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ORIGINAL ARTICLE

Comparative analysis of passive play and torque expression in self-ligating and traditional lingual brackets

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Abstract

Introduction The aim of this study was to determine and compare the play and torque expression of self-ligating and conventionally ligated lingual brackets, with square and rectangular slots, when engaged with archwires of different size, cross section and material.

Methods Passive play and torque expression of 3 types of archwires and 5 types of brackets from four different manufacturers were measured and compared using a dynamometer. Each archwire was tested five times in each bracket; passive play was compared to ideal values, while torque expression was tested at 5, 10 and 20 Nmm as clinically efficacious values.

Results Regarding full thickness stainless steel archwires, the lowest passive play was found in STb brackets (2.66 ± 0.89°, Ormco, Glendora, CA, USA), which was statistically significantly lower than for ALIAS brackets (4.44 ± 0.75°, Ormco), In-Ovation L brackets (6.14 ± 3.22°, Dentsply GAC, Bohemia, NY, USA), Harmony brackets (7.76 ± 2.94°, American Orthodontics, Sheboygan, WI, USA) and eBrace brackets (9.46 ± 3.94°, Riton Biomaterial, Guangzhou, China). Increasing the torsional load to the greatest torsional load clinically applicable, there were no statistically significant differences between STb, ALIAS, In-Ovation L and Harmony brackets.

Conclusions STb and ALIAS brackets generated the lowest passive play; STb and In-Ovation L brackets showed the lowest angle of play at the greatest torque expression. These measurements allow to understand the accuracy of lingual systems and at the same time the amount of overcorrections to be applied in the setup in order to obtain high quality orthodontic treatments.

Keywords Tooth inclination · Tooth movement · Orthodontic archwires · Malocclusion · Tooth root movement

Vergleichende Analyse des Torquespiels und der Torqueexpression in selbstligierenden und konventionellen lingualen Klammern

Zusammenfassung

Einführung Ziel dieser Studie war es, das Spiel und die Torqueexpression von selbstligierenden und konventionell ligierten lingualen Brackets mit quadratischen und rechteckigen Slots zu bestimmen und beim Einsatz mit Drahtbögen unterschiedlicher Größe sowie unterschiedlichen Querschnitts und Materials zu vergleichen.

Methoden Das Torquespiel und die Torqueexpression von 3 Arten von Drahtbögen und 5 Brackettypen von 4 Herstellern wurden gemessen und unter Verwendung eines Dynamometers miteinander verglichen. Jeder Drahtbogen wurde 5-mal in jedem Bracket untersucht. Das Torquespiel wurde mit idealen Werten verglichen, während die Torqueexpression bei den klinisch wirksamen Werten 5, 10 und 20 Nmm getestet wurde.

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Ergebnisse Bei den Edelstahlbögen in voller Stärke wurde das geringste Torquespiel bei STb-Brackets (2,66 ± 0,89°, Ormco, Glendora, CA, USA) festgestellt, es war statistisch signifikant niedriger als bei ALIAS- (4,44 ± 0.75°, Ormco), In-Ovation-L- (6,14 ± 3,22°, Dentsply GAC, Bohemia, NY, USA), Harmonie- (7,76 ± 2,94°, American Orthodontics, Sheboygan, WI, USA) und eBrace-Brackets (9,46 ± 3,94°, Riton Biomaterial, Guangzhou, China). Bei Erhöhung der Torsionsbelastung auf die maximale klinisch anwendbare Torsionsbelastung gab es keine statistisch signifikanten Unterschiede zwischen STb-, ALIAS-, In-Ovation-L- und Harmony-Brackets.

Schlussfolgerungen STb- und ALIAS-Brackets verursachten das geringste Torquespiel; STb- und In-Ovation-L-Brackets zeigten den geringsten Spielwinkel bei der größten Torqueexpression. Diese Messungen ermöglichen es, die Genauigkeit der lingualen Systeme zu verstehen und damit auch das Ausmaß der im Setup anzuwendenden Überkorrekturen, um qualitativ hochwertige kieferorthopädische Behandlungen zu erhalten.

Schlüsselwörter Zahninklination · Zahnbewegung · Kieferorthopädische Drahtbögen · Malokklusion · Zahnwurzelbewegung

Introduction

Torque is a moment generated by the twisting of a rectangular wire in the bracket slot, thereby resulting in torsional load and labiolingual teeth inclination [20]. Many malocclusions show an incorrect axial inclination of the teeth and, for treatment, it is absolutely necessary to express torque to obtain controlled root movement [22]. Furthermore, because third-order movements are also related to first order movements, failure to generate the torque in the setup will affect tooth height [5].

Torque expression is influenced by tooth morphology and many factors concerning wires or brackets, such as material properties, dimensions, accuracy, edge bevels, teeth position, and angle of torsion [12, 13, 19, 23]. The lack of fit between slot and wire is known as the angle of "play" or engagement angle. This angle represents the amount of rotation in degrees that a rectangular or square wire must be twisted to engage the slot and generate a biomechanical torque.

The lingual technique is often used to achieve a given treatment result. Ideally, the relationship between wire and slot should be given by the manufacturer, but due to the factors mentioned above, inaccuracies emerge. Daratsianos et al. [6] studied the total torque play and the precision of the slot size of various lingual systems. However, studies analyzing passive play and torque expression in different clinical situations are lacking. Thus, the aim of this study was to determine and compare the play and torque expression of self-ligating and conventionally ligated lingual brackets, with square and rectangular slots, when engaged with archwires of different size, cross section and material. The experiments for the study were investigator initiated and the involved manufacturers were not informed that their materials would be tested.

