Design and characterization of OpenUSARm - a continuum 3D printed borescope arm for early urban search and rescue imaging and sensing

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When a natural or man-made disaster occurs, people may become trapped within collapsed buildings and many require urgent assistance. For large disasters, national governments may request rescue support from international groups; in these instances it is important to quickly transport skilled international rescue teams to the site within 48 hours after the disaster as thirst and starvation limit survivability of entrapped people. There are a number of factors that may limit this rapid deployment: The rescue teams' logistics of moving equipment to the site in the first 48 hours is one factor that may limit this fast deployment; for disasters in remote areas, international teams may only reach the affected region more than 48 hours after the incident, possibly due to a disrupted transport infrastructure. When a remote disaster occurs, experience has shown that the majority of rescues are performed by local people in the area, who may have little or non-expertise in urban search and rescue. Here we report a 3D printed design for a flexible arm, intended as a borescope, that could either be printed in-country following an earthquake or as a means to reduce the equipment transport burden out to a disaster site. The borescope design is a tendon-based continuum arm design, comprising orthoplanar spring design modules and can be operated by non-experts alike. The borescope design requires string or nylon filament (fishing line) for tendons and may be adapted to carry an ad-hoc mobile phone, feeding tube or other sensors to a person trapped in a collapsed building. This report characterises and describes the range of compression and tilting movement that the arm has for variations of the spring module design.

I. INTRODUCTION

Urban search and rescue (USAR) seeks to locate, extract and medically aid those trapped within failed building structures. A wide variety of man-made and natural disasters can trap people in failed urban structures such as earthquakes, terrorist attacks, industrial accidents, avalanche, and volcano eruptions. In response to widespread urban structural collapse that can occur, highly trained teams are deployed to the site and, after setting-up and initial assessments, start to methodically search the collapsed buildings. USAR teams are highly trained in a variety of methods to detect trapped people including canine search, calling-out, and technologically-assisted search through optical or infrared video camera (for instance, using fiber-optic cameras or rigid borescopes).

Time is a critical factor in search and rescue [1]. Although there have been reports of many surviving longer, starvation and thirst limit human survivability and the majority of rescues occur within 48 hours. For international teams being deployed to the disaster site, arrival within 48 hours is often difficult due to transport infrastructure damage from the disaster. The 2005 South Asia Pakistan earthquake is one example where many international teams arrived after the first 48 hours and the majority of the search and rescue phase of disaster relief was performed by local private individuals [2]. Similarly, for the first 48 hours of the May 2006 Yogyakarta earthquake, around 78% of rescues were performed by private individuals; this was also the case for 1988 Armenian earthquake in which it is estimated that 90% of rescues were effected by local residents in the first 24 hours using simple tools [3]. These instances of the first response by local persons suggest that locally-deployed non-expert, trapped person detection technologies would be very effective in reducing deaths and enhance the on-the-ground USAR capability [4].

For the highly-trained USAR international response teams, there are challenges too in the amount of equipment that can be moved quickly to the site. The first response of USAR teams typically deploy with less equipment in order to retain speed in their deployment. With advances in 3D printing, simple tools that could be digitised and the design information, which could be carried in digital form or sent over to the USAR operations area, could help to reduce the equipment burden.

Disaster response and resilience has received much attention from the 3D printing community and many diverse applications of 3D printing are being explored including: fittings for piping and sanitation post-disaster [5], novel 3D printed earthquake columns for recovery shelters [6], bricks for building structures [7], and the production of emergency shelters [8]. Here we add to the community's body of work, reporting a study of the characterization of 3D printed design module that can be assembled into a simple continuum arm, flexible enough to move through gaps in rubble and examine internal voids, and capable of carrying ad-hoc sensors (such as a mobile phone with camera) or water/feed tubes to trapped survivors. An important characteristic of the design is that it could be produced locally and cheaply using one or more 3D fused deposition modelling printers(similar to those manufactured in Ref. [9]); low-cost 3D printers are readily available and relatively mature.

Due to the importance of the ∼48 hours of survival time, it is clear that any printed tool should be produced as quickly as possible and with cheap components. Any non-printed component parts of the arm would also have to be easily accessible and be controlled by those searching, possibly those inexpert, early first responders. The design should also need to be scalable to meet the challenges of moving through rubble of different grades and sizes of access points, be universal in terms of the sensor package it would carry. The design should also be simple enough so that it could be used by non-experts in the field [10].

