

Bent out of shape: Bioinspired vertebral column morphology and mechanics

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Abstract

Vertebral centra are often characterized by the shape of the anterior and posterior faces, which can be flat, convex or concave. The platycoelus vertebrae of most mammals have flat faces, while the mono- and diphycoelus vertebrae of fishes, reptiles and amphibians have one or two concave faces. Some marine mammals even have slightly convex vertebral faces. There is a strong phylogenetic signal for centrum shape, and we are interested in the functional implications of the intervertebral cavity. We used a rapid prototyper and a molding technique to test the effects of centrum morphology and intervertebral joint length on the mechanical outputs of the vertebral column. Five models, inspired by the vertebral morphology of fishes, humans, and marine mammals, were designed and printed. We constructed motion segments (centrum–joint–centrum) of varying joint length for each centrum morphology. A moment arm was added to the motion segment to ensure loading in pure bending. From force outputs, we calculated moment (Nm), work (J), and bending stiffness (Nm²). Increasing the bending angle during testing, doubled moment and increased work produced by an order of magnitude, while decreasing bending stiffness by an average of 0.15 Nm². Increasing joint length decreases each of these mechanical properties by three to four times. The slightly convex vertebral face of marine mammal models, regardless of joint length, produced the largest moment, work, and bending stiffness values while the intermediate concave fish model had the lowest. These data suggest that convex and flat models are consistently stiffer than concave models. Our data show the relation between centrum shape, joint length, and their associated mechanical outputs is not linear. Research was funded by NSF grant DBI 1262239.

Introduction

During aquatic locomotion, body stiffness directly affects the external forces needed to reach ideal swimming speeds. The American Eel (*Anguilla rostrata*) uses muscle to triple their body stiffness. Increasing body stiffness decreases the cost of body movement during steady swimming, and also increases net positive muscle work done by the body on the surrounding water (Long 1998). As the fish body pushes against the water, increased external work creates a moving wave of muscle matching the body's natural bending frequency. In engineering, when a beam, which can be compared to the body of the eel, reaches its natural bending frequency, it can flex continuously at the same amplitude throughout its length. For the eel, this principle means that the work needed to swim at this pace is reduced. Conversely, decreasing body stiffness also decreases the net work done on the environment by the fish. Body stiffness in the Longnose Gar (*Lepisosteus osseus*) decreases when skin scales are removed (Long *et al.*, 1996). Decreasing body stiffness increases the ideal tail beat amplitude and total power used by the fish to swim at its body's natural bending frequency (Long *et al.*, 1996). Increasing amplitude and power, results in higher energy use by the fish to travel at its ideal speed.

Increasing vertebral column stiffness has a significant effect on a number of mechanical properties that play a role in swimming. Increasing the number of vertebra per unit length increases stiffness in a bioinspired column. As stiffness increases, several mechanical properties also increase such as storage modulus (E'), loss modulus (E''), peak acceleration, and mean speed (Long *et al* 2011). Knowing these internal mechanical properties, the structure of the vertebral column can be inferred by measuring external properties such as bending angle externally during a turn. For example, the second moment of area (m^4) of the vertebral centra is an important factor predicting body curvature (Porter *et al.*, 2009). Spring stiffness (N/m) of the

vertebral column is proportional to the ratio of the second moment of area in the centra (related to centra radius) and the centra length (Porter *et al.*, 2009). Our goals are to look at the effect of centra depth and angle on the stiffness of the vertebral column.

In addition to the vertebrae, intervertebral joint (IVJ) morphology can also impact the stiffness of the whole vertebral column. The intervertebral joint is comprised of several structures. The vertical septum, external connective tissue, is essential for keeping the column intact; however, it has little effect on the stiffness (Nowroozi and Brainerd 2012). The encapsulating tissue (including the elastic externa, external intervertebral ligament, and fibrous sheath) surrounds the IVJ and connects to the adjacent centra cup edges. This plays a crucial role, and when it is cut, the stiffness of the joint drops drastically (Nowroozi and Brainerd 2012). As the stiffness of the IVJ increases, the required work by the muscle to bend them increases (Long, 1992). Increasing stiffness of the IVJ causes an increase in the bending moment of the vertebral column as a whole (Long, 1992).

Changing the morphology of the biomimetic vertebral column in some swimming robots causes changes in the swimming speed and frequency (tail beats per second). Several aquatic robots have been built using biomimetic vertebral columns such as Tadpole4 and MARMT (Long *et al.*, 2011). Data from these robots suggests that in biological systems, centra morphology affects the overall performance of the vertebral column when it is used as a propulsive tail. For example, IVJ length plays a large role in spinal mechanics. When intervertebral joints are small, the storage and loss moduli are large, resulting in overall greater stiffness. When E values (Young's Modulus) are larger, more work is required to bend the column, but that work is then stored as potential energy and released onto the external environment during every tail beat (Long *et al.* 2011). Biomimetic models are powerful tools when looking at mechanical properties

because they allow us to explore a wide range of morphospace, differing shapes and arrangements, which would not be possible in biological systems.

Our goal is to explore a wider range of the morphospace by examining the role of centra angle and IVJ length on the mechanical outputs of one motion segment: a centrum–IVJ–centrum system. Previous work on vertebral column morphology and mechanical outputs has been done on a variety of species, but it can be difficult to compare morphological differences across species due to differences in skeletal building (bone and cartilage) and IVJ materials.

Biomimetic models are way to compare morphology of the vertebrae and IVJ's without having to account for material composition and structure. In this study, motion segments were inspired from the Bonnethead shark (*Sphryna tiburo*), Blacktip Shark (*Carcharinus limbatus*), Spiny Dogfish (*Squalus acanthias*), California Sea Lion (*Zalophus californiacus*), Grey Whale (*Eschrichtius robustus*), and Humans (*Homo sapien*), encompassing both fish and mammals.

We hypothesized that as concavity of the centra increases that resulting forces would decrease due to larger volume of IVJ material resulting in decreased reaction forces against solid centra model. Also, as IVJ length increases, we hypothesized that resulting forces due to bending of the motion segment will decrease. Finally, as applied bending angle increases, we expect required forces generated by the motion segment to increase.

Methods

3D Models and Printing

The 3D centra models were created with the program Google SketchUp. Three of the models are based off of fish centra. In Long et al (2011), the three bioinspired fish models were based on measurements of Bonnethead (*Sphryna Tiburo*) and Blacktip (*Carcharinus limbatus*)

shark vertebra (Table 1). The three centra cone angles they use are 90 °, 120 °, and 150°. In addition, we measured vertebrae from a spiny dogfish (*Squalus acanthias*), and found the angle of its centra to be 101°. For comparative purposes, we designed our models similar to those in Long *et al.* (2011). We scaled models appropriately to fit in our testing systems. The angles we used were 87.76 °, 118.10 °, and 148.70° for the fish models (Fig. 1). For naming convention purposes, we will call them 90 °, 120 °, and 150°. The fourth and fifth models were based on terrestrial and marine mammals. The terrestrial model is flat (180°), causing the IVJ to be a flat disc, as in humans. The aquatic mammal model has an outward protrusion measuring 211.30° (called 210 ° here after). This model was based on measurements taken from Grey Whale and Sea Lion vertebrae at The Whale Museum at Friday Harbor (Fig. 2). All of the centra models were 30mm high at the perimeter and had a diameter of 25mm. The centrum cup was added at one end of the model while the other ends were used to attach a moment arm to the end of the motion segment and to be mounted in the bending rig (Fig. 3). Once the models were drawn in SketchUp, they were exported to universal .stl file format, a standard file type used by a variety of 3D printers and programs.

We printed models on a ZCorporation ZPrinter 310 using High Performance Composite Powder and adhesive for binding (Fig. 4). Immediately after printing, the models are soft and easily damaged. We solidified models by spraying them with an epsom salt solution, hardening the models while still allowing them to be porous. The porous surface was better for binding with the silicone used as the IVJ material. On the ZPrinter, up to 30 of centra models were printed in one batch. ZPrinter models are nearly identical to the SketchUp files. The models are smooth and consistent in their shape and fill density allowing us to assume constant material properties of the model in our calculations.

