Original Article

Comparative analysis of real and ideal wire-slot play in square and rectangular archwires

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ABSTRACT

Objective: To evaluate the degree to which the height, width, and cross-section of rectangular and square orthodontic archwires affect the play between the archwires and the bracket slot.

Materials and Methods: The stated measurements (height and width) of 43 archwires from six different manufacturers were compared with real values obtained using a digital gauge. The curvature (radius) of the edge bevels was also measured to calculate the play within the slot, and this measurement was compared with the ideal value.

Results: The real height and width of the archwires differed from those stated by the manufacturers, falling within the range −6.47% and +5.10%. The curvature of each bevel on each archwire cross-section was shown to differ, and consequently increased the real play between the archwire and slot with respect to the ideal to different degrees.

Conclusions: The archwire-slot play was greater than the ideal for each archwire considered, inevitably leading to a loss of information within the system. (*Angle Orthod.* 2015;85:848–858.)

KEY WORDS: Edge bevel; Third-order play; Archwires; Wire imprecision

INTRODUCTION

Straight-wire orthodontic systems transmit first-second- and third-order information from the archwire to the teeth when the former comes into contact with the walls of the bracket slots.[1] However, the real position of the teeth often differs from that expected at the end of orthodontic treatment, especially in terms of dental inclination (torque). This means the clinician has to resort to special measures to compensate for gaps in the information expressed by the system, for example, with finishing bends.[2] For complete transmission of information, in particular the torque, from the appliance to the teeth, the archwire dimensions must coincide as closely as possible with those of the bracket slot. Indeed, the greater the difference between the two, the more degrees of freedom the archwire is allowed (the archwire-slot play), and the smaller the capacity of the system to express the preprogrammed information.[3]

However, even when full-dimension archwires are used, there is always a small loss of information, which is correlated with the dimensional tolerance of the appliance components on the market, that is, the real dimensions of the slot, archwire, and edge bevel with respect to the ideal.[3] If the real dimensions of these components were as stated by the manufacturers, and the edges were precisely 90°, the ideal archwire-slot play would result, but this is rarely, if ever, the case (Figure 1). In fact, real bracket slots have been shown to be consistently larger than their stated dimensions, although the extent to which values differ naturally vary widely among samples. Electronic microscopy has shown that both lingual and labial bracket slot heights are between +0.56 and +11.16% greater than those declared,[4] and Demling et al.,[5] using a pin gauge to measure the slot height in three lingual systems, found

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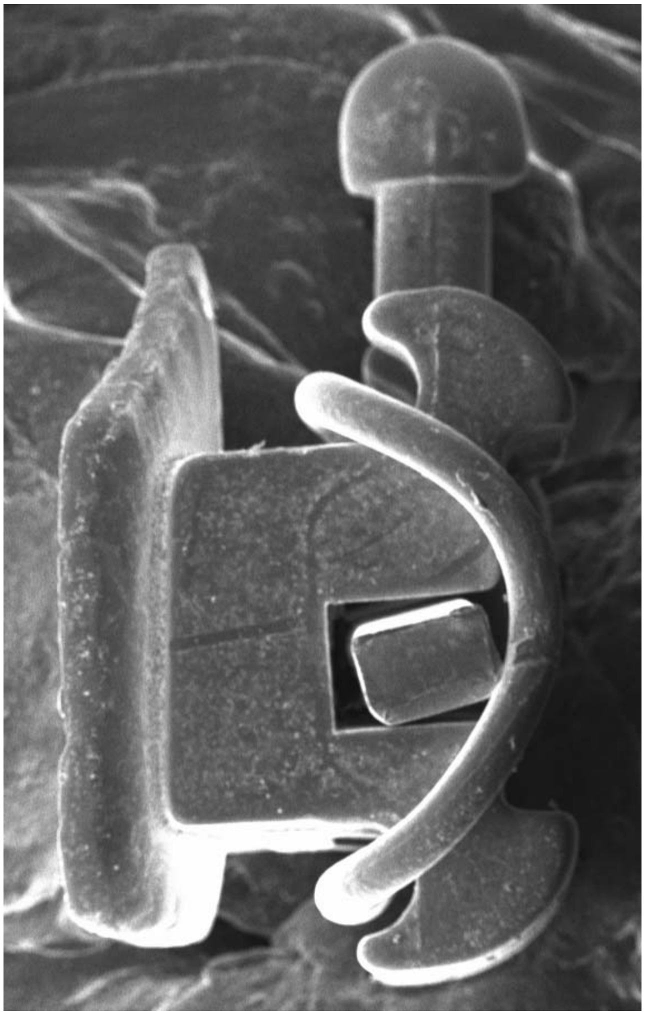

Figure 1. Real relationship between archwire and slot, as seen under an electronic microscope.

that they were oversized by up to 2.2%. In a selection of labial brackets, Cash et al.[6] also found that slots were 6% to 17% larger than claimed.

The real dimensions of orthodontic archwires have also been studied extensively, but results have been less consistent. Fischer-Brandies et al.,[7] for example, used a digital micrometer to measure the cross-section of 15 types of square and rectangular steel archwires and found that all were smaller than the manufacturers claimed; the difference ranged from −9.7% to −10.7%. In contrast, other authors have highlighted cases of undersized and oversized archwires, stating, however, that the discrepancy seldom exceeded 0.0005 inch with respect to the ideal.[3,4,8,9] It is unclear, therefore, what, if any, role the dimensional imprecision of archwires may play in increasing the archwire-slot play.

