Methodology for Measuring the In Vitro Seating and Unseating Forces of Prefabricated Attachment Systems Used to Retain Implant Overdentures

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Abstract

Purpose: The purpose of this in vitro investigation was to measure the forces generated during the continuous seating and unseating of prefabricated attachment systems used to retain implant overdentures.
Materials and Methods: An experimental design consisting of interchangeable fixture mounts, a radially indexable fixture holder, and a materials testing systems (MTS) machine was used to measure forces generated during the insertion and removal of spherical stud attachments (Straumann, Inc, Waltham, WA). Three separate experiments were conducted measuring the seating and unseating forces of a vertically aligned patrix/matrix assembly, a 20° angled patrix opposing a vertically positioned matrix, and a vertically positioned patrix opposing a 20° angled matrix. For each patrix/matrix combination, three specimens were tested. Measurements were continuously recorded under reproducible conditions in the presence of artificial saliva. All specimens were subjected to 10,000 seating/unseating cycles. Statistical analysis was performed with rank analysis of variance (ANOVA) for a group comparison ($\alpha = 0.05$).
Results: Results showed variability in the initial insertion and removal forces among experimental groups and among specimens within each experiment. A marked increase in the seating and unseating forces was recorded for all specimens during the first 300 cycles, followed by a gradual decrease in these forces. The exact p-values for the Kruskal–Wallis test showed no significant difference between the initial and final seating/unseating forces ($p > 0.1$) nor in the maximum seating/unseating forces ($p > 0.6$) among the three experimental groups.
Conclusions: Spherical stud attachments exhibited consistent seating and unseating forces over 10,000 cycles. A 20° angle between the patrix and matrix had no effect on the overall seating and unseating force values.

Implant-retained overdentures supported by two implants have broadened the prosthodontic treatment rehabilitation spectrum for patients experiencing retention problems with conventional mandibular dentures.[1-4] Several studies have confirmed the benefits of implant-retained overdenture treatment in comparison to the conventional denture therapy.[5-8] In particular, overdentures retained by two or more non-splinted implants offer a simple and effective solution to increase the prosthesis retention at a reduced cost.[9,10]

There is strong evidence that the retention of implant overdentures is an important factor for patient satisfaction.[6,11] Although an array of prosthodontic attachments are available on the market to secure implant-retained overdentures during oral function, little is known about the retentive properties of the various attachment systems under a continuous load protocol.[12] Moreover, little data are available on the impact of implant angulation on the retentive properties and component wear that may ensue under normal clinical conditions.[13,14] Although a

10° to 30° angulation tolerance between two non-splinted implants is considered acceptable for implant-retained overdentures,[13-15] little is known about the short- and long-term impact of implant angulation on the retention properties of the attachment system and the premature wear that may ensue.[16] To achieve long-term success with an implant-retained overdenture, forces applied parallel to the path of insertion of a prosthesis are recommended.[17-20] This implies that the retentive matrices and the implants should be positioned parallel to each other and to the path of insertion of the prosthesis.[21] Clinical situations and operator experience, however, may preclude the achievement of such a goal, and a shift from optimal implant angulation may be encountered.

Spherical stud attachments (ball-and-socket attachments) used to secure implant-retained overdentures consist of a titanium implant abutment (patrix) and a corresponding retentive gold alloy housing (matrix)[15] that is typically retained in the intaglio surface of the overdenture. Although several studies have reported favorable results using various spherical stud attachment systems to retain mandibular implant overdentures,[2,3,9,22,23] others have reported a decrease or loss of retention as well as structural failures following insertion of implant-retained prostheses.[24-28]

The primary objective of this investigation was to measure the in vitro forces generated during the seating and unseating of spherical stud attachments over 10,000 cycles using a continuous load protocol. The secondary objective was to validate the in vitro experimental design in measuring the forces generated during the seating and unseating of prosthodontic attachment systems used to retain implant overdentures.