We built motion segments by placing two centra models in a PVC tube marked with the desired IVJ length (Fig. 5). The gap was filled with 3M marine grade silicone as the IVJ material. Through the curing process, the silicone expanded the previously marked length of the IVJ. As a result, the IVJ lengths varied among motion segments, and were analyzed as a continuous variable. The individual motion segments cured in the PVC for three days before being removed. Motion segments were then allowed to air dry for an additional three days.

After that, a ¼” diameter, steel moment arm was added to one end of the segments and secured with cyanoacrylate and an accelerator spray. The hole in the centrum model was 6.5mm in diameter and was included in the SketchUp file so it could be incorporated during 3D printing. Moment arm length ranged from 11.5 to 13cm and was inserted 1cm into the motion segment. To assure a consistent moment arm length, the moment arm was marked at 10cm from the free end of the model.

Mechanical Testing

Each motion segment was inserted and secured with a blunt ended screw into a bending rig with a set height of 26.0cm and insertion depth of 1.7cm (Fig. 3). The moment arm was positioned under the motion head of the MTS Synergie100 test system (MTS, Eden Prairie, MN, USA) with a 10 N load cell. The addition of the arm was necessary to create a bending moment at the IVJ, rather than pull the end of the segment directly and cause shear forces. To allow for pure bending we used a round wire to pull the moment arm upwards rather than having the motion head grip the arm directly (Fig. 4). The wire was placed 10 cm from the proximal centrum at the end of the moment arm. This allowed the moment arm to rotate about the center of the IVJ as it was being pulled, eliminating shear. In addition, the bending rig was secured to the table with clamps to keep its position relative to the MTS standard.

We controlled the MTS and collected data using TestWorks. The TestWorks method has several steps. First, we pre-load the motion segment with 0.1 N to ensure any slack is pulled out of the wire. After the pre-load, the MTS pulled the moment arm to a calculated height for bending the IVJ at four specified angles, 1°, 2°, 3°, and 4°. The motion segment is measured prior to every test to determine the height in mm (H) the MTS will have to travel to reach the desired angle in degrees (θ) assuming rotation about the center of the IVJ (Equation 1) (Fig. 6).

Equation 1.

where:

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Lastly, the MTS returns the wire and moment arm to a height of 0mm. This is repeated 5 times with a speed of 100mm/min and a data collection speed of 100hz.

Calculations

The raw data from the MTS was collected at 100 hz and gave us displacement of the motion head and the resulting force. All of our mechanical data were calculated using our measurements, and these results. First, the average peak load was taken from the peaks of the five cycles done per test. Once we found average load, several other mechanical properties could be calculated.

The first property calculated was Moment (N). Moment was calculated using:

Equation 2:

Where M is the moment, F is the force required to bend the joint at the specified angle, and MA is the distance from the center of the IVJ to the location on the moment arm gripped by the wire (Fig. 7).

Work (J) was calculated as:

Equation 3:

Where W is work, F is the force required to bend the joint at the specified angle, and H is the height the motion head travels to create the specified angle between the center of the IVJ and the horizontal.

We also calculated Bending Stiffness ($N \cdot m^2$) as:

Equation 4:

Where EI is bending stiffness, F is the force required to bend the joint at the specified angle, MA is the distance from the center of the IVJ to the point where the MTS gripped the moment arm, and H is the height the motion head travels with the end moment arm.

Once Bending Stiffness was calculated, Young's Modulus (E) could be calculated by dividing by the moment of Inertia. Moment of Inertia is given by:

Equation 5:

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Where r is the radius of the cylindrical model. Once E was calculated for each model, the average (E^*) was taken.

Storage modulus (E') and loss modulus (E'') can be calculated using E^* and δ . The time labeled data from the MTS tests are used to measure δ . To get a value, the difference between

the time of the peak extension of the motion head and the peak force is taken. This was done for seven random samples which were bent at 2 degrees and the average was taken to get the δ value used in these calculations (Table 2). Storage and loss modulus were then calculated using:

Equation 6:

and

Resilience can also be calculated using δ . The equation used was:

Equation 7:

Statistical Analysis

To determine significance of our results, we used a mixed regression model. Our variables are Centra Angle, IVJ length, and Degree of Bending. All of our variables were treated as continuous variables. The response variables calculated are Average Force (N), Work (J), Moment (N*m), and Bending Stiffness (N*m²). JMP was used to analyze these data, and a Bonferoni correction, to account for multiple comparisons, was used to modify the standard significance value of $p < 0.05$. Because we are using each model 4 times, our p value must be less than 0.0125 to be significant.

Results

Mechanical Properties

We found moment (Equation 2) in relation to Centra Angle, IVJ length, and Bending angle was significant ($p < 0.0001$, adjusted $r^2 = 0.877172$, $F_{7,247} = 260.13$) (Table 3, Fig. 8).

Moment increases as Bending angle increases ($p < 0.0001$). Also, as IVJ increases, moment decreases. As the Bending angle increases, the differences in motion segment morphologies become apparent. At 1° Bending angle, the values for moment range between $0.1 \text{ N}\cdot\text{m}$ and $0.2 \text{ N}\cdot\text{m}$, a difference of only $0.1 \text{ N}\cdot\text{m}$ (Fig 8). However, at 4° Bending angle, Moments range from $0.15 \text{ N}\cdot\text{m}$ to $0.51 \text{ N}\cdot\text{m}$, a difference of $0.35 \text{ N}\cdot\text{m}$ (Fig. 8). Though the range changes with the different Angles of Bending, the trends are consistent for the 210° motion segment models, which always have the highest average moment, and the 120° motion segment models, which always have the lowest (Fig 8). Moment describes the tendency of a force to rotate an object around a point at the end of a moment arm. Our data suggest that 120° motion segment models tend to rotate more easily and 210° motion segment models rotate less.

Work (Equation 3) in relation to Centra Angle, IVJ length, and Bending angle was significant ($p < 0.0001$, adjusted $r^2 = 0.919843$, $F_{7,247} = 417.4001$; Fig. 9; Table 3). The amount and range of work required to bend the motion segments increases drastically with degree. At 1° Bending angle, all of the models require less than 0.0035 J to bend (Fig. 9). At 4° Bending angle the maximum work required is 0.035 J , and entire order of magnitude higher than at 1° Bending angle (Fig. 9). In general, the most work is required to bend the 210° motion segment and the least work to bend the 120° motion segment.

Bending Stiffness (Equation 4) in relation to Centra Angle, IVJ length, and Bending angle showed that the model was significant ($p < 0.0001$, adjusted $r^2 = 0.73127$, $F_{7,247} = 99.74$; Figure 10, Table 3). At 1° Bending angle, the max Bending Stiffness is produced with the 180° motion segment model around $0.455 \text{ N}\cdot\text{m}^2$ while, at 4° Bending angle, the max is only around $0.325 \text{ N}\cdot\text{m}^2$ (Fig 10). Though the range changes, the 210° motion segments has a consistently

higher Bending Stiffness and the 120° motion segment has a consistently lower Bending Stiffness.

Discussion

Implications for Swimming

Fishes have been observed to swim in four distinct patterns; Anguilliform, Subcarangiform, Carangiform, and Thunniform (Hebrank 1982). In Anguilliform Swimming, which is used by fish such as eels, a wave of bending travels from the head through the length of the body and terminates at the tail. We would expect the body to be consistently stiff throughout its length for this type of swimming because of the reliance on uniform wave propagation. Subcarangiform swimmers, like Koi, have a body wavelength that is not continuous. The wave begins with a certain magnitude at the anterior end and increases as it travels through the length of the body to the posterior. We expect, in this case, that vertebral column mechanics would allow for consistently varying stiffness to from head to tail. In Carangiform swimming, only the last half of the fish's body is involved in the bending motion. The vertebrae at the posterior end would need to be stiffer than the vertebrae at the anterior end to allow for higher resistance against the water while swimming. Lastly, Thunniform swimming, named after the Tuna, only the peduncle and caudal fin bend to create forward movement (Hebrank 1982). In fish which use this type of swimming, there may be room for greater variation in vertebral morphologies and stiffness throughout the length of the body.

