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Mechanical Characterization of Orthodontic Archwires in a Pseudo *In-Vivo* Context

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Abstract. Orthodontic fixed appliances are used to correct dental malocclusions by optimizing tooth movement and associated bone remodelling. Currently, orthodontic archwires made of shape memory alloys (SMAs) are widely used to initiate these treatments. We conduct experiments on SMA wires in pseudo in-vivo conditions, complementary to ISO standards, to assess the influence of temperature and humidity and to highlight their expected mechanical behaviour for clinical use. For this, an in-house built measurement device was developed to carry out experiments at controlled temperatures (21°C and 35°C) and in dry or wet conditions (artificial saliva). The dental arch was reproduced by 3D printing. The results show that the temperature has a major influence on the delivered forces whereas wet or dry conditions seem to have less impact. Also, we emphasize that at 35°C (in mouth conditions), in wet or dry conditions, SMAs superelasticity is only effective for displacements up to about 3 mm when an entire dental arch is considered.

Keywords. SMAs, superelasticity, temperature, humidity

1. Introduction

The purpose of orthodontic treatment is to correct a dental misalignment by applying a constant force of low intensity to obtain an ideal dental movement. For this, Nickel-Titanium shape memory alloys (SMAs) are widely used due to their superelasticity property [1,2]. Starting a tooth alignment using SMAs allows light and continuous forces to be applied during a long phase of deactivation [3]. This optimal force is at the origin of a physiological cellular response [4, 5] triggering a cascade of biological reactions and resulting in efficient bone remodelling [6–16].

The reference for marketing authorization of orthodontic archwires is based on mechanical standardized tests such as simple tension and three point bending according to the ISO standard 15841 (Dentistry-Wires for use in Orthodontics, 2006, updated in 2014). But these standardized test conditions do not correspond to the *in-vivo* mechanical load conditions where a complete dental arch is present. We conducted experiments in pseudo *in-vivo* conditions, complementary to ISO standards to define the influence of temperature and humidity on the behaviour of SMAs and consequently their expected properties under oral conditions.

2. Material and Methods

Orthodontic manufacturers rely on ISO standards to validate their products characteristics and the practitioner relies consequently on this information. To better highlight useful data for clinical use, we fabricated a curved

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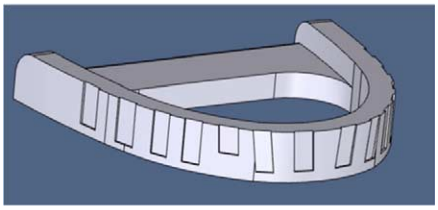

Figure 1. 3D printing of an ideal maxillary dental arch made of a thermoplastic polymer (acrylonitrile butadiene styrene ABS).

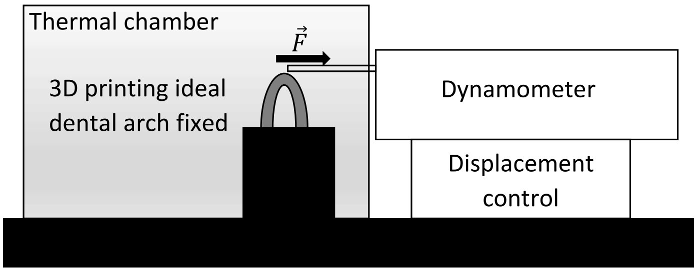

Figure 2. Measurement device [16] integrating the 3D printed dental arch and fixtures for measurements under dry and wet conditions and controlled temperature.

maxillary dental arch (Fig 1.) using 3D printing to represent an average patient [17, 18], integrating a conventional fixed appliance. 018-inch metallic brackets (Victory Seriess™, 3M Unitek, Seefeld, Germany) and elastomeric ligatures (mini stick, RMO, Denver, USA) were used. Tests were run with an .014 inches (0.356 mm) NiTi archwire (Orthonol reference WON 7000, RMO, Denver, USA).

There currently exists no device on the market to measure 3D forces on supports reproducing a dental arch. The dental arch must be fully fixed with perfect orientation to make precise measurements. Landmarks are also necessary for good repeatability. Finally, an adapted measuring device is necessary to record data in the force range from 0 to 30 N.

