An investigation into the mechanical characteristics of select self ligated brackets at a series of clinically relevant maximum torquing angles: Loading and unloading curves and bracket deformation

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Summary: Edgewise orthodontic treatment utilizes a force couple in order to achieve labial- lingual tooth angulation. Two self-ligating (Damon Q and Speed) brackets were examined across a range of clinically relevant torques in order to assess the loading and unloading curves and bracket deformation.

A previously developed torquing and load measurement system was utilized to rotate a 0.199x0.25in stainless steel wire in a fixed bracket slot to the following angles: 16º, 20º, 24º, 28º, 32º and 40º. The torque on the bracket was measured during both wire loading and unloading cycles.

The torque play for the Damon brackets was determined to increase by less than 0.4º when torqued to 70Nmm, whereas the increase for the Speed brackets was 2.1º at the same torque magnitude. The deformation curves for the Damon and Speed brackets were found to be different for loading and unloading. Speed brackets were found to start to plastically deform when torqued to 24º (26Nmm of torque) while Damon brackets did not plastically deform until 28º (38Nmm of torque).

Damon brackets were found not to plastically deform as easily and to have a smaller increase in torque play than Speed brackets. Both the Damon and Speed brackets demonstrated minimal effect of plastic deformation and torque play at maximum angles

of twist less than 20º. Torque measured in the brackets was different for loading and unloading.

Keywords: torque, torque play, plastic deformation, self-ligating, torque expression

Introduction

In edgewise orthodontic treatment, change in labial-lingual tooth angulation (root torque) is achieved by introducing a force couple within the orthodontic bracket. This moment is produced by twisting the rectangular orthodontic wire against the walls of the rectangular orthodontic bracket slot. In orthodontic literature "torque" or "torque expression" refers to the physical moment generated within a bracket during third order torquing.

In typical orthodontic treatment mechanics, the initial torque expression is achieved by the bracket slot angulation (bracket prescription and initial tooth angulation) relative to a straight arch wire. Due to differences in wire and slot dimensions there is a range of angulations where the wire can twist within the bracket slot without producing a moment (Meling et al., 1997). The amount of rotation without producing a moment is referred to as "slot" or "torque play" (Sebanc et al., 1984; Meling et al., 1997). Additional torque expression can be achieved by bending a twist into the archwire prior to insertion into the bracket slot. Material properties of wire and bracket as well as the physical design of wire and bracket will influence torque expression (Vena et al., 2007).

In the experimental setting, “angle” unless otherwise specified, refers to the angle the wire is twisted within the bracket. “Loading curve” is the curve generated while the angle is increasing up to the maximum angle, and “unloading curve” is the curve generated while the angle decreases from the maximum back to zero. Wire and bracket strain may result in deformation which may play an important role in torque expression. “Plastic deformation” is permanent deformation, while “elastic deformation” is temporary deformation. Simply “deformation” refers to the total deformation; that is the sum of the plastic and elastic deformations.

Most studies report torque expression with loading as the wire is progressively twisted relative to the bracket slot (Morina et al., 2008; Grymrek et al., 2002). In clinical practice the wire is engaged into the slot and unloading characteristics will define the torque expression. To achieve predictable results, it is important for the clinician to have a clear understanding of the moments generated by various wire/bracket combinations.

The purpose of this study was to develop a method of measuring plastic deformation over a series torquing magnitudes, determine the resultant change in torque play, and perform an investigation on these parameters for selected self-ligating brackets. The second purpose of this study was to investigate the loading and unloading curves of third order torque expression across a range of clinically relevant torques

Methods and Materials

This investigation used a modified version of the apparatus previously reported by Lacoursiere et al [2010]. Figure 1 shows the measurement apparatus. Wires are clamped using dies 5mm from the edge of each side of the bracket. The wire and clamps are rotated via a worm gear and stepper motor (Cool Muscle CM1-C-11L30, Myostat Motion Control, Inc., Newmarket, ON, Canada), thus simulating the mechanical effects of a clinical third order torque. The bracket is mounted on top of a load cell (ATI Industrial Automation Nano 17 Multi-Axis force/torque transducer, Apex, NC, USA), which measures forces and moments in all 3 dimensions, and logged using a data acquisition card (DAC 16-bit series NI PCI-6033E, National Instruments, Austin, Texas, USA). The distance between the center of the bracket slot and the load cell origin is measured using a point probe (FaroArm FARO USA, Lake Mary, Florida, USA). A mathematical transformation is applied to the data so that the reported moments are at the bracket slot instead of the load cell, using the following formula:

$$T_x = T_{x'} - (F_{y'} \times \Delta z) + (F_{z'} \times \Delta y) \qquad \textbf{(Equation 1)}$$

The x direction is along the length of the wire, z direction is vertical, and y direction is perpendicular to both. The above formula is derived using left hand rule because the load cell was calibrated using this rule. T_x is the torque at the bracket slot in the x direction while $T_{x'}$ is the measured torque at the load cell. $F_{y'}$ and $F_{z'}$ are the measured forces in the y and z directions, respectively. Δy and Δz are the measured distances between the bracket slot center and load cell in the y and z directions, respectively. Preload forces in the bracket due to the wire are zeroed to within 0.08N in the y and z directions prior to starting an experiment, using translation stages (Thorlabs, Newton, New Jersey, USA). Similarly, preload torque in the z direction is zeroed to within 0.8Nmm using a rotation stage (Thorlabs, Newton, New Jersey, USA). Preload force in *x* direction and preload torque in the *y* direction are difficult to control with the current set-up, and are typically within 0.3N and 3Nmm of zero, respectively. Measurement accuracy of the device has been reported by Major et al 2011.

A high resolution CCD camera (piA2400-12gm, 2448 x 2050 pixels, 8bit, gray scale, Basler Vision Technologies, Exton, PA, USA) takes photographic images of the top of each bracket through a microscope (Edmund Optics, 55-908 MMS R4, Barrington, NJ, USA). Example overhead photos are shown in Figure 2.