Materials and methods

The experiment was designed to measure the forces generated during the continuous cyclic seating and unseating of spherical stud attachments under reproducible conditions. The testing apparatus consisted of three parts:

Interchangeable fixture mounts

Upper fixture mounts

Interchangeable upper fixture mounts that connected to a materials testing system (MTS) machine unit crosshead were designed to hold the patrix or matrix of a prefabricated spherical stud implant attachment system (Fig 1). The internal aspect of the fixture mount was machined to match the threads of the implant abutment being tested (Fig 1A) or to passively accommodate the spherical stud attachment housing (Fig 1B). To secure the implant abutment in place, the abutment was hand-tightened into its corresponding fixture mount using the appropriate abutment driver. In comparison, the retentive gold alloy housing was secured into its respective fixture mount through the provision of a custom-engineered recess machined into the fixture mount. The dimensions of the recess were designed to match the geometry of the retentive gold alloy housing. The prosthodontic attachment housing was secured in place by tightening three lateral screws. The screws were carefully designed to provide a firm grip along the base of the gold alloy housing, without interfering or distorting the retentive mechanism of the prosthodontic attachment.

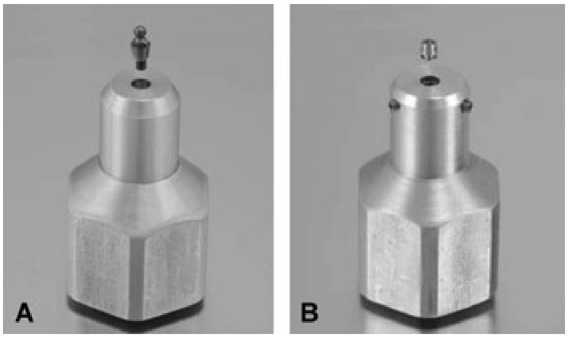

Figure 1 (A) Upper fixture mount designed to hold a spherical stud implant abutment. (B) Upper fixture mount designed to hold the gold retentive housing for the corresponding spherical stud implant abutment.

Lower cylindrical fixture mounts

Interchangeable, lower cylindrical fixture mounts, connecting to the MTS actuator, were also designed to hold the patrix and matrix of the prefabricated spherical stud implant attachment system (Fig 2). Similar connection mechanisms used for the upper fixture mounts were built in the lower fixture mounts to hold the prosthodontic attachment components. The cylindrical lower fixture mounts were engineered to seat into a radially indexable fixture holder, described below. Additional upper and lower fixture mounts (Fig 3) were designed to test elliptical and locator prosthodontic attachment systems using a similar experimental method described herein.

Radially indexable lower fixture mount holder

A radially indexable mount holder was fabricated to permit reproducible testing of various prosthodontic attachment systems both vertically and at varying angles to the vertical plane. The radially indexable mount consisted of a fixed and a moveable element. The moveable element of the fixture mount holder

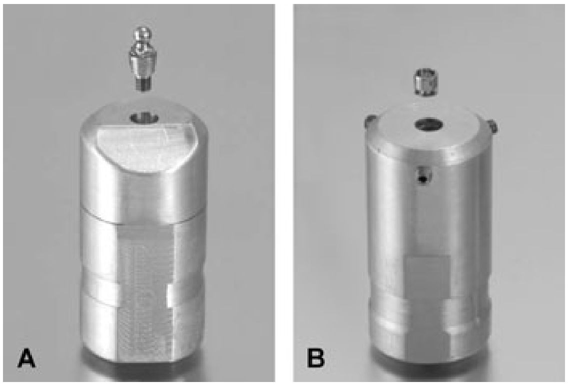

Figure 2 (A) Lower cylindrical fixture mount designed to hold a spherical stud implant abutment. (B) Lower cylindrical fixture mount designed to hold the gold retentive housing for the corresponding spherical stud implant abutment.