Materials and methods

Five different lingual brackets produced by four different manufacturers were selected for this study: two active self-ligating brackets with slot height of 0.018 inch, one passive self-ligating bracket with a square slot of 0.018 inch, one conventionally ligated bracket with a rectangular slot of 0.018×0.025 inch, and one conventionally ligated bracket with a rectangular slot of 0.025×0.017 inch (Table 1).

Five lingual upper first premolar brackets per type—having a torque prescription which is more neutral than that for anterior teeth—were welded to metal supports. The slots were ensured to be perfectly oriented perpendicular to the metal support axis thanks to the guidance of a viewfinder (×5 magnification) during fixation, in order to eliminate their tip and torque values.

The metal support with brackets attached was then photographed using a Leica MZ6 optical microscope (Leica Microsystems GmbH, Wetzlar, Germany). Aquinto A4I Docu software (Excel Technologies Inc., Enfield, CT, USA) was used to verify the effective perpendicularity of the bracket to the base of the support, and to measure the distance between the top of the support and the lower edge of each slot, in order to determine its position with as much precision as possible (Fig. 1a, b).

Three different archwires, produced by the same manufacturer, were selected for the study (one CuNiTi wire with square cross section and two stainless steel wires with both square and rectangular cross section), except for the brackets eBrace and Harmony, where the archwires were provided by the manufacturer (Table 2).

Each archwire was then engaged into a "torquing key", a type of plier purposely designed for the present study, to clamp the wire at two points, 6 mm apart (Fig. 2) in order to simulate the interbracket distance. The device also featured a perpendicular rod in the same plane as the orthodontic archwire, marked at a fixed distance of 22.87 mm to the plier clamps and archwire. The purpose of this key

Table 1 Brackets tested in the study
Tab. 1 In der Studie untersuchte Brackets

Manufacturer	Bracket brand name	Bracket type	Slot declared dimensions (inch)
Dentsply GAC (Bohemia, NY, USA)	In-Ovation L	Interactive self-ligating	0.018 height
American Orthodontics (Sheboygan, WI, USA)	Harmony	Interactive self-ligating	0.018 height
Ormco (Glendora, CA, USA)	STb	Traditional	0.018 × 0.025
Ormco (Glendora, CA, USA)	ALIAS	Passive self-ligating	0.018 × 0.018
Riton Biomaterial Co. Ltd. (Guangzhou, China)	eBrace	Traditional	0.025 × 0.017

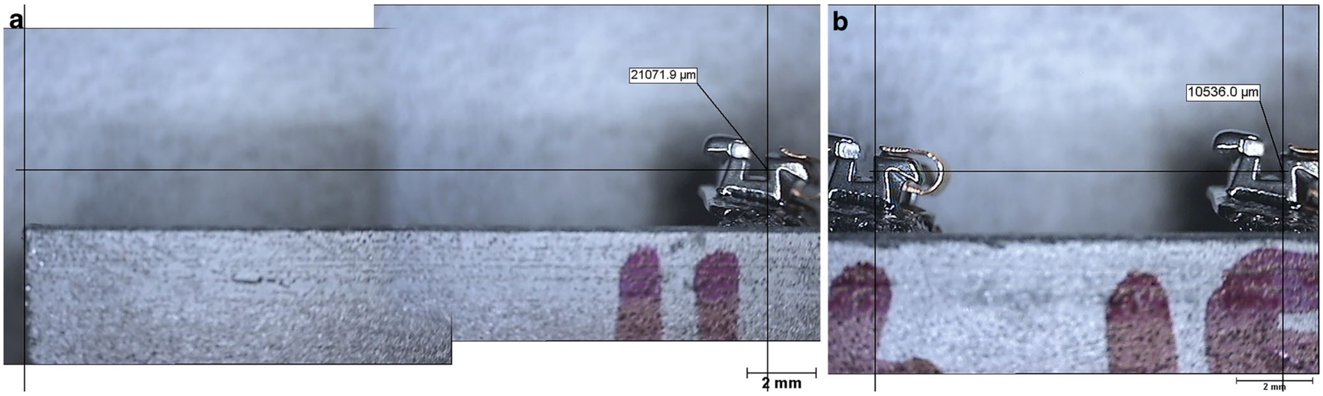

Fig. 1 Measurement of the distance between the top of the metal support (**a**) and the lower edge of each slot (**a**, **b**) (In-Ovation L brackets)
Abb. 1 Messung des Abstands zwischen der Oberseite des Metallträgers (**a**) und der Unterkante jedes Slots (**a**, **b**) (In-Ovation L-Brackets)

Table 2 Archwires selected for the study
Tab. 2 Für die Studie ausgewählte Bogendrähte

Manufacturer	Archwires brand name	Wire declared dimensions(inch)	Material	Declared slot/wire ratio
Ormco (Glendora, CA, USA)	Kleen Pak	0.018 × 0.018	SS	Full thickness
Ormco (Glendora, CA, USA)	Kleen Pak	0.017 × 0.025	SS	Undersized
Ormco (Glendora, CA, USA)	Kleen Pak	0.018 × 0.018	CuNiTi	Full thickness
American Orthodontics (Sheboygan, WI, USA)	GAC Pak	0.018 × 0.025	SS	Full thickness
American Orthodontics (Sheboygan, WI, USA)	GAC Pak	0.018 × 0.025	β titanium[c]	Full thickness
American Orthodontics (Sheboygan, WI, USA)	GAC Pak	0.017 × 0.017	NiTi	Undersized
Riton Biomaterial Co. Ltd. (Guangzhou, China)	Biolingual	0.025 × 0.017	SS	Full thickness
Riton Biomaterial Co. Ltd. (Guangzhou, China)	Biolingual	0.022 × 0.016	NiTi	Undersized
Riton Biomaterial Co. Ltd. (Guangzhou, China)	Biolingual	0.018 × 0.018	TMA	Undersized

SS stainless steel, *CuNiTi* copper nickel titanium, *β titanium* beta-titanium, *NiTi* nickel titanium, *TMA* titanium–molybdenum alloy (i.e. β-titanium)

was to transfer the precise information that is created between archwires and slots, facilitating the reading of the play and, through simple geometric calculations, allowing the analysis of the individual clinical situations (Fig. 3).