Using a commercial software (LaVision GmbH, DaVis 7.2, Gottingen, Germany, 2007), images are processing using correlation techniques. Prior to experimentation, brackets are etched (The Arum Group, Spokane, WA, USA) to improve contrast, which aids in the algorithm's analysis of the images. The output file from the commercial software is further processed in custom software (The MathWorks Inc., MatLab, Natick, MA, USA). The software enables the selection of 4 regions, which would represent the four tie-wings in a typical bracket, as illustrated in Figure 2. The *y* difference between the left hand side regions (LHS) and right hand side regions (RHS) are set to zero at zero degrees of wire twist. Changes in the *y* difference of the LHS and RHS regions through the torquing process represent the bracket deformation. Final data is reported in millimeters of deformation. LHS and RHS deformation measurements should be nearly identical, but small differences exist due to asymmetries in the bracket/wire design and/or the bracket/wire manufacturing process, and experimental error in lining up the wire in the bracket slot.

Motor control, data acquisition, and the CCD camera are controlled by a custom software (LabWindows CVI National Instruments, Austin, Tex, USA). Images are taken in 2° increments during the loading and unloading of the bracket. The maximum torque is reported for each experiment, which occurs at the highest angle.

This study investigated two types of self-ligating 0.022in slot size orthodontic brackets: Damon Q (Ormco Corporation, Orange, CA, USA) and Speed (Strite Industries, Cambridge, Ontario, Canada). Torsion was applied using a 0.019x0.025in stainless steel wire (Ormco Corporation, Orange, CA, USA). The first group of brackets were torqued to a maximum of 16° and then unloaded. This test was done to 6 Damon Q and 6 Speed brackets. Similarly, groups brackets were torqued to maximum of 20°, 24°, 28°, 32°, and 40°. A total of 36 Damon and 36 Speed brackets were tested.

An average deformation curve and torque expression curve was generated for each each experimental group and bracket type. As an example, Figure 3 shows the average deformation curve of Damon brackets torqued to a maximum of 32 degrees. For this curve, the deformation does not return to zero at zero degrees which represents the plastic deformation in the bracket due to torquing. In this case, the plastic deformation for the average bracket is approximately 0.001mm. In this manner, the plastic deformation was investigated at a series of angles from 16 to 40 degrees of twist.

For each experimental group and bracket type an average torque (moment) curve was also generated to demonstrate the change in torque measured due to loading and unloading.

A Mann- Whitney non- parametric test was used to determine if a statistically significant difference exists between the Damon and Speed brackets for the maximum average torque at each angle. The Mann- Whitney test was used due to the small sample size of each bracket (6). A statistically significant difference exists between the two brackets if the measured P Value is less than 0.05. This non- parametric test was also used to compare the plastic deformation of the Damon and Speed brackets.

Results

Table 1 reports the average maximum torque expression and average maximum bracket deformation values for each wire angulation group. In Figure 2 it can be seen that the bottom right image selection region was smaller than the bottom left selection region. This was a normal phenomenon in the 36 Speed samples, so the only the LHS deformation was reported. The curves of LHS deformation versus angle at all the investigated maximum angles are shown in Figure 4 and Figure 5 for Damon and Speed, respectively.

Deformation is caused directly by torque induced stress, meaning direct comparisons between torque and plastic deformation are important to properly investigate the mechanical effects of third order torquing. The measurements of plastic deformation are plotted against torque in Figure 6. At 10 degrees, 0.019x0.025in wire is in the torque play region for a 0.022in slot (Sebanc et al., 1984): therefore to complete Figure 6 a plastic deformation of 0 is plotted after 10 degrees of maximum twist. In addition, using the formula derived by Meling et al., 1998a, 1998b), the increase in torque play due to plastic deformation is calculated at a series of torques and presented in Figure 7.

Figure 8 shows the torque expression curves for the Damon bracket loaded at a maximum of 16 to 40 degrees. The blue line indicates torque loading while the red indicates torque unloading. Similarly, Figure 9 shows the loading and unloading torque expression curves for Speed brackets. For visualization purposes the graphs do not maintain a consistent torque scale between the different maximum angles. The separation of the loading and unloading curves is visually noticeable as the curves exhibit different torques at the same angle.

From the torque expression curves it also can be seen that the Speed and Damon brackets behave differently when loaded and unloaded. The Damon brackets return to approximately the same origin when loaded and unloaded. Conversely, the Speed brackets do not return to the same origin when loaded and unloaded. The 16 º and 20º loading curves best illustrate the deviation for the Speed brackets from the origin. It is not as noticeable in the 24º, 28º, 32º and 40º curves since the scale is different in these graphs. In addition, it is observed that the Speed unloading curve has a larger relative and absolute difference from its loading curve compared to Damon, with the exception of the 20º data set.

Comparisons of maximum torque and plastic deformation for each of the six groups of wire rotation for Damon and Speed brackets are provided in Table 1. Maximum torque expression was significantly less for wire rotation to 16, 32 and 42 degrees ($p < 0.05$) in Speed brackets. Plastic deformation was significantly greater for Speed brackets at 20, 24, 28, 32 and 40 degrees ($p<0.05$).

The maximum difference between loading and unloading torque measurements along with the degrees of wire where the maximum difference was recorded for each of the 6 groups are reported in Table 2.

Discussion

The deformation curve is typically horizontal and near zero up to about 10° of twist. This horizontal portion corresponds to the torque play region. At approximately 10°of twist, the wire engages the slot and applies a torque to the bracket. This corresponds to a linear increase in deformation versus angle. In Figure 4(a), the maximum bracket deformation at 16° is about 4μm. The Damon loading and unloading curves appear to visually be nearly identical at 16°.

In the 20° of maximum angle curve, it can be visually observed in Figure 4(b) that above angles of 10° the Damon bracket's unloading curve has higher deformation than the loading curve at any given angle. In the 24° of maximum angle curve, the trend is easier to visually identify, and the unloading curve is also noticeably less linear than the loading curve. At angles of below 10°, both the loading and unloading curves are horizontal and have near zero deformation. At 28° of maximum angle, the same trend as before is observed above 10°, but below 10° it is visually identifiable that the unloading curve becomes horizontal at a non-zero deformation. These are the first signs of bracket plastic deformation. Presumably, plastic deformation of the wire contributes to the separation between the load and unloading curve. If the wire is plastically deformed to a new effective twist angle, it would keep the bracket tie wings spread further apart with greater deformation in the unloading curve. Once in the torque play region, the curve returns to zero unless the bracket has also plastically deformed.

