ORIGINAL ARTICLE

AJO-DO

Peak loads on teeth from a generic mouthpiece of a vibration device for accelerating tooth movement

Amin Akbari,[a] Dongcai Wang,[a] and Jie Chen[b]
Indianapolis, Ind

Introduction: The effect of vibrational force (VF) on accelerating orthodontic tooth movement depends on the ability to control the level of stimulation in terms of its peak load (PL) on the tooth. The objective of this study was to investigate the PL distribution on the teeth when a commercial VF device is used. **Methods:** Finite element models of a human dentition from cone-beam computed tomography images of an anonymous subject and a commonly used commercial VF device were created. The device consists of a mouthpiece and a VF source. The maxilla and mandible bites on the mouthpiece with the VF applied to it. Interface elements were used between the teeth and the mouthpiece, allowing relative motion at the interfaces. The finite element model was validated experimentally. Static load and VF with 2 frequencies were used, and the PL distributions were calculated. The effects of mouthpiece materials and orthodontic appliances on the PL distribution were also investigated. **Results:** The PL distribution of this kind of analyzed device is uneven under either static force or VF. Between the anterior and posterior segments, the anterior segment receives the most stimulations. The mouthpiece material affects the PL distribution. The appliance makes the PL more concentrated on the incisors. The VF frequencies tested have a negligible influence on both PL magnitude and distribution. **Conclusions:** The device analyzed delivers different levels of stimulation to the teeth in both maxilla and mandible. Changing the material property of the mouthpiece alters the PL distribution. (Am J Orthod Dentofacial Orthop 2021;■:■-■)

One of the most common concerns among patients who need orthodontic treatment is treatment duration which normally takes years.[1] The ability to accelerate orthodontic tooth movements would be beneficial to reducing treatment time and the undesired effects of prolonged treatment, such as severe root resorption, dental caries, gingival inflammation as well as decalcification.[2-6]

Orthodontic tooth movement is initiated by the stress generated in the periodontal ligament (PDL) when the orthodontic load is applied.[7] PDL is compressed on one side and stretched on the other, which leads to a change in mechanical environment (ME) in terms of stress and strain. The ME change generates mechanotransduction effects on cells, especially on the osteoclast and osteoblast,[8] that play significant roles in the tooth movement process.[9] On the tension side of PDL, osteoblasts are recruited to generate new bone, and on the compression side, osteoclasts are needed to absorb the bone, especially the hyalinization area, because of necrosis resulting from disruption of blood supplies.[10,11] These processes are called bone modeling and remodeling, which is critical for tooth movement.

Currently, methods to accelerate tooth movement in the clinic include surgery-related methods, which include alveolar corticotomy[12,13]; piezopuncture[14]; microosteoperforations[15]; osteotomies[16]; and peizocision,[17,18] gene therapy with receptor activator of the nuclear factor-kB ligand[19]; parathyroid hormone to increase alveolar bone turnover rate[20]; laser stimulation of alveolar bone remodeling[21]; pulsed electromagnetic fields[22]; and mechanical vibration.[23,24] Some of the techniques are invasive, and many have been associated with adverse side effects, such as harmful inflammatory

[a]Department of Mechanical Engineering, Indiana University Purdue University Indianapolis, Indianapolis, Ind.
[b]Department of Mechanical Engineering, and Department of Orthodontics and Oral Facial Genetics, Indiana University Purdue University Indianapolis, Indianapolis, Ind.
All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest, and none were reported.
Address correspondence to: Jie Chen, Department of Mechanical Engineering, and Department of Orthodontics and Oral Facial Genetics, Indiana University Purdue University Indianapolis, 723 W Michigan St SL260, Indianapolis, IN 46202; e-mail, jchen3@iupui.edu.
Submitted, January 2020; revised and accepted, April 2021.
0889-5406/$36.00

https://doi.org/10.1016/j.ajodo.2021.04.022

This is the author's manuscript of the article published in final edited form as:
Akbari, A., Wang, D., & Chen, J. (2022). Peak loads on teeth from a generic mouthpiece of a vibration device for accelerating tooth movement. American Journal of Orthodontics and Dentofacial Orthopedics, 162(2), 229–237. https://doi.org/10.1016/j.ajodo.2021.04.022

response and discomfort, except for the vibrational force (VF), which is noninvasive.