The flexible borescope presented here is based on a continuum robot arm design that was first invented by Victor Anderson in 1968 and known at the time as the tensor arm manipulator [11]. Anderson developed a design that could work well in an unknown underwater environment and was inspired by nature, looking at animals and plants that demonstrated complicated movement with a soft structure, such as cephalopods. Cephalopods are class of mollusc such as octopus, squid, cuttlefish and nautiluses which have tentacles for appendages. Tentacles, tongues and trunks come under the biological group known as muscular hydrostats; this means they are muscular organs which lack skeletal support. The lack of skeletal support within the limb results in the capability of highly flexible motion. This makes it perfect for interaction with an unknown and diverse environment or complete a range of difficult tasks [12]; therefore a design, similar to a cephalopod, was developed that had multiple degrees of freedom as well as exhibiting a significant compliance to move through collapsed building structures.

In section II, the design for a 3D printed continuum arm is presented and, following the motion designations of pull and search, studies of the spring properties undergoing compression/extension and tilting motions are presented in III. We draw our initial conclusions in section IV on this desgin and look to define future modifications that might help the USAR application.

II. 3D PRINTED CONTINUUM ARM DESIGN

A. Orthoplanar Spring Module Design

Tendon-based designs are a direct and simple solution to manually drive the motion of a continuum arm so that everyday string or nylon fishing line can be used for the tendon actuators. The actuation mechanism can also be operated manually in a simple manner by pulling the tendons appropriately.

The printed part of the design uses orthoplanar spring sections to form the arm's backbone and an assembled six module arm is shown in Figure 3. The tendons within the arm structure are responsible for the changes in shape of the finite series of sections in the arm by producing a torque force at the base of the arm. The design is based on earlier work by the Kings College London (KCL) University group, who first studied this type of a orthoplanar spring design [13] for robotic arms.

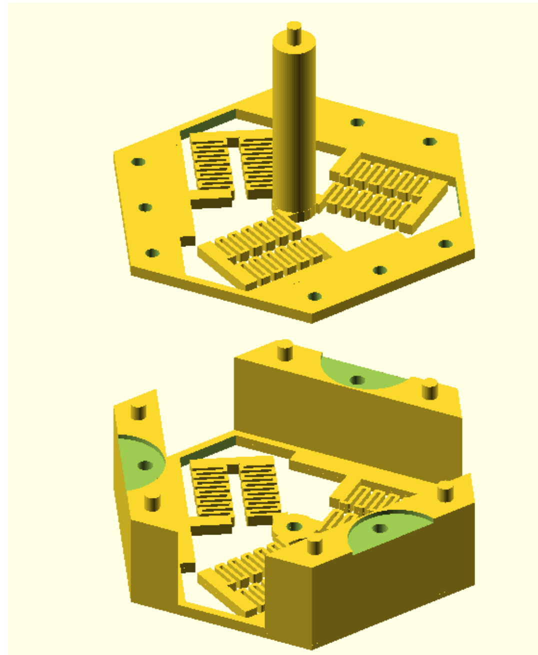

FIG. 1. An exploded view of two parts to each repeating module of the continuum arm studied here. The lower part forms the base and has six studs that push into the upper part. The planar zig-zag structure forms the spring and is responsible for the motion. The tendon is passed through the middle hole on three sides and, for those modules that require movement, can be secured around the edge of the uppper spring part to the module. The design is freely available [14].

The orthoplanar spring design has hexagonal symmetry with three bi-spring structures supporting a central platform [14]. The hexagonal symmetry ensures the platform is stable with respect with the action of the tendons [15]. The orthoplanar spring modules were printed using a RepRap Prusa i3 using orange polylactide acid (PLA) filament, purchased from ref. [16]. This is a common and mature design of fused deposition modelling printer.

This spring design can scale in size making it possible to fit this 3D-printed flexible borescope into different sizes of voids. Different sizes of spring are presented in 2, which demonstrate this scaling in size.

