UNIVERSITY *of York*

This is a repository copy of *A Novel Two-Hand-Inspired Hybrid Robotic End-Effector Fabricated Using 3D Printing*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/id/eprint/189122/

Version: Accepted Version

Proceedings Paper:
Marsh, Benjamin and Liu, Pengcheng orcid.org/0000-0003-0677-4421 (Accepted: 2022) A Novel Two-Hand-Inspired Hybrid Robotic End-Effector Fabricated Using 3D Printing. In: Proceedings. (In Press)

Reuse
Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

A Novel Two-Hand-Inspired Hybrid Robotic End-Effector Fabricated Using 3D Printing*

Benjamin Marsh[1[0000−0003−1809−3893]] and Pengcheng Liu[1[0000−0003−0677−4421]]

Department of Computer Science, University of York, York, YO10 5DD, UK
pengcheng.liu@york.ac.uk

Abstract. The field of soft robotics aims to improve on limitations of traditional rigid robots by using naturally compliant materials. This work designed a novel robotic end-effector, inspired by two-handed human grasping and fabricated using 3D printing, that is capable of lifting target objects without exerting large forces. The end-effector is a hybrid of rigid and soft materials, and aims to be simple, low-cost, and fabricated using a reliable process. Grasp tests were performed on a wide range of target objects and the success of the design is evaluated in terms of grasping capability and fabrication process. Results show the capability of the novel design to lift a range of target objects, and highlight improved grasping performance over other types of gripper. Material costs and fabrication/assembly time of the 3D printed components are also presented.

Keywords: Soft robotics · Robotic grasping · 3D printing.

1 Introduction

Soft robotic grippers used for grasping and pick-and-place operations have many advantages over traditional rigid designs. They also present challenges, requiring different methods of design, fabrication, actuation, and control. One such challenge is that soft robots are more structurally vulnerable [17]; [14] suggests that some soft materials are "not suitable for manipulating heavy objects". Hybrid robots that combine hard and soft materials, such as the designs presented in [1] and [21], can therefore leverage the strengths of both approaches [20].

Many soft robots are biologically inspired due to the soft bodies of animals providing abilities such as conforming to surfaces, adapting to changing environments, and damping impact forces, influencing soft robots to be equipped with capabilities based in material properties, rather than complex control systems [18]. There are also challenges in building bio-inspired soft robots; without a skeleton soft animals cannot support much weight [18], and there is no mechanical equivalent to animals' complex muscle structures [14] with comparable size and performance [11] so alternative actuation methods are required.

A specific biological influence is the human hand (e.g. [4, 5]), a popular source of design inspiration due to its ability to manipulate objects of various shapes,

* Supported by The University of York

sizes, and materials [2]. However, robotic hands that attempt to mimic human capabilities are often expensive, difficult to design, and require complex sensing and control [5]. Many designs use just the idea of how human fingers are used to grasp objects, such as [6–9, 12–14, 21, 25], which demonstrate a wide range of finger-based designs, suggesting that fingers are a good source of inspiration, with much variation possible based on the same structure. While hand-based designs have superior dexterity and can perform a wider range of motion, finger-based designs are much simpler in design, construction, and control, while still exhibiting successful grasping of target objects.