Animal studies have shown the stimulating effects of VF on increasing the rate of bone modeling and remodeling, which is essential for tooth movement,[23,25] and on accelerated tooth movement (ATM).[24] However, this technology has inconsistent outcomes in human studies.[26-35] The reason needs to be understood for effective clinical use of the technology.

The VF has an ATM effect only if the tooth senses the stimulation with a certain level of intensity. The intensity, called dose, can be represented by the peak load (PL) of the VF because it directly affects the stress in the PDL and bone in which the cells reside. Thus, PL is considered as one of the dominant factors. The dose typically is within a range—either underdose or overdose results in no ATM. The animal studies have more consistent results than clinical studies because the dose is better controlled. The VF is directly applied to the tooth with known VF intensity in terms of its PL.[23,24] However, the clinical studies commonly used a device that consists of a mouthpiece and a vibrational source. The VF is delivered to the teeth through the mouthpiece. When biting on the mouthpiece, it forms a static indeterminate system, which increases the level of difficulty to determine the PL distribution. Currently, the level of stimulation on the individual tooth in clinical studies is unknown and is not controllable. To have consistent clinical results, the PL needs to be quantified and controlled so that the right dose can be guaranteed.

This study aimed to quantify the PL distribution among the teeth when a commercial VF device is used. The objectives of this study are to (1) show the PL applied on the individual tooth in a dentition by a generic VF device commonly used clinically, (2) demonstrate the effects of device material on the distribution, and (3) illustrate the effects of 2 VF frequencies used in the commercial products on the PL distribution.

Q5 MATERIAL AND METHODS

A VF device similar to commonly used commercial products was modeled for this study. This device commonly consists of a vibratory source and a U shape tray (mouthpiece).[29,32] The mouthpiece had generic upper and lower surfaces interacting with the teeth. The vibratory source vibrates the mouthpiece in the vertical directions, and the VF is distributed among the teeth in the maxillary and mandibular arches. The entire process was simulated using the finite element (FE) method.

The FE models consist of the maxillary and mandibular teeth with surrounding tissues and the vibrational device. The mouthpiece was created using computer-aided design software (Creo Parametric 2.0; Parametric Technology Corporation, Needham, Mass). Q6 The maxillary and mandibular teeth and the surrounding alveolar bone and PDL were obtained from cone-beam computed tomography (CBCT) scans from an anonymous volunteer. The purpose was to ensure that the teeth are in the correct locations in the arches. All teeth were segmented from the image using Mimics (Materialise, Leuven, Belgium). Because of CBCT's low resolution, the PDL was not reliably identifiable. Thus, the PDL and surrounding cortical bone were built by offsetting the root surface with 0.25 mm for the PDL.[9,36] After segmentation, the polylines of the teeth were exported to Creo to reconstruct the geometry (Fig 1, *A*). To study [F1] the effect of the appliance on the PL distribution, brackets (0.022 × 0.028-in) and an archwire (0.022 × 0.028-in) were attached to the teeth (Fig 1, *B*). The teeth were assembled digitally to the mouthpiece model. To simulate ideal occlusion, the teeth were adjusted vertically to ensure contact with the mouthpiece. The assembly was then imported to Ansys workbench 2019 R1 (Ansys, Canonsburg, Pa), FE analysis software, for creating the FE model (Fig 1). A global coordinate system was created, which is defined by the frontal y-z, sagittal x-z, and transverse x-y planes. The directions of the 3 axes are shown in Figure 1.

The upper surface of the maxilla and bottom surface of the mandible were fixed (Fig 1). The dentition and mouthpiece were meshed using 10-node tetrahedral elements. Interface elements were created at the interfaces between the teeth and the mouthpiece and between the archwire and the brackets, which allow the teeth to slide on the mouthpiece's surfaces and relative motion between the wire and the bracket surfaces. The friction coefficient was set at 0.05, simulating the lubricating effects of saliva. There were no initial gaps at the tooth-mouthpiece interfaces, simulating an ideal biting condition.