Our data supported the hypothesis that moment ($N \cdot m$) work (J), and bending stiffness ($N \cdot m^2$) decrease as IVJ length increases (Fig. 8-10). In the saddleback dolphin (*Delphinus delphis*), the intervertebral joint length ranges from 0.53 to 0.87 cm (Long et al., 1996). Bending

tests in these vertebrae result the same negative correlation between intervertebral joint length and bending stiffness. The spine of the dolphin was most stiff in the lumbo-caudal region. During swimming, this stiffer region would cause the highest resistance against the water and produce the most speed relative to other spinal regions. There is also consistent variation in stiffness with bending angle. Moment and work both increase as bending angle increases whereas bending stiffness decreases (Fig. 8-10). Work takes into account the height traveled by the motion head along with measured force. Moment takes into account the measured force and the length of the moment arm, rather than the height. As a result, work varies orders of magnitude more than moment. The moment arm length is relatively constant between motion segment models, varying by only a small fraction (less than 1%), so changes in moment are driven by the forces measured from bending each motion segment morphology resulting in changes of only 2x-3x from 1° to 4°. Height traveled of the motion head ranges from just over 2mm, to over 9mm, an increase of over 400%. As a result, work increases by an entire order of magnitude from 1° to 4°. Bending stiffness does not follow the pattern, and actually decreases as bending angle increases. Rather than measuring the resulting force in relation to some distance, bending stiffness measures the motion segments resistance to bending. For this reason, it makes sense that bending stiffness decreases with an increase in degree of bending. As the MTS applies more force to the end of the moment arm, the motion segment is less able to resist that force.

The stiffer an animal's body is, the less energy it will use while swimming at its ideal speed (Long *et al.*, 2011; Long, 1998; Long 1997; Long, 1995; Long 1992; Long *et al.*, 1990; Nowroozi, 2012). In aquatic vertebrates, the vertebral column provides structure and support for swimming. The stiffer the vertebral column, the stiffer the body will be. As a result, the animal

will be better able to swim and maneuver through the water. In this case, we would assume that aquatic vertebrates would favor centra morphologies that allow their vertebral column to be stiffer. In blacktip and bonnethead sharks, their centra angles range from 70° to 140° degrees (Long *et al.*, 2011). In our motion segment models, those with 120° Centra Angle tend to be the least stiff, and, from there, stiffness increases with Centra Angle. Stiffness also increases as Centra Angle decreases to 90° in our models. We would need to test motion segments with centra angles both less than 90° and between 90° and 120° to determine whether or not stiffness consistently increases as centra angle decreases. Though concave centra angles in nature tend to require less force to bend, the regional variation in fish vertebral columns could make up for the lower stiffness (Nowroozi 2012). The stiffer angles, such as the 150° or 90° motion segment models, could be present in areas needed for motion, such as the region at the base of the tail, while less stiff angles such as 120° motion segment model may be found closer to the head or at the tip of the tail where the body does not need to produce as much force against the water.

There are four possible hypotheses, which can be inferred from the effects of centrum morphology on average bending stiffness (Fig. 11). A positive trend in our data (Fig. 11A) suggests the resulting forces decrease as centra angle decreases. Also, the 90° motion segment model does not fit the trend produced by the rest of the morphologies. This model suggests that the motion segments are stiffer based on centra shape alone. If true, the parabolic trend (Fig. 11B) shows stiffness increasing in both small convex and larger concave angles with the 120° motion segment model as the inflection point of the curve. In this case, when found in nature, the morphologies with centra angles around 120° would have to be selected for in specific regions along the spine which require less stiffness. The two hypothetical exponential decay trends (Fig. 11C and D) also support the hypothesis that stiffness decreases with centra angle, but

plateaus around either 90° motion segment model (Fig. 11C) or 120° motion segment model (Fig. 11D). Similar to the positive trend (Fig. 11A), either the 120° motion segment model (Fig. 11C) or the 90° motion segment model (Fig. 11D) models would not fit the exponential decay curve. These models suggest that a centra angle around 120° (Fig. 11C) would be less stiff than the trend or more stiff than the trend around a centra angle of 90° (Fig. 11D). This same thought experiment is true for all mechanical properties examined here.

Biological and Biomimetic Systems

To determine the biological relevance of our models, we compared our results to Nowroozi's work with striped bass (Nowroozi 2012). When scaled up to the size of our motion segment models, the average IVJ length of the Striped Bass is about 8mm and the centrum angle is 90°. The max moment from bending striped bass centra at the IVJ is between 0.13 and 0.14 N*m. If we also examine the resulting moment from our bioinspired motion segments at 8mm IVJ, values of 0.13-0.14 N*m occur during 2° bending in the 90° model. Based on these data. Our models are biologically relevant. In other studies, biomimetic vertebral columns have been used to test other mechanical properties such as Storage and Loss Modulus (E' and E'') (Long *et al.*, 2011). In previous models, both E' and E'' have been shown to decrease as IVJ increases. Our data show the same trend (Fig. 12).

Further work

To test the trend related to decreasing centra angle, we would make several additional motion segment models at degrees less than 90° such as 75°, 60° and 45°. We would also like to determine the nature of the dip in stiffness in our 120° motion segment models by creating more

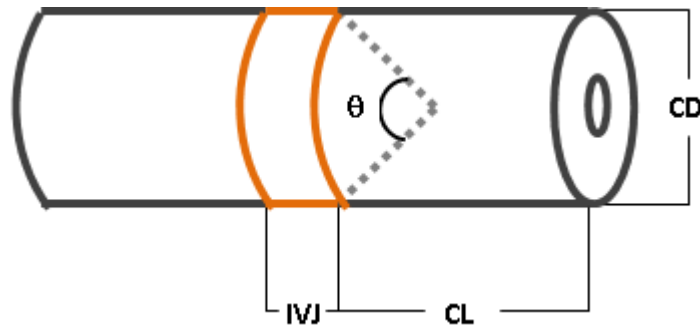
concave models between 90° and 150° at 15° increments (90° , 105° , 120° , 135° , and 150°). In addition to these concave models, we would make several convex models to test if stiffness continues to increase as the centra angle becomes more convex than our 210° motion segment model. Another interesting effect would include looking at different IVJ materials. The silicone we used is stiff and elastic relative to other possible IVJ materials. It would be good to look at how different materials, especially viscoelastic materials, interact with our different centra shapes.

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Tables

Table 1



Model		Centra Length (CL) (mm)	IVJ Length (IVJ) (mm)	Centra Diameter (CD) (mm)	Centra Cone Angle (θ) (degrees)
Bonnethead (<i>Sphryna tiburo</i>) (Long et al 2011)	Measured	11	2.8	10	90, 120, 150
	Scaled	27.5	7	25	
Blacktip (<i>Carcharinus limbatus</i>) (Long et al 2011)	Measured	6	1.3	8	~100
	Scaled	18.75	4.06	25	
Dogfish (<i>Squalus acanthias</i>)	Measured	~ 3.8	~0.57	~4.43	90, 120, 150, 180, 210
	Scaled	21.432	3.21	25	
Bioinspired Motion Segments		30	6, 7, 10, 13	25	

Table 1. Bioinspiration for the models used in this study. Measurements reported in Long et al. (2011) were from the maximum values found in the Bonnethead and Blacktip sharks. The Centra Cone angles presented from Long et al were the values they chose to use in their biomimetic models. We measured the dogfish morphology from a dissection of a fresh specimen.

Table 2

Model	E' (MPa)	E'' (MPa)	Material	δ	Resilience
Silicone	9.153	0.3598	Silicone	0.0393	0.883837
MARMT (max) (Long et al 2011)	0.825	0.1275	Bone (Curry 2002)	0.0996	0.730403
Blacktip (max) (Long et al 2011)	1.35	0.14	Cartilage (Curry 2002)	0.010	0.969072
Bonnethead (max) (Long et al 2011)	0.55	0.045			

Table 2. Mechanical properties calculated from our data. Average Storage Modulus (E') and Loss modulus (E'') were calculated using E^* and Equation 6. Resilience was calculated (Equation 7) using the δ value calculated from 7 random data sets from the MTS.