The formula provided by Meling et al. (1998a, 1998b) can be used to estimate the wire's plastic deformation in degrees. First, the theoretical angle of the wire is calculated at a given angle in the loading curve, assuming a nominal 0.019x0.025in wire and 0.022in slot. Then by taking the difference in loading and unloading deformation at the given angle and adding it to the nominal slot width, the theoretical wire angle in the slot can be recalculated with the different slot width. The difference in these angles is an estimate of the changed wire angle due to its plastic deformation. For example, in Figure 4(c) the maximum measured difference between loading and unloading curves is 1.5µm, found at an angle of 18°. The nominal slot width is 0.5588mm (0.022in), and to engage the slot the wire needs to rotate 7.24° from the zero position. At the new hypothetical slot width of 0.5588mm + 0.0015mm = 0.5603mm, the wire must rotate 7.39° to engage the slot. We know from the deformation data point at 0° on the unloading curve that the bracket does not plastically deform while subjected to a maximum angle of 24°, and therefore it can be inferred that the difference (7.39° - 7.24° = 0.15°) is actually due to plastic deformation of the wire and not from an increase in the slot width. The edge bevel of the wire is not included in the calculation, but it only will have a small impact since this investigation is not interested in the magnitudes of engagement angle, but only difference between them. In fact, the calculated magnitudes of engagement, which in this example is 7.39° and 7.24°, have no physical meaning; only the difference between them has a physical interpretation. In cases where the bracket plastically deforms, this calculation is still valid by subtracting the plastic deformation of the bracket from the new hypothetical slot width. In summary, the plastic deformation in the wire can be calculated using the following simplified formula:

$$\varphi = \arcsin\left(\frac{H + \Delta d - d_p}{\sqrt{w^2 + h^2}}\right) - \arcsin\left(\frac{H}{\sqrt{w^2 + h^2}}\right) \qquad \textbf{(Equation 2)}$$

In equation 2, φ is the wire's plastic deformation in degrees. H is slot height (mm), w and h are wire height and width (mm), Δd is the maximum difference between loading and unloading bracket deformation at a given angle (mm), and d_p is the plastic deformation of the bracket (mm), as measured to be the deformation at zero degrees of the unloading curve. Equation 2 assumes that the bracket slot and wires are both perfectly rectangular at all times. It also assumes the difference in the bracket deformation of the loading and unloading curves (Δd) at any given angle is the result of plastic deformation, either from the wire or bracket. However, it is possible that friction among other potential factors between the wire and slot walls could also impact Δd. The suitability of these assumptions used to generate equation 2 need to be tested in future studies by directly measuring the wire's plastic deformation.

The magnitude of the plastic deformation of the Damon bracket and the non-linearity of the unloading curve are more pronounced as the wire is twisted to greater angles. The increased non-linearity is the result of the unloading interaction between the wire and bracket slot, including friction and possibly binding between the wire and slot, beveling of wire corners, warping of the slot profile, and plastic deformation of the wire/bracket.

Figure 4(f) visually demonstrates the greatest amount of plastic deformation to the bracket. Using equation 2, the plastic deformation of the wire is calculated to be 0.54°. This permanent deformation of the wire is not clinically significant.

Like the Damon deformation curves, Speed shows no signs of bracket or wire deformation at a maximum twisting angle of 16°, as can be seen in Figure 5. At a 20° of maximum twisting angle, the unloading curve has higher bracket deformation than the loading curve, indicating plastic deformation of the wire. Plastic deformation can be visually seen on the Speed curve at a maximum twisting angle of 24°, whereas it was not observed on the Damon brackets until a maximum twisting angle of 28°. At a maximum twisting angle of 40° Speed has greater plastic deformation than Damon, as seen in Figure 5(f). Using equation 2 the plastic deformation of the wire is negligible because Δd is approximately equal to d_p; in other words, the formula is indicating that only the bracket is plastically deforming while the wire remains robust. Although the wire's deformation may be relatively small, it is unlikely the wire deforms in Damon but not in Speed. Warping of Speed bracket's slot walls could be causing binding of the wire in the slot or increasing wire/slot friction, violating the assumptions used in creating equation 2. This goes to illustrate the limitations of equation 2.

It can be seen in Table 1 that both Damon and Speed are within 1 standard deviation of zero plastic deformation at 16° and 20°. At 24°, Damon remains at near zero plastic deformation, whereas Speed has 1.4µm of plastic deformation and is outside 1 standard deviation of zero plastic deformation. The Damon bracket's first indication of plastic deformation is at 28°, which corresponds to 38Nmm. The plastic deformation is 0.6µm and is 2 standard deviations away from zero plastic deformation. At the equivalent angle, Speed plastically deforms 2.5µm at 35Nmm. Speed is expressing less torque but still plastically deforms over 4 times more than Damon. At 40°, Damon plastically deforms 3.6µm at 70Nmm of torque and Speed deforms 15.9µm at 62Nmm of torque. By interpolation, Speed would plastically deform 20.6µm at 70Nmm of torque, which is a factor of 5.7 greater than Damon. Using the formula by Meling et al. (1998a, 1998b), the difference in torque play due to plastic deformation at 40° of twist is 0.4° and 1.6°, respectively.

Different size wires will express different amount of torque at the same angle of twist (Huang et al., 2009). For example, a smaller wire 0.018x0.025in stainless steel wire will express less torque at the same angle than a 0.019x0.025in because of its smaller cross sectional area. Similarly nickel-titanium alloys will produce less torque because they have a smaller shear modulus than stainless steel (Vena et al., 2007; MatWeb, 2009). However, the torque in Newton-millimeters is the physical parameter that causes the brackets to deform. For example, a nickel titanium wire in a Damon Q bracket that is expressing 70Nmm of torque will likely plastically deform the bracket on average 3.6μm just like the stainless steel wire, no matter what is the angle of twist required to achieve that level of torque. Figure 6 provides a comparison between plastic deformation of Speed and Damon as a function of applied torque.

Plastic deformation impacts the clinician by increasing torque play, which could result in lower than anticipated torque expression. It can be seen in Figure 7 that the torque play is increased by less than 0.4° for Damon up to wire twisting angles of 70°, whereas the impact torquing has on Speed's torque play is far more substantial. By interpolation, the increase in torque play of a Speed bracket is 2.1° after 70Nmm of torque. This increase in torque play may be clinically relevant. If a clinician had available a series of charts where he/she could read how much torque a particular bracket expresses at a clinically relevant range of angles with any given wire, he/she could predict and account for the increase in torque play of Damon and Speed brackets using Figure 7. It is unknown if repeated torque applications would result in additive plastic deformation.