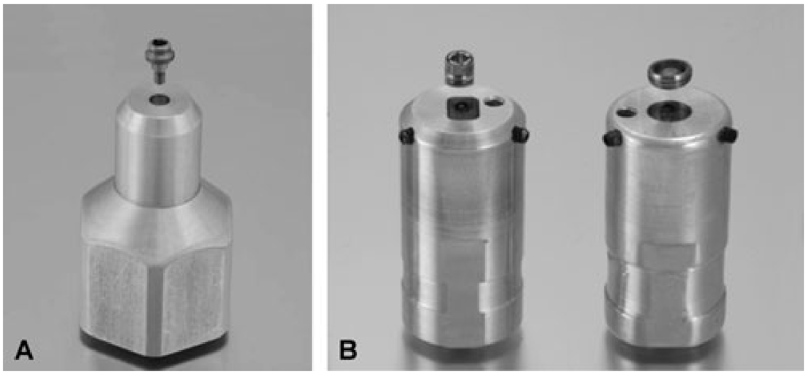

Figure 3 (A) Upper fixture mount designed to hold a locator implant abutment. (B) Lower cylindrical fixture mounts designed to hold an elliptical and locator retentive housing, respectively.

was designed to hold the lower cylindrical fixture mount (described in the previous paragraph). The lower cylindrical fixture mount was secured in place by manually tightening a lateral hex wrench (Fig 4). Care was taken to provide a flat surface along the length of the cylindrical fixture mount for antirotational purposes (Fig 2). The fixture holder allowed 5° angulation increments of the moveable element radially around a point corresponding to the center of rotation of the attachment component being tested. A lateral alignment pin locked the fixed and moveable elements at the desired angle. Artificial saliva (Saliva Substitute, Roxane Laboratories, Inc, Columbus, OH) was used during the entire experimental period to lubricate the prosthodontic components and simulate the in vivo oral conditions. A plastic cylinder surrounding the prosthodontic components acted as a saliva reservoir (Fig 5). The artificial saliva also served to minimize the build-up of metal residue smears on the interface of the attachment components to reduce the likelihood of accelerated wear and temperature rise within the prosthodontic components.

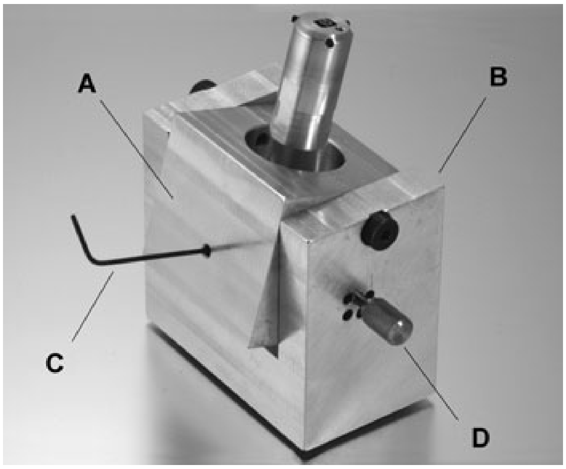

Figure 4 Radially indexable lower fixture mount holder. (A) Moveable element. (B) Fixed element. (C) Lateral hex wrench. (D) Lateral alignment pin.

MTS machine

An MTS machine unit (Model 810, MTS Systems Corp, Eden Prairie, MN) provided cyclic seating and unseating of the prosthodontic components under reproducible conditions (Fig 5). Calibration of the MTS machine was performed at the start of the experiment using a set of precision weights. Test specimens were first seated in their respective lower fixture mounts. The lower fixture mounts were then inserted in the radially indexable fixture holder. The fixture holder was connected to a 220 N load cell (Model 3167-50, Lebow Products, Troy, MI) that was fixed to the MTS' linear actuator. The upper interchangeable fixture mounts were directly attached to the MTS crosshead. The upper and lower fixture mounts were then brought together until complete seating of the patrix and matrix was achieved. Care was taken to operate the MTS machine during the seating of the test specimens at zero force. The upper fixture mounts were slightly loosened to allow for limited off-axis freedom between the prosthodontic components during cycling, to reproduce in vivo conditions. The MTS machine was then programmed to apply 10,000 ramp displacement cycles of 1 mm magnitude at 2 Hz with complete seating and unseating of the prosthodontic components. Load and displacement data for each test specimen were collected on two separate files using the MTS software. The peak/valley data for the seating and unseating forces were collected over each cycle at a sensitivity of 6 N. A second file intermittently collected data at 1000 Hz over full ramp cycles; these data were collected at cycles 1, 2, 5, 10, 20, 50, and 100, then every 100 cycles from 100 to 1000, and every 500 cycles from 1500 to 10,000.