The effect of a third geometric parameter, however, does seem to be decisive, namely the bevelled edge of the archwire. Observed in cross-section, it is evident that neither square nor rectangular archwires possess

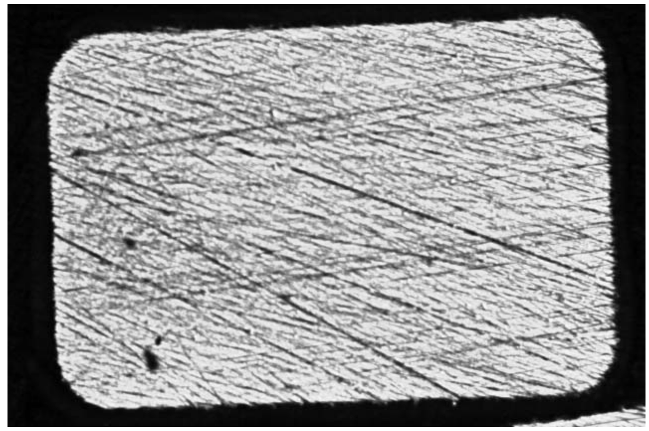

Figure 2. Cross-section of rectangular archwire, as seen under an optical microscope.

exactly square corners; instead, they are rounded to varying degrees (Figure 2). This edge bevel owes its presence to two main factors: primarily, the need to promote patient comfort, as sharp 90° edges could cut the lips or inner cheeks,[10] but also the manufacturing process itself. Nevertheless, the beveling means that the archwire meets the walls of the slot at greater angles than the ideal, thereby increasing the play between the two and lessening the system's capacity to express torque (Figure 3). For this reason the beveled edge of commercially available archwires has been studied by numerous authors.[7] Juvvadi et al.,[11] for instance, measured the radius of the bevel in 30 archwires of different materials on photographs of the archwire cross-section magnified 150 times. Meling and Ødegaard[3,8] also used photographic enlargements to measure the cross-sections of nickel titanium (NiTi0 and steel archwires, estimating the dimensions of their edge bevels by means of an acetate template. All authors mentioned compared the

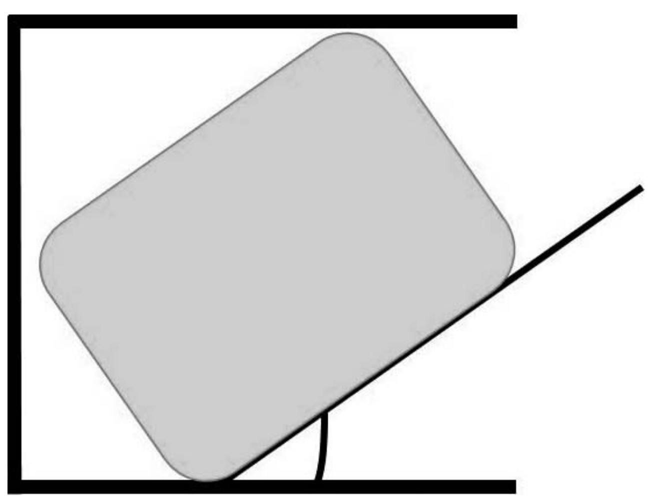

Figure 3. Representation of real archwire-slot play.

Table 1. Archwires Investigated in the Study[a]

Manufacturer	Size	Material
3M	.014 × .025	NiTinol SE
3M	.017 × .025	NiTinol SE
3M	.019 × .025	NiTinol SE
3M	.019 × .025	NiTinol Classic
3M	.019 × .025	NiTiHA
3M	.021 × .025	NiTiHA
3M	.019 × .025	SS
Lancer	.019 × .025	Thermal NiTi
Lancer	.021 × .025	TMA
Lancer	.019 × .025	SS
Leone	.016 × .022	NiTi
Leone	.019 × .025	NiTi
Leone	.019 × .025	Coated NiTi
Leone	.016 × .022	SS
Leone	.018 × .025	SS
Ortho Technology	.019 × .025	NiTi
Ortho Technology	.019 × .025	SS
Ortho Technology	.019 × .027	Coated NiTi
Ortho Technology	.019 × .027	Coated SS
GAC	.016 × .022	Super-tempered SS
GAC	.018 × .022	Super-tempered SS
Ormco	.016 × .016	STB CuNiTi
Ormco	.017 × .017	STB CuNiTi
Ormco	.018 × .018	CuNiTi
Ormco	.014 × .025	Damon CuNiTi
Ormco	.016 × .025	Damon CuNiTi
Ormco	.017 × .025	NiTi reverse curve
Ormco	.018 × .025	Damon CuNiTi
Ormco	.0175 × .0175	TMA
Ormco	.017 × .025	Damon TMA
Ormco	.019 × .025	Damon TMA
Ormco	.021 × .025	TMA
Ormco	.016 × .016	Straight length SS
Ormco	.018 × .018	STb SS
Ormco	.016 × .022	Straight length SS
Ormco	.017 × .022	Straight length SS
Ormco	.017 × .025	Straight length SS
Ormco	.018 × .022	Straight length SS
Ormco	.018 × .025	Straight length SS
Ormco	.019 × .025	Damon SS
Ormco	.019 × .025	SS
Ormco	.019 × .025	Straight length SS
Ormco	.021 × .025	Straight length SS

[a] NiTi indicates nickel titanium; TMA, titanium alloy; SS, stainless steel; TMA = titanium molybdenum alloy; SE = superelastic; HA = heat activated; CuNiTi = copper nickel titanium.

3M Unitek, Monrovia, CA, USA; Lancer, Vista, CA, USA; Leone, Firenze, Italy; Ortho Technology, Tampa, FL, USA; GAC Dentsply, Bohemia, NY, USA; ORMCO, Orange, CA, USA.

edge bevel dimensions of various samples to determine their relative curvature, but none attempted to quantify the real increase in play that such a feature brings about. Hence, we set out to determine how the real archwire dimensions and edge bevel affect the play between archwire and slot in square and rectangular orthodontic wires. The null hypothesis was that the real archwire dimension does not differ significantly from the ideal one, and the edge bevel does not affect the play between the archwires and the bracket slot.

Figure 4. Measuring archwire dimensions using a digital gauge (MMT 0.001 mm, Vogel).

MATERIALS AND METHODS

Forty-three widely available orthodontic archwires from six different manufacturers were selected for their differing fabrication materials—stainless steel, super-tempered stainless steel, NiTi, titanium alloy (TMA), and coated esthetic wires—cross-section (square and rectangular), and dimensions (Table 1). Three samples of each type of archwire were randomly selected, and the 25-mm terminal portion of each was sectioned off, it being the straightest and therefore most reliable for measurement purposes. The height, width, and edge bevel radii were measured for each sample, and a mean of the three sample measurements was obtained for each type of archwire. The height and width of each archwire sample was measured by the same operator using a digital gauge (MMT 0.001 mm, Vogel, Brescia, Italy) (Figure 4). The same measurements were repeated 24 hours later by a second operator on seven randomly selected samples, giving a total of 14 measurements for calculating the reproducibility of the protocol via the intraclass correlation (ICC) coefficient ρ.[12] The measured heights and widths of the archwires were compared with those claimed by the manufacturers, and a one-way *t*-test was used to determine the significance of any differences. For the statistical analysis, R Core Team (2014) and specialized R packages were used (Lucent Tech, Murray Hill, NJ, USA).