Both static and dynamic (vibrational) loading were simulated. The magnitude of the static load and the PL of the dynamic loading was 0.3 N. The static load was applied downward in the negative z-direction. In the dynamic loading cases, 2 frequencies of 30 Hz and 120 Hz used in the commercial products were applied respectively to study the effects of frequency on the distributed PL. The application point of both static and dynamic forces is close to the mass center of the vibrational source. The following cases were analyzed: for the study of the PL distribution, models with or without appliances for the mouthpieces made of either acrylonitrile butadiene styrene (ABS) + polycarbonate (PC) plastics (heat resistant 3-dimensional printing material) or silicone were created because their properties are close to the commercial products. Either static or VF forces were

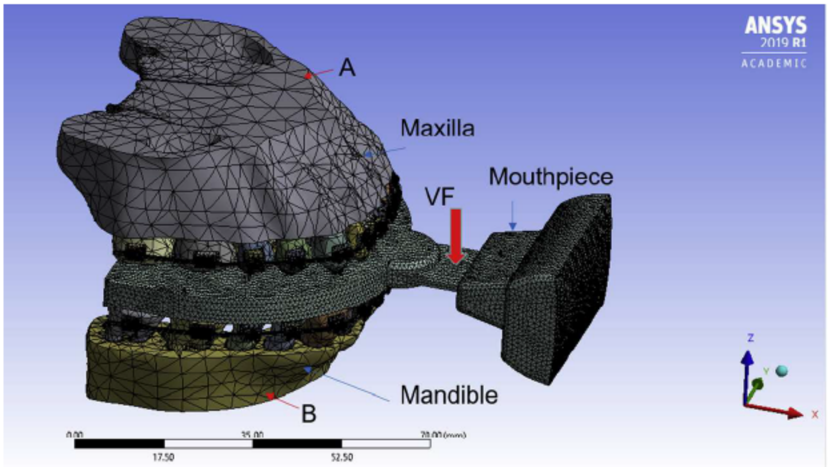

Fig 1. FE model of the assembly with the applied VF and boundary conditions. The surfaces **(A)** and **(B)** are fixed. A vibration force is applied to the mouthpiece.

applied. In addition, for the study of the effects of material property, a model with a mouthpiece made of structural steel was added. Typically, the mouthpiece is made of material similar to silicone rubber and plastics. However, other biocompatible materials may also be used. Adding structural steel helps illustrate the effect of stiffer material on the PL distribution.

The materials involved were considered isotropic and elastic. Material properties used in the models are shown in the Table.[37-39] [T1]

The element size of the FE model was determined through a convergence test. The same model with different element sizes was analyzed. The convergence tests were performed by reducing the element size from 1.2 mm to 0.6 mm with an increment of 0.1 mm under the same loading and boundary conditions. The stress variations were assessed. The model is considered to converge if the variation is <5% of the stress value. Results showed that the stress converged when the number of elements reached 554,145, which was used for our analysis.

The FE model was validated experimentally. A 3-dimensional printed ABS + PC Plastic denture and mouthpiece were assembled. The PL distribution relies primarily on the model and boundary conditions. Because of the resolution of the load cells, a larger force would provide more accurate force readings. Therefore, for this validation, a 2 N static force was applied to the mouthpiece, and reactions on a central incisor and second molar on both arches would be measured (Fig 2). [F2] For the maxillary or mandibular arches, a central incisor and a second molar were separated from the denture and were connected to 2 load cells (Multiaxis force/torque Nano17; ATI Industrial Automation, Apex, NC), respectively (Fig 2). When the force was applied, the reactions on the teeth were measured by the load cells, which could simultaneously measure 3 force and 3-moment components. For comparison purposes, the FE model of the experimental setup was created. The agreement of experimentally measured reaction forces with these from the FE model validates the modeling method.

RESULTS

Experimental results were compared with the results obtained from the FE analysis. Figure 3 illustrates force [F3] distribution over the teeth from FE analysis and reaction forces of central incisor and second molar in the maxilla and mandibular measured from the experiments. The distribution from the experiments was coincident with their corresponding FE results, which validated the FE model.

The reaction distributions from the models of the mouthpiece made of silicone with or without the appliance because of a 0.30 N static force on the mouthpiece are shown in Figure 4. [F4] A downward static force results in a major compression on the anterior teeth of the mandible and relatively high reactions at the maxillary molars because of bending of the mouthpiece. The reaction distribution depends on the stiffness of the mouthpiece, see Figure 5. [F5] In both cases, the highest forces were on the anterior teeth. The maximum force (0.085 N or 19.77%) and the static force (0.070 N or 15.68%) occurred on the mandibular central incisor for the model without and with the appliance, respectively (Figs 4, *C* and *D*). The second molar received the highest forces on the maxilla, which are much lower than on the mandibular incisors. The force varied significantly among