For this, a specially designed measurement device was built to test the corresponding *in-vivo* conditions [16] (Fig. 2).

We chose to develop a test bench specially dedicated to our tests (Fig. 2). This device was validated [16] and allowed all measurements to be made (Fig. 3) on this in-house built device. Here, we were mainly interested in the influence of the test conditions. First, the temperature with tests conducted at room temperature (21°C) and intra-oral average temperature of 35°C [19]. We measured the vertical forces (occluso-apical) applied at the centre of the attachment on the right maxillary canine for displacements ranging from 0 to 5 mm. Next, we measured the influence of dry and wet conditions using an artificial saliva [20]. The test consisted in the measurement of the frictional forces (of the wire within the conventional brackets along the wire principal axis) in both dry and wet conditions on the curved dental arch. All tests were repeated 3 times by the same operator. Finally, we quantified the influence of friction on the superelastic SMAs behaviour when set within a wire/brackets/ligatures system.

3. Results

3.1. Influence of Temperature

SMAs cristallographic phase in the temperature range from 21 to 35°C was determined by Differential Scanning Calorimetry as fully austenitic since the austenitic phase finish temperature Af was measured at 19.8°C [21]. This

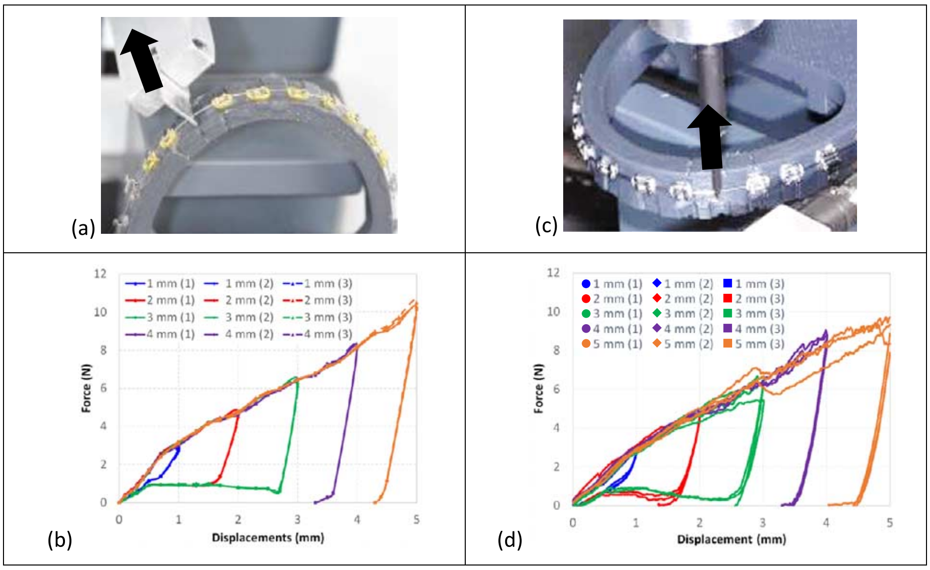

Figure 3. (a) Applied displacement at the centre of the maxillary right cuspid's bracket on our measurement device, (c) similar measurement made on the Instron Zwick equipped with a 100 N load cell. The displacements are made perpendicular to the archwire principal plane (defined by its curvature) in the apical direction. (b) and (d) Measured forces as a function of the applied displacement ranging from 0 to 5 mm for each set-up.

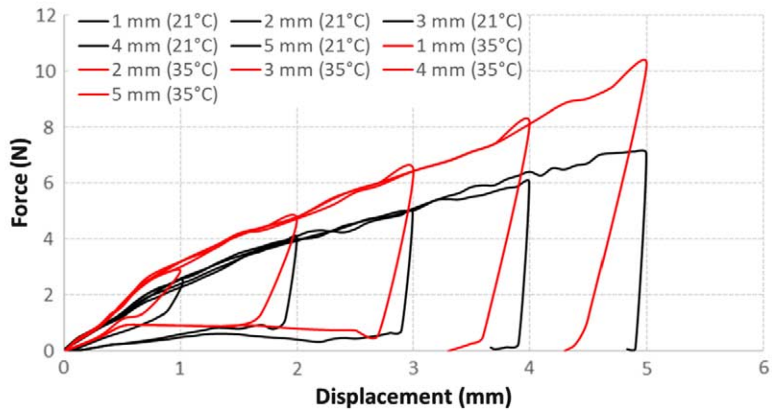

Figure 4. Measured forces as a function of the applied displacement at 21°C (black) and 35°C (red).