To measure the bevel at each of the four corners in the cross-section of each archwire, groups of four samples at a time were inserted into a metal support to ensure their vertical position, perpendicular to the work surface (Figure 5). Each group was then embedded in a phenolic resin to hold the wires in place (Figure 6). The resin was heated to 180° under pressure for 10 minutes and left to cool until completely set. The surfaces of each sample were then subjected to standard grinding and polishing procedures down to a width of 3 mm to remove any surface irregularities or distortions and to aid visibility of the archwire cross-sections. Each sample was then placed under an optical microscope (Leica Microsystem, Wetzlar,


Figure 5. Archwire sample support.

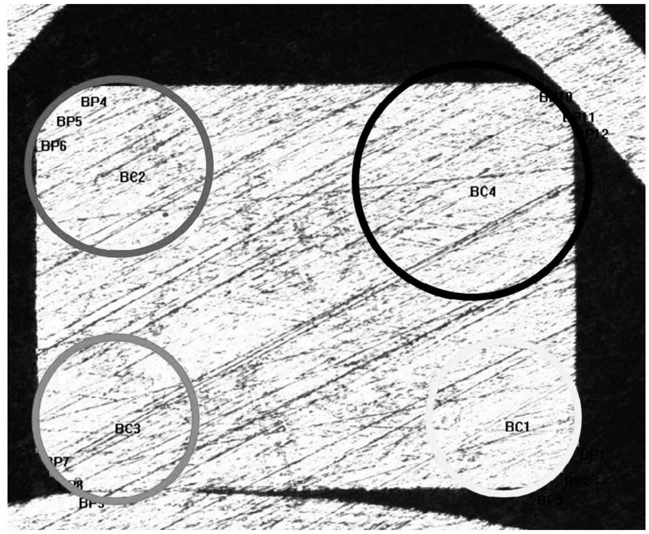

Figure 7. Calculating the radius of each edge bevel.

Germany) and micrographs were acquired using the integrated camera (magnification 100×). Each micrograph was then processed using digital image analysis software as follows: three points, corresponding to the terminal and central points of the curve, were selected and marked on each edge bevel on each sample and used to calculate the radius of their curvature (Figure 7). Measurements were repeated by a second operator on five randomly selected archwires 24 hours later. Thus, 22 measurements were subjected to calculation of the intraclass correlation coefficient ρ to determine the reproducibility of the measurement protocol.[12]

A modified version of the mathematical formula proposed by Meling et al.[13] was used to calculate the real value of the archwire-slot play from the variables archwire dimensions, slot size, and edge bevel radius (Figure 8). Archwire height, width, and bevel radius measurements were recorded as variables on an Excel spreadsheet (Microsoft Excel 2007, Redmond, WA, USA). As the aim was to define the role of archwire variables in determining the archwire-slot play, the slot height was maintained as an ideal constant parameter at 0.018″ for the square archwires and 0.022″ for the rectangular archwires. Thus, the spreadsheet was


Figure 6. Archwire samples embedded in phenolic resin.

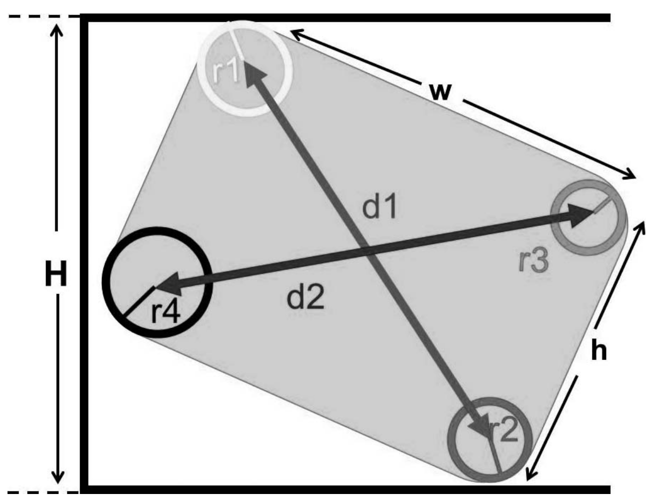

Figure 8. Geometric parameters used to calculate the real archwire-slot play. H indicates slot height; h, archwire height; w, archwire width; d, diagonal distance between opposing curvature radii; r, radius edge bevel.

Table 2. Real and Ideal Dimensions of the Archwires Tested[a]