B. Assembled borescope arm

The length of the flexible section of the borescope is up to the requirements of the rescue. It's important to demonstrate that the design can flex through collapsed building voids. Assembly is simple with successive sections pushed into the arm in order to lengthen it. Once the modules are assembled into a continuum arm then three tendons are strung through the holes positioned

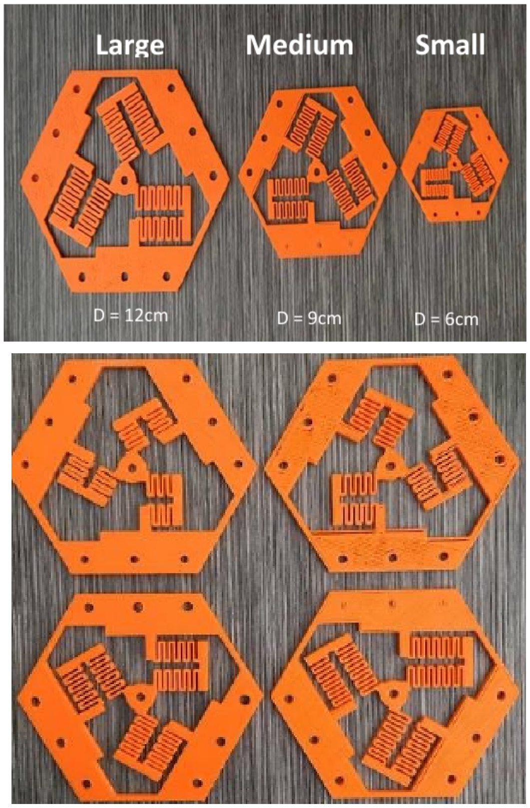

FIG. 2. Upper panel : Simple scaling of the planar springs is possible and 6cm, 9cm, and 12cm diameter springs are shown from right to left. The diameter measurement refers to the diameter of the circumscribed circle around the hexagonal shape. Lower panel : In order to alter the spring properties, making the borescope more or less flexible, the spring lengths can also be changed and 2, 3, 4, and 5 periods of the zig zag spring structure are shown from top-left to bottom-right.

around the edge. By pulling on the nylon strings the arm can be made to tilt and compress, which is shown in Figure 3.

It's important to stress that the arm design is independent of the camera or sensor, there are a wide range of other 3D printing project designs available means that these can be easily modified to provide an adaptor. For example, if a mobile phone is available for a non-expert rescue attempt, then existing mobile phone clamps, similar to ref. [17], might be modified for this purpose.

III. RESULTS

As with any tendon based arm the challenge is the control of the arm under the action of tension in the tendons and gravity. The spring characteristics in the planar section need to be understood before advancing development further. Consequently, our initial testing sought to understand the behaviour the spring modules.

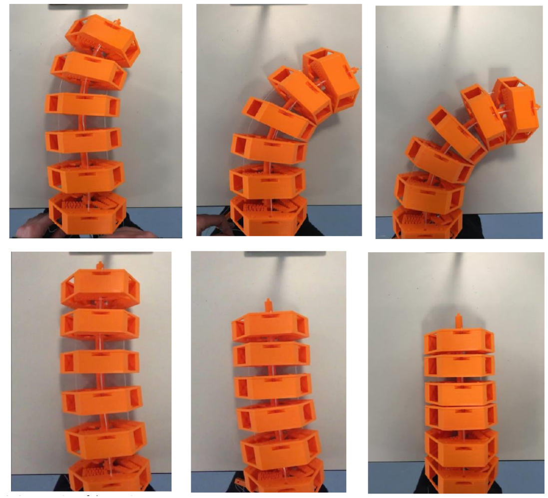

FIG. 3. The continuum borescope arm undergoing tilting (upper row) and compression (lower row) motions.

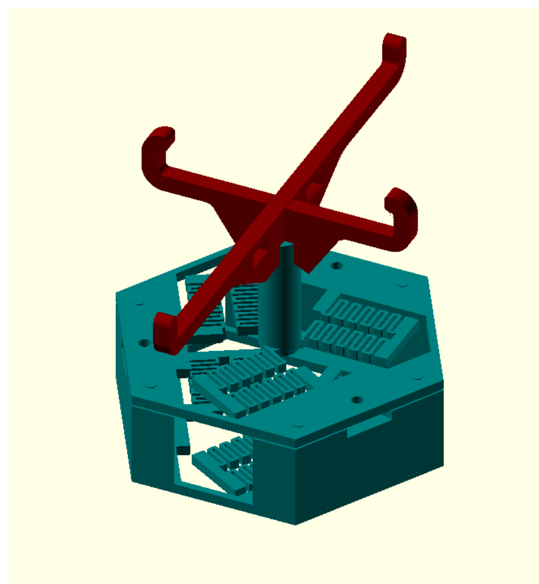

FIG. 4. An example modification of a module (in teal) to hold a mobile phone (dark red), taken from reference [17].