Experimental and statistical approaches

To test the validity of the experimental design, the forces generated during the insertion and separation of single spherical stud attachments (Straumann USA, Inc, Waltham, WA) were continuously measured. Three separate experiments were conducted to measure the forces generated during the linear seating and unseating of a vertically aligned patrix/matrix assembly (0°P/0°M experimental group), a 20° angled patrix opposing a vertically positioned matrix (20°P/0°M experimental group), and a vertically positioned patrix opposing a 20° angled matrix (0°P/20°M experimental group) (Fig 6). For each patrix/matrix combination, three specimens were tested. All specimens were

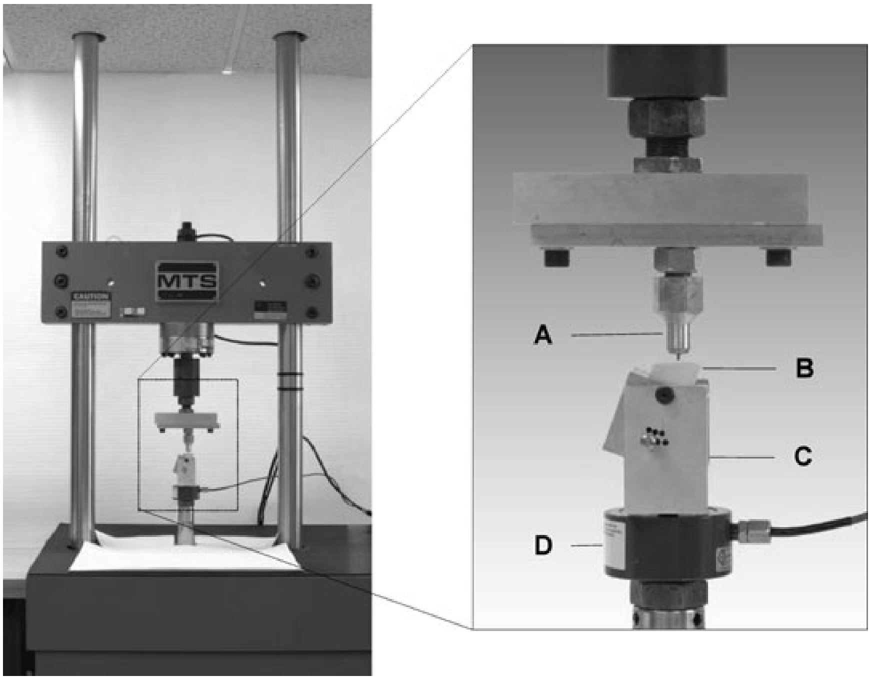

Figure 5 MTS unit. (A) Upper fixture mount. (B) Saliva reservoir. (C) Radially indexable lower fixture mount holder. (D) Load cell.

subjected to 10,000 seating/unseating cycles in the presence of artificial saliva at room temperature. Forces generated during the seating and unseating of the retentive gold housing (matrix) over the spherical abutment (patrix) were continuously recorded throughout the fatigue loading experiment. For each specimen, the initial, final, and maximum seating and unseating force was reported. The average change of force from the initial to the final seating and unseating force as well as the average change of force before reaching the maximum seating and unseating force was also reported. Non-parametric testing for location and scale differences across a one-way classification was used to compare the three experimental groups. The exact version of the Kruskal–Wallis[29] test was used to test whether the mean initial, maximum, and final seating and unseating forces were the same for the three experimental groups.

Results

The values for the seating and unseating forces in each of the three experimental groups were recorded throughout the duration of the fatigue loading period, and were displayed as a curve showing the forces at every insertion/separation cycle.