Table 3

Effect	p Values			
	Average Force	Moment	Work	Bending Stiffness
Entire Model	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Centra angle	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Degree of Bending	< 0.0001	< 0.0001	< 0.0001	< 0.0001
IVJ Length	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Centra angle *Degree of Bending	= 0.0003	< 0.0001	< 0.0001	= 0.2648
Centra angle*IVJ length	< 0.0001	= 0.0003	= 0.0002	< 0.0001
IVJ length*Degree of Bending	< 0.0001	< 0.0001	< 0.0001	= 0.0013
Centra angle * Degree of Bending * IVJ length	= 0.0532	= 0.0532	= 0.0050	= 0.6905

Table 3. The significance of our three main mechanical calculations using Degree of Bending, IVJ length, and Centra angle as the three effects. P values were calculated using a regression model in JMP.

Figures

Figure 1

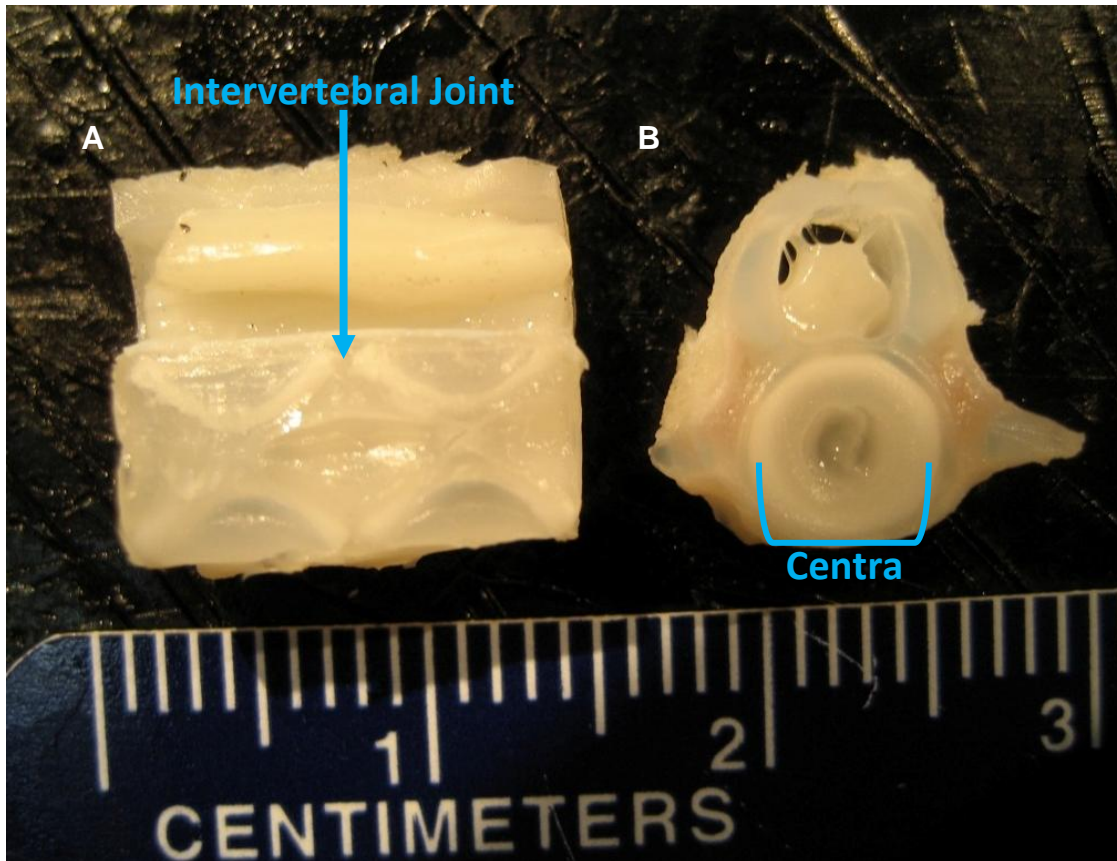


Figure 1. Sagittal (A) and Transverse (B) cut of the Dogfish vertebral column. The mineralized centra and Intervertebral joint are our areas of interest. Also present is the neural arch located above the centra cone in both the Lateral (A) and Anterior (B) view.

Figure 2

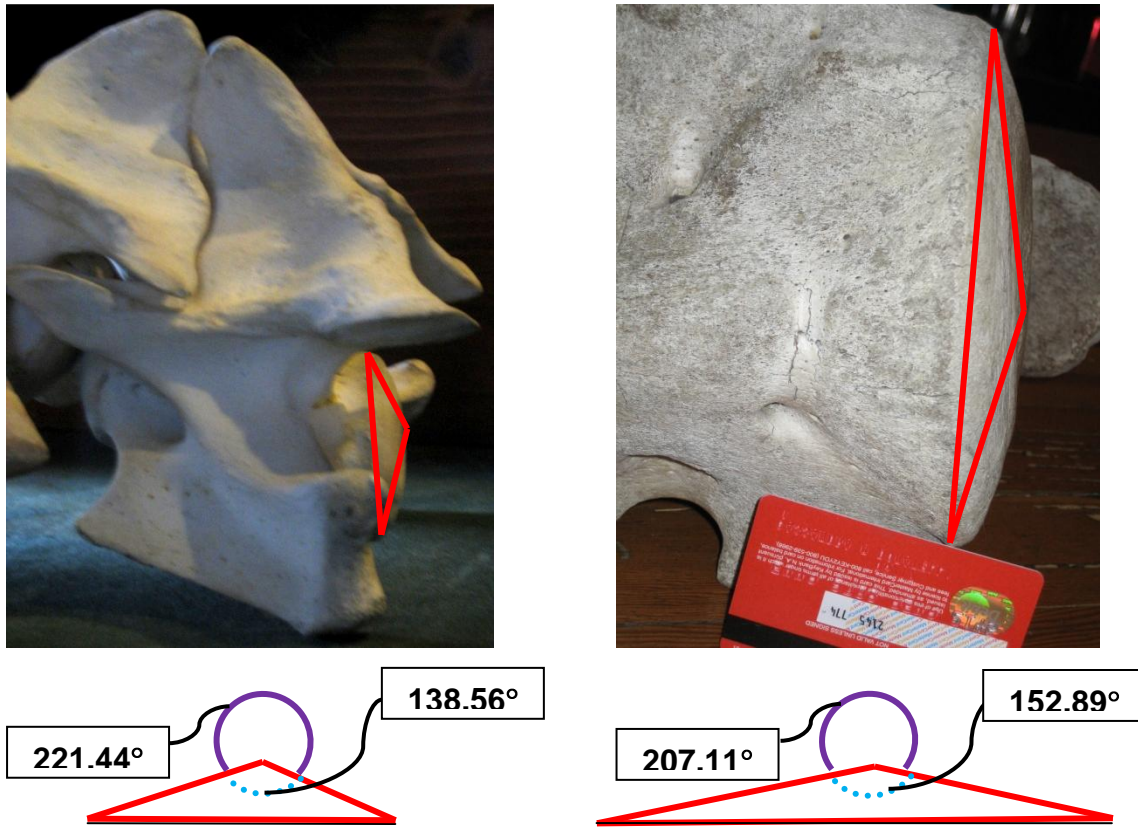


Figure 2: Image of California Sea Lion (Left) and Grey Whale (Right) vertebrae with measurements for use in designing 3D models. Models were traced by hand and angles were calculated.