In Figure 8(a) a horizontal region is observed in the loading and unloading curves under 10º of twist. This corresponds to the torque play region, which is the same on every loading curve. In Figure 8(c) at 24 degrees of maximum twist, there is a torque play region up to 10 degrees, and from 10 to between 16 and 18 degrees the curve is ramping up into the linear region, which is above 18 degrees of twist. 10 degrees until 16 to 18 degrees could be considered a region where the wire is engaging the slot, but the edges of the wire are bevelling and/or any spaces in the bracket are closing up. At 16 degrees of maximum torque, the curve reaches its maximum prior to the linear range. Above 18 degrees of the wire rotation, the bracket is deforming as a single solid object and the deformation is predictably linear with respect to angle. A similar trend is observed with a maximum rotation of 28 and 32 degrees, as seen in Figure 8(d) and Figure 8(e). With a maximum angle of 20 degrees, the curve is linear at the high angles but is not easy to visually recognize because the linear portion is relatively small.

In Figure 8(a), there is a non-zero uncharacteristic torque at 8 degrees. It is likely due to the wire pushing against one of the slot walls which causes a small frictionally induced moment, even though the wire has not properly engaged the slot. In addition, the graph is scaled such that a small torque is easy to visualize and would likely go unnoticed in the scaling of a figure with higher maximum torque, such as Figure 8(f).

At the Damon bracket's highest maximum angle of 40 degrees, seen in Figure 8(f), the loading curve deviates from the linear trend at 34 and 36 degrees. Vena et al. (2007) stated that the edge bevels of the wires are more chamfered than rounded. At 34 to 36 degrees, the diagonal of the wire is nearly perpendicular with the wall; therefore the frictional interaction between the irregular shape of the bevel and the wall is unique at this angle, which causes the non-linear torque curve.

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The loading curve is useful to determine what the maximum torque will be at any given angle. For example, it can be read off Figure 8 (f) that if the wire is twisted to 20 degrees, the maximum torque would be approximately 23-25Nmm, and this is confirmed by inspecting Figure 8 (c). However, besides the magnitude of maximum torque, the loading curve is not clinically representative of third order torque in a patient. The wire is twisted to the desired angle, and as the tooth moves the torque is unloaded. Therefore, the unloading curve has greater clinical significance as it represents the continuing torque applied to the tooth as the tooth continues to move. In Figure 8, it can be seen the Damon unloading curve is nearly identical to the loading curve at a maximum angle of 16 degrees. At a maximum angle of 20 degrees, a slight difference between the loading and unloading curves can been between 10 and 16 degrees. At a maximum angle of 24 degrees, the unloading curve is noticeably lower in torque magnitude at all angles above the torque play region. This trend is more pronounced as the maximum angle is progressively increased. Unlike the loading curve which is linear, the unloading curve demonstrates concavity. Therefore once the tooth has started to move (unloading has begun), there is no valid clinical rule of thumb that can state that there is a certain magnitude of torque expression per degree of wire twist.

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It is generally accepted in literature that a minimum torque of 5Nmm is required for clinical significance (Vena et., 2007; Gymrek et al,. 2002; Jarabak and Fizzel, 1972; Moyers, 1973). Therefore, by inspecting all the sub-images in Figure 8 it can be seen that the minimum clinically relevant torque is achieved just above 14 degrees when a

0.019x0.025in stainless steel wire is torquing a 0.022in slot Damon Q bracket. At 16 degrees, the maximum torque is clinically significant, and it continues to be all the way up to 40 degrees, which expresses a maximum torque of 70Nmm.

The standard deviations of the maximum torques of Damon brackets range from 2.8Nmm to 7.0Nmm, as seen in Table 1. Six (6) samples are used for each bracket at each angle in this study. In small sample studies, a single outlier has a large impact on standard deviations, which is the case at 24 degrees of maximum torque. The maximum separation between the loading and unloading curves increases with angle up to 9.9Nmm at 40 degrees of maximum wire twisting angle. The maximum separation between the loading and unloading curves occurs at an angle outside the torque play region in every Damon test.

It is most clearly seen in Figure 5(e) and (f) that Speed has a torque play of approximately 12 degrees. However, when the torque play is observed in Figure 9(a), it is not as horizontal as Damon's torque play region appears in Figure 8(a). This is partly due to the difference in the torque scales of the graphs. Additionally, the actively ligating door is pressing on top of the wire, even in the torque play region. The forces and friction as a result of the wire moving again the door and base of the slot causes positive and negative fluctuations in torque expression before the wire properly engages the slot. Presumably, the interaction between the door and wire is also the reason the unloading curve is more negative than the loading curve in the torque play region. As the wire returns to the zero position, it continues to apply a transverse frictional force on the door,

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which generates a moment about the slot center. All the fluctuations in the torque play region are within 1.5Nmm of zero torque which is well below the 5Nmm clinical relevance threshold (Vena et., 2007; Gymrek et al,. 2002; Jarabak and Fizzel, 1972; Moyers, 1973). Speed expresses torque in its loading curve in a linear fashion at above 16 degrees. Between the torque play and linear regions is a short non-linear ramping up or torque, corresponding to between 12 and 16 degrees.

Similar to Damon, Speed does not have a significant difference between the loading and unloading curves at 16 and 20 degrees of maximum wire rotation. The separation between the loading and unloading curves is greater in the torque play region than it is when the wire is fully engaging the slot, due to the force the actively ligating bracket door applies to the wire in the torque play region. Above a maximum angle of 20 degrees, the non-linearity and lower magnitude of the unloading curve compared to the loading curve continues to become more visually identifiable, as seen in Figure 9; this trend becomes more pronounced as the maximum angle increases. At the maximum tested angle of 40 degrees, the unloading curve is substantially different from the loading curve. In fact, at 26 degrees in the Speed curve with a maximum angle of 40 degrees, the unloading curve expresses half the torque of the loading curve.