0°P/0°M experimental group

The average seating/unseating force with a 5% error bar of the three specimens for 10,000 cycles is summarized in Figure 7A. The mean (standard error) of the initial seating and unseating forces were 31.0 (2.4) N and 36.9 (4.1) N, respectively. In comparison, the mean and standard error of the final seating and unseating forces were 30.4 (2.7) N and 33.3 (3.1) N, respectively. The median of the maximum seating force for the three

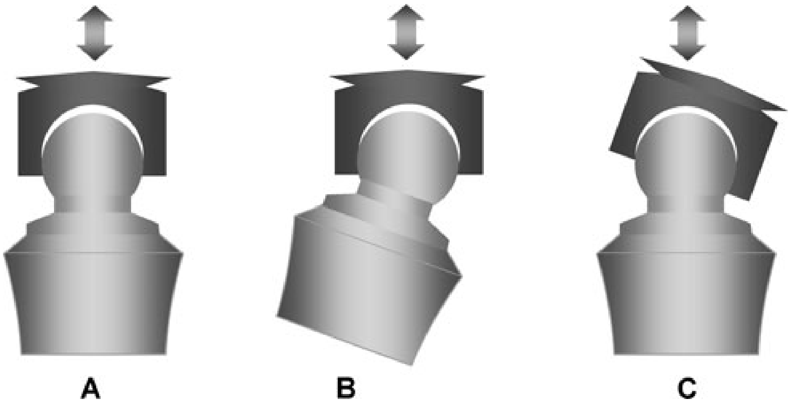

Figure 6 Schematic drawing of spherical stud attachment patrix/matrix assembly. (A) 0°P/0°M. (B) 20°P/0°M. (C) 0°P/20°M experimental groups. Double arrow refers to plane of insertion/separation of prosthodontic components.