Figure 3

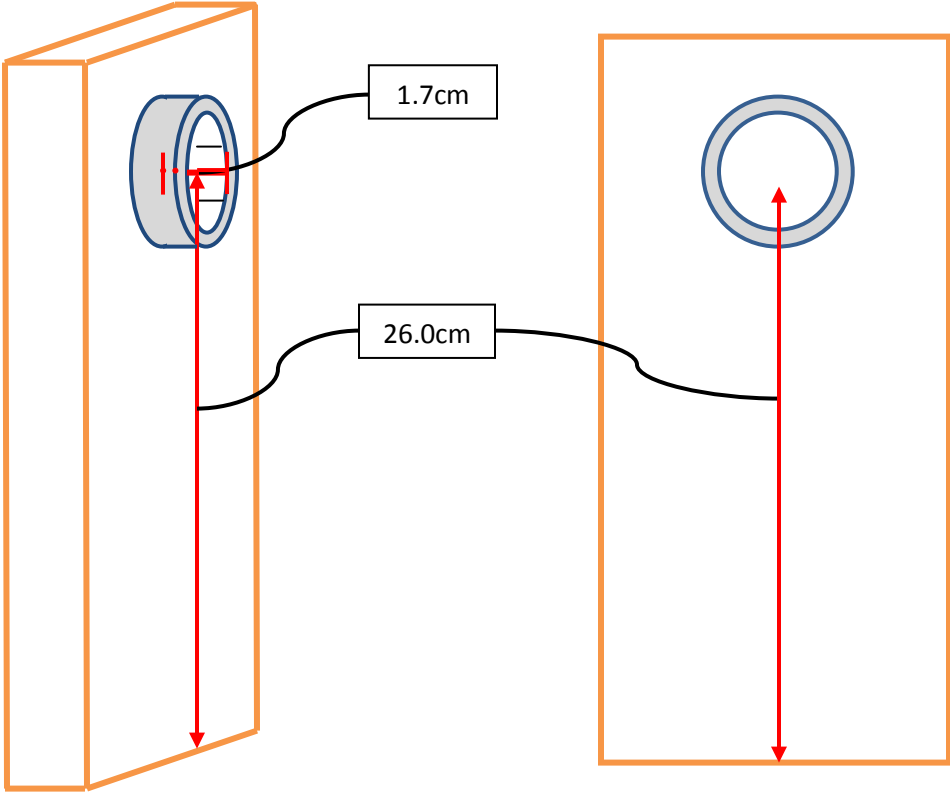


Figure 3: Schematic of testing rig with height and depth measurements.

Figure 4

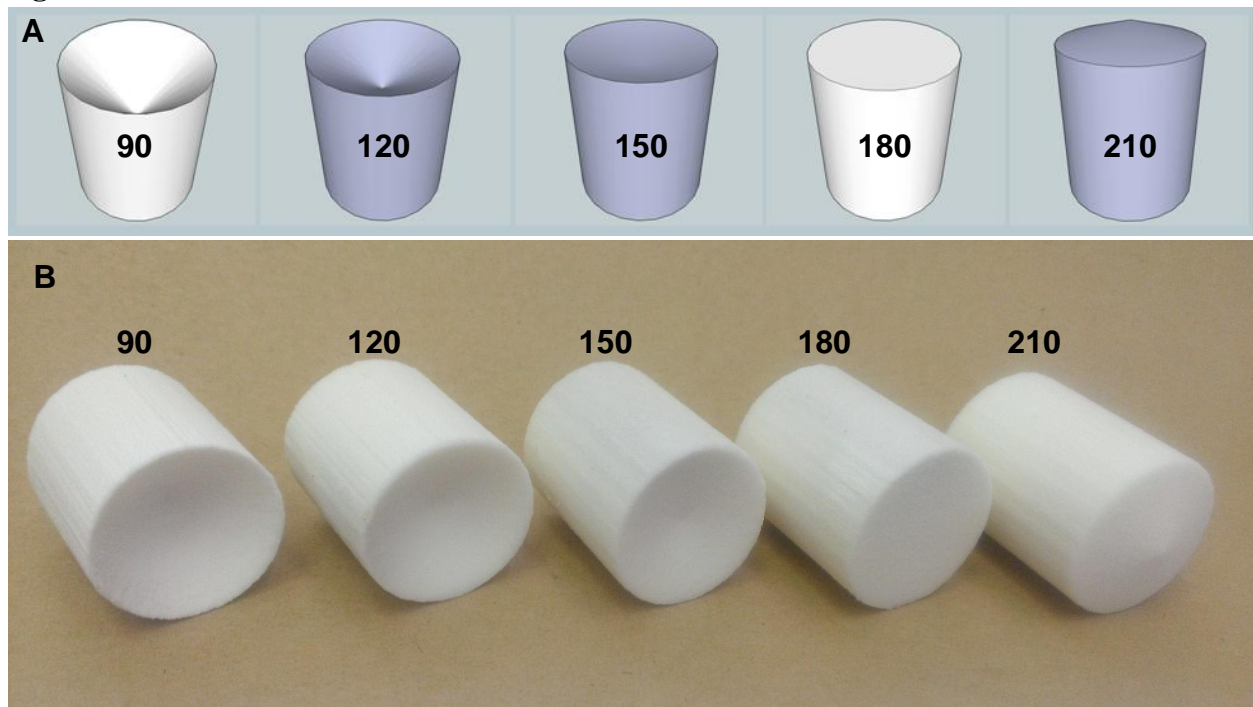


Figure 4. Computer and physical models. These bioinspired models are based on biological morphology reported in **Table 1**. A. SketchUp drawings of bioinspired vertebrae. B. Physical models printed from the Z-Corporation 310 printer following Epsom Salt treatment.

Figure 5



Figure 5: Assembled models. The 6 shown are 180 degree models with various intervertebral joint lengths. The moment arms have been attached with cyanoacrylate.