Referring to Fig. 3a, let y denote the vertical distance between the upper edge of the metal support and the free edge of the torquing key. Also, let x denote the vertical distance between the support's upper edge and the centerline of the slot, while the horizontal distance between the slot and the force application point will be indicated with d, which is the constant value of 22.87 mm as stated earlier. As a result, the angle of play in degrees, α, can be obtained from the vertical displacement (i.e. y–x) from the slot to the torquing key, which is connected through the archwire to the slot (Fig. 3a, c).

To assess the real play between the different archwires and the lingual bracket slots, load-deflection tests were performed using an INSTRON 4467 (Instron, Norwood, MA,

Fig. 2 Torquing key

Abb. 2 Torqueschlüssel

USA) dynamometer (load weighing accuracy, ±0.04% of the reading down to 1/100 of load cell capacity) featuring a 100 N load cell and a loading knife with a tip radius of 1 mm (Figs. 3a and 4).

The conventionally ligated brackets, for obvious repeatability reasons, were linked to the archwires with elastic ligatures, while for the self-ligating ones their own closure mechanism was used.

Engaging the archwire, the free end of the torquing key rod was spontaneously lowered with respect to the horizontal plane due to 'passive' play (Fig. 3c, d). In order to use Eq. 1, the x length was obtained by microscopy measurements (Fig. 1a, b). Concerning the y length, this measurement was obtained using the INSTRON 4467 cross head position indicator by manually lowering the loading knife from the upper edge of the metal support to the point of first contact with the free end of the torquing key.

$$\alpha = \arctan\frac{y-x}{d} \quad (1)$$

Using the INSTRON dynamometer to lower the loading knife further, a load is exerted on the key. The archwire, then, rotates within the slot and a torque is exerted, which is obtained by the Instron Da/DN Software. From the results of this test, we plotted a load-deflection curve for each experimental bracket/wire combination. Knowing the distance d and fixing the torque K at 5 Nmm, 10 Nmm and 20 Nmm (the extremes of the clinically efficacious range suggested by some authors [2, 17]), the load F at which the archwire expressed the fixed moments could be obtained by means of the formula $F = K/d$.

Each compatible archwire was tested five times in each bracket, and in each test, the passive play (i.e. the situation between two components in frictional contact) angle and