A. Borescope Arm Module Compression Motion

The arm is capable of a number of different types of motion. The simplest is when all three tendons pull or push in unison, shortening or lengthening the arm at the same time. In order to examine this longitudinal motion, a single orthoplanar spring was studied by attaching weights and examining the central platform extension.

Orthoplanar springs with diameters of 6cm, 9cm and 12cm were printed in polylactide acid (PLA) and studied by hanging calibrated masses (100g to 1000g) on a central loop. The calibrated masses caused the planar springs's central platform to experience an extension relative to the outside of the spring design. With the masses applied, the extension displacement was then measured by Vernier calipers from the planar platform to the center of the springs; this is termed as the displacement with mass in Figures 5, 6 and 7. The mass was then removed and the spring displacement between the two same positions was measured again - this is defined as displacement after mass in Figures 5, 6 and 7. Ideally, the spring there should be no hysteresis and no residual displacement. However, after some initial testing it could seen quickly that these springs exhibited some hysteresis.

Figures 5, 6 and 7 depict the data taken during testing for all three sizes of orthoplanar springs. The smallest spring is shown in Figure 5. For displacements upto 1.5cm, the 6cm spring exhibits very little residual displacement of less than 1mm. At larger displacements the 6cm springs quickly exhibit significant residual displacement, suggesting that the spring is starting to overextend, until around 7N and a displacement of 2.5cm, the residual displacement is 5mm. With larger springs, in Figures 6 and 7, the residual displacement is significant for the smaller vertical displacements upto 1.7cm (9cm diameter) and 4.8cm (12cm diameter).

The spring constant is a good measure of the stiffness and strength of the printed orthoplanar springs. The results show that the small spring is the stiffest and the largest spring is the most compliant. A future design modification to this arm could place a stiffer spring at the tip of the arm to allow for finer movement and a more flexible spring will be needed for freer movement towards the base to enable accurate movement.

These results are useful as they help to understand the tip placement accuracy and repeatability of movement for the CRA. They can be used to calibrate the linear contraction motion of the arm e.g. for a medium sized spring, a force of 7353N should be applied to enable a displacement of 2cm; but to allow for movement repeatability the deformation of each orthoplanar spring should also be considered in calculations. A force restriction needs to be applied i.e. a maximum force of around 4900 N, so only small amounts of deformation occurs of the orthoplanar spring.

B. Borescope Arm Module Tilting Motion

After exploring the orthoplanar springs with the compression test, the next step was to develop the design and produce a module that could be used in series as a continuum arm. By putting two of these modules together in series it was possible to perform a tilt test. The tilting test described here enables an understanding of the dynamics of the deflective motion on the continuum arm and the results collected can be seen in Figure 15. The results allow for accurate tip placement for the continuum arm when undergoing a tilting motion; e.g. for medium sized spring module, a force of 0.25N produces a deflection angle of 0.30 radians. Consequently, this information would be used by the future continuum arm control mechanism.

Through the compression and tilt test, calibrate both the pull and search functions of the continuum arm motion; for the designs given here it is also well-within the typical pulling force of most people.

IV. CONCLUSIONS

In conclusion, a continuum-style arm for urban search and rescue has been designed and characterized; the design is based on a 3D printed orthoplanar spring design used previously in robotics [13, 15]. The modules of a tendon-based continuum arm were printed using a RepRap Prusa i3 and was fabricated using a basic polylactide acid filament and nylon fishing line and equivalent materials would be expected to be available in-country after a disaster. It has also been demonstrated that the arm can flex using three manually-driven tendons. If automated control were required in future, the compression and tilting data calibrate the range of motion available and enable control of the 3D-printed borescope arm.