Figure 6

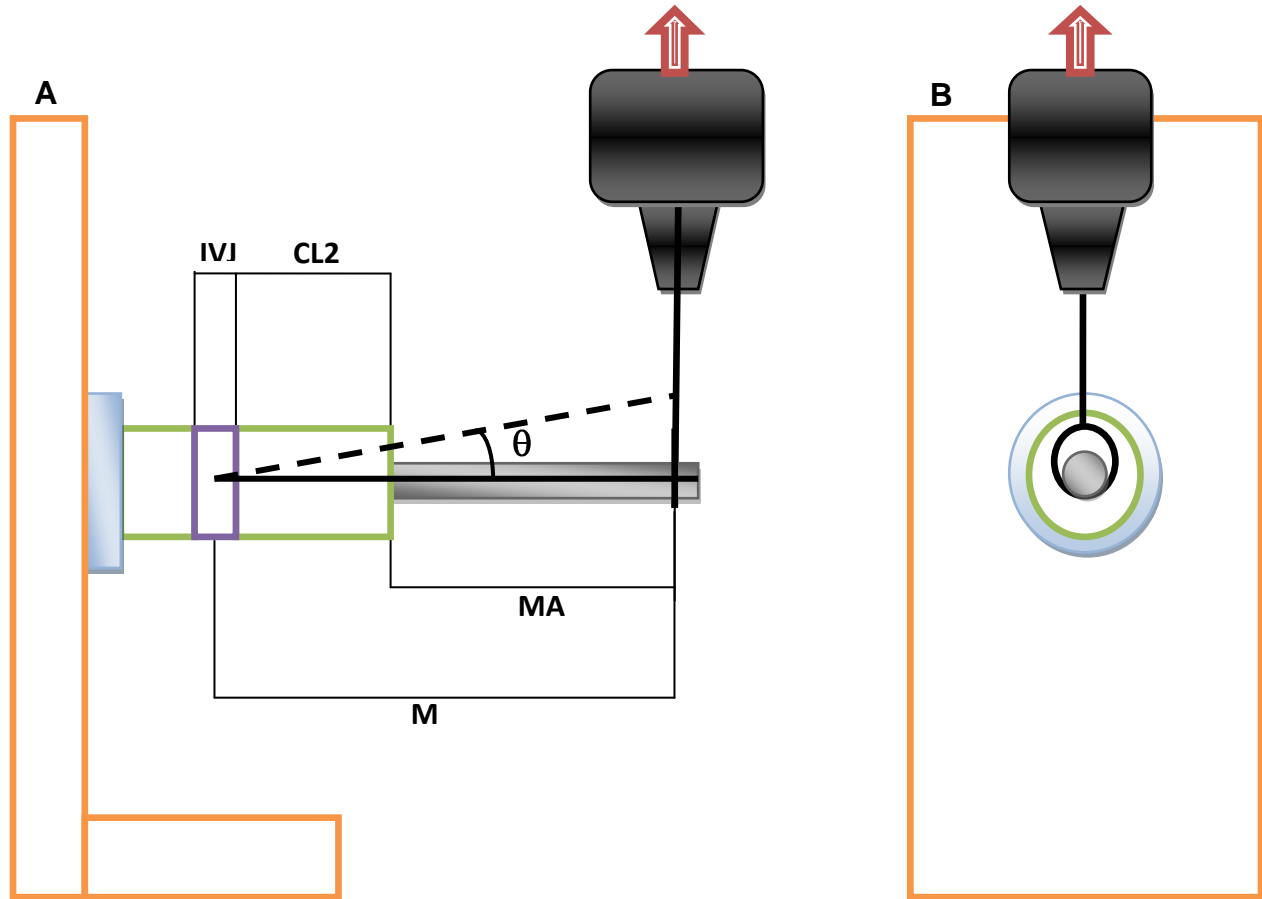


Figure 6. Schematic of the Mechanical testing setup. After calculating the motion head height (Fig. 4), we mounted each motion segment. The motion segment is mounted in the rig with a screw to prevent motion up until the start of the IVJ. In panel A we see a front view with the motion head pulling up on the moment arm of the model. This creates the angle θ calculated using Equation 1. In Panel B we see a side view of the motion head pulling up with a view of the wire looped around the moment arm.

Figure 7

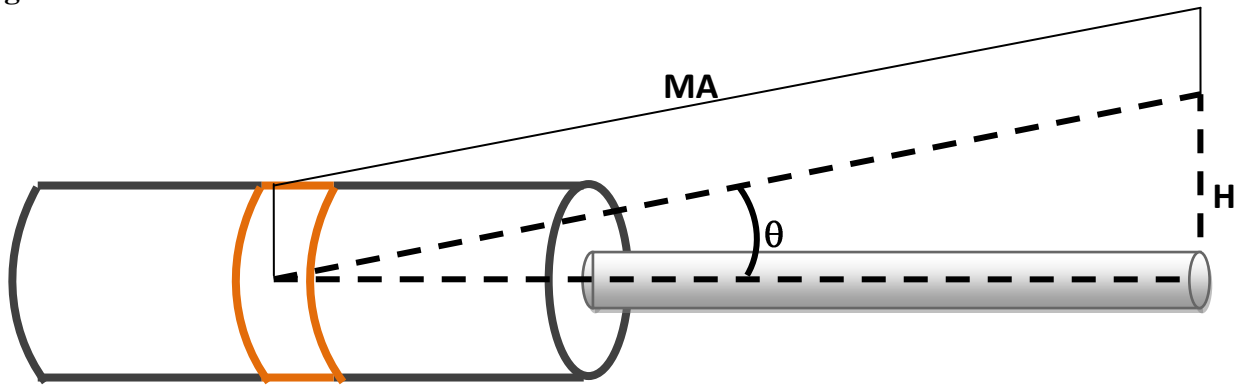


Figure 7. Height (H, mm) of the motion head on the MTS was determined using the moment arm length (MA) and the desired bending angle (θ) according to **Equation 1**.

Figure 8

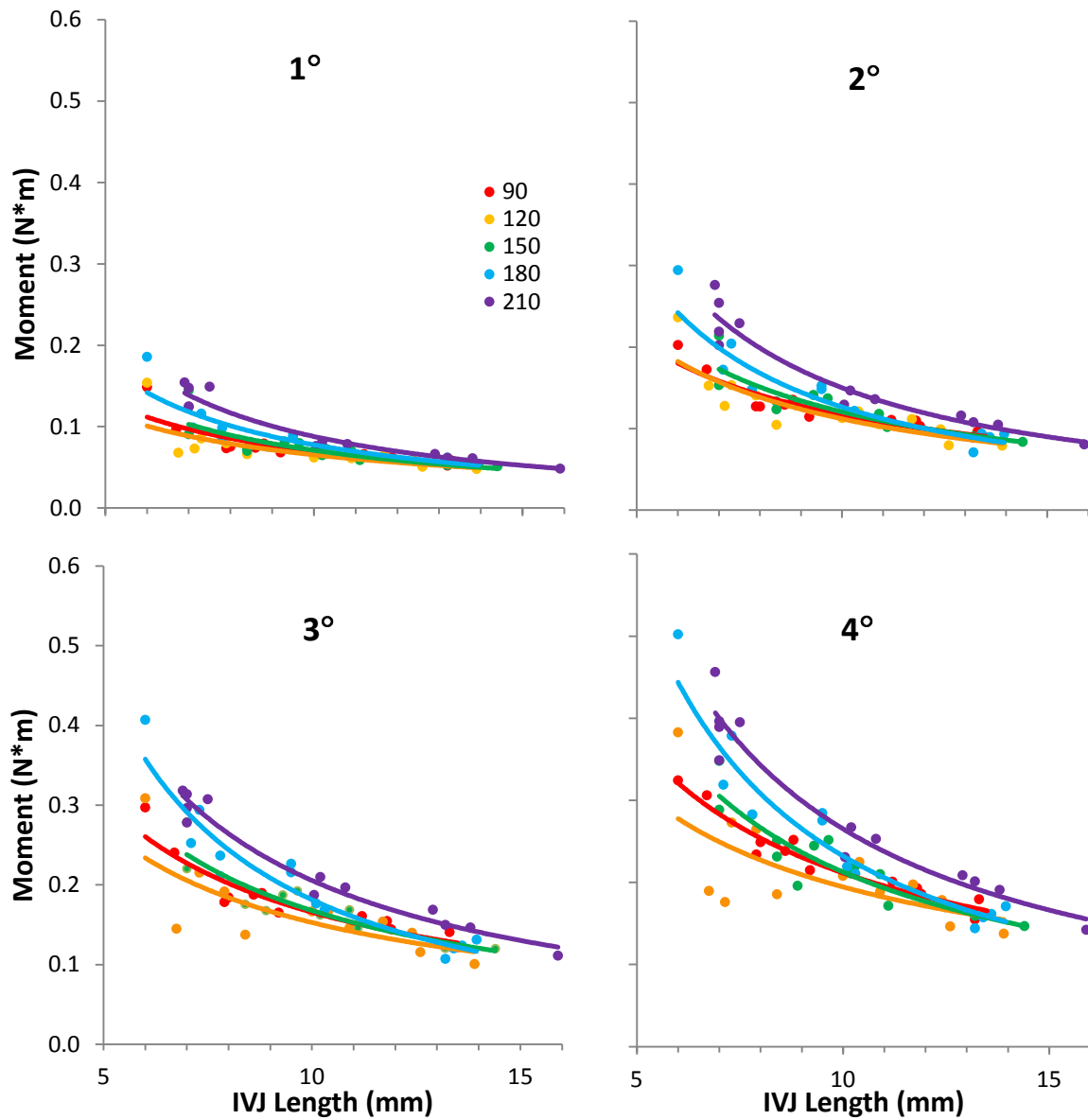


Figure 8. Moment vs. IVJ length per degree of bending. Increasing IVJ length (mm) decreases the moment (Nm) produced. Each panel corresponds to the angle motion segment is bent. Trend lines correspond to each of the 5 centra morphologies tested. A Regression analysis was done in JMP which revealed the model to be significant ($p < 0.001$). At each bending angle, the 210° motion segment morphology generates the largest moment, while the 120° motion segment model has the lowest.