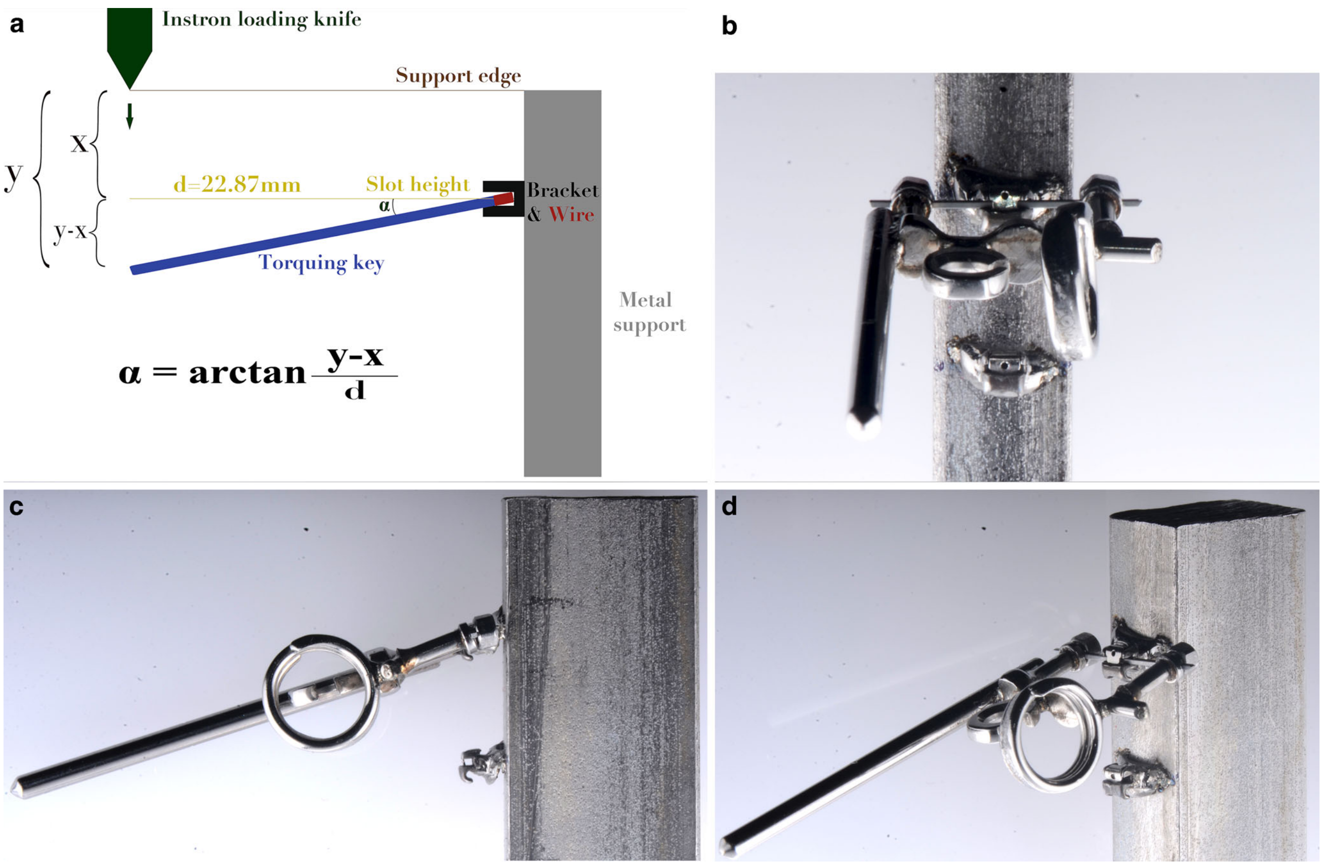

Fig. 3 Reading play between archwire and slot: schematized (**a**) and real with Harmony brackets (**b–d**)

Abb. 3 Ablesen des Spiels zwischen Drahtbogen und Slot: schematisiert (**a**) und real mit Harmony-Brackets (**b–d**)

Fig. 4 INSTRON 4467 dynamometer featuring a 100 N load cell and a loading knife
Abb. 4 Dynamometer INSTRON 4467 mit 100-N-Kraftmessdose und Lademesser

the torque angle at 5 Nmm, at 10 Nmm and at 20 Nmm was measured. These data were analyzed as follows:

- Using geometric calculations suggested by some authors, the ideal play for each archwire in each slot was identified. This is the angle of engagement that would result if the real-world dimensions of the slot and archwire matched those declared by the respective manufacturers, and assuming the archwire had 90° edge bevels [18].
- This angle was then compared with the real-world play measured earlier, using the standard error of the mean calculation to determine whether the differences were statistically significant ($P < 0.01$).
- Finally, for each single archwire in each compatible bracket of nominally identical slot dimension, the clinical significant torque angles were calculated.

The one sample t-test was used to verify if passive play was different from 0 among the various systems. Analysis of variance (ANOVA) statistical testing was use to compare different archwires. The two sample t-test using Bonferroni correction was used to assess the order of passive play between the various systems.

Results

The mean values, shown in Table 3, could be simplified and better understood by calculating the slope and the intercept of each load-deflection test with 0, 5, 10 and 20 Nmm (Fig. 5).

Table 3 shows the results of the load-deflection tests, where the mean of the 5 repeated measurements was entered for each box. Regarding full thickness SS archwires, significant differences between the various systems were found with ANOVA statistical testing ($p < 0.05$). Second, the t-test using Bonferroni correction was used to assess the amount of passive play between the various systems.

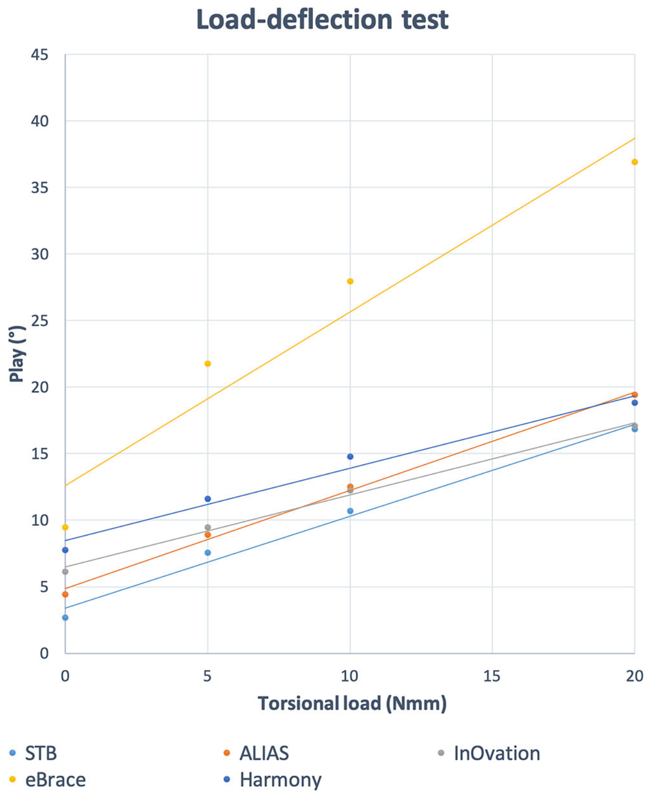

Fig. 5 Slope and intercept of each load-deflection test
Abb. 5 Steigung und Achsenabschnitt jedes Last-Auslenkung-Versuchs

The lowest passive play was found for the STb brackets (2.66 ± 0.89° with 0.018 × 0.018 inch SS), which was significantly different from zero as assessed through one-sample t-test ($p < 0.01$). This value was significantly lower than that for ALIAS brackets (mean 4.44 ± 0.75° with 0.018 × 0.018 inch SS), which was in turn significantly lower than that for the other systems, i.e., In-Ovation L brackets (mean 6.14 ± 3.22° with 0.018 × 0.018 inch SS), Harmony brackets (mean 7.76 ± 2.94° with 0.018 × 0.025 inch SS) and eBrace brackets (mean 9.46 ± 3.94° with 0.025 × 0.017 inch SS). Differences between the last three systems was not significant, mainly due to their higher standard deviations.