Table. Material properties used in the models

Material	*Young's modulus (MPa)*	*Poisson's ratio*	*Reference*
Tooth	20,000	0.2	Yadav et al[35]
Bone	2000	0.3	Yadav et al[35]
PDL	0.47	0.45	Hedayati and Shomali[36]
Silicone rubber	190	0.495	Qian et al[9]
ABS + PC plastic	2510	0.398	Ansys database
Structural steel	200,000	0.3	Ansys database

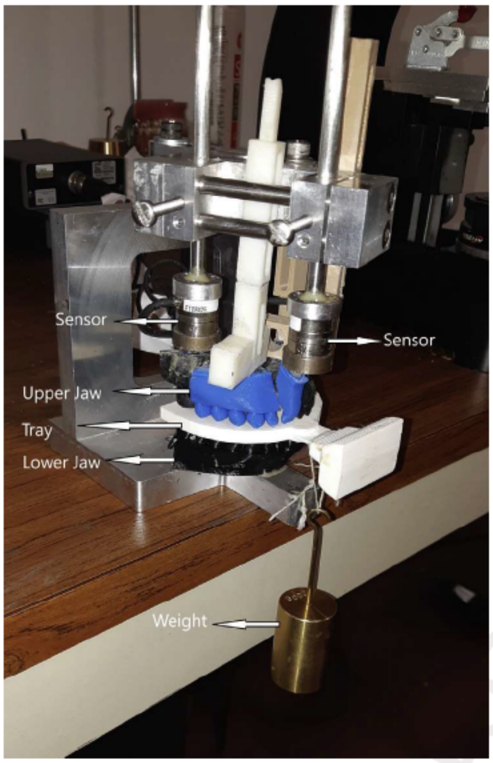

Fig 2. The laboratory setting for measuring reaction forces on the central incisor and second molar in response to the applied 2 N force on the mouthpiece for validating the results from the finite element analysis.

the teeth in both mandible and maxilla. The reaction distributions from the models of the mouthpiece made of ABS + PC plastic show a similar trend. With the stiffer material, the forces on the anterior teeth became more evenly distributed. Adding an appliance also made the force more concentrated to the central incisor. The force distributions of the 2 cases with or without appliances are similar; thus, only the forces from the model without appliances were presented in the following analyses.

Mouthpieces with 3 different materials, silicone, ABS + PC plastic, and structural steel, were modeled. The resulting distributions of the reaction forces are shown in Figure 5. Changing the material altered the location of the peak forces slightly. Both ABS + PC plastic and the steel resulted in more even distributed forces on the anterior teeth, although their Young's modulus is very different, whereas the softer material, such as silicone rubber, caused more concentrated forces on the central incisors. Both ABS + PC and steel cases generated high forces on the second molars on the maxillary teeth.

A VF with a PL of 0.30 N was applied to the FE models with the mouthpiece made of ABS + PC and silicone rubber. Two different frequencies of 30 Hz and 120 Hz were analyzed. The PLs on the teeth are shown in Figure 6. The distributions and magnitudes from the ABS + PC mouthpiece models were remarkably similar for 30 Hz and 120 Hz frequencies. The maximum PLs were about 0.04 N. For the silicone material, the 120 Hz resulted in a higher PL (0.08 N) than 30 Hz (0.06 N), although the distributions are similar. The molars, in general, received a much lower level of stimulation than the anterior teeth.

DISCUSSION

ATM due to VF can only be initiated if the tooth is stimulated, meaning that the PL on the tooth needs to be within a favorable range, called dose. This is necessary but may not be sufficient because other factors may be needed. Understanding the PL distributions among the teeth in the arches is necessary for treatment planning, and the ability to manipulate the PL on an individual tooth is critical to effectively achieve ATM on the target teeth. The results also help understand why inconsistency of clinical outcomes[29,32-35,40] occurs. This study demonstrates the PL distributions associated with the type of VF devices available commercially.

The VF is transmitted to the teeth by the mouthpiece. The force on an individual tooth is affected by whether the appliance is applied. The level of effect was assessed. From the models of ABS + PC and silicone, with the appliance, the forces are more concentrated on the incisors than without appliance cases. Because of this, the central incisors receive a slightly higher force with the appliance. The distributions of the forces are similar. Although we only analyzed 1 type of appliance, the results indicate that adding an appliance does not significantly alter the force distribution pattern.