is consistent with the manufacturer's data. Figure 4 shows the *influence* of temperature for the test in the vertical direction (Fig. 3a). We can observe that the forces recorded at 35°C (red) are greater than those at 21°C (black) during the activation and deactivation phases. An average difference of about 1 N is observed between the two test temperatures which is considered significant for the practitioner [22, 23].

3.2. Influence of Wet and Dry Conditions

Figure 5 shows the measured frictional forces according to the number of current brackets available. When the experiment was carried out on one single bracket (pulling the wire through the bracket) friction forces were reduced by about 20% in presence of artificial saliva. However, when the number of brackets increased, the change of environment no longer seemed to have an impact on the frictional force values.

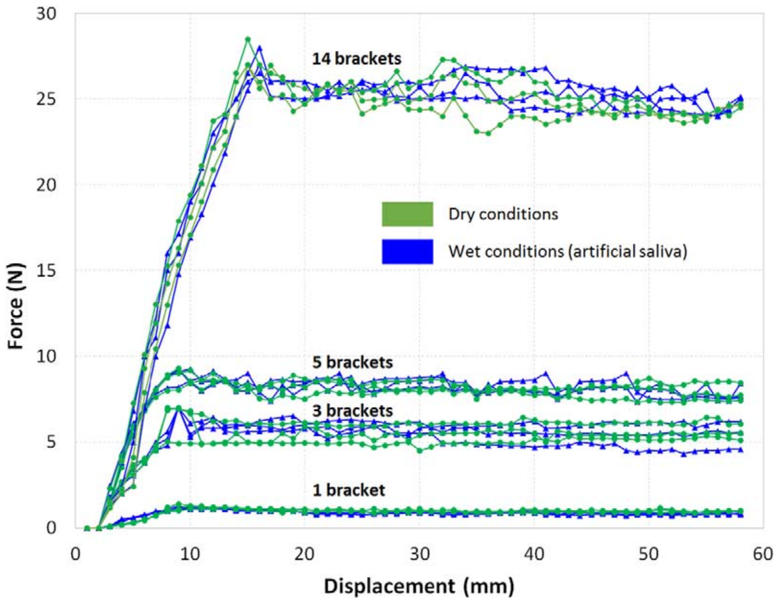

Figure 5. Friction forces as a function of the applied displacement when 1, 3, 5 and 14 brackets are fixed on the curved printed dental arch at 35°C.

Under conditions approaching the reproduction of an entire dental arch, the choice of the wetting medium is not a major determinant compared to the multiple contacts between wires, brackets and ligatures. On Fig. 5, dry conditions are represented in green and circles and wet conditions (artificial saliva) are shown in blue and triangles.

Other results exist in the literature on this issue, but a controversy was found on the effect of using lubricating artificial saliva or not [24–27]. Since, the methodology used was different to the one used in the current work (regarding the number of brackets included, and their alignment), this did not allow us to make a direct comparison.