At 16 degrees, Speed produces 3.9Nmm, which is less than the 5Nmm clinically relevant threshold. However, by interpolation it would express 5Nmm of torque at just 16.4 degrees. Up to 28 degrees of maximum wire angle, the maximum magnitude of torque in the Speed brackets are consistently between about 3Nmm and 4.5Nmm less than in the

Damon brackets. Since Speed's torque play region is up to 2 degrees larger than Damon, Speed's effective torquing angle will be up to 2 degrees less. This could account for some of the disparity between the brackets' torque expression magnitudes. In addition, it was found that Speed brackets deform more than Damon, both elastically and plastically. Greater deformation also results in a decreased effective torquing angle, which explains why the disparity between maximum torque expression magnitudes climbs as the maximum torquing angle increases past 28 degrees, to a maximum difference of 7.8Nmm at 40 degrees.

The average standard deviation of Speed is less than Damon by 0.5Nmm. The force of the actively ligating door ensures the wire is in a more repeatable position within the bracket slot to make certain the preload requirements are met prior to beginning the experiment. However, Damon has a passively ligating door, so the wire is freer to move within the Damon bracket while still meeting the preloading requirements. Therefore, just before torquing a Damon bracket, the wire can be at a slight angle to the bracket slot in any direction, or could be closer to one side of the slot than the other. Once the wire engages the slot wall, the nature of the engagement could be different dependent on the initial bracket/wire alignment, causing the Damon standard deviation to be higher than that of Speed. The Damon and Speed brackets maximum torque were compared in Table 1. The results show that for the tests conducted at 16, 32 and 40 degrees there was a statistically significant difference between the two brackets as the P Value was less than 0.05. Alternatively, for the tests conducted at 20, 24, and 28 degrees it was found that there is no statistically significant difference between the mean maximum torque of the

Damon and Speed brackets as the P Value was determined to be greater than 0.05. However, a conclusion cannot be drawn about the statistical significance due to the large difference in standard deviations for the 20, 24, and 28 degree tests. The large difference in standard deviation indicates that there is a significant amount of noise in the data and as a result a comparison between the two brackets at 20, 24 and 28 degrees cannot be made.

Between the 24 and 40 degrees of maximum torque curve, the maximum separation between the loading and unloading curves of Speed are on average 1.5 times that of Damon. Once the tooth has tipped between 2 and 4 degrees, corresponding to an unloading of 2 to 4 degrees, the difference between the loading and unloading curves becomes relevant, as can be readily seen in Figure 8 and Figure 9. At 32 degrees of twist in the wire during the unloading of a maximum angle of 40 degrees, the torque is 41.1 degrees and 32.3 degrees for Damon and Speed, respectively. This is a 21% difference between the Damon and Speed unloading curve, whereas it is only a 14% difference in the loading curve at the same angle of twist.

Conclusions

The purpose of this study was to investigate plastic deformation of Damon Q and Speed brackets as a result of third order torque, and its impact on torque play. The second purpose of the study was to investigate the loading and unloading torque expression curves in a clinically relevant range:

- A novel procedure has been developed to investigate plastic deformation at a range of clinically relevant torques, and a figure provided to assist the clinician in knowing how much additional torque play will results from torquing
- Being measured in 4° intervals, Damon brackets demonstrate their first signs of plastic deformation at 28°, corresponding to 38Nmm of torque. Speed brackets demonstrate their first signs of plastic deformation at 24°, corresponding to 26Nmm of torque.
- Damon brackets do not plastically deform as much as Speed brackets due to torquing. At 70Nmm of torque, Speed plastically deforms approximately 6 times more than Speed
- The torque play of Damon brackets is not impacted as substantially as Speed after torquing. After 70Nmm of torque, the bracket's torque play increases 0.4° and 2.1° for Damon and Speed, respectively. After 35Nmm of torque, the bracket's torque play increases 0.25° and 0.05°, respectively.
- Damon and Speed loading curves both have a torque play region of near zero torque until 10 to 12 degrees, then a non-linear torque increase, followed by a linear torque increase at torques above approximately 4Nmm.
- When a bracket is torqued above approximately 15Nmm, the unloading curve expresses less torque than the loading curve. The unloading curve is the more clinically relevant than the loading curve, as it represents the torque applied to the tooth after the tooth has started to move.

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Table 1: Average Maximum Torque (Nmm) and plastic bracket deformation (mm)

	Average Maximum Torque (Nmm)				Plastic Deformation (mm)			
Max Angle	Damon (Stdev)	Speed (Stdev)	Diff	P value	Damon (Stdev)	Speed (Stdev)	Diff	P value
16	8.26 (2.81)	3.89 (3.89)	4.37	0.015	0.0000 (.0001)	-0.0003 (0.0002)	-0.0003	0.026
20	19.04 (4.91)	14.61 (14.61)	4.43	0.132	0.0001 (0.0001)	0.0003 (0.0005)	- 0.0002	0.002
24	23.45 (4.52)	26.31 (26.31)	-2.86	0.394	0.0002) (0.0002)	0.0014 (0.0010)	-0.0012	0.015
28	38.22 7.04)	35.13 (37.25)	3.09	0.394	0.0006 (0.0003)	0.0025 (0.0006)	-0.0019	0.002
32	51.44 (4,98)	44.29 (44.29)	7.15	0.015	0.0011 (0.0003)	0.0047 (0.0018)	-0.0036	0.002
40	70.23 (3.54)	62.40 (62.40)	7.83	0.026	0.0034 (0.0007)	0.0159 (0.0086)	-0.0125	0.002

Table 2: Maximum torque and maximum separation of Speed and Damon Brackets at a given maximum angle

	Damon			**Speed**		
Max Angle (degrees)	*Average Maximum Torque in Nmm(Stdev)*	*Max Separation between. loading & unloading curves Nmm(Stdev)*	*Angle at Max Separation (Degrees)*	*Average Maximum Torque Nmm(Stdev)*	*Max Separation between. loading & unloading curves (Nmm)*	*Angle at Max Separation (Degrees)*
16	8.3 (2.8)	0.7	12	3.9 (2.34)	2.4	4
20	19.0 (4.9)	1.6	14	14.6 (6.5)	1.2	0
24	23.5 (4.5)	2.4	20	26.3 (3.9)	3.2	20
28	38.2 (7.0)	3.8	20	35.1 (2.0)	5.8	20
32	51.4 (5.0)	5.8	20	44.3 (4.1)	8.7	24
40	70.2 (3.4)	9.9	26	62.4 (5.4)	14.8	26