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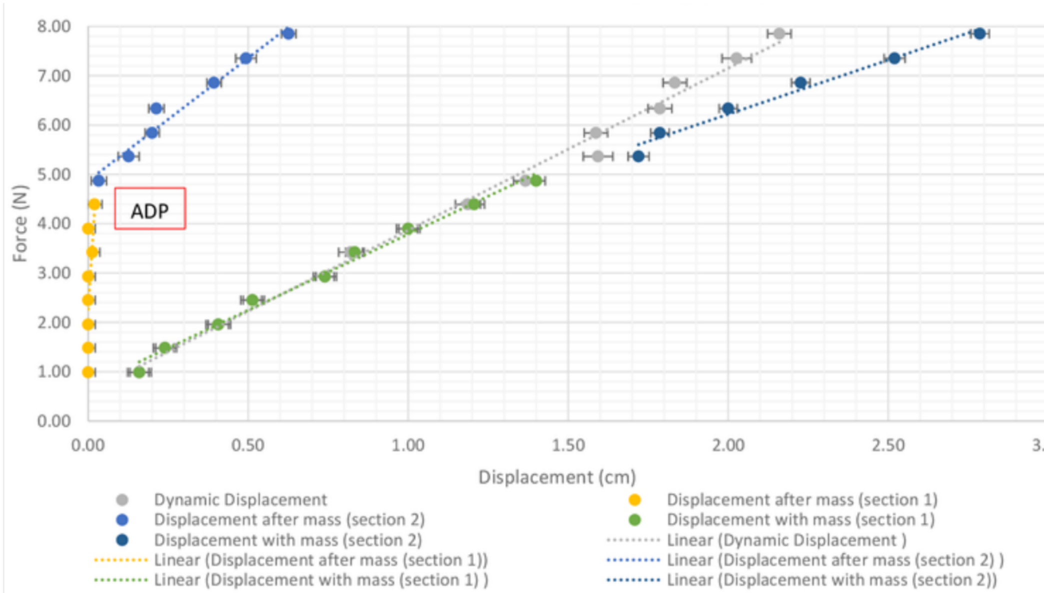

FIG. 5. The longitudinal motion data for 6cm orthoplanar springs. The rightmost series of points in all plots is the vertical displacement for the given force from hanging the weight. After removing the weight the residual displacement measurement is shown as the left-most series of points. The middle series of points is the difference of the rightmost and leftmost series of data points. The point at which the residual displacement changes gradient is indicated as the anomalous displacement point, and is labelled as ADP.