All systems increased their angle of play as a function of the applied torque, their slope being very close, with the possible exception of the e-Brace bracket. In fact, the e-Brace bracket had a slope of 1.31, while the other systems had a slope between 0.5 and 0.75. Moreover, as can be seen in Fig. 5, the load-deflection diagram of the eBrace system is also not perfectly aligned along a straight line. The differences in slope between the various systems were significantly different with ANOVA.

Although the STb and ALIAS brackets showed the best results concerning passive play, there were no significant differences between these two brackets and the In-Ovation L and Harmony brackets when increasing the torsional

Table 3 Results of the load-deflection tests

Tab. 3 Ergebnisse der Last-Auslenkung-Prüfungen

STb	Ideal play (°)	Passive play (°)	Load 5N (°)	Load 10N (°)	Load 20N (°)	ALIAS	Ideal play (°)	Passive play (°)	Load 5N (°)	Load 10N (°)	Load 20N (°)	In-Ovation L	Ideal play (°)	Passive play (°)	Load 5N (°)	Load 10N (°)	Load 20N (°)	eBrace	Ideal play (°)	Passive play (°)	Load 5N (°)	Load 10N (°)	Load 20N (°)	Harmony	Ideal play (°)	Passive play (°)	Load 5N (°)	Load 10N (°)	Load (N)
Full thickness SS arch-wire	–	–	–	–	–	*Full thickness SS arch-wire*	–	–	–	–	–	*Full thickness SS arch-wire*	–	–	–	–	–	*Full thickness SS arch-wire*	–	–	–	–	–	*Full thickness SS arch-wire*	–	–	–	–	–
0.018 × 0.018 SS	–	–	–	–	–	*0.018 × 0.018 SS*	–	–	–	–	–	*0.018 × 0.018 SS*	–	–	–	–	–	*0.025 × 0.017 SS*	–	–	–	–	–	*0.018 × 0.025 SS*	–	–	–	–	–
Avg bracket #1	0	1.75	6.55	9.92	16.49	Avg bracket #1	0	4.90	9.32	13.42	25.50	Avg bracket #1	0	5.93	8.80	11.23	15.55	Avg bracket #1	0	7.40	24.28	30.94	49.69	Avg bracket #1	0	5.45	8.67	10.84	14.55
Avg bracket #2	0	1.79	6.50	9.51	15.32	Avg bracket #2	0	4.65	8.87	12.43	17.89	Avg bracket #2	0	8.35	12.14	14.42	18.65	Avg bracket #2	0	6.27	17.33	22.18	28.01	Avg bracket #2	0	10.45	14.29	17.35	22.21
Avg bracket #3	0	3.81	9.88	13.67	20.12	Avg bracket #3	0	3.48	8.41	11.72	17.30	Avg bracket #3	0	8.60	11.34	15.21	21.33	Avg bracket #3	0	15.51	24.29	28.94	30.96	Avg bracket #3	0	7.35	11.51	14.62	18.64
Avg bracket #4	0	3.17	7.94	10.88	17.18	Avg bracket #4	0	3.87	8.22	11.57	17.64	Avg bracket #4	0	1.67	5.51	8.08	12.84	Avg bracket #4	0	11.35	26.80	33.26	47.57	Avg bracket #4	0	11.07	15.01	18.28	23.35
Avg bracket #5	0	2.79	7.01	9.41	15.02	Avg bracket #5	0	5.31	9.72	13.40	18.69	Avg bracket #5	0	–	–	–	–	Avg bracket #5	0	6.75	16.16	24.45	28.29	Avg bracket #5	0	4.46	8.46	12.87	15.32
Descr. statistics	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Average	–	2.66	7.58	10.68	16.83	–	–	4.44	8.91	12.51	19.40	–	–	6.14	9.45	12.24	17.10	–	–	9.46	21.77	27.95	36.90	–	–	7.76	11.59	14.79	18.81
SD*	–	0.89	1.41	1.77	2.04	–	–	0.75	0.62	0.89	3.45	–	–	3.22	2.99	3.26	3.69	–	–	3.94	4.72	4.57	10.79	–	–	2.94	3.05	3.08	3.95
ST Err	–	0.40	0.63	0.79	0.91	–	–	0.33	0.28	0.40	1.54	–	–	1.61	1.49	1.63	1.84	–	–	1.76	2.11	2.04	4.83	–	–	1.31	1.37	1.38	1.77
T	–	6.65	12.02	13.47	18.45	–	–	13.27	32.07	31.59	12.59	–	–	3.82	6.32	7.51	9.27	–	–	5.37	10.31	13.67	7.65	–	–	5.90	8.48	10.74	10.64
p value	–	0.00**	0.00**	0.00**	0.00**	–	–	0.00**	0.00**	0.00**	0.00**	–	–	0.00**	0.00**	0.00**	0.00**	–	–	0.00**	0.00**	0.00**	0.00**	–	–	0.00**	0.00**	0.00**	0.00**
P %	–	0.13	0.01	0.01	0.00	–	–	0.01	0.00	0.00	0.01	–	–	1.58	0.40	0.24	0.13	–	–	0.29	0.02	0.01	0.08	–	–	0.21	0.05	0.02	0.02
Undersized height	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	*Undersized TMA archwire*	–	–	–	–	–	*Full thickness β-Ti archwire*	–	–	–	–	–
0.017 × 0.025 SS	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	*0.018 × 0.018 TMA*	–	–	–	–	–	*0.018 × 0.025 β-Ti*	–	–	–	–	–
Avg bracket #1	2.35	1.11	6.07	9.75	15.73	–	–	–	–	–	–	–	–	–	–	–	–	Avg bracket #1	43.95	/	/	/	/	Avg bracket #1	0	4.07	8.47	11.74	18.47
Avg bracket #2	2.35	2.34	5.64	9.29	15.12	–	–	–	–	–	–	–	–	–	–	–	–	Avg bracket #2	43.95	/	/	/	/	Avg bracket #2	0	9.73	17.01	21.95	31.13
Avg bracket #3	2.35	4.33	9.85	13.13	15.50	–	–	–	–	–	–	–	–	–	–	–	–	Avg bracket #3	43.95	/	/	/	/	Avg bracket #3	0	7.61	14.00	18.81	26.12
Avg bracket #4	2.35	2.90	7.43	10.32	15.28	–	–	–	–	–	–	–	–	–	–	–	–	Avg bracket #4	43.95	/	/	/	/	Avg bracket #4	0	9.84	17.99	23.47	33.58
Avg bracket #5	2.35	2.22	9.79	13.64	13.17	–	–	–	–	–	–	–	–	–	–	–	–	Avg bracket #5	43.95	/	/	/	/	Avg bracket #5	0	3.10	8.57	17.54	22.57