Figure 9

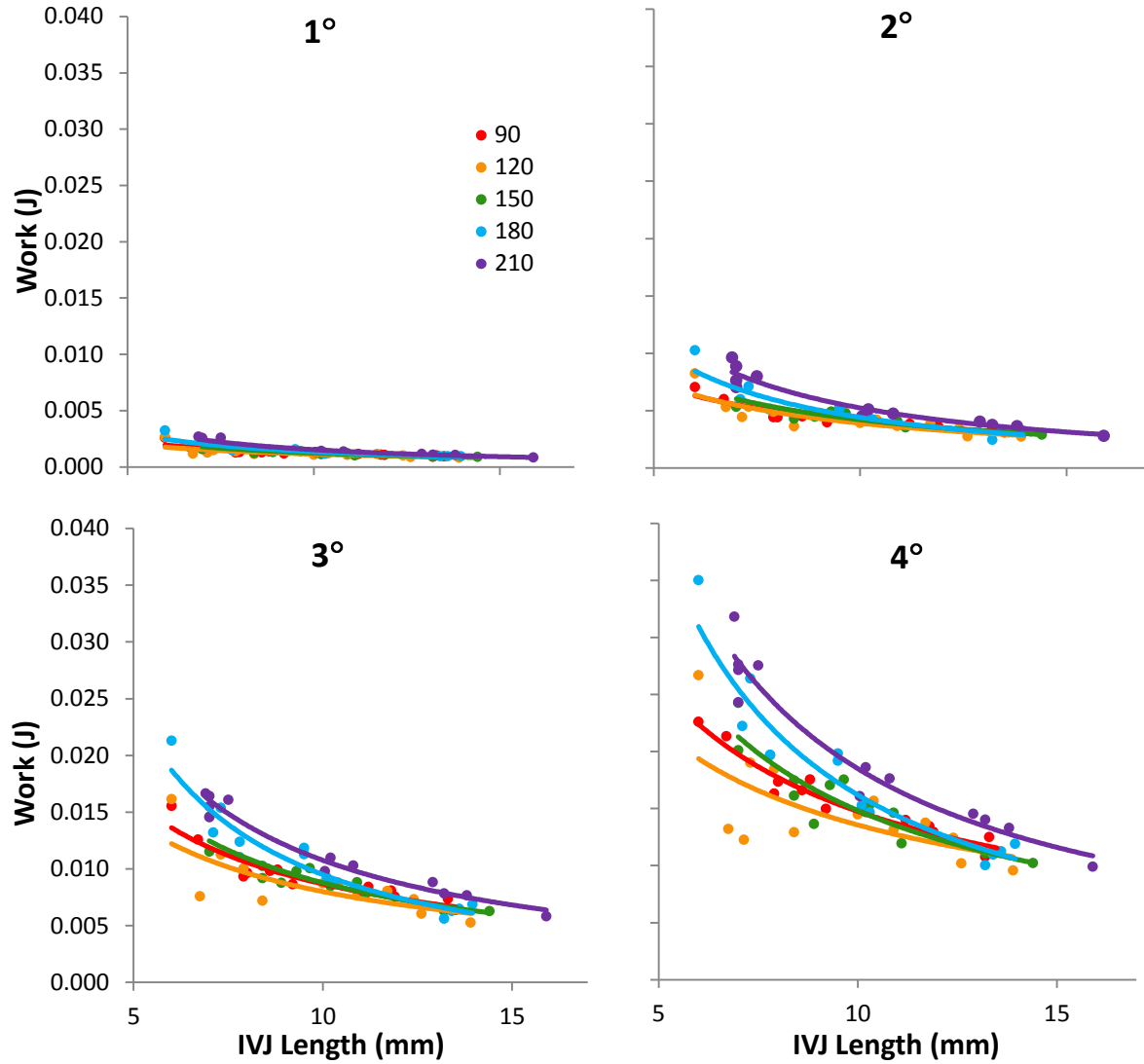


Figure 9. Work vs. IVJ length per Degree of Bending. As IVJ length (mm) increases the Work (J) produced by the motion segment decreases. The panels correspond to the motion segment bending angles. Trend lines are a power fit and correspond to each of the 5 centra morphologies tested. A Regression analysis was done in JMP which revealed the model to be significant ($p < 0.001$). For every bending angle, the 210° motion segment models produce the highest average work where the 120° models produce the lowest.

Figure 10

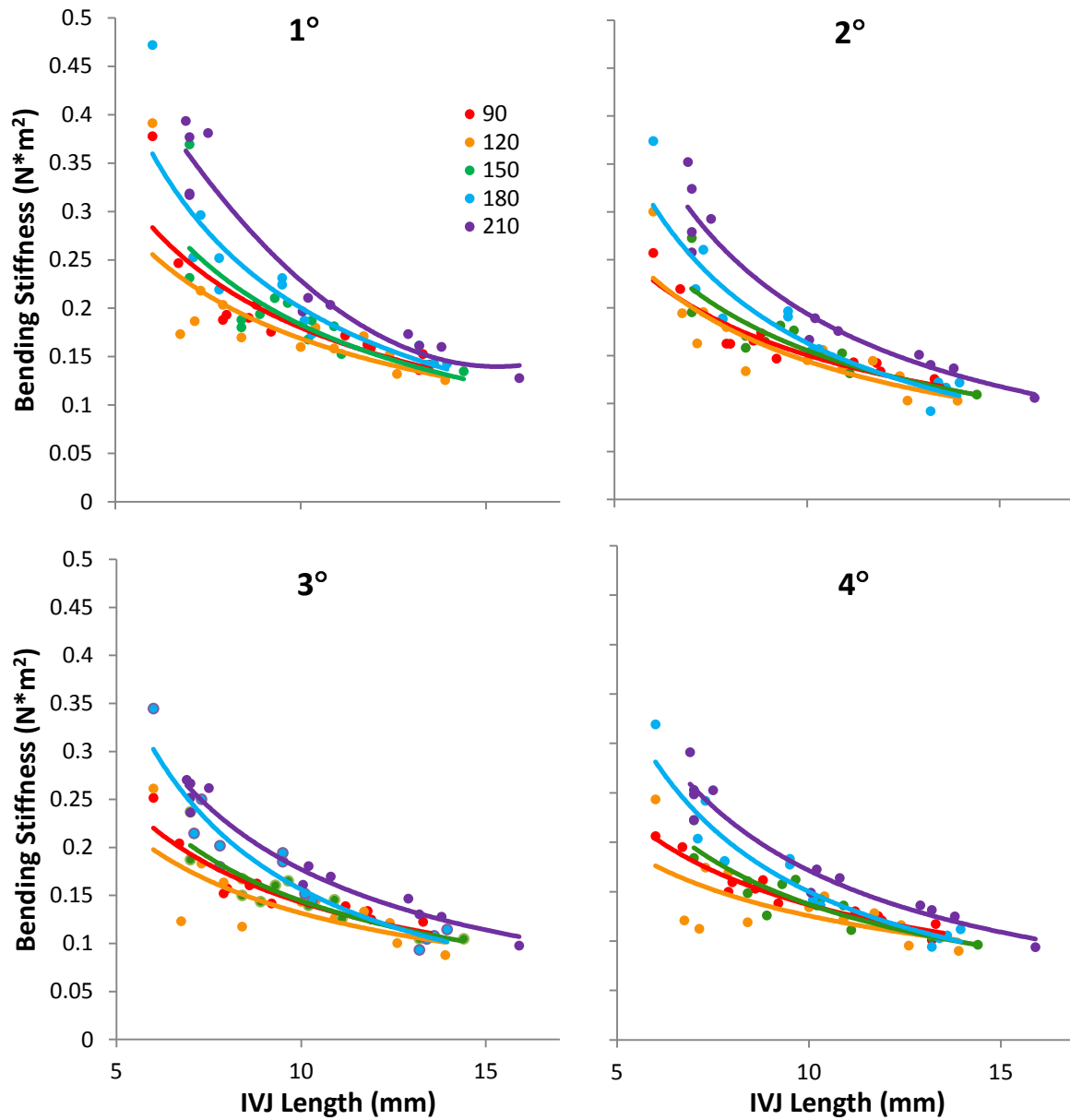


Figure 10. Bending Stiffness vs. IVJ Length per Degree of Bending. Flexural Stiffness (N*m²) decreases with IVJ length (mm). The panels correspond to the motion segments being bent at various angles. Trend lines are power fit and correspond to each of the 5 centra morphologies used. A Regression analysis was done in JMP which revealed the model to be significant ($p < 0.001$). For every bending angle, the 210° motion segment model has the highest average flexural stiffness; while the 120° motion segment model has the lowest.