Our results show that the commercial device cannot guarantee delivery of VF on the entire dentition. The reaction force distribution on the teeth under the 0.3 N static force was not even (Fig 4, C). With the silicone rubber as the mouthpiece material used by most commercial

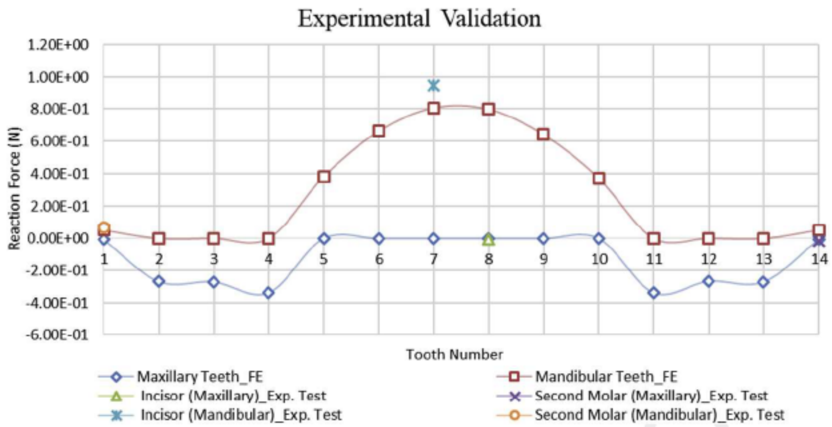

Fig 3. Comparison between results of FE analysis and experimental test in terms of reaction force.
Q17 Teeth 1 and 14 correspond to second molars, whereas teeth 7 and 8 are the 2 central incisors.