Table 3 (Continued)
Tab. 3 (Fortsetzung)

STb	Ideal play (°)	Passive play (°)	Load 5N (°)	Load 10N (°)	Load 20N (°)	ALIAS	Ideal play (°)	Passive play (°)	Load 5N (°)	Load 10N (°)	Load 20N (°)	In-Ovation L	Ideal play (°)	Passive play (°)	Load 5N (°)	Load 10N (°)	Load 20N (°)	eBrace	Ideal play (°)	Passive play (°)	Load 5N (°)	Load 10N (°)	Load 20N (°)	Harmony	Ideal play (°)	Passive play (°)	Load 5N (°)	Load 10N (°)	Load (N)
Descr. statistics	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Average	–	2.58	7.75	11.23	14.96	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6.87	13.21	18.70	26.37
SD*	–	1.17	2.00	2.01	1.03	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3.15	4.53	4.55	6.15
ST Err	–	0.52	0.89	0.90	0.46	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.41	2.02	2.04	2.75
T	–	4.91	8.67	12.47	32.53	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4.88	6.53	9.18	9.58
p value	–	0.00**	0.00**	0.00**	0.00**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.00**	0.00**	0.00**	0.00**
P %	–	0.40	0.05	0.01	0.00	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.41	0.14	0.04	0.03
Full thickness SE archwire	–	–	–	–	–	*Full thickness SE archwire*	–	–	–	–	–	*Full thickness SE archwire*	–	–	–	–	–	*Undersized SE archwire*	–	–	–	–	–	*Undersized SE archwire*	–	–	–	–	–
0.018 × 0.018 CuNiTi	–	–	–	–	–	*0.018 × 0.018 CuNiTi*	–	–	–	–	–	*0.018 × 0.018 CuNiTi*	–	–	–	–	–	*0.022 × 0.016 NiTi*	–	–	–	–	–	*0.017 × 0.017 NiTi*	–	–	–	–	–
Avg bracket #1	0	2.57	14.14	/	/	Avg bracket #1	0	5.34	14.45	/	/	Avg bracket #1	0	10.15	17.98	/	/	Avg bracket #1	13.24	/	/	/	/	Avg bracket #1	3.49	8.67	15.34	19.48	29.27
Avg bracket #2	0	6.36	15.93	/	/	Avg bracket #2	0	5.58	15.19	/	/	Avg bracket #2	0	7.76	15.44	/	/	Avg bracket #2	13.24	/	/	/	/	Avg bracket #2	3.49	14.80	23.08	29.59	/
Avg bracket #3	0	6.04	16.37	/	/	Avg bracket #3	0	6.27	15.30	/	/	Avg bracket #3	0	10.39	18.62	/	/	Avg bracket #3	13.24	/	/	/	/	Avg bracket #3	3.49	10.82	18.11	23.45	32.62
Avg bracket #4	0	4.17	8.94	/	/	Avg bracket #4	0	5.55	14.22	/	/	Avg bracket #4	0	4.68	12.66	/	/	Avg bracket #4	13.24	/	/	/	/	Avg bracket #4	3.49	18.97	27.06	34.63	/
Avg bracket #5	0	3.79	8.01	/	/	Avg bracket #5	0	5.10	13.65	/	/	Avg bracket #5	0	7.18	16.13	/	/	Avg bracket #5	13.24	/	/	/	/	Avg bracket #5	3.49	12.70	18.35	27.95	32.92
Descr. statistics	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Average	–	4.59	12.68	–	–	–	–	5.57	14.56	–	–	–	–	8.03	16.16	–	–	–	–	–	–	–	–	–	–	13.19	20.39	27.02	31.60
SD*	–	1.59	3.94	–	–	–	–	0.44	0.69	–	–	–	–	2.35	2.35	–	–	–	–	–	–	–	–	–	–	3.95	4.65	5.81	2.02
ST Err	–	0.71	1.76	–	–	–	–	0.20	0.31	–	–	–	–	1.05	1.05	–	–	–	–	–	–	–	–	–	–	1.77	2.08	2.60	1.17
T	–	6.44	7.20	–	–	–	–	28.52	47.27	–	–	–	–	7.64	15.39	–	–	–	–	–	–	–	–	–	–	7.47	9.80	10.40	27.08
p value	–	0.00**	0.00**	–	–	–	–	0.00**	0.00**	–	–	–	–	0.00**	0.00**	–	–	–	–	–	–	–	–	–	–	0.00**	0.00**	0.00**	0.00**
P%	–	0.15	0.10	–	–	–	–	0.00	0.00	–	–	–	–	0.08	0.01	–	–	–	–	–	–	–	–	–	–	0.09	0.03	0.02	0.07