Manufacturer	Size	Material	Height				Width			
			Ideal	Mean	SD	% Variation	Ideal	Mean	SD	% Variation
3M	.014 × .025	NiTinol SE	.014	.01392	.00003	−0.60	.025	.02518	.00013	+0.73
3M	.017 × .025	NiTinol SE	.017	.01693	.00003	−0.39	.025	.02515	.00010	+0.60
3M	.019 × .025	NiTinol SE	.019	.01878	.00008	−1.14	.025	.02483	.00008	−0.67
3M	.019 × .025	NiTinol Classic	.019	.01861	.00045	−2.04	.025	.02473	.00018	−1.07
3M	.019 × .025	NiTiHA	.019	.01880	.00013	−1.05	.025	.02493	.00014	−0.27
3M	.021 × .025	NiTiHA	.021	.02083	.00008	−0.79	.025	.02493	.00006	−0.27
3M	.019 × .025	SS	.019	.01907	.00006	+0.35	.025	.02475	.00020	−1.00
Lancer	.019 × .025	Thermal NiTi	.019	.01892	.00012	−0.44	.025	.02482	.00023	−0.73
Lancer	.021 × .025	TMA	.021	.02078	.00003	−1.03	.025	.02477	.00003	−0.92
Lancer	.019 × .025	SS	.019	.01900	.00005	+0.00	.025	.02507	.00010	+0.27
Leone	.016 × .022	NiTi	.016	.01633	.00004	+2.06	.022	.02209	.00008	+0.42
Leone	.019 × .025	NiTi	.019	.01913	.00006	+0.70	.025	.02503	.00006	+0.13
Leone	.019 × .025	Coated NiTi	.019	.01904	.00012	+0.18	.025	.02628	.00120	+5.10
Leone	.016 × .022	SS	.016	.01664	.00012	+3.98	.022	.02250	.00010	+2.26
Leone	.018 × .025	SS	.018	.01820	.00010	+1.11	.025	.02537	.00012	+1.47
Ortho Technology	.019 × .025	NiTi	.019	.01947	.00015	+2.46	.025	.02530	.00010	+1.20
Ortho Technology	.019 × .025	SS	.019	.01970	.00000	+3.68	.025	.02573	.00006	+2.91
Ortho Technology	.019 × .027	Coated NiTi	.019	.01967	.00026	+3.52	.027	.02810	.00018	+4.06
Ortho Technology	.019 × .027	Coated SS	.019	.01950	.00056	+2.64	.027	.02786	.00030	+3.19
GAC	.016 × .022	ST SS	.016	.01590	.00000	−0.62	.022	.02197	.00006	−0.15
GAC	.018 × .022	ST SS	.018	.01742	.00010	−3.24	.022	.02213	.00007	+0.58
Ormco	.016 × .016	STB CuNiTi	.016	.01613	.00006	+0.83	.016	.01607	.00006	+0.42
Ormco	.017 × .017	STB CuNiTi	.017	.01682	.00013	−1.08	.017	.01678	.00013	−1.27
Ormco	.018 × .018	CuNiTi	.018	.01777	.00008	−1.30	.018	.01770	.00013	−1.67
Ormco	.014 × .025	Damon CuNiTi	.014	.01409	.00002	+0.62	.025	.02505	.00005	+0.20
Ormco	.016 × .025	Damon CuNiTi	.016	.01645	.00005	+2.81	.025	.02483	.00008	−0.67
Ormco	.017 × .025	NiTi reverse curve	.017	.01702	.00008	+0.10	.025	.02460	.00013	−1.60
Ormco	.018 × .025	Damon CuNiTi	.018	.01758	.00003	−2.31	.025	.02458	.00008	−1.67
Ormco	.0175 × .0175	TMA	.018	.01742	.00003	−0.48	.0175	.01742	.00023	−0.48
Ormco	.017 × .025	Damon TMA	.017	.01705	.00005	+0.29	.025	.02498	.00003	−0.09
Ormco	.019 × .025	Damon TMA	.019	.01912	.00008	+0.61	.025	.02443	.00008	−2.27
Ormco	.021 × .025	TMA	.021	.02123	.00006	+1.11	.025	.02445	.00010	−2.20
Ormco	.016 × .016	Straight length SS	.016	.01598	.00003	−0.10	.016	.01613	.00003	+0.83
Ormco	.018 × .018	STb SS	.018	.01760	.00009	−2.22	.018	.01762	.00010	−2.13
Ormco	.016 × .022	Straight length SS	.016	.01585	.00030	−0.94	.022	.02188	.00014	−0.53
Ormco	.017 × .022	Straight length SS	.017	.01590	.00049	−6.47	.022	.02190	.00022	−0.45
Ormco	.017 × .025	Straight length SS	.017	.01710	.00000	+0.59	.025	.02483	.00016	−0.67
Ormco	.018 × .022	Straight length SS	.018	.01762	.00016	−2.13	.022	.02183	.00012	−0.76
Ormco	.018 × .025	Straight length SS	.018	.01758	.00006	−2.31	.025	.02485	.00000	−0.60
Ormco	.019 × .025	Straight length SS	.019	.01882	.00003	−0.96	.025	.02483	.00008	−0.67
Ormco	.019 × .025	Damon SS	.019	.01903	.00003	+0.18	.025	.02503	.00006	+0.13
Ormco	.019 × .025	SS	.019	.01877	.00010	−1.23	.025	.02500	.00010	+0.00
Ormco	.021 × .025	Straight length SS	.021	.02110	.00000	+0.48	.025	.02490	.00000	−0.40

[a] SD indicates standard deviation; SS, stainless steel; NiTi, nickel titanium; TMA, titanium alloy.

used to calculate the play imputable to the orthodontic archwire. This real play value was then compared with the ideal play, calculated mathematically. The difference between the two values was calculated as an absolute and as a percentage, and a one-way *t*-test was used to determine the statistical significance of said difference.

RESULTS

As shown Table 2, of the 43 archwires considered, the archwire height was greater than claimed in 21 cases, and smaller in 22. The width was greater than claimed in 18 cases and smaller in 25. The most undersized wire was the Ormco 0.017 × 0.025″ stainless steel (height −6.47%), and the most oversized was the coated Leone 0 019 × 0.025″ NiTi (width +5.10%). In several cases the real dimensions were significantly different from the ideal, but in other cases they were not (Tables 3 and 4).

The results of the archwire-slot play analysis shown in Table 5 reveal that the real play was invariably greater than the ideal, in a range varying between +34.26% (Leone 0.016 × 0.022″ NiTi) and +313.73% (Ormco 0.0175 × .0175″ TMA). All such differences were found to be statistically significant (Table 6).

Table 3. Statistical Analysis of Archwire Precision in Terms of Height[a]