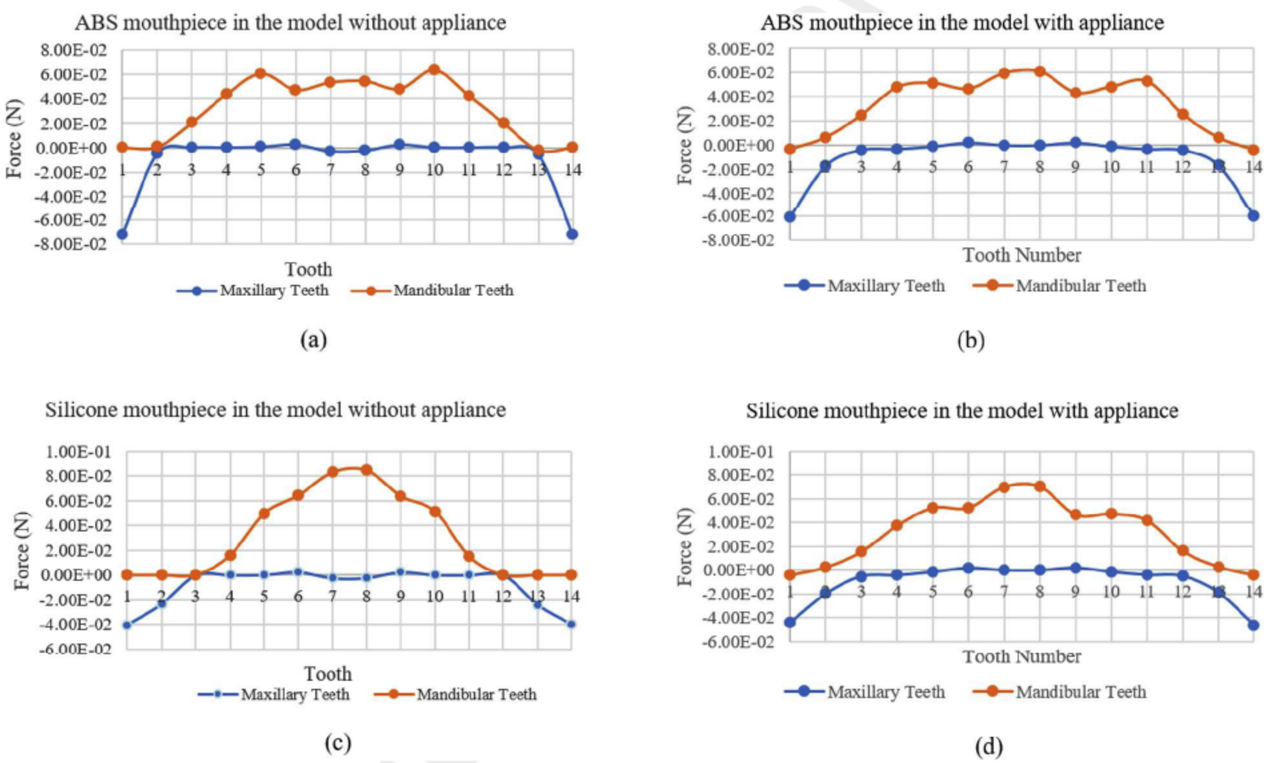

Fig 4. Load distributions on the teeth by using a mouthpiece made of silicone and ABS + PC mouth-
Q18 piece under a static force with and without an appliance.

products, under the static load, the anterior segment, including the mandibular incisors, receives a much higher reaction force than the posterior teeth. The molars, on average, received much lower force than the force on the incisors, which is attributed to the bending of the mouthpiece. A large portion of the force is supported by the anterior mandibular teeth as they are closer to the applied force. The maximum force was at the central incisors, 0.08 N. Among the maxillary teeth, the posterior teeth received higher forces. The second molar from the no appliance case received the highest force of 0.04 N, which is only about 50% of the force on the mandibular central incisors.

Materials of the mouthpiece affect both force magnitude and distribution. The material with lower Young's modulus, like silicone rubber, resulted in the highest