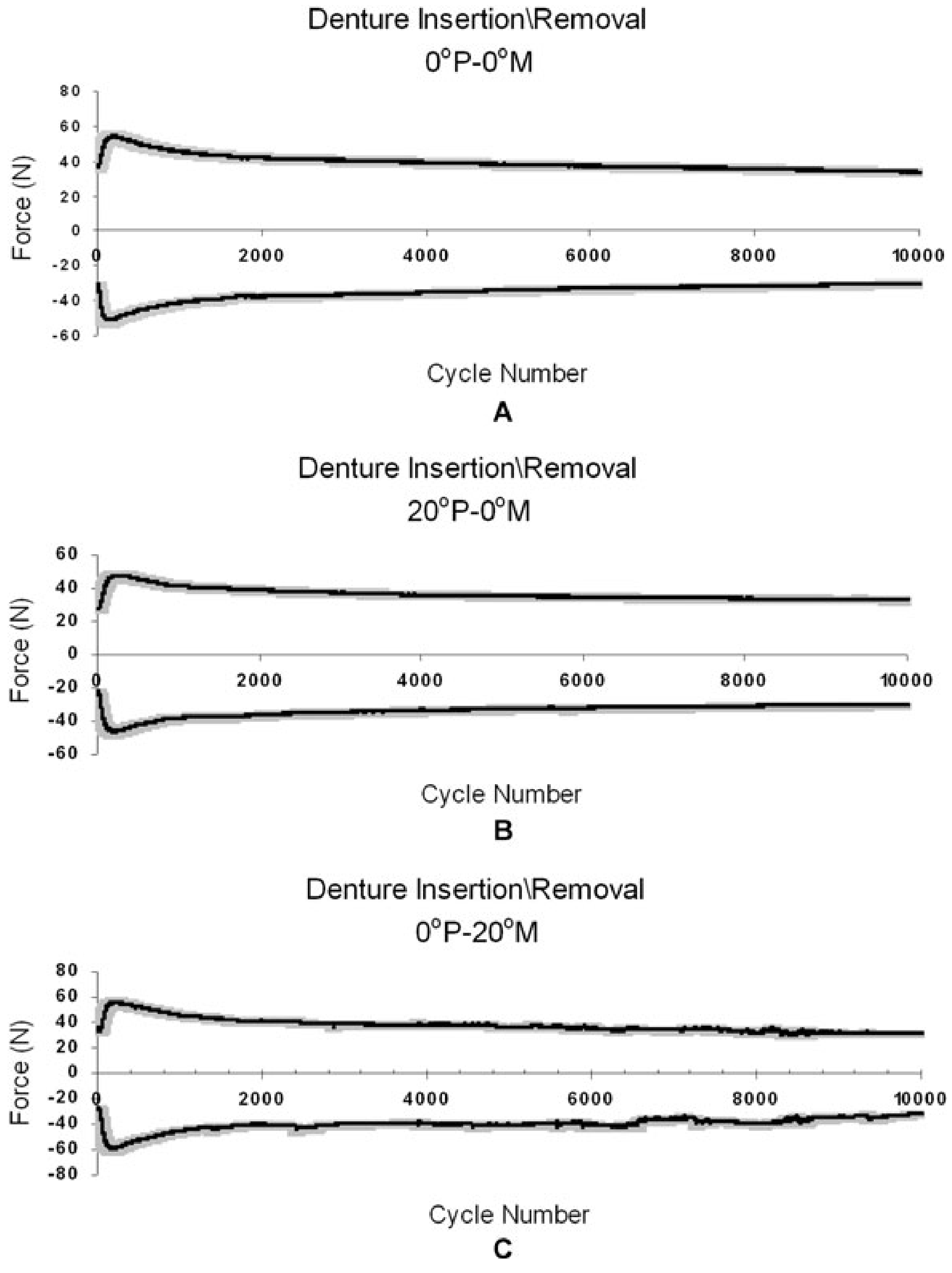

Figure 7 Average seating and unseating forces with 5% error bar over 10,000 cycles for three specimens of spherical stud attachments tested in each of the three experimental groups: (A) 0°P/0°M, (B) 20°P/0°M, (C) 0°P-20°M.

specimens (57 N) was recorded at cycle 135, while the median of the maximum unseating force (62 N) was recorded at cycle 231. The maximum seating force increased by 37% relative to the baseline value, and the corresponding increase for the unseating force was 31%. The absolute and percentage changes of the unseating force before (ΔF_I) and after (ΔF_F) reaching the maximum force are reported in Table 1. The difference between the initial and final seating/unseating force was not statistically significant ($p > 0.25$, Signed Rank test).

20°P/0°M experimental group

The average seating/unseating force with 5% error bar of the three specimens for 10,000 cycles is summarized in Figure 7B. The mean and standard error of the initial seating and unseating forces were 22.4 (2.9) N and 27.6 (2.6) N, respectively. In comparison, the mean of the final seating and unseating forces and their corresponding standard error were 30.4 (3.9) N and 32.7 (3.3) N, respectively. The median of the maximum seating force (41 N) was recorded at cycle 164, while the median of the

Table 1 For each specimen, maximum removal force (N) recorded at corresponding insertion–removal cycle. Absolute and percent change in force before (ΔF_I), and after (ΔF_F) reaching the maximum removal force displayed for each patrix–matrix combination

	Specimen	Max removal force	Cycle	ΔF_I	% ΔF_I	ΔF_F	% ΔF_F
0°P/0°M	1	63	136	24.7	39.2	27.3	43.3
	2	62	231	19.0	30.6	25.0	40.3
	3	38	249	9.0	23.7	11.0	28.9
0°P/20°M	1	65	274	27.0	41.5	28.1	43.3
	2	56	197	19.0	33.9	30.4	54.2
	3	47	109	14.4	30.7	18.3	38.9
20°P/0°M	1	43	290	20.0	46.5	11.0	25.6
	2	58	241	26.0	44.8	19.0	32.8
	3	43	140	15.6	36.2	15.2	35.4

maximum unseating force (43 N) was recorded at cycle 290. From baseline, there was a 43% increase in the seating force and a 52% increase in the unseating forces. The difference in initial and final seating/unseating forces was not statistically significant ($p = 0.25$, Signed Rank test).