Manufacturer	Material	Nominal Value	No. of Samples	Mean Error	Standard Error	Statistic	*P* Value
3M	NiTinol SE	.014	3	−0.0001	0.0000	−5.00	.10*
3M	NiTinol SE	.017	3	−0.0001	0.0000	−4.00	.11
3M	NiTinol SE	.019	3	−0.0002	0.0001	−4.91	.10*
3M	NiTinol Classic	.019	3	−0.0004	0.0005	−1.48	.32
3M	NiTiHA	.019	3	−0.0002	0.0001	−2.62	.18
3M	NiTiHA	.021	3	−0.0002	0.0001	−3.78	.11
3M	SS	.019	3	0.0001	0.0001	2.00	.23
Lancer	Thermal NiTi	.019	3	−0.0002	0.0003	−1.26	.37
Lancer	TMA	.021	3	−0.0002	0.0000	−13.00	.04**
Lancer	SS	.019	3	0.0000	0.0000	0.00	1.00
Leone	NiTi	.016	3	0.0003	0.0000	14.29	.04**
Leone	NiTi	.019	3	0.0001	0.0001	4.00	.11
Leone	Coated NiTi	.019	3	0.0000	0.0001	0.43	.75
Leone	SS	.016	3	0.0006	0.0001	9.55	.06*
Leone	SS	.018	3	0.0002	0.0001	3.46	.12
Ortho Technology	NiTi	.019	3	0.0005	0.0002	5.29	.10*
Ortho Technology	SS	.019	3	0.0007	0.0000	6.5	.04**
Ortho Technology	Coated NiTi	.019	3	0.0007	0.0003	4.47	.11
Ortho Technology	Coated SS	.019	3	0.0005	0.0006	1.56	.32
GAC	Super-tempered SS	.016	3	−0.0001	0.0000	3.43	.31
GAC	Super-tempered SS	.018	3	−0.0006	0.0001	−9.71	.06*
Ormco	STb CuNiTi	.016	3	0.0001	0.0001	4.00	.11
Ormco	STb CuNiTi	.017	3	−0.0002	0.0001	−2.52	.18
Ormco	CuNiTi	.018	3	−0.0002	0.0001	−5.29	.10*
Ormco	Damon CuNiTi	.014	3	0.0001	0.0000	6.5	.08*
Ormco	Damon CuNiTi	.016	3	0.0004	0.0000	15.59	.04**
Ormco	NiTi Reverse Curve	.017	3	0.0000	0.0001	0.38	.76
Ormco	Damon CuNiTi	.018	3	−0.0004	0.0000	−25.00	.03**
Ormco	TMA	.0175	3	−0.0001	0.0000	−5.00	.10*
Ormco	Damon TMA	.017	3	0.0000	0.0000	1.73	.28
Ormco	Damon TMA	.019	3	0.0001	0.0001	2.65	.18
Ormco	TMA	.021	3	0.0002	0.0001	7.00	.08*
Ormco	Straight length SS	.016	6	−0.0001	0.0002	−0.99	.40
Ormco	STb SS	.018	3	−0.0004	0.0001	−8.00	.07*
Ormco	Straight length SS	.017	6	−0.0005	0.0007	−1.68	.21
Ormco	Straight length SS	.018	6	−0.0004	0.0001	−8.94	.01***
Ormco	Straight length SS	.019	6	0.0010	0.0013	1.88	.18
Ormco	Damon SS	.019	3	0.0000	0.0000	2.00	.23
Ormco	SS	.021	3	−0.0002	0.0001	−3.88	.11

[a] SS indicates stainless steel; NiTi, nickel titanium; TMA, titanium alloy.

* $P < .10$; ** $P < .05$; *** $P < .01$.

Sometimes there was a correlation between manufacturer and dimensional precision. In the sample we analyzed, Ortho Technology, Ormco, and Leone archwire dimensions were statistically less precise than those of other firms, and 3M, GAC, and Lancer exhibited smaller, comparable mean errors (Table 7). As regards the edge bevel analysis, the archwires produced by GAC tended to display greater play values, and those produced by Lancer and Ortho Technology the least. That being said, the difference between real and ideal play was highly significant for all manufacturers considered (Table 7).

The statistical correlation between archwire material, dimensional precision, and real play is reported in Table 8. This analysis revealed that coated and TMA archwires display greater imprecision in terms of width than those made of NiTi, stainless steel, or super-tempered stainless steel and were statistically similar in this regard. The construction material was also significantly correlated with the real play values, which were smaller in coated archwires, followed by TMA and NiTi, and were greater in stainless steel and super-tempered stainless steel wires.

Reproducibility of the Experiment

Calculation of the ICC ρ was used to test the reproducibility of the protocol.[12]

- For the parameter archwire height, the ICC ρ was 1 and the 95% confidence interval was 0.99–1, thereby showing very good agreement between raters.
- For width, the ICC ρ was 0.94 and the 95% confidence interval was 0.70–0.99, showing adequate inter-rater agreement.

Table 4. Statistical Analysis of Archwire Precision in Terms of Width[a]

Manufacturer	Material	Nominal Value	No. of Samples	Mean Error	SD Error	Statistic	*P* Value
3M	NiTinol SE	.025	9	0.0001	0.0002	29.50	.47
3M	NiTinol Classic	.025	3	−0.0003	0.0002	−2.63	.21
3M	NiTiHA	.025	6	−0.0001	0.0001	−1.66	.25
3M	SS	.025	3	−0.0003	0.0002	−2.17	.25
Lancer	Thermal NiTi	.025	3	−0.0002	0.0002	−1.41	.38
Lancer	TMA	.025	3	−0.0002	0.0000	−15.06	.05**
Lancer	SS	.025	3	0.0001	0.0001	1.11	.46
Leone	NiTi	.022	3	0.0001	0.0001	1.94	.27
Leone	NiTi	.025	3	0.0000	0.0001	1.00	.47
Leone	Coated SS	.025	3	0.0013	0.0012	1.84	.28
Leone	SS	.022	3	0.0005	0.0001	9.05	.06*
Leone	SS	.025	3	0.0004	0.0001	5.50	.09*
Ortho Technology	NiTi	.025	3	0.0003	0.0001	5.20	.09*
Ortho Technology	SS	.025	3	0.0007	0.0001	19.58	.04**
Ortho Technology	Coated NiTi	.027	3	0.0011	0.0002	10.78	.06*
Ortho Technology	Coated SS	.027	3	0.0009	0.0003	4.86	.09*
GAC	Super-tempered SS	.016	6	0.0000	0.0001	1.10	.40
Ormco	STb CuNiTi	.017	3	0.0001	0.0001	2.00	.27
Ormco	STb CuNiTi	.018	3	−0.0002	0.0001	−2.98	.18
Ormco	CuNiTi	.018	3	−0.0003	0.0001	−3.93	.12
Ormco	Damon CuNiTi	.025	9	−0.0002	0.0002	3.00	.09*
Ormco	NiTi reverse curve	.025	3	−0.0004	0.0001	−5.24	.09*
Ormco	TMA	.0175	3	−0.0001	0.0002	−0.63	.62
Ormco	Damon TMA	.025	6	−0.0003	0.0003	−2.37	.12
Ormco	TMA	.025	3	−0.0006	0.0001	−9.53	.06*
Ormco	Straight length SS	.016	3	0.0001	0.0000	8.00	.07*
Ormco	STb SS	.018	3	−0.0004	0.0001	−6.38	.09*
Ormco	Straight length SS	.022	9	−0.0001	0.0001	3.00	.09*
Ormco	Straight length SS	.025	12	−0.0001	0.0001	0.00	.04**
Ormco	Damon SS	.025	3	0.0000	0.0001	1.00	.47
Ormco	SS	.025	3	−0.0000	0.0001	−0.00	1.00

[a] SS indicates stainless steel; NiTi, nickel titanium; TMA, titanium alloy.
* $P < 0.10$; ** $P < .05$; *** $P < .01$.