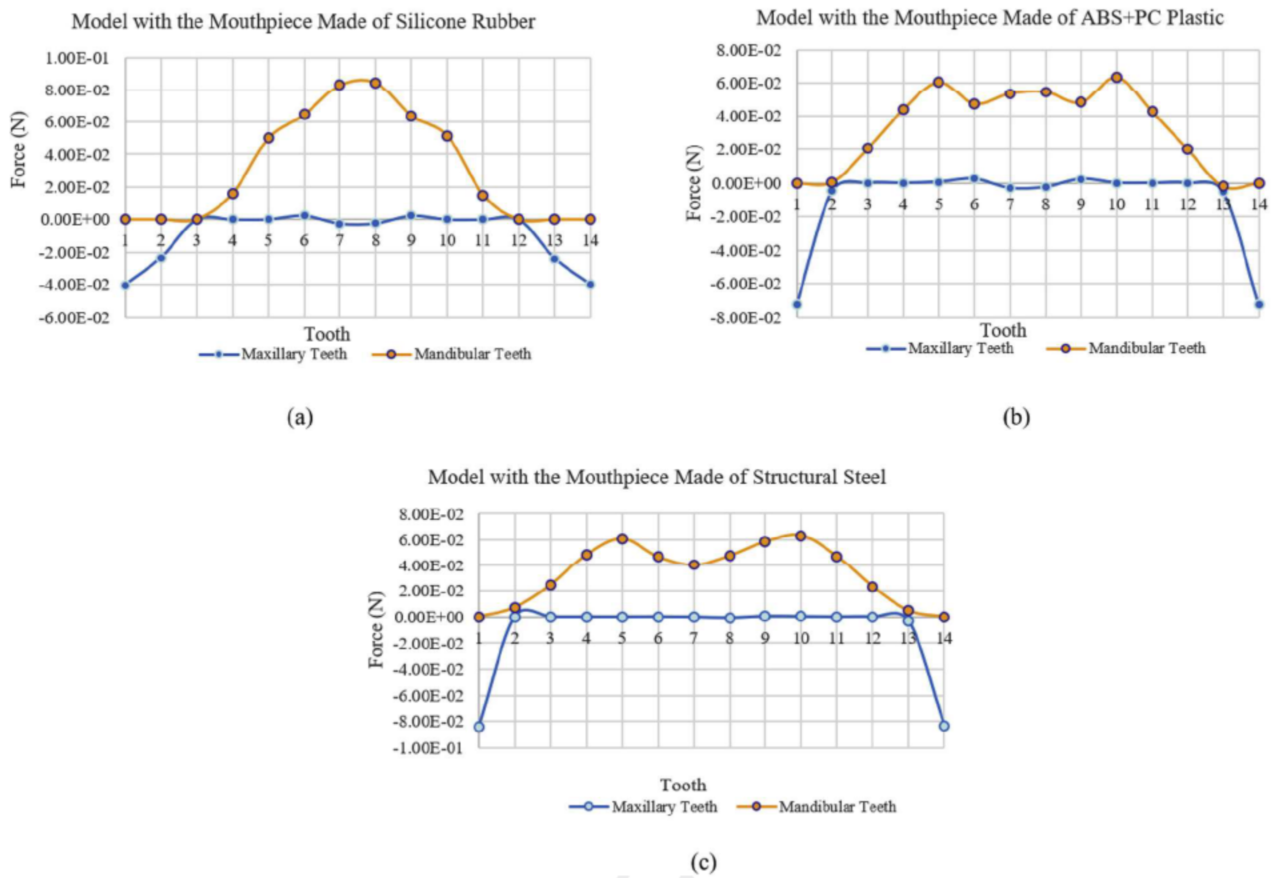

Fig 5. Effect of mouthpiece material on the distributed reaction forces: **A,** silicone; **B,** ABS + PC plastic; **C,** structural steel.

force being applied on the mandibular central incisor, whereas the material with higher Young's modulus, like ABS + PC and steel, shifted the highest force to the mandibular canine. The silicone case has a bell-shaped force distribution on mandibular teeth. As Young's modulus increases and exceeds ABS + PC, the forces are more evenly distributed among the anterior teeth. Among the 3 materials, the silicone rubber, which has the lowest Young's modulus, has the highest reaction force of 0.08 N on the mandibular central incisor, whereas the steel and ABS + PC, which has the higher Young's modulus, have the maximum reaction force on the mandibular canine with the magnitude of 0.06 N (Fig 4). Although Young's modulus of steel is much higher than ABS + PC plastic, the distribution patterns remain the same (Fig 4). Thus, the location of the highest reaction force depends on the material property of the mouthpiece (Fig 5). However, the effects become negligible if stiffer material than ABS + PC plastic is used for the mouthpiece.

Commercial devices were operated at a dynamic load. Instead of calculating reaction force for a static load, the PL is used to characterize VF. When a VF is applied, the PL on each tooth in the maxilla and mandible becomes symmetrical to the transverse plane because the VF changes directions. Thus, for each tooth, its PL is the maximum force during the full stimulating cycle. The PL on individual tooth varies significantly. The anterior segment receives more stimulation than the posterior segment, meaning only a small portion of the VF can be transmitted to most posterior teeth (Fig 6). Thus, a lower level of ATM can be expected.

Two frequencies are being used by different companies; 30 Hz and 120 Hz. Both magnitudes and distributions of the PL corresponding to the 2 frequencies were similar, meaning that the frequencies at these levels have minimum impacts on the level of stimulation (Fig 6).

The PL needs to be in an effective range to cause ATM. Either understimulation or overstimulation may