3.3. Mechanical Characterization of Orthodontic Archwires in a Pseudo In-Vivo Context

When applying a tensile force in the apical direction on the canine on a curve typodont at 35°C and in wet conditions, the expected reversal superelasticity effects for the treatment were not clearly defined for all ranges of displacement (0 to 5 mm). As presented on Fig. 6, critical loads were observed for the deactivation plateau upon unloading, which was no longer present for displacements greater than 2 or 3 mm. The resulting applied force amounted to around 1 N for applied displacements up to about 3 mm but disappeared completely for loads above this value. Hence, there is probably no resulting force left upon unloading for orthodontic purposes. On Fig. 6, a comparison was made between our measurements with experimental data provided by Nucera *et al*. [28]. The data by Nucera *et al*. [28] were obtained with a classical three-points bending test (CTPT) as defined by ISO standard, and a conventional ligated brackets system (CLBS) using three brackets simulating the apical displacement for bending, thus including wire friction within brackets. An important point to note here is that the CTPT test is a classical mechanical characterization test whereas the CLBS test is a structure test (including other effects than just the wire mechanical behaviour such as kinematic conditions associated with the supports in the mechanical response of the entire structure including wire and brackets). When comparing our results with the data provided by Nucera *et al*. [28], we observed two main differences. The standard classical bending test used for orthodontic wire validation of superelastic effect is far from being representative of the *in-vivo* conditions; hence other tests are required for better assessment. As compared to our data, the CLBS test showed higher force delivery as a function of the applied displacement. This may be because this test was implemented using three brackets whereas our test was implemented using only two brackets and simply pulling the wire in the middle of the third bracket. Hence

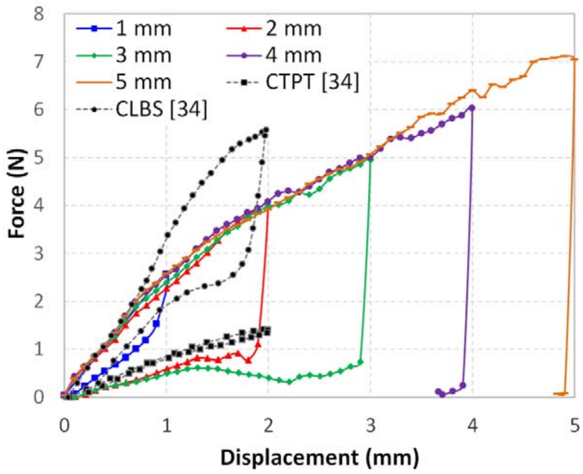

Figure 6. Evolution of the reactive force following the displacement of the cuspid bracket. Test conditions: 35°C and wet case. Vertical loads for curved plates for 0 to 5 mm displacement. Comparison with three-point bending tests published by Nucera et al. [28].

due to the structural effect (as described before), this generated higher forces. Nevertheless, forces as a function of applied displacement were similar. More work is required to fully validate this point.

It is well known that the superelastic effect based on ISO standardized tests is essential for the SMAs mechanical characterization. However, it is not enough for their clinical application as they are mostly subjected *in-vivo* to both tensile and bending forces [29] compared to the forces developed during standard tests [30]. In addition, the friction resistance developed while the wire is sliding within the brackets is not considered in standardized tests. The literature describes partially this effect to improve therapeutic effectiveness [9,31,32] but without proper quantification for practical use. Our protocol implementing wire/brackets/ligatures systems can account for these effects on an idealized dental arch, and therefore closer to the forces encountered by orthodontic archwires [33] under clinical conditions.

4. Conclusion and Prospects

We conducted orthodontic archwire characterization close to *in-vivo* conditions.

- We showed that the experimental setup, especially the choice of the temperature and to a lesser extent the media, are important to consider getting more accurate results.
- Using curved typodont and wire/brackets/ligatures system was useful in that the sliding resistance was also integrated into the quantification of mechanical forces.
- ISO tests corroborate superelastic mechanical behaviour during the unloading phase for the deactivation plateau and displacements lower than 2 or 3 mm. However, we were not able to demonstrate it for clinical use with larger displacements, which is in accordance with expert opinions [34]. These elements should be considered to optimize dental displacement and associated bone remodelling while limiting adverse effects [16].
- All these considerations explain the differences between the promotional materials put forward by the orthodontic distributors, praising the merits of SMAs and their superelasticty, and the experimental results in pseudo *in-vivo* conditions.

We highlighted the major role of the experimental temperature and the design of the supports where brackets and wire are introduced into the set-up on a reproduced curved maxillary dental arch. These two experimental characteristics are not included in the ISO standard test protocol. The integration of the sliding behaviour between the wire and brackets on a curved arch largely improved the reproduction the forces encountered in-vivo. Even if our measured mechanical behaviour for SMAs corroborated ISO tests for displacement up to 2 mm in-vivo, this was not true for displacements greater than 3 mm. This needs to be integrated in future works to optimize the dental displacement and associated bone remodelling while limiting adverse effects.

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