- For play, the ICC ρ was 1 and the 95% confidence interval was 0.99–1, demonstrating very good interrater agreement.

This confirms the high reproducibility of the methods used to measure the archwires and analyze the play.

DISCUSSION

All straight-wire orthodontic techniques rely on preprogrammed brackets. The tip and torque values may vary between straight-wire systems, albeit by few degrees, and the advantages and disadvantages of these minor variations in prescription have been amply debated in the literature.[14–16] Although this is a valid issue from a theoretical perspective, in practice such small differences in torque can only be expressed if very precisely manufactured straight-wire components are available.[13] However, in the real world the archwire and bracket slot dimensions declared by manufacturers do not always correspond to the real measurements, and no information on the size tolerance of the materials on the market is provided. Hence, clinicians cannot determine how the preprogrammed information, in particular third order, will be transmitted to the teeth.

Extensive investigation into real orthodontic appliance components have shown that bracket slots are invariably oversized,[4–6] whereas some archwire cross-sections are larger and some smaller than claimed by the manufacturers.[3,4,7–9] This is confirmed by our measurements, although we found that the stated measurements were more precise than those reported by other authors, with a tolerance range of −6.47% to +5.10%, as opposed to the 17% reported elsewhere.[6]

The role of the archwire edge bevel has not yet been studied in depth. Fischer-Brandies et al.,[7] Meling and Ødegaard,[8] and Juvvadi et al.[11] all measured and compared the bevel radius of orthodontic wires produced by different manufacturers, but no author has yet attempted to quantify the consequent increase in archwire-slot play.

Measurement of the radius of the curvature of the archwire edge bevel needs to be performed with care. Specifically, the cross-section of the archwire must be photographed so that its surface is perfectly parallel to the work surface to prevent optical distortion. We

Table 5. Analysis of Archwire-Slot Play[a]

Manufacturer	Size	Material	Slot	Ideal Play (°)	Mean of the Real Play (°)	SD	Difference (°)	Difference (%)
3M	.014 × .025	NiTinol SE	.022	20.9	30.08	0.90	9.18	43.94
3M	.017 × .025	NiTinol SE	.022	12.5	17.22	0.99	4.72	37.73
3M	.019 × .025	NiTinol SE	.022	7.2	11.10	0.43	3.90	54.17
3M	.019 × .025	NiTinol Classic	.022	7.2	11.10	0.43	3.90	54.17
3M	.019 × .025	NiTiHA	.022	7.2	10.62	0.48	3.42	47.45
3M	.021 × .025	NiTiHA	.022	2.3	3.28	0.39	0.98	42.75
3M	.019 × .025	SS	.022	7.2	10.80	0.72	3.60	50.00
Lancer	.019 × .025	Thermal NiTi	.022	7.2	10.55	0.19	3.35	46.53
Lancer	.021 × .025	TMA	.022	2.3	4.43	1.49	2.13	92.75
Lancer	.019 × .025	SS	.022	7.2	11.03	1.20	3.83	53.24
Leone	.016 × .022	NiTi	.022	17.9	24.03	0.91	6.13	34.26
Leone	.019 × .025	NiTi	.022	7.2	10.15	0.42	2.95	40.97
Leone	.019 × .025	Coated NiTi	.022	7.2	10.73	1.44	3.53	49.07
Leone	.016 × .022	SS	.022	17.9	26.97	3.20	9.07	50.65
Leone	.018 × .025	SS	.022	9.8	14.40	2.46	4.60	46.94
Ortho Technology	.019 × .025	NiTi	.022	7.2	10.53	0.22	3.33	46.30
Ortho Technology	.019 × .025	SS	.022	7.2	11.77	0.64	4.57	63.43
Ortho Technology	.019 × .027	Coated NiTi	.022	6.7	9.75	0.34	3.05	45.52
Ortho Technology	.019 × .027	Coated SS	.022	6.7	10.83	0.45	4.13	61.69
GAC	.016 × .022	Super-tempered SS	.022	17.9	29.53	2.86	11.63	64.99
GAC	.018 × .022	Super-tempered SS	.022	11.4	22.18	4.11	10.78	94.59
Ormco	.016 × .016	STB CuNiTi	.018	7.7	19.13	3.49	11.43	148.48
Ormco	.017 × .017	STB CuNiTi	.018	3.5	7.72	2.39	4.22	120.48
Ormco	.018 × ,018	CuNiTi	.018	0	2.23	0.03	2.23	–
Ormco	.014 × .025	Damon CuNiTi	.022	20.9	34.17	3.46	13.27	63.48
Ormco	.016 × .025	Damon CuNiTi	.022	15.2	28.68	2.13	13.48	88.71
Ormco	.017 × .025	NiTi reverse curve	.022	12.5	19.50	1.42	7.00	56.00
Ormco	.018 × .025	Damon CuNiTi	.022	9.8	19.15	0.92	9.35	95.41
Ormco	.0175 × .0175	TMA	.018	1.7	7.03	4.37	5.33	313.73
Ormco	.017 × .025	Damon TMA	.022	12.5	22.20	2.24	9.70	77.60
Ormco	.019 × .025	Damon TMA	.022	7.2	16.43	3.10	9.23	128.24
Ormco	.021 × .025	TMA	.022	2.3	4.12	1.06	1.82	78.99
Ormco	.016 × .016	Straight length SS	.018	7.7	17.00	2.89	9.30	120.78
Ormco	.018 × .018	STb SS	.018	0	2.40	0.19	2.40	–
Ormco	.016 × .022	Straight length SS	.022	17.9	34.40	2.06	16.50	92.18
Ormco	.017 × .022	Straight length SS	.022	14.6	31.98	3.49	17.38	119.06
Ormco	.017 × .025	Straight length SS	.022	12.5	23.48	3.03	10.98	87.87
Ormco	.018 × .022	Straight length SS	.022	11.4	20.47	2.48	9.07	79.53
Ormco	.018 × .025	Straight length SS	.022	9.8	18.02	2.72	8.22	83.84
Ormco	.019 × .025	Straight length SS	.022	7.2	16.43	3.10	9.23	128.24
Ormco	.019 × .025	Damon SS	.022	7.2	16.43	3.10	9.23	128.24
Ormco	.019 × .025	SS	.022	7.2	10.70	0.79	3.50	48.61
Ormco	.021 × .025	Straight length SS	.022	2.3	5.58	0.95	3.28	142.75