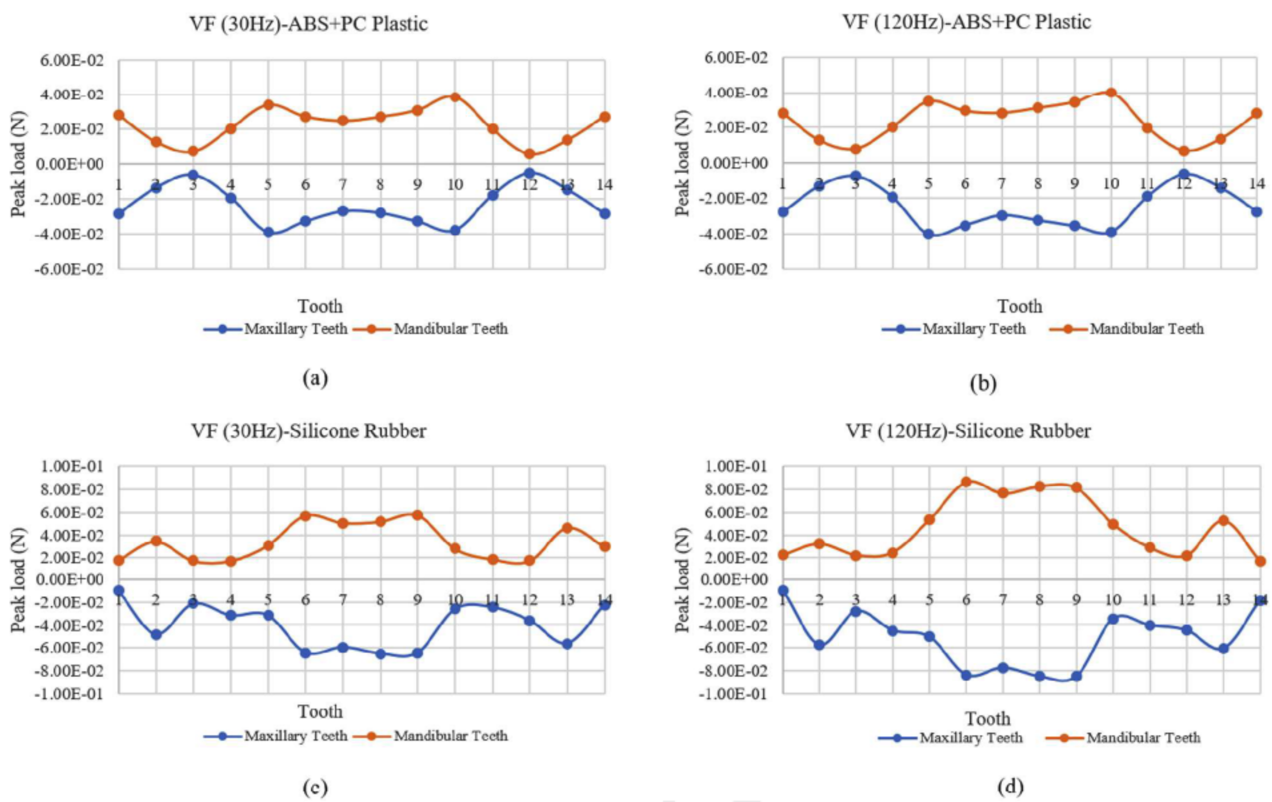

Fig 6. Effect of frequencies on load distribution on a mouthpiece made of silicone and ABS + PC plastic in response to 2 VF frequencies, 30 Hz and 120 Hz.

result in adverse effects. This study quantified the PL on the individual tooth when a commercial VF device is used. The results clearly demonstrated that the associated PL distribution is uneven. Furthermore, the simulated teeth-device system was under an ideal condition, which enabled perfect tooth-mouthpiece contacts. However, in the clinic, the patients' crown profiles are most likely to be uneven, meaning that some teeth may not be in contact with the mouthpiece initially. These teeth will receive less VF, which will change the PL distribution. Therefore, when a similar commercial VF device was used in the previous clinical studies,[26,27,29,30,32,40] the level of PL on the individual tooth might vary drastically because of the mouthpiece design and initial contact conditions between the tooth and mouthpiece. For example, for the alignment case,[32] only the incisors might receive relatively high PL, whereas for space closure cases,[26,27,29] the canine might not be able to receive the desired PL, see Figure 6, *C* and *D*. In addition, the level of initial alignment might also be a factor because it determined the initial contact conditions between the mouthpiece and the teeth. The uncertainty of the levels of stimulation on the teeth certainly contributes to the inconsistency of the clinical outcomes.

This study shows the PL distribution on teeth in an ideal occlusal condition with the mouthpiece. Simplification was made on PDL width because of the low resolution of the CBCT scan. However, this will not affect the conclusion for the following reason. PDL is a layer of soft tissue between the root and the bone. Its stiffness is only less than 0.02% of the neighboring tissues, see the Table. The variation in thickness has insignificant effects on the force experienced by the tooth.

Future study on the biological response to the VF technology requires knowledge of the ME changes in the PDL and alveolar bone, which can be done using the FE models developed in this study. This is not a clinical study. The purpose is to qualitatively determine the PL distribution when teeth are in their anatomic positions. However, the method can be used for clinical studies.

CONCLUSIONS

1. The commercial VF device design results in an uneven PL distribution among the teeth in both maxilla and mandible.

2. The major portion of the stimulation is applied to the anterior segment.
3. The distribution of the PL depends on the material properties of the mouthpiece.
4. The vibrational frequencies of 30 Hz and 120 Hz have a negligible influence on the magnitude and distribution of the PL.
5. The kind of commercial VF devices analyzed does not guarantee the right stimulation on the teeth.

AUTHOR CREDIT STATEMENT

Jie Chen contributed to conceptualization, methodology, supervision, and reviewing and editing manuscript; Amin Akbari contributed to methodology, original draft preparation, validation, formal analysis, and visualization; Dongcai Wang contributed to model development and analysis.

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