SD Standard deviation, *Avg* Average, *Descr. statistics* Descriptive statistics, *TMA* Titanium-Molybdenum alloy (i.e. beta-titanium), *β-Ti* beta-titanium, *SE* Superelastic, / The archwire is spinning in the slot; play is maximum, *ST ERR* standard error
* $p < 0.05$, ** $p < 0.01$

load to the greatest torque that is clinically applicable. The STb and In-Ovation L brackets showed the lowest angle of play when applying the greatest torsional load clinically applicable. Furthermore, the eBrace brackets showed the highest play and lowest moment at all torsional loads applied in this study.

Discussion

In this study, the materials and methods used allowed measurement of the in-built precision differences between the investigated brackets; however, the play angles in degrees will not correspond exactly to those of any different clinical situation, due to different positions of the teeth and different interbracket distances between each tooth [8].

No study in the literature has calculated passive play and torque expression in different clinical situations considering the repeatability of the measurements. In the present study, 5 brackets for each bracket type combined with 5 different wires each were analyzed, allowing us to obtain the mean values and standard deviations (Table 3). Daratsianos et al. [5] studied the torque generated by other types of lingual brackets with other methods and measurement devices; therefore, although there were two brackets in common, it is not possible to compare their results with the ones of the present study. Furthermore, there is no agreement in the literature about the ideal values for the amount of moment for torque expression [3, 9, 11, 14–16, 21]. However, the value of 5 Nmm is considered by most authors as the minimum moment value required for the torque of an upper central incisor [9, 11, 14–16]. The extremes of the clinically efficacious range suggested by some authors were 5–20 Nmm, where the value 20 Nmm could represent the situation after imprecise repositioning of a detached bracket while using a SS archwire or if a particularly accentuated third-order bend is placed during the finishing phase. For these reasons, in this study 0 Nmm, 5 Nmm, 10 Nmm and 20 Nmm were selected to analyze passive play and torque expression.

The difference in the materials of the wires with equal thickness (full thickness), as expectedly led to differences in the slope of the curves with increasing torsional load from 0 to 20 Nmm. In fact, values for 5 Nmm in load-deflection tests with NiTi wires were similar to those for 10 Nmm in load-deflection tests with SS wires [1].

The difference in the thickness of the wires of the same material (full thickness and undersized stainless steel) led to differences in the intercept of the curves. Thus, the differences became evident already from the passive play analyses. The play was strongly dependent on the relationship between the wire and slot size. This is clearly shown in Fig. 6, where the scanning electron microscope pictures of the different bracket types are shown for comparison purposes. As can be seen, in the STb system the full thickness SS archwire fit perfectly into the slot (Fig. 6a). Thus, it was able to develop the smallest play, both under passive conditions and after 20 Nmm of applied torque. The situation was analogous to the ones obtained for the ALIAS and the In-Ovation L systems (Fig. 6b, c), where the minimal gap between archwires and slots was insufficient for the development of remarkable play, and also after torque application, the angle of play remained relatively low. On the other hand, the eBrace and the Harmony systems (Fig. 6d, e) seemed to have a smaller amount of wire in contact with the slots, which was reflected both on the passive play and on the play after torque application.

The brackets in the electron microscope pictures were steel-ligated in order to reproduce the clinical situation. Unfortunately, as can be seen from those images, the steel ligature leads to differences between the various ligatures. In this study, the elastic ligatures led to more reproducible measurements, but do not agree with clinical torque application, which is a limit of this article. Self-ligation led to good reproducibility of the measurements and the slot closing mechanism is the same as that applied clinically. Compared with traditional ligation, self-ligation has the highly debated advantage of friction reduction. However, up to now, the only certain advantage for this type of brackets described in the literature is a decrease in appointment time [4, 7, 10].

Torque expression is not particularly influenced by the type of ligation or by the slot shape, but the determining factor is the dimensional accuracy of archwires and slots. Differences in the results between archwires of the same size but from different material allow us to understand the importance of the sequence of archwires for an adequate transmission of the torque information. However, no statistically significant differences were found between the 0.018 × 0.018 inch SS wire and the 0.017 × 0.025 inch SS wire when used together with the STb bracket. The reason for this lack of difference in play between these two wires in the same slot is explained by the formula of Meling et al. [18], which considers not only height of the slot, height of the wire, edge bevels as play variables, but also the distance between the two opposite corners in the wire cross section. This formula has also been used in order to calculate the ideal play and to compare it with the real play, quantifying the inaccuracy of bracket and archwire production.

The presented results showed that passive play allows us to understand the dimensional slots accuracy. However, the differences between the slopes (Fig. 5) emphasize that passive play is not perfectly proportional to the maximum clinically applicable torque (load-deflection test at 20 N).