Actuation is an important consideration and challenge in soft robots, particularly due to their compliant structures that require under-actuation and cannot support heavy actuators. Whereas rigid robots typically use an electric motor in every joint [24], the compliant and flexible material of soft robots must move unrestrained by rigid joints, and controlling the shape and tip position of a continuum-like structure is more challenging [22, 24]. Pneumatic actuation is a popular method [22], and has been successfully used in many soft robots [5, 7, 8, 12, 14, 21, 25]. Advantages include rapid actuation [14], robustness to impact [5, 8], and actuation of multiple fingers simultaneously [12]. Pneumatic actuators also have many limitations; they can rupture [22], easily be cut or pierced [5], and require extensive additional pressure infrastructure [20] which is usually big, bulky, and inefficient [8, 22]. Another common method of actuation is tendon-driven actuation [22], also used in many soft robot designs [3, 4, 6, 9–11, 13, 16, 19] and chosen due to advantageous properties such as tendon cables' light weight, flexibility, and possibility of miniaturization [19] and ability to bend a soft structure with a single cable [3, 6]. [13] used tendon-driven actuation as it was low cost, compact, and required simple controls, and highlighted how it allowed for an under-actuated mechanism requiring only a single motor and cable to control three soft fingers. Tendon-driven actuation can also provide an under-actuated adaptive grasp, where a robot can conform to an uneven or unexpected object shape [4, 16]. Tendon-driven actuation does have some limitations, such as the possibility of tendon derailment – often specifically accounted for [11, 15, 16] – and reliability and lifetime of the system – often not considered but discussed extensively in [17]. Despite these limitations, tendon-driven actuation is a very promising technique for the actuation of soft robots.

One of the main benefits of soft robots is their potential to interact with unknown and irregular target objects, however grasping capabilities are often not tested on a wide range of objects, making it difficult to be confident in the grasping capability of existing soft robots. Another factor is the level of human assistance required to achieve a stable grasp. The soft gripper designed in [7] was intended for use with fragile target objects and shows the ability to gently grasp a tomato, but no other objects are reported to have been tested, while the gripper in [25] is stated to be able to hold various objects but provides little evidence of this. Only one target object grasp was attempted in [6] and three in [9]. The robotic hand designed in [5] was tested extensively with 33 different grasps and disturbance forces, showing impressive grasping capabilities, however the grasps are achieved with human assistance. The robot developed in [10] was specifically intended to grasp large or irregularly shaped objects and was tested on some but not many such objects, while the soft gripper in [14] demonstrated grasping and lifting an uncooked egg, an anaesthetized mouse, and plastic spheres with increasing diameter and weight. The under-actuated soft gripper designed in [13] was tested on target objects of varying size, shape, and material, but could only grasp with human assistance, the grasp is supported from beneath by the fixed parts of the gripper, and there is no evidence of the gripper being used to lift objects. Finally, the tests in [12] are some of the most extensive, showing the gripper's ability to grasp and lift a large variety of different objects, varying in size, shape, weight, and material, more convincingly demonstrating the ability and versatility of the gripper.

Fabrication is another key consideration in soft robotic design. Most designers fabricate their own custom parts, as standardized components are not available [20], limiting the techniques that can be used. [22] identifies that for soft robots to deliver on their full potential, rapid design tools and fabrication recipes for low-cost soft robots are needed, and this is still a challenge in this field. Curing silicone rubber is the most common technique for fabricating soft grippers, popular due to the low forces needed to cause high strain deformations and the convenience of a room-temperature vulcanizing process [18]. Cured silicone rubber has been used in many soft robots [1, 3–5, 8, 12–14] due to benefits such as the low cost of materials [8, 14], ease to acquire and work with [14], suitable elastic modulus [3], and ability to directly embed actuation components into the material [13]. Often, the molds used to cure the silicone rubber are 3D printed [5, 8, 12, 25], as this technology is becoming affordable to users outside of industry [8] and allows rapid iterative fabrication [12]. Another fabrication technique is shape deposition manufacturing (SDM), used in [6] to embed sensing and actuation components during fabrication. Silicone curing and SDM share a common limitation: they are both manually involved processes, requiring human time and limiting scalability and consistency. 3D printing has been used to directly print final components of robots, such as the links and pulleys in [10] and the rigid base support in [12]. However, in both of these cases the 3D printed parts were hard and non-compliant. The scaffold in the robotic hand designed in [5] was also 3D printed using solid material, but in such a way that it was deformable. [23] used microstructures to 3D print a deformable object using rigid material, and created a simple gripper using this technique to prove its applicability to the field of soft robotics, suggesting their method could be an "important step towards a design tool for printable soft robots". Another option for 3D printing soft structures is to use flexible material. [1] used multi-material 3D printing to manufacture a robot body that employed a stiffness gradient, while [7] directly 3D printed a soft gripper without the need for molds and curing. Direct 3D printing is more accurate and consistent than multi-stage curing processes [7], requires fewer assembly steps, and does not require creating multiple complex molds for constantly evolving prototype designs [1].

