INTRODUCTION

Dental plaque is the leading cause of periodontal diseases and dental caries (Organization, 2017). Dental plaque deposits in the form of a thin biofilm (microbial community organized with a specific structure and function) (Marsh, 2006) usually exhibiting itself on the tooth surface initially as a colourless deposit and form tartar progressively (pale yellow or brown layer) (Darby & Walsh, 2010; Summitt, 2006). The oral biofilm (starting in the sub- or supragingival area) houses a plethora of bacteria, majorly constituting Streptococcus mutants (S mutants) and other anaerobes (Chetruş & Ion, 2013; Kolenbrander, 2000). The build-up of plaque causes severe consequences to oral health like resulting in gingivitis (inflammation of gingival tissue) (Armitage, 1999), which might progress onto periodontitis (infection of the gums) (Noble, 2012). Eventually, it leads to bone destruction in that area (Tonetti et al., 2015). More than half of the adults in the U.S. suffer from gum diseases, with 47.2% having periodontal disease (Prevention, 2013). The biofilm needs to be periodically removed using a toothbrush, which is the most effective dental device.
for removing dental plaque (Rosema et al., 2011). 23% of Americans skip brushing their teeth more significantly than 2 days, with 37% of adults between 18 and 24 (O’Keefe, 2018). Poor oral health care can act as a symptom or a cause for various ailments affecting other parts of the body, like the link between diabetes and periodontitis. It is also linked to other diseases affecting the cardiovascular system (Herzberg & Meyer, 1998); oral infections may cause bacterial endocarditis and may increase pulmonary infection risk in susceptible patients (Fenton et al., 2003).

Due to manual toothbrushes’ limitations, the electric or power toothbrushes were designed with various technologically advanced movements like side to side, circular, rotational oscillation, counter oscillation, ultrasonic vibration, and sonic action to improve oral hygiene and health care (Terezhalmy, 1994; Van der Wijden et al., 1998). These brushes were shown to be efficient to a certain extent (Goyal et al., 2009); however, they could not fulfil all demands, especially for the people with limited dexterity who required caregivers for their routine oral hygiene tasks (Tesini & Fenton, 1994). Due to these limitations, automated toothbrushes have emerged to improve dental plaque removal ability as well as usability. Automation was introduced to help the users perform the toothbrushing action without or with less skill. One of these recently introduced toothbrushes is a new U-shaped, fully automatic electric toothbrush with silicone bristles, which was introduced recently claiming that it can simultaneously clean both the maxilla and the mandible time. The mouthguard design enabled it to remain firmly in place and allow the teeth to be swept through the vibrations of its bristles (Figure 1a,b) (SongZe Lee, 2018).

The other brush is a recently patented ‘Electromagnetic toothbrush’ known as ‘Cyberbrush’ (Saghiri et al., 2019). This toothbrush has a U-shaped mouthpiece with an electromagnetic levitation controlled abrasive system, which maintains a ball with bristles (Figure 1c). This brush has two separate parts, including an extra-oral device that contains two rails forming a chassis. These rails house two Y-shaped solenoids, which move along the fence, creating a magnetic field to control the ball where one solenoid results in its horizontal motion and the other in its vertical (Figure 1d). This ball moves across the mouthpiece through magnetic levitation and can conform to any surface shape within its range of motion. Along with this, its vertical and horizontal range of motion enables it to reach any of the tooth surfaces in the oral cavity to perform the brushing action. The brushing step can be performed automatically and limited assistance of users. However, these automated toothbrushes were not well-discussed in the literature.

Hence, the present study intended to evaluate the dental plaque removal ability of mentioned automated toothbrushes and compare their knowledge with an ultrasonic power toothbrush. The null hypothesis was tested that the ultrasonic and testing mechanical toothbrushes cannot effectively remove the dental plaque.

### 2 | MATERIALS AND METHODS

#### 2.1 | Teeth Model

A typodont with thirty-two teeth and perfect occlusion was used for this study (ModuPro One MP-R320, Accidental). This model’s teeth were divided into four quadrants; two in the maxillary arch and two in the mandibular arch. These quadrants consisted of eight teeth and were further divided into four zones (Figure 2a). Each of the zones,
in turn, consisted of two teeth. This segregation was done to ensure more accurate image analysis, since multiple teeth in a picture would not provide a precise view of the surface view given the natural curvature of the human dentition. These quadrants were numbered in a clockwise manner starting from the left maxillary quadrant and ending at the left mandibular quadrant. The zones were also numbered in a clockwise manner starting from the left maxillary quadrant. For the purpose of this study, only the mandibular teeth were considered. A mechanical arm was used for the brushing movements in this study to reduce human error and apply a constant force and motion pattern to maintain uniformity.