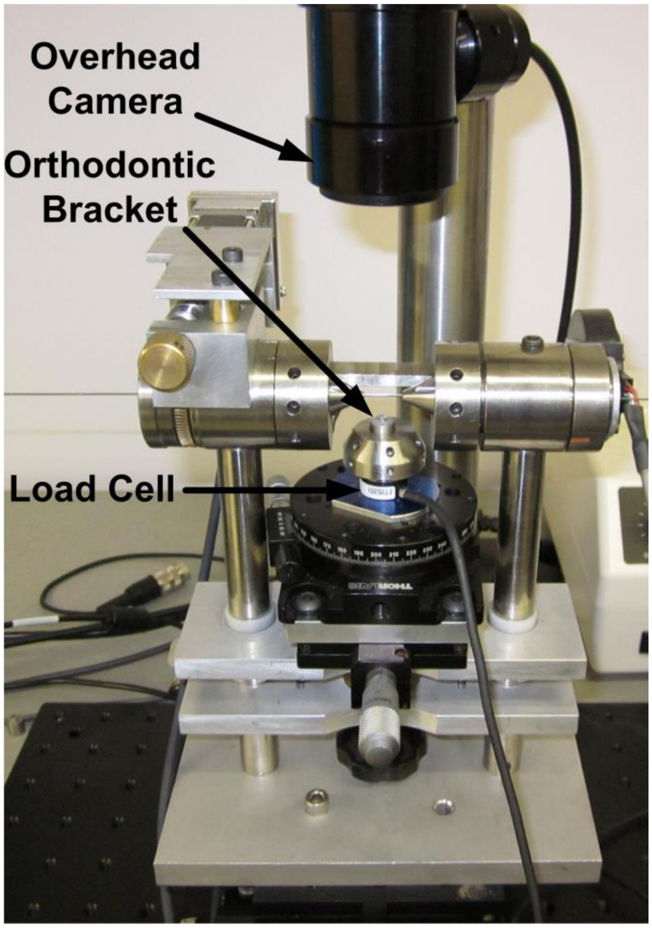
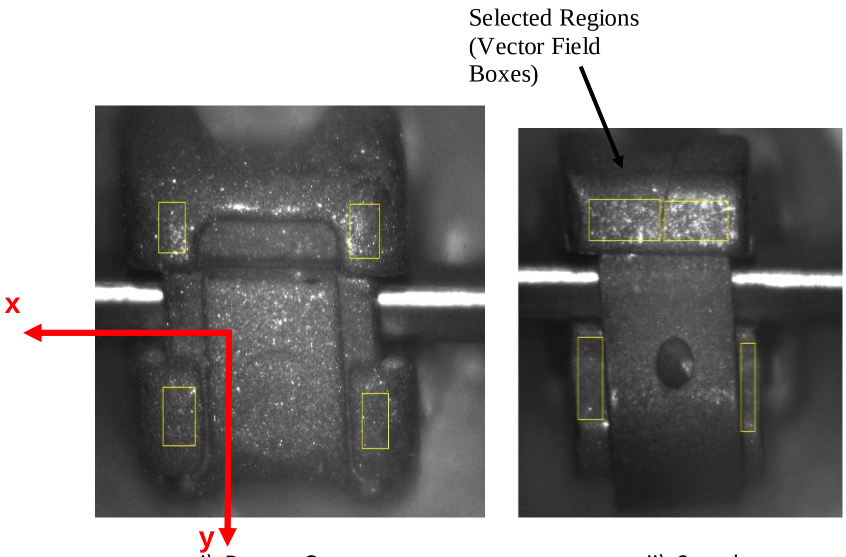


Figure 1: Apparatus Showing Load Cell, orthodontic bracket and overhead camera used for bracket torque data collection



i) Damon Q

ii) Speed

Figure 2: Example Overhead Images Showing Vector Field Boxes and Coordinate System

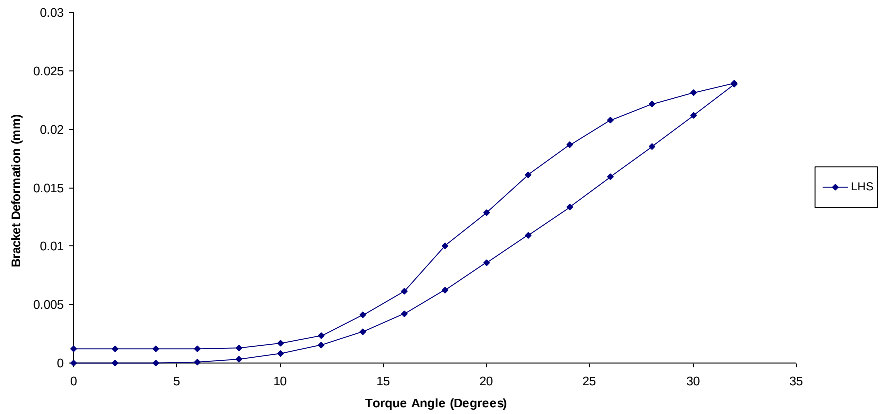
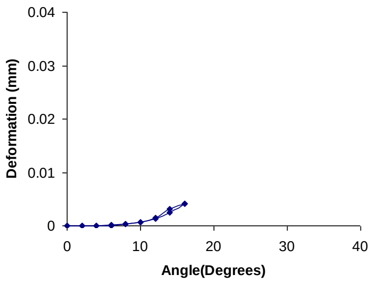
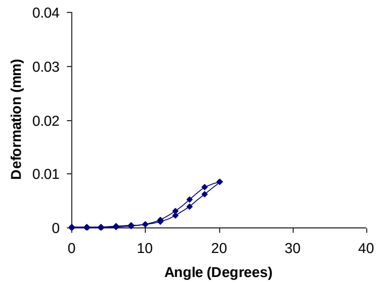


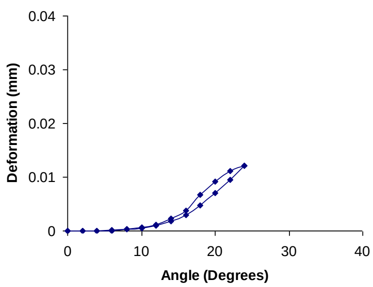
Figure 3: Example of the Damon bracket deformation curve at 32 degrees of maximum twist