0°P/20°M experimental group

The average seating/unseating force with 5% error bar of the three specimens for 10,000 cycles is summarized in Figure 7C. The mean and standard error of the initial seating and unseating forces was 28.5 (7.8) N and 35.9 (1.7) N, respectively. In comparison, the mean of the final seating and unseating forces and the corresponding standard error were 32.3 (3.6) N and 30.4 (3.3) N, respectively. The median of the maximum seating force (57 N) was recorded at cycle 178, while the median of the maximum unseating force (56 N) was recorded at cycle 197. From baseline, there was a 53% increase in the seating force and a 35% increase in the unseating forces. The differences between the initial and final seating/unseating forces were not significant ($p = 0.25$, Signed Rank test).

Non-parametric testing for location and scale differences across a one-way classification was used to compare the mean initial, maximum, and final seating/unseating forces among the three experimental groups. Although results showed variability in the initial, maximum, and final insertion/separation forces among experimental groups and among specimens within each group, the differences in the recorded forces were not significant. The mean absolute change between the initial and final cycle for all the experimental groups revealed little loss in the seating/unseating force value after 10,000 cycles. A marked increase in the seating and unseating forces was recorded for all specimens during the first 300 insertion/separation cycles. Although the mean absolute change between the initial and maximum force varied somewhat for each of the experimental groups, all specimens reached their maximum seating/unseating force values relatively early, between cycles 109 and 290. The exact version of the Kruskal–Wallis test showed no evidence of a significant difference in the maximum ($p > 0.6$), initial ($p = 0.13$), or final ($p = 0.83$) seating/unseating force among the three experimental groups.

Discussion

The experimental methodology described was designed to measure the seating and unseating forces of prefabricated freestanding prosthodontic attachment systems used to secure implant-retained overdentures under a continuous in vitro displacement protocol. Measurement of the seating and unseating forces for spherical stud attachments was performed under standardized and reproducible conditions. Each prosthodontic component was subjected to 10,000 cycles representing an average of 10 years of clinical use of a prosthesis assuming it is removed and replaced three times daily for oral hygiene and cleaning. The retentive values of the spherical stud attachments, as reported in this study, are comparable to values reported in the literature both in vitro[12,14] and in vivo.[23] No other study has reported data on the forces generated during the seating of prefabricated implant attachments that the present results could be compared to.

The initial increase in the forces observed in the present study was followed by a gradual decrease in the recorded forces. A similar force pattern has been reported by other investigators using tooth- and implant-borne prefabricated prosthodontic attachments.[12,30] Several hypotheses have been advanced to explain the increase in the retentive forces observed during the initial fatigue loading phase. Owall[31] suggested surface release and wear of metal particles as a possible explanation for the observed increase in initial forces. Stewart and Edwards[17] related the initial force increase to an increase of surface roughness after initial wear has taken place. Another explanation to the initial increase in forces could be related to the hardening of the contact surfaces of the attachments by cold working. In light of these findings, prefabricated prosthodontic attachment systems may require an initial load cycling phase before they achieve consistent, optimal functioning. It would, therefore, seem reasonable to recommend that studies measuring the seating and unseating forces of prosthodontic attachment systems account for multiple insertion/separation cycles before any definitive conclusions are made relative to their performance.