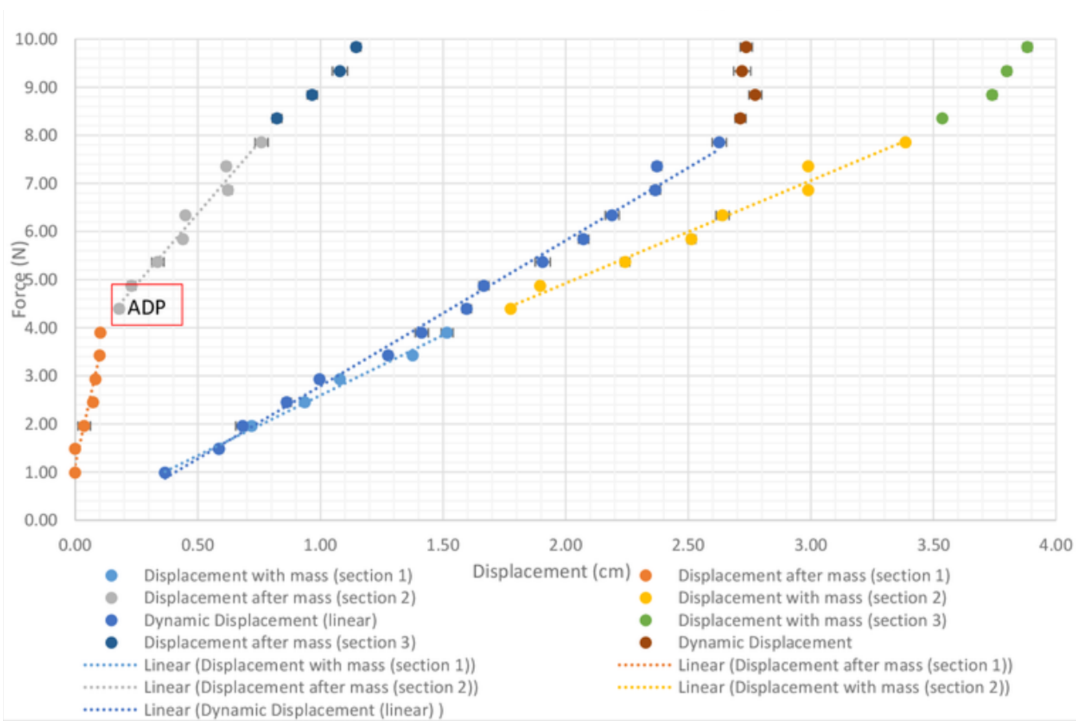

FIG. 6. The longitudinal motion data for 9cm orthoplanar springs. The rightmost series of points in all plots is the vertical displacement for the given force from hanging the weight. After removing the weight the residual displacement measurement is shown as the left-most series of points. The middle series of points is the difference of the rightmost and leftmost series of data points. The point at which the residual displacement changes gradient is indicated as the anomalous displacement point, and is labelled as ADP.

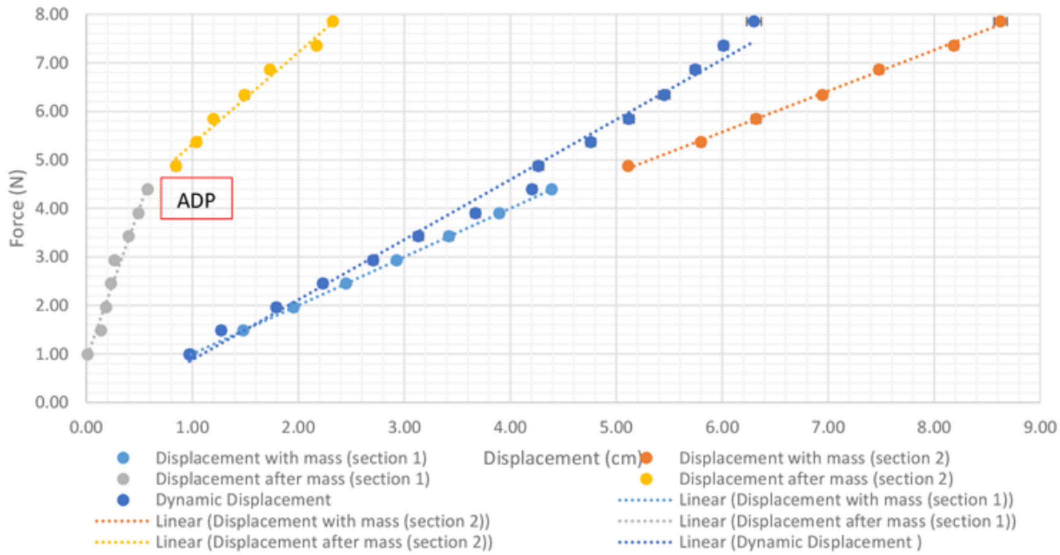

FIG. 7. The longitudinal motion data for 12cm orthoplanar springs. The rightmost series of points in all plots is the vertical displacement for the given force from hanging the weight. After removing the weight the residual displacement measurement is shown as the left-most series of points. The middle series of points is the difference of the rightmost and leftmost series of data points. The point at which the residual displacement changes gradient is indicated as the anomalous displacement point, and is labelled as ADP.

Orthoplanar Spring Size (cm)	Spring Constant Before ADP (N/cm)	Spring Constant After ADP (N/cm)
6	3.2 ± 0.2	2.45 ± 0.06
9	3.0 ± 0.1	2.53 ± 0.06
12	2.41 ± 0.09	1.78 ± 0.02

TABLE I. The fitted spring constant

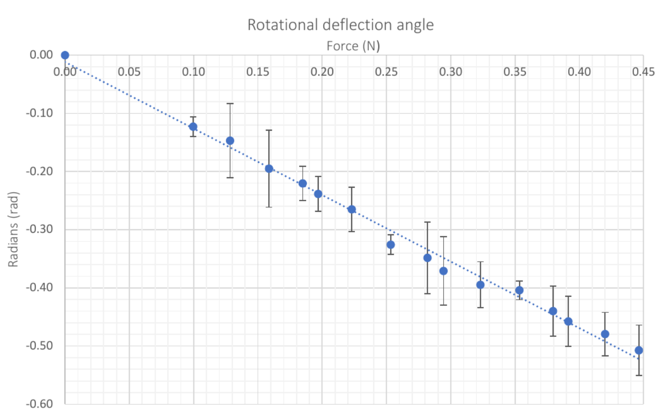

FIG. 8. The angle of rotation of the module for a given applied force.

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