In this paper, a novel design of robotic end-effector, inspired by the use of two human hands and combining hard and soft materials, is firstly evaluated based on its ability to manipulate a range of target objects of varying size, shape, weight, material, and fragility. Evaluation will focus particularly on the range of target objects that can be grasped and the benefits of the novel two-handed design. Secondly, 3D printing is evaluated as a fabrication technique for soft robots, based on its feasibility, consistency, repeatability, and manual involvement, as well as cost, time, and quality of fabricated parts. The rest of this paper is organised as follows. Section 2 will explore in depth the design of this work, the methods used, and the procedures used to test the design and evaluate its success. Section 3 will present the results of testing and evaluate the strengths and limitations of the design and fabrication process. Section 4 will summarise the findings, consider the extent to which this work has met its initial aims, and discuss potential future research.

2 Design and Methods

2.1 High-Level Design and Methods

The robotic end-effector presented is a hybrid design combining a rigid base lifting plate and soft fingers, inspired by two human hands lifting objects with one hand supporting from beneath and the other hand grasping the sides gently. The addition of the base lifting plate reduces the force needed by the fingers to grasp objects, allowing fragile objects to be handled more gently without causing deformation. This end-effector could be combined with a robotic arm for pick-and-place tasks, so size and weight are minimised to reduce the strain that would be put on an arm. The end-effector works by gently grasping an object with the fingers and rotating the base lifting plate underneath the object. All components are designed using 3D CAD software and are 3D printed. An iterative design, prototyping, and evaluation process was used, where parts were first designed and improved in 3D CAD software to eliminate some issues before fabrication. Parts were then printed individually, evaluated, and improved and re-printed where necessary. This iterative process enabled parts to be produced to a high standard while minimising fabrication time and material use.

The 3D printing process involves designing a component in CAD software, slicing the 3D model with appropriate parameters for the component, and printing. The choice of material is important to obtain the desired mechanical properties of components. Rigid components were printed from PLA, an easy to print, inexpensive, environmentally friendly, and strong material. PLA components have a good surface quality and can withstand reasonable force. Soft components were printed from NinjaFlex, a flexible filament that is compliant after printing, producing parts that can bend, stretch, and absorb forces. Flexible materials are more challenging to print with, so the design and print parameters are even more important.

2.2 Base Lifting Plate

The CAD model of the base lifting plate is shown in Figure 1. This component lifts target objects from beneath and so must be strong and rigid. The plate is thin at its edges so that it can slide under objects with minimal resistance and thicker in the middle to bear weight without bending. The design of the plate with an attached arm, similar to a hand on the end of an arm, allows the base lifting plate to be rotated around the main body. The base lifting plate was printed from PLA with 100% infill density (the amount of material inside a part) for maximum strength and minimum flexibility. A high resolution layer height (0.1mm) was used to create smooth slopes on the edges of the plate, resulting in less resistance when sliding under objects.