[a] SD indicates standard deviation; SS, stainless steel; NiTi, nickel titanium; TMA, titanium alloy.

attempted to ensure stable and reproducible archwire position by enveloping samples in phenolic resin and abrading 3 mm off their surface to remove any irregularities and or deformations in the wire produced by the cutting action.

Previous investigations have relied on acetate sheet templates of increasing size to measure the edge bevel curvature.[3,8] However, today a much more precise and reproducible measurement can be obtained with the aid of imaging software, as shown by our repeated measures analysis.

One unexpected finding from our investigation was that the four edge bevels of each archwire differed from each other in terms of radius. In practical terms this means that the archwire-slot play will also differ depending on whether the wire rotates clockwise or counterclockwise, as its contact angle with the slot will differ. Furthermore, the photographic evidence shows that the bevel cross-sections do not follow a perfect circle and instead present irregularities (Figure 9).

Nevertheless, using the formula proposed by Meling et al.[13] in 1998, we were able to calculate the archwire-slot play. Meling's formula was initially conceived to calculate the real slot height from the dimensions of the archwire, measured using a digital gauge, and the real archwire-slot play, measured by means of a

Table 6. Statistical Analysis of Archwire-Slot Play[a]

Manufacturer	Material	Nominal Value	No. of Samples	Mean Error	Standard Error	Statistic	*P* Value FDR
3M	NiTinol SE	.014 × .025	6	9.1833	0.9042	24.88	<.01***
3M	NiTinol SE	.017 × .025	6	4.7167	0.9948	11.61	<.01***
3M	NiTinol SE	.019 × .025	6	3.9000	0.4336	22.03	<.01***
3M	NiTi HA	.019 × .025	6	3.4167	0.4792	17.46	<.01***
3M	NiTi HA	.021 × .025	6	0.9833	0.3869	6.23	<.01***
3M	SS	.019 × .025	6	3.6000	0.7155	12.32	<.01***
3M	NiTinol	.019 × .025	6	3.9000	0.4336	22.03	<.01***
Lancer	Thermal NiTi	.019 × .025	6	3.3500	0.1871	43.86	<.01***
Lancer	TMA	.021 × .025	6	2.1333	1.4882	3.51	0.02**
Lancer	SS	.019 × .025	6	3.8333	1.2011	7.82	<.01***
Leone	NiTi	.016 × .022	6	6.1333	0.9136	16.44	<.01***
Leone	NiTi	.019 × .025	6	2.9500	0.4231	17.08	<.01***
Leone	Coated NiTi	.019 × .025	6	3.5333	1.4418	6.00	<.01***
Leone	SS	.016 × .022	6	9.0667	3.2017	6.94	<.01***
Leone	SS	.018 × .025	6	4.6000	2.4568	4.59	.01***
Ortho Technology	NiTi	.019 × .025	6	3.3333	0.2160	37.80	<.01***
Ortho Technology	SS	.019 × .025	6	4.5667	0.6377	17.54	<.01***
Ortho Technology	Coated NiTi	.019 × .027	6	3.0500	0.3450	21.66	<.01***
Ortho Technology	Coated SS	.019 × .027	6	4.1333	0.4502	22.49	<.01***
GAC	Super-tempered SS	.016 × .022	6	11.6333	2.8605	9.96	<.01***
GAC	Super-tempered SS	.018 × .022	6	10.7833	4.1131	6.42	<.01***
Ormco	STb CuNiTi	.016 × .016	6	11.4333	3.4904	8.02	<.01***
Ormco	STb CuNiTi	.017 × .017	6	4.2167	2.3878	4.33	.01***
Ormco	CuNiTi	.018 × .018	6	2.2333	0.0516	105.94	<.01***
Ormco	Damon CuNiTi	.014 × .025	6	13.2667	3.4639	9.38	<.01***
Ormco	Damon CuNiTi	.016 × .025	6	13.4833	2.1264	15.53	<.01***
Ormco	NiTi Reverse Curve	.017 × .025	6	7.0000	1.4184	12.09	<.01***
Ormco	Damon CuNiTi	.018 × .025	6	9.3500	0.9203	24.89	<.01***
Ormco	TMA	.0175 × .0175	6	5.3333	4.3661	2.99	.03**
Ormco	Damon TMA	.017 × .025	6	9.7000	2.2432	10.59	<.01***
Ormco	Damon TMA	.019 × .025	6	9.2333	3.0975	7.30	<.01***
Ormco	TMA	.021 × .025	6	1.8167	1.0591	4.20	.01***
Ormco	SS	.016 × .016	6	9.3000	2.8921	7.88	<.01***
Ormco	Steel	.018 × .018	6	2.4000	0.1897	30.98	<.01***
Ormco	Straight length SS	.016 × .022	6	16.5000	2.0620	19.60	<.01***
Ormco	Straight length SS	.017 × .022	6	17.3833	3.4942	12.19	<.01***
Ormco	Straight length SS	.017 × .025	6	10.9833	3.0301	8.88	<.01***
Ormco	Straight length SS	.018 × .022	6	9.0667	2.4801	8.95	<.01***
Ormco	Straight length SS	.018 × .025	6	8.2167	2.7213	7.40	<.01***
Ormco	Straight length SS	.019 × .025	6	9.2333	3.0975	7.30	<0.01***
Ormco	Damon SS	.019 × .025	6	9.2333	3.0975	7.30	<0.01***
Ormco	SS	.019 × .025	6	3.5000	0.7950	10.78	<.01***
Ormco	Straight length SS	.021 × .025	6	3.2833	0.9453	8.51	<.01***