2.2 | Teeth Model set-up and brushing

Black chalk was applied to the teeth surface (facial surface) in a uniform layer (Testor black spray chalk) to indicate plaque build-up on the teeth of the typodont (Figure 2b). The typodont was then attached to a cast iron support ring stand (American Educational Products) attached to a wooden base. This was done to hold the typodont stationary to avoid micro-movements of the typodont. These micro-movements may affect the results obtained and is a confounding factor in this study. In this study, three different toothbrushes’ plaque removal capacity was tested (Figure 2c). (1) FairyWill Sonic Electric Toothbrush, Crystal black (FairyWill, Zhuhai City, China) (FairyWill) (Figure 2c-i, 2d), (2) Teeth Whitening V-White 360° Automatic Toothbrush, 2020 model (V-white, Hong Kong) (V-White) (Figure 2c-ii), and (3) Cyberbrush (Figure 2c-iii). A programmed robot (Microbot model TeachMover, Questtech, MI) arm was used for holding the testing toothbrushes and performing the toothbrushing action for 2 min during the experiment. These tests were conducted without the use of toothpaste or chemical cleaning agents. Once the toothbrush would complete its toothbrushing action, pictures of the typodont were taken for each zone; that is, sixteen photographs per experiment were taken. The black chalk would be applied on the typodont again in a similar manner, and the next set of experiments would be conducted.

2.3 | Photograph processing

The images obtained were processed using the ImageJ software (Rasband WS, ImageJ; US National Institute of Health, Bethesda, MD). All sixteen photographs per toothbrush were transferred into the software and analysed using the steps detailed in Figure 3. Briefly, the images taken after toothbrushing process were transferred into the ImageJ software. Then by using the freehand selections tool, the outline for the teeth was drawn to exclude the gum and the background. Then, a separate image was created for the selected area in the previous step (Image > Duplicate Tab). In next step, the number of pixels was measured in the selected area (Analyze > Measure Tab). Then the image was converted into an 8-bit black and white image to see the contrast properly (Image > Type > 8-Bit Tab). After converting the image, the threshold was changed (Image > Adjust > Threshold...
Tab). The threshold was set by using the max and min bars such that the red area depicted the clean surface and the black area depicted the uncleaned surfaces of the teeth in the selected area. Once the appropriate settings were achieved, the number of pixels in red was counted (Analyze > Measure Tab). The value, both in pixels and percentage format of black area (uncleaned surfaces) were recorded for further evaluation and comparison between the groups. This same procedure was done for all the images obtained from each toothbrush to compare the results obtained.

2.4 | Statistical analysis

Data were analysed using Kolmogorov–Smirnov, one-way ANOVA and post hoc Tukey tests at the level of significance of $p < .05$. All statistical analyses were conducted using SAS Version 9.4 (The SAS Institute).

3 | RESULTS

Descriptive statistics of the three toothbrushes’ plaque removal ability were assessed from a total of 24 observations (three readings from the eight zones). The means and standard deviations of the percentage of dental plaque removal values of the experimental groups were: FairyWill (7.13 ± 4.99, 8.83 ± 5.56, 7.98 ± 5.29) %, V-White (51.90 ± 20.23, 66.01 ± 15.51, 58.96 ± 18.88) %, and Cyberbrush (9.60 ± 7.17, 12.75 ± 5.35, 11.18 ± 6.49) %. Kolmogorov–Smirnov test showed normal distribution of data, and differences between the groups were evaluated using the one-way ANOVA test. A significant difference was observed amongst the experimental groups ($p < .000$). The post hoc Tukey test revealed that the percentage of plaque remaining in the V-White group was significantly higher than the other two groups ($p < .05$). At the same time, no significant differences were detected between Cyberbrush and FairyWill groups ($p > .05$). Figure 4, shows the box plots of means and standard deviations of percentages of values remaining plaque (uncleaned surfaces) in experimental groups in the mandible (Figure 4a) and maxilla (Figure 4b).