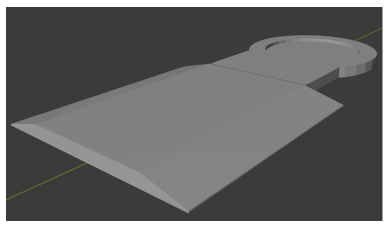

Fig. 1: CAD model of base lifting plate

2.3 Fingers

Figure 2 and Figure 3 show the standard finger and extended finger that were designed. The standard finger was inspired by [13] and is similarly constructed from a soft material, actuated by tendons, and features three phalanges similar to the human finger. However, unlike the finger in [13], all three phalanges are actuated. Also, the maximum angular displacement between phalanges is 70 degrees, chosen as a balance between sufficient bending at each joint while reducing the tendon force needed and increasing the surface area of each phalange. [13] recognised that their phalanges bend together when it is desirable for proximal phalanges to bend before distal phalanges, a behaviour demonstrated in [6] by varying joint stiffness. Here, this behaviour is achieved by increasing joint thickness from proximal to distal; thinner joints bend more easily so bend first. Tendon-driven actuation was chosen for the fingers due to its light weight, small size, simplicity, low cost, low power requirements, simple control, and adaptive grasp capabilities. Each finger has square channels for rounded tendon cables, as square channels are simpler to 3D print and reduce friction against the rounded cable. The channel openings in the finger base feature slopes rather than sharp edges, also to reduce friction. These design features are shown in Figure 2.

Fingers are 3D printed from NinjaFlex, allowing the fingers to bend easily and the phalanges to passively comply to target objects for a gentle adaptive

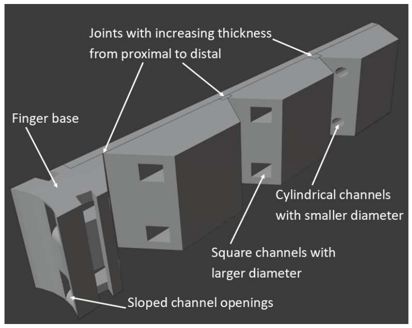

Fig. 2: CAD model of standard finger labelled with design features

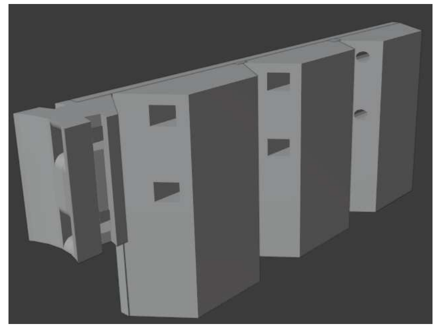

Fig. 3: CAD model of extended finger

grasp. The fingers were printed with 20% "Lightning" infill, reducing material use and increasing compliance of the fingers, while the finger base was printed with 100% infill to provide a rigid and stable mounting. The wall thickness and top/bottom thickness were reduced, increasing finger compliance for gentle grasping and passive adaptation to target objects. NinjaFlex, being a flexible material, is more prone to "stringing", so print speed was reduced to increase quality.

The extended finger is identical to the standard finger except the phalanges are extended such that when the finger is mounted in the main body of the end-effector, the finger can grasp objects vertically below it – this can be seen more clearly in Section 2.5 and Figure 11. The extended fingers were designed as the mounting of the fingers in the main body must be some distance higher than the base lifting plate, and therefore the standard fingers would be unable to grasp small objects.

2.4 Tendon Cables

The tendon cables used for actuation are 3D printed from NinjaFlex, meaning cables need not be specially acquired; they are instead fabricated using the same material and process used for the fingers. The NinjaFlex cables designed have the benefits of being flexible but with some rigidity and not too stretchy, with a slight limitation that they are not perfectly smooth. Cables can also be printed to the perfect length, and different lengths are used for different fingers. Figure 4 shows a cable inserted into a finger. These cables feature a thin section at the end of each cable (Figure 5) which provides an easy mechanism for attachment to the winding spool, as shown in Figure 6. The cables were printed solid (no internal space) to reduce elasticity and with high resolution 0.1mm layer height to achieve a smoother finish, reducing friction when sliding through the finger channels.