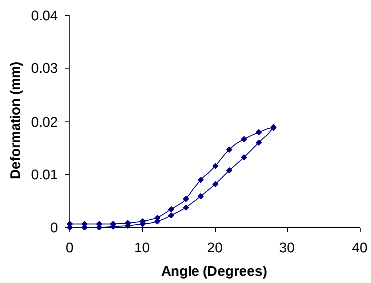
(a) 16° max



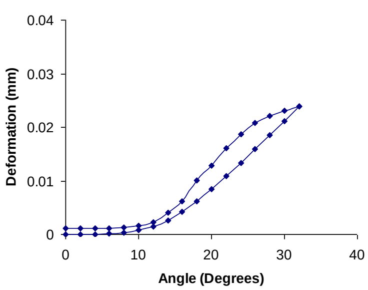
(b) 20° max



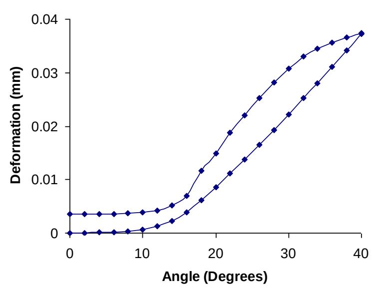
(c) 24° max



(d)28° max



(e) 32° max



(f) 40° max

Figure 4: Loading and Unloading LHS Deformation curves of Damon Brackets at maximum angles of 16° to 40°

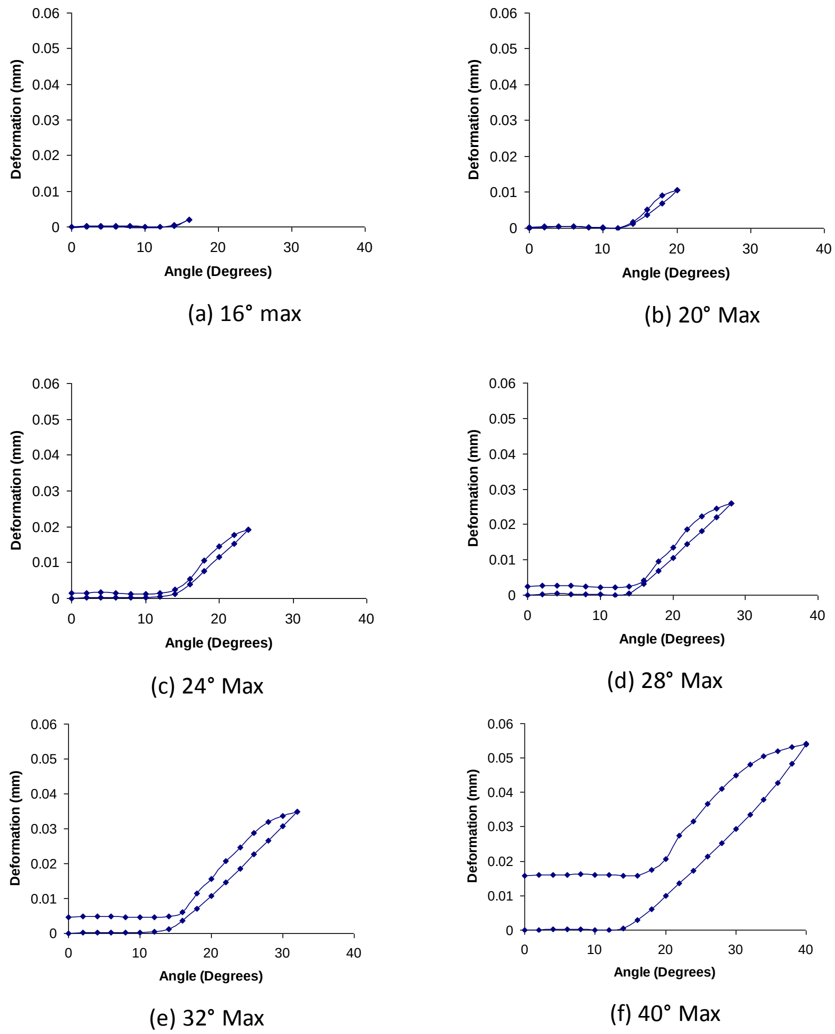


Figure 5: Loading and Unloading LHS Deformation curves of Speed Brackets at maximum angles of 16° to40°

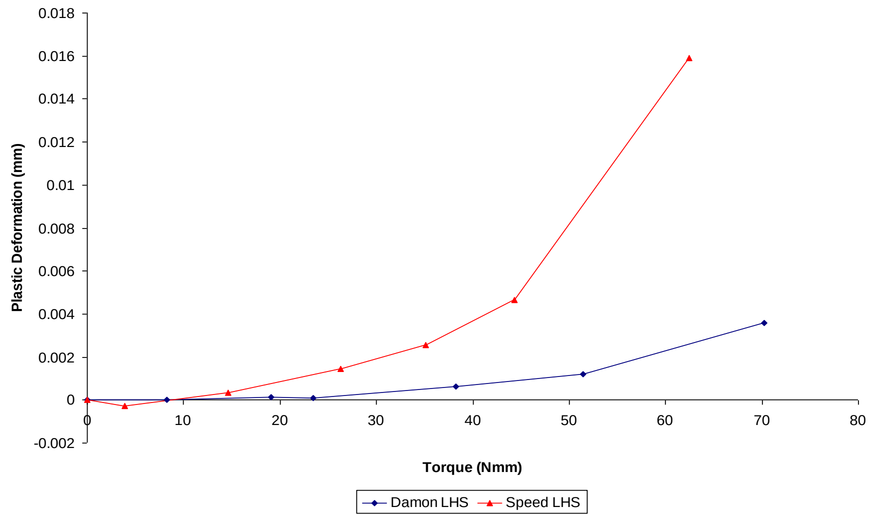


Figure 6: Plastic deformation (mm) of Damon and Speed brackets as a result of varying levels of torque (Nmm)

