the inexperienced dental students. This result suggests that with increased experience, the pinch forces applied during scaling are more directly related to the required tip forces. On the other hand, the elevated safety margin in dental students (4.88 vs. 3.35 in dentists) and the lack of a relationship between tip and pinch forces demonstrate wasted forces and a lack of consistent work methods for students. Of the three components of the model, the factor contributing most to pinch force is the perpendicular tip force (F_t), followed by the axial tip force (F_z) and the mass of the tool.

The model, using F_z and F_t values, was moderately successful in tracking the pinch force, as is shown by the 10-s force time-series in Fig. 6. It shows a very good relationship for the experienced subject from time 0 to 3 s and again from 7 to 10 s. In the middle portion, however, it predicts a lower pinch force. The rapid dips in the predicted pinch force occur because there are low or no forces on the tip of the tool. It is likely that the actual pinch force remains high, however, because the period of time where there are no tip forces is too short for the pinching muscles to relax. Thus, the user continues to apply a high pinch force for that time even though there are no tip forces on the tool. The graph for the inexperienced user shows a similar pattern, though much more exaggerated. The inexperienced dentist has a constant rhythm of removing and replacing the tool tip from the tooth, but they pinch the tool with more force than is necessary throughout the task.

The peak pinch forces in our study (28–37 N) exceeded those recorded in a previous study from our group (23–31 N) (Dong et al., 2006). While both studies used similar scaling tools, two differences in the methods may account for the variation in reported peak pinch forces. First, Dong et al. performed scaling on mannequin teeth using paint to mimic plaque, while our study used actual plaque on human teeth. Second, our study added a load cell to the end of the scaling tool, which increased the weight of the tool from 30 to 100 g. The higher forces applied in our study may be due to differences in the mechanical quality of plaque on real patients compared to the painted tooth surface on the mannequin or the increase in weight of the scaling tool.

Our study also found median pinch forces of 22.3 ± 4.8 N across all subjects. Previous studies assessing mean pinch force required for tooth scaling have reported values of 48 ± 24 N using electromyography to estimate force (Bramson et al., 1998). The median pinch force in our study is less than the Bramson study, however, estimating pinch force using electromyography is difficult and force may be overestimated due to cross-talk from adjacent muscles.

The safety margin of three to five that we calculated for pinch force during periodontal scaling is greater than that reported for simple tasks involving moving of objects. Other studies on pinch force safety margin showed a range of values between one and two for a load of 100 g (Johansson and Westling, 1987). In that study, subjects were instructed to resist an applied horizontal load using a pinch grip. Our subjects, however, completed a more dynamic task where the pinch grip force was used as leverage to apply the necessary tool tip forces to complete the tooth scaling. The difference in the complexity of the task is likely the reason why our safety margin was larger than previous studies.

Several limitations of our model should be considered. First, the safety factors used in the model are based on the mean value from each group. Therefore, the model fit is only determining whether the variability introduced by the three components of the model explains the variability in pinch force between subjects. Another potential limitation is the mass (100 g instead of 30 g) and bulk of the load cell, which may have required subjects to exert higher pinch forces than usual. The peak pinch forces in our study were 5–6 N greater than the peak pinch forces found in the Dong et al. (2006) study, which was similar, but did not use a load cell. Based on Eq. (2), the difference in weight between the typical 30 g tool and our 100 g tool increases pinch force between 2 and 3 N. Given the high pinch forces in our study, it is likely that the force these dentists apply during scaling (with the typical 30 g tool) would still be a cause for concern. Finally, some of the simplifying assumption in the model (e.g., force at the tool tip is equal in magnitude to the force at the MCP joint) may not always hold, in which case the model may underestimate thumb force.

In summary, our study demonstrates that in experienced dentists, the pinch force applied during periodontal scaling is linearly related to applied tip forces. Using tool weight, tip forces and tool–finger friction our model can predict pinch forces for experienced dentists but not for inexperienced dental students. Students apply excess pinch force to the tool in comparison to experienced dentists. The model can be used to investigate other tool design factors that may influence pinch force, such as tool surface friction, glove type, blade length, blade sharpness, and scaling methods. The findings and the model suggest that pinch force may be reduced with tool surface textures of higher friction, lighter tools, and sharper blades. There may also be a role for force feedback in training students learning to scale.

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