The STb and ALIAS brackets generated the lowest passive play, but by increasing the torsional load to the greatest torque clinically applicable, there were no statistical differ-

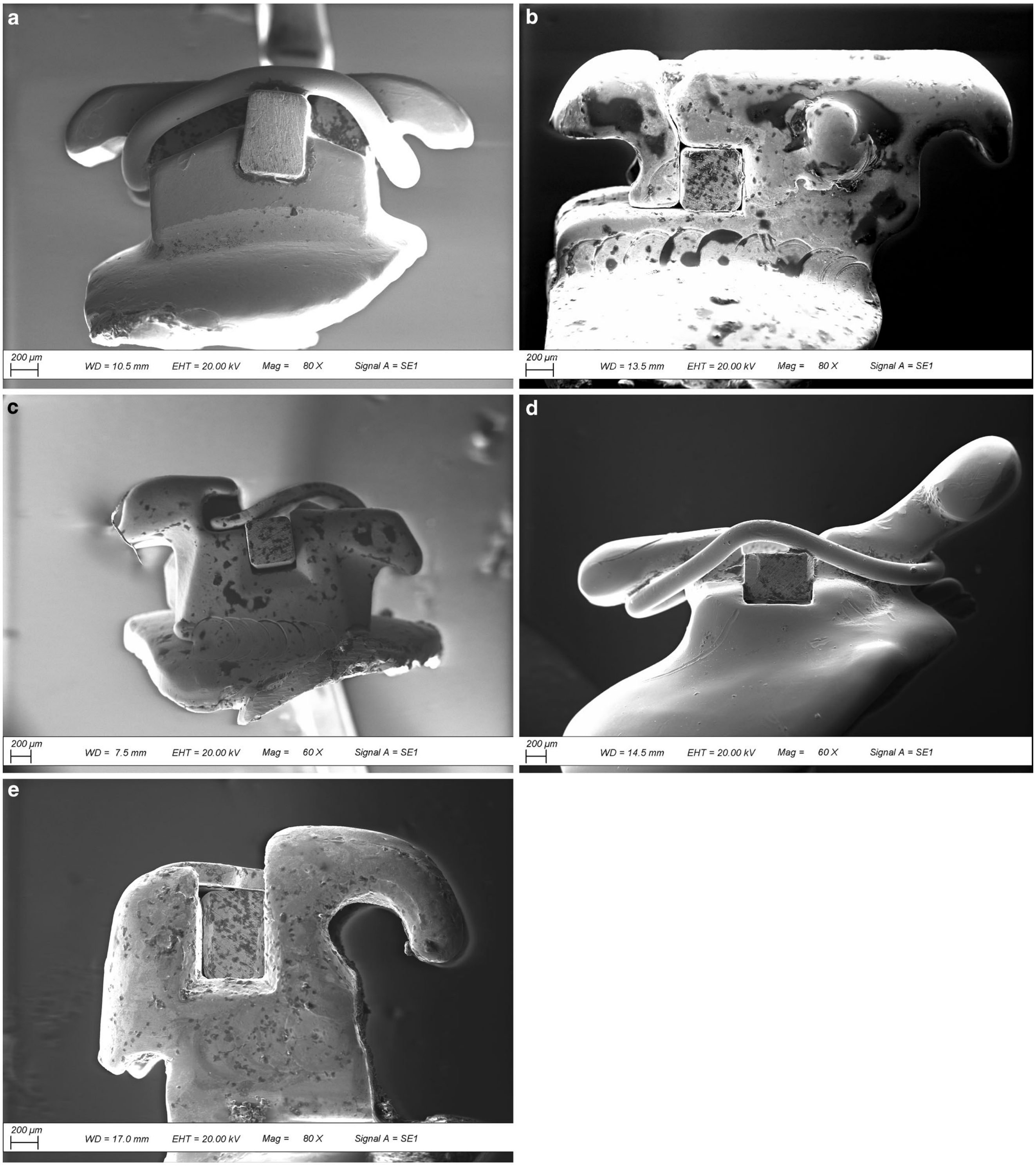

Fig. 6 Scanning electron microscope pictures of the different types of brackets: **a** STb, **b** ALIAS, **c** In-Ovation L, **d** eBrace, **e** Harmony

Abb. 6 Rasterelektronenmikroskopische Aufnahmen der verschiedenen Brackettypen: **a** STb; **b** ALIAS; **c** In-Ovation L; **d** eBrace; **e** Harmony ences between these two bracket types and the In-Ovation L and Harmony brackets.

Although there are differences between the lingual systems analyzed, the results did not reveal an excessive lack of precision; indeed, the most accurate appliances showed a high manufacturing accuracy. The recommended archwire sequence, especially for applying torque, in comparison with the customized brackets, must be analyzed in further studies.

In the lingual technique, refinement bends are very difficult to place, requiring manual operator skills and could be partly reduced by overcorrections in the setup. Therefore, it is important to understand the accuracy in the different systems, depending on whether we are using active and passive self-ligating or conventionally ligated brackets.

Conclusion

STb and ALIAS brackets generated the lowest passive play; STb and In-Ovation L brackets expressed the lowest angle of play when applying the greatest clinically applicable torsional load. Torque expression in lingual orthodontics is not influenced by the type of ligation. The dimensional accuracy of archwires and slots led to differences in third order force expression between the systems analyzed.

These measurements allow us to understand the accuracy of lingual systems and at the same time to estimate the amount of overcorrections to be applied in the setup in order to obtain high-quality orthodontic treatments.

Declarations

Conflict of interest P. Albertini, V. Mazzanti, F. Mollica, L. Lombardo and G. Siciliani declare that they have no competing interests.

Ethical standards All procedures performed in the study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1975 Helsinki declaration and its later amendments or comparable ethical standards. The study design was reviewed and approved by the Ethics Committee of Postgraduated School of Orthodontics of Ferrara University ,via Borsari 46, Ferrara, Italy (approval number 9/2017).

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