Figure 11

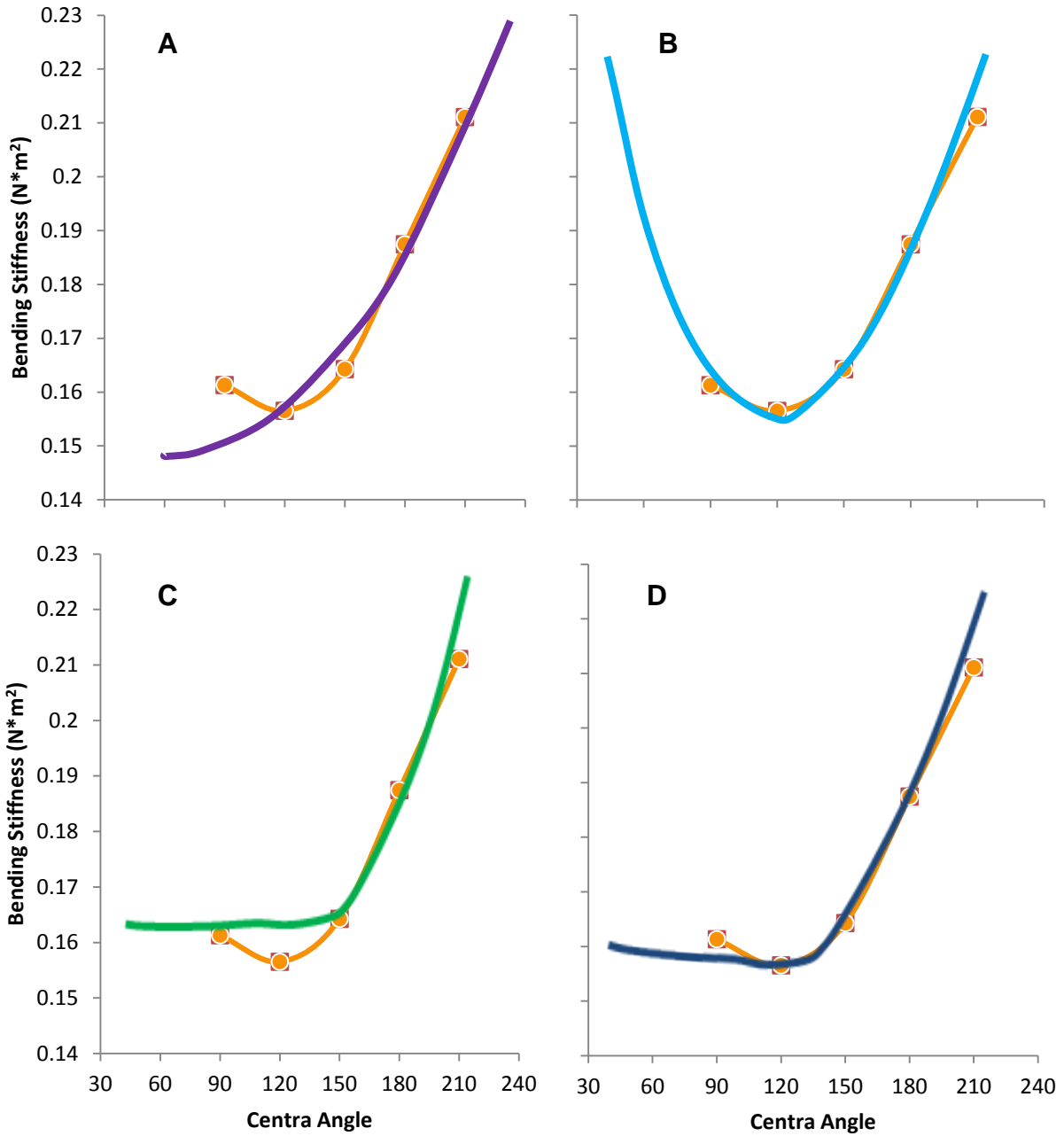


Figure 11. Potential trend lines for further studies. Panel A shows a decaying trend. Panel B shows a parabolic trend line. Panel C shows an exponential trend with the 120 degree model as the anomaly. Panel D shows an exponential trend with the 90 degree model as the anomaly.

Figure 12

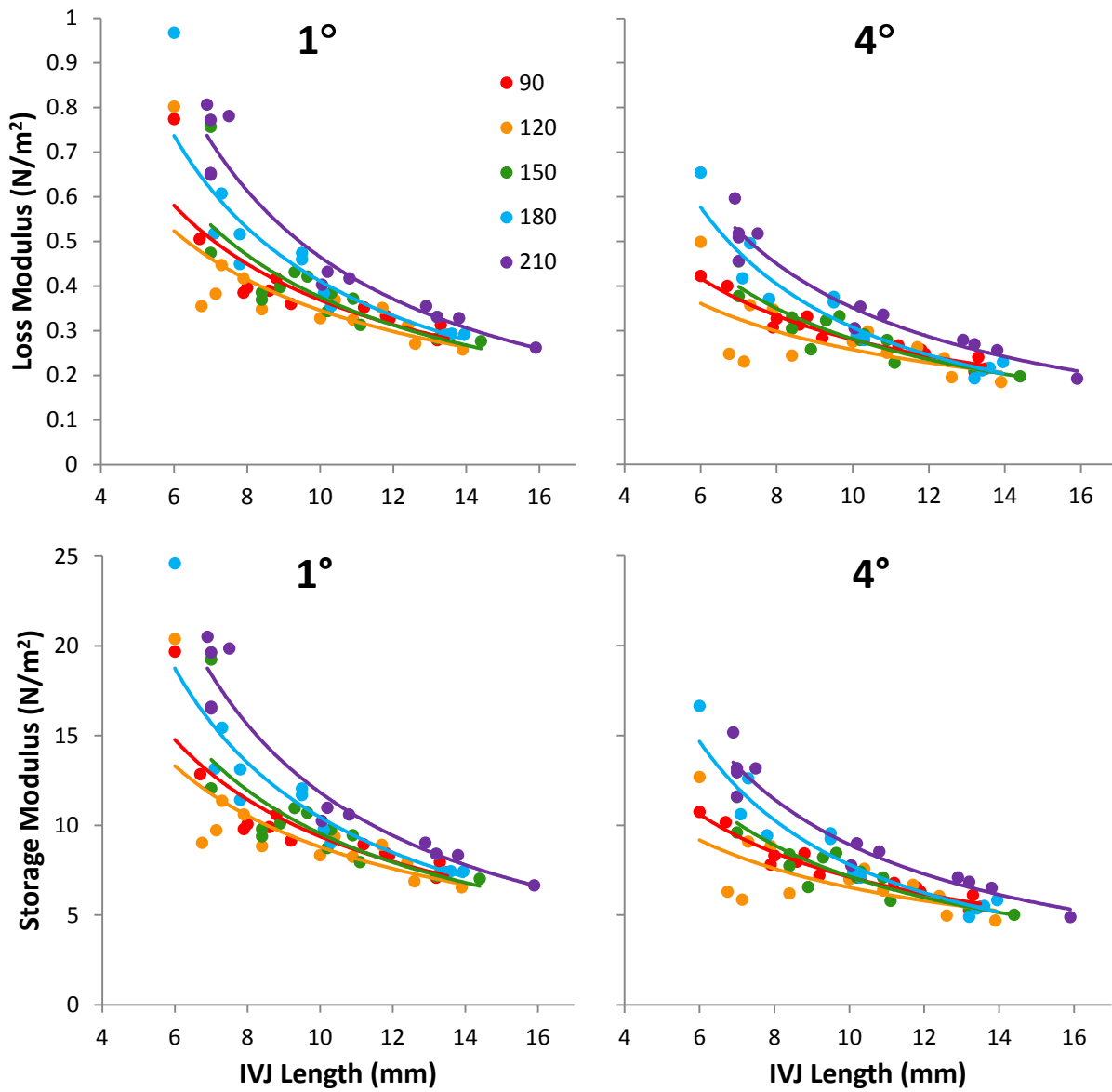


Figure 12. Storage and Loss Modulus plotted against IVJ length. Trend lines correspond to each of the 5 centra morphologies used. Equation 6 was used to calculate these properties.

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