[a] FDR indicates false discovery rate; SS, stainless steel; NiTi, nickel titanium; TMA, titanium alloy.
* $P < .10$; ** $P < 0.05$; *** $P < .01$.

torsion test. Reversing the formula, considering the slot height as a constant (0.022″ for rectangular archwires and 0.018″ for square archwires) and inserting the real bevel radius, the resulting calculation yields the play. As expected from the literature,[4] this calculation revealed that in the real world the play is invariably greater than the ideal, within the range +34% to +313%. Translated into degrees, the increase in play seen in our sample ranged from +1° (Ormco 0.021 × 0.025″ NiTi heat activated) to +17° (Ormco 0.017 × 0.022″ SS) with respect to the ideal. This conforms to values reported by Sebanc et al.,[17] who estimated that the presence of beveled edges increases the play by between 0.2° and 12.9°. This in turn translates into a major change in the capacity of the orthodontic appliance to transmit preprogrammed information.

Our findings also show a correlation between the materials the archwires are made of and the resulting play. The more rounded edge bevels in our sample were found to belong to the stainless steel and super-tempered stainless steel wires. This contrasts with findings by Sebanc et al.,[17] who found that TMA wires have a more rounded edge bevel, followed by stainless steel and then NiTi. This discrepancy, coupled with the correlation we noted between archwire manufacturers and resulting play, highlights the great geometric variability of the archwires on the market.

Table 7. Manufacturer Effect: Analysis

Manufacturer	Height	Width	Play
3M	−0.15	−0.7	4.24***
	(0.10)	(0.07)	(0.60)
GAC	−0.34	0.05	11.21***
	(0.18)	(0.12)	(1.13)
Lancer	−0.13	−0.12	3.11***
	(0.15)	(0.10)	(0.92)
Leone	0.27*	0.45***	5.26***
	(0.11)	(0.08)	(0.71)
Ormco	−0.02	−0.17***	8.46***
	(0.05)	(0.04)	(0.34)
Ortho Technology	0.58***	0.74***	3.77***
	(0.13)	(0.09)	(0.80)
R^2	0.21	0.51	0.77
Adjusted R^2	0.17	0.49	0.77
Number of Observations	129	129	258

*** $P < .001$; ** $P < .01$; * $P < 0.05$.

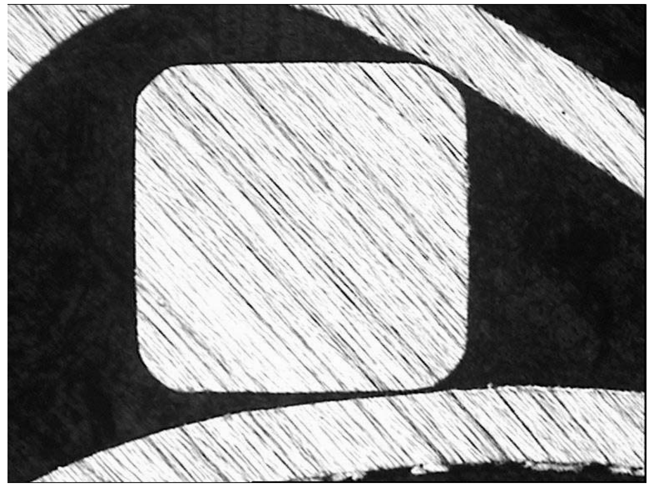

Figure 9. Four different edge bevels in a square archwire seen in cross-section.

It is also known that beveled edges affect not only the torque expression capacity of an orthodontic archwire but also its stiffness. Rucker and Kusy[9] estimated that on average each edge bevel reduces the cross-sectional area of a wire by 1.75%, giving a total loss in archwire volume of 7%–8%. Aside from the consequent loss of torque, such wires present a reduction in stiffness, amounting to roughly 15%–19% with respect to the theoretical value the same wire would have with perfectly square edges.

As we considered the height of the slot as constant and ideal, the increase in play we observed is imputable to the orthodontic archwire and its beveled edges alone. In real life, the play will also be affected by the slot itself and is likely to be even greater. It is therefore essential that manufacturers of archwires and brackets pay closer attention to the precision of their production processes, and that they declare the dimensional tolerance of the edge bevel radii and slot measurements, respectively, so that clinicians are able to estimate more accurately the real capacity of an individual appliance to express the information it is programmed with.

Table 8. Material Effect: Analysis[a]

Material	Height	Width	Play
Coated Wires	0.40*	1.08***	3.57***
	(0.16)	(0.10)	(1.01)
NiTi	−0.03	0.05	6.05***
	(0.07)	(0.04)	(0.42)
SS	−0.06	−0.01	7.80***
	(0.07)	(0.04)	(0.44)
Super-tempered SS	−0.34	0.05	11.21***
	(0.20)	(0.12)	(1.23)
TMA	0.02	−0.29***	5.64***
	(0.12)	(0.08)	(0.78)
R^2	0.08	0.52	0.73
Adjusted R^2	0.04	0.50	0.72
Num Obs.	129	129	258

[a] NiTi indicates nickel titanium; SS, stainless steel; TMA, titanium alloy.

*** $P < .001$; ** $P < .01$, * $P < .05$.

CONCLUSIONS

The null hypothesis must be partially rejected.

- The orthodontic archwires on the market have different dimensions to those declared by the manufacturers; some are oversized and some are undersized, in a range between −6.47% and +5.10%.
- These size discrepancies are statistically significant from the ideal in some cases and not significant in others.
- There are weak correlations between the dimensional precision of the archwires and both the construction material and manufacturer.
- In cross-section, both square and rectangular archwires present variable bevel radii at each corner, which has a significant influence on the archwire-slot play.
- The real archwire-slot play is invariably greater than the ideal, falling within the range +0.98° and +17.38°; in some cases the real play is up to three times greater than the ideal.
- The degree of edge beveling is correlated with the material used to make the orthodontic archwire; coated and TMA present smaller bevel radii, while this measurement is larger in conventional and super-tempered stainless steel archwires.
- To more accurately estimate the third-order information expression capacity of orthodontic appliances, clinicians would benefit from more information regarding the dimensional tolerance of it components, in particular regarding the edge bevels.

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