When the initial and final insertion/separation forces were compared among the three experimental groups, a 20° angle between the patrix and matrix did not result in an accelerated loss of the seating/unseating forces over 10,000 cycles. These findings seem to indicate that an angle of divergence of up to 20° between an individual patrix and matrix may not be detrimental to the retentive properties of spherical stud attachments over time. A divergence of up to 10° between two unsplinted implants has been considered acceptable by implant manufacturers,[15] Wiemeyer et al[13] determined that two spherical abutments may be divergent up to 60° from one another without compromising the complete seating of the prosthesis, as long as the gold matrices were positioned parallel to each other. Several investigators, however, have suggested that implants supporting overdentures need to be parallel to one another to prevent premature wear and loss of retention of the prosthodontic attachment mechanisms.[18,21,32] The presence of wide divergences or convergences between implants is believed to result in excessive wear and a decrease in retention of the overdenture.[14,20] Because of the limitations inherent to in vitro fatigue tests[12] and in the absence of supporting prospective evidence, limited comparison between the published data is possible. Walton et al,[16] for example, found no significant relationship between the number of adjustments and repairs of mandibular implant-retained prostheses and inter-implant angles. Of interest, however, were the findings from the same study that a lingual inclination of ≥6.0° or a facial inclination of <6.5° of implants resulted in significantly greater numbers of implant-retained prosthesis repairs, usually to the matrix. Although the results from the present study did not identify a significant difference in the force value between the initial and last cycle for both the 20°P/0°M and 0°P/20°M test groups, the experimental design used in the present study could not provide any quantification of the component wear that may have taken place. Such analysis may have been most informative for the 0°P/20°M experimental group given that specimens showed the least uniform course of seating–unseating forces (Fig 7C).

According to Wiemeyer et al,[13] when the matrices of spherical stud attachments are not positioned parallel to the path of insertion of the prosthesis, the retentive mechanism of the gold housing is susceptible to increased wear. The greater the angle between the path of withdrawal of the prosthesis and the gold housing, the more likely the retentive mechanism of the matrix will engage the undercut on one side of the spherical abutment, resulting in potential accelerated wear, permanent deformation, or fracture of the retentive matrix lamellae. In the present study, neither a marked loss of retention nor structural failures of the prosthodontic components were observed when using a 20° angle between the patrix and matrix over 10,000 cycles. Such results indicate that the use of spherical stud attachments to retain mandibular overdentures could be used in situations where unfavorable and nonparallel alignment of implants is present without a compromise to the retentive properties of the prosthesis over time. Because the prosthodontic components, as described in the present experimental design, were rigidly connected to the fixture mounts, the potential for a structural failure between the matrix and the overdenture acrylic resin housing could not be assessed. Dislodgment of the matrix or fracture of the acrylic housing has been reported in clinical studies, [23,26-28] and may represent the weakest link in the system.[27] To minimize such complications, several investigators have recommended that cast frameworks be incorporated in the overdenture design to reinforce the acrylic resin.[33-35]

The seating and unseating cyclic displacements described in the present study were exclusively applied in the vertical plane. Unlike the 3D loads that have been shown to occur intraorally,[36] the in vitro experimental design used in this study to analyze the behavior of the prosthodontic attachments under functional loading did not fully replicate the complex in vivo conditions. Non-axial forces present clinically are suspected to result in plastic deformation of the prosthodontic components resulting in possible component wear, decreased retention, and possible fractures.[19] Moreover, polymerization shrinkage of the autopolymerizing acrylic resin often used clinically to secure the matrix may also affect the precise alignment between the prosthodontic components. Caution should therefore be applied against extrapolating the results of the present study to the actual magnitude of seating and unseating forces that might be observed intraorally.

Considering the small number of specimens, it cannot be concluded with certainty that a spherical stud attachment will perform intraorally as described in this study. It would be reasonable, however, to assume that the reported results are indicative of the characteristics of the attachment system used, and that the spherical stud attachments that were tested represent standardized specimens of manufactured components. Further studies with a larger sample of attachments are indicated to provide more definitive conclusions. Parallel in vivo tests would also be valuable in corroborating the in vitro findings and to examine the influence of clinical variables that cannot be simulated in the laboratory setting.

Conclusions

Within the limits of this study, the following conclusions were drawn:

1. Under in vitro conditions, spherical stud attachments evaluated showed an initial increase of the seating and unseating forces followed by a gradual decrease in these forces.
2. The seating and unseating forces of spherical stud attachments demonstrate a minimal force value change over 10,000 cycles.
3. A 20° angle between the patrix and matrix had no negative influence on the retentive force values of spherical stud attachments over 10,000 cycles.
4. The methodology described in this article could provide clinically relevant measurement of the retention performance of various prosthodontic attachment systems used for implant-retained overdentures.

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