4 | DISCUSSION

The rationale behind the choice of toothbrushes used was to encompass electric toothbrush technologies such as sonic toothbrush...
(FairyWill) (Toothbrush, 2020), the U-shaped toothbrush (V-White) (SongZe Lee, 2018), and the recently introduced Cyberbrush designed and patented previously (Saghiri et al., 2019). Any study intended to evaluate toothbrushing activity needs to account for the different variables and control them to ensure that the results were accurate. These variables include the movement of the persons’ arm, toothbrushing motion, and dental arch anatomy (Van der Weijden, 2002; Van der Weijden et al., 1993). In the study performed here, a typodont exhibiting perfect occlusion was used with a robotic arm for the FairyWill toothbrush and a fixed mechanical appendage to hold the other two (V-White and Cyberbrush) in place with the toothbrushing time set for 2 min to control the variables of this study. The study set-up, the toothbrushing action and image processing were similar to a previously performed study (Saghiri et al., 2020).

The V-White toothbrush recorded a higher percentage of plaque remaining than the other toothbrushes studied in this experiment. There was no significant difference between the other two. The ultrasonic technology FairyWill toothbrush and the Cyberbrush showed similar performances in terms of plaque removal. The V-White toothbrush outcome was consistent with a previously performed study, which also showed limited plaque removal activity (Nieri et al., 2020). These results might be explained by the different mechanisms of action and method utilized in this system, such as the silicone bristles, limitations of fitting this toothbrush to the various alveolar sizes of the users. These issues might affect the rubbing motion and access of toothbrush bristles to the gingival third of tooth surfaces that might remain uncleaned.

The present study results showed that the FairyWill toothbrush with the ultrasonic action had the lowest amount of dental plaque remaining after 2 min of brushing. These outcomes are consistent with previous studies, which verified the efficacy of sonic and ultrasonic toothbrushes’ ability to remove dental plaque (Costa et al., 2007). It was indicated in other similar tasks that ultrasonic toothbrushes could reduce plaque formation and gingivitis over 6 months (Terezhalmy et al., 1995). In another study, ultrasonic toothbrushes were shown to be more effective than manual brushes in removing plaque and preventing gingivitis in patients without periodontal diseases (Zimmer et al., 2002). The increased mechanical scrubbing can explain these sonic and ultrasonic toothbrushes’ superior efficacies along with fluid agitation, which makes it conducive to plaque removal (Grossman et al., 1995). These action mechanisms might also explain the results of the plaque removal ability of Cyberbrush in the present study. Cyberbrush, with its electromagnetic technology, which controls the micro-abrasive ball to conform to the contours of different teeth and fully automatic nature, gives it an added advantage in reaching the unclean surfaces of teeth (Saghiri et al., 2019). Also, the scrubbing motion of Cyberbrush has the primary role in the cleaning efficacy of this brush.

One of the limitations of this study is that it only measures dental plaque as a performance parameter for the toothbrushes. Other aspects, like gingivitis and dental caries, have not been assessed in this study. Another limitation is that this study was conducted on typodonts with perfect occlusion and did not account for malocclusions in teeth, one of the most common dental conditions (Proffit et al., 1998). Furthermore, since this study was performed on typodonts with a fixed jaw size, this aspect could limit this study’s scope. It may not provide a perfect representation for people with jaw sizes and occlusions different from the typodont.

5 | CONCLUSIONS

Under the limitations of this study, the following conclusions can be drawn:

- Toothbrushes that can establish better and intimate contact with tooth surfaces and perform the brushing action with scrubbing
motion have better dental plaque removal ability.

- Other features, such as ultrasonic or sonic actions, can improve the plaque removal ability of toothbrushes.

- The automated toothbrushes that can have better adaptation with tooth surfaces can be regarded as good toothbrushes for dental plaque removal. However, these toothbrushes are still new in concept. They require more preclinical and clinical studies to be established as useful oral healthcare devices compared to the currently used power toothbrushes.

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CONFLICT OF INTEREST

The authors hereby declare that they do not have any conflict of interest with regard to this research. MAS, AMS and AA have US patent application on electromagnetic toothbrush.

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