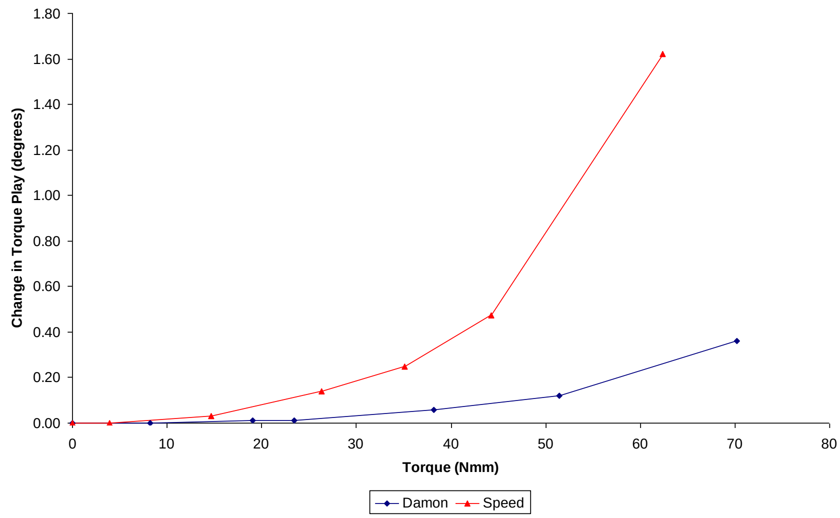
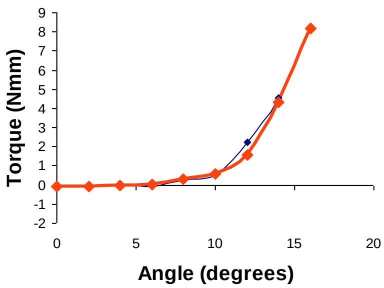
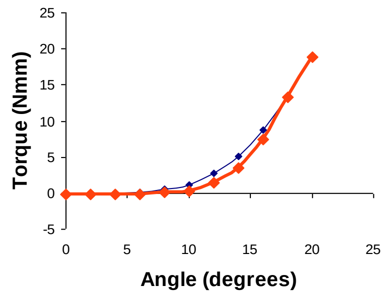


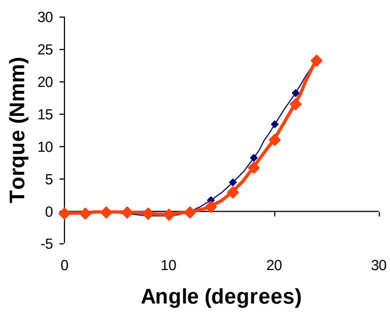
Figure 7: Increase in torque play of Damon and Speed brackets after torque application



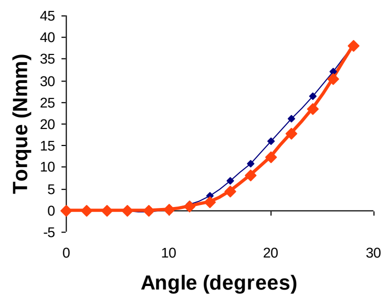
(a) 16°



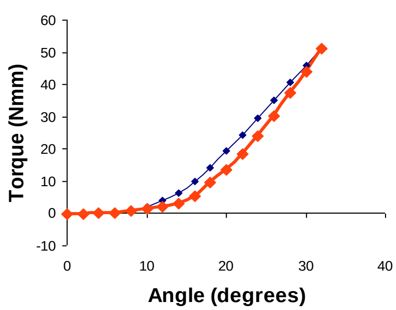
(b) 20°



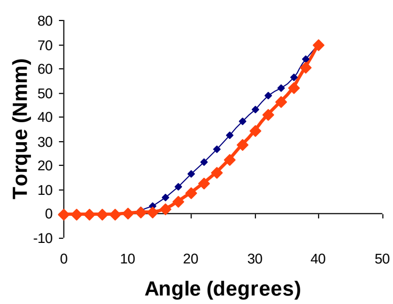
(c) 24°



(d) 28°

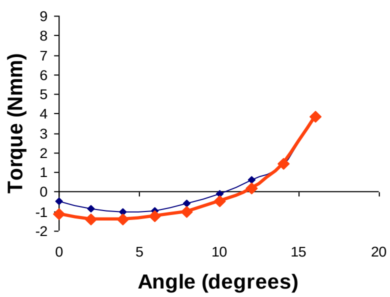


(e) 32°

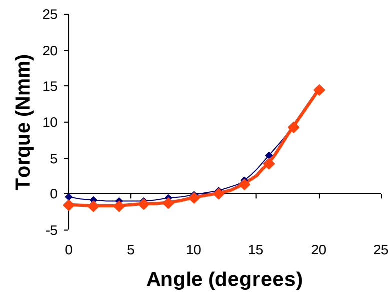


(f) 40°

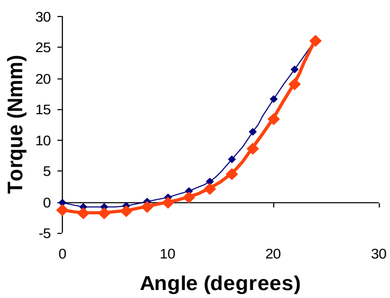
Figure 8: Average Torque versus angle of Damon brackets up to a maximum angle of (a) 16° (b) 20° (c) 24° (d) 28° (e) 32° (f) 40°. Blue indicates torque loading while red indicates torque unloading



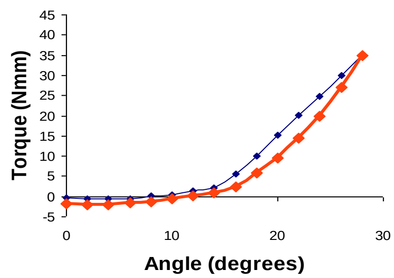
(a) 16°



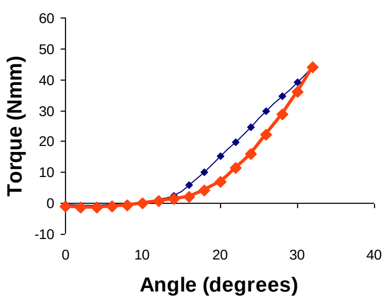
(b) 20°



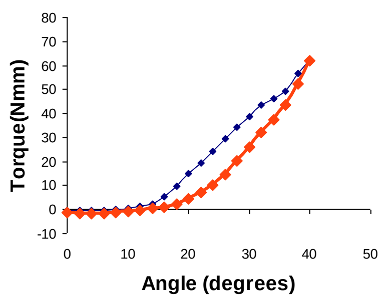
(c) 24°



(d) 28°



(e) 32°



(f) 40°

Figure 9: Average Torque versus angle of Speed brackets up to a maximum angle of (a) 16° (b) 20° (c) 24° (d) 28° (e) 32° (f) 40°. Blue indicates torque loading while red indicates torque unloading