Fig. 4: Printed finger with cable inserted

Fig. 5: Thin end sections of printed cable

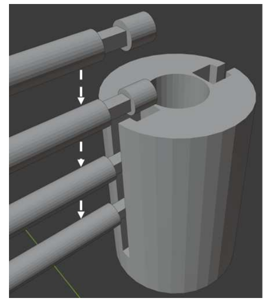

Fig. 6: CAD model showing cable-to-spool attachment mechanism

2.5 Main Body

The main body of the end-effector (Figure 7) provides the housing for the motors and the mounting for the base lifting plate and fingers. The design is highly modular; all parts fit together with non-permanent attachments, allowing parts, such as a larger base lifting plate or different fingers, to be easily swapped out. Tightly interlocking parts can be fabricated easily using 3D printing where complexity comes at almost no cost and high accuracy components can be fabricated consistently. Components can be printed with mostly default settings, except the main body housing which was printed with supports in the cut-out sections.

The base lifting plate is mounted in the main body using interlocking blocks and rings, allowing it to rotate within the main body, using parts that are all held together tightly using just friction and gravity. The fingers are mounted in the main body using sliding attachments (Figure 8). The positions of the slots were chosen such that the fingers could grasp reasonably wide and reasonably small objects. The main body can hold up to four fingers (two on each side) but can also hold just two bottom fingers or just two top fingers.

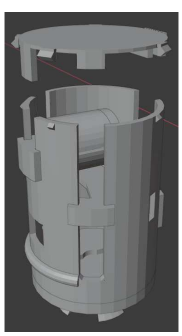

Fig. 7: CAD model of main body

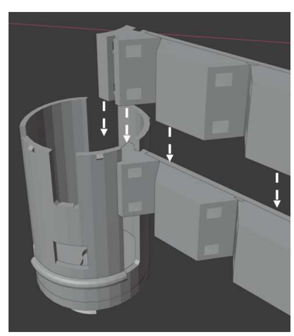

Fig. 8: CAD model showing attachment of finger to main body

Each component actuated by a motor features a plate with a recess, allowing the motor blade to fit tightly and rotate without slipping (Figure 10). The spool used to pull the tendon cables is shown in Figure 9. No slack-enabling mechanism [11, 15, 16] was used as this would increase complexity and initial prototypes suggested that the flexible fingers naturally return to full extension when cable tension is released. Figure 11 shows the complete assembled end-effector with base lifting plate, two standard fingers, and two extended fingers.

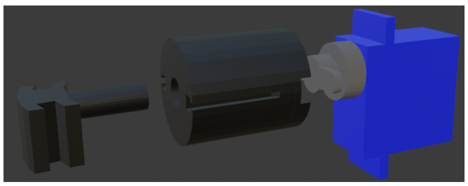

Fig. 9: Winding spool and mechanism

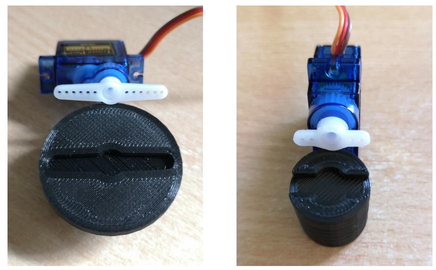

Fig. 10: Motor blade recess of components actuated by a motor

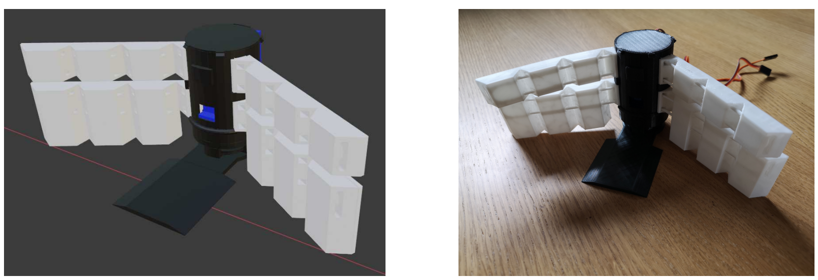

Fig. 11: Assembled end-effector; (a) CAD model, (b) Real fabrication

2.6 Experimental Design

Tests were carried out on a range of objects of varying size, shape, weight, and material to evaluate the capabilities of the end-effector, particularly the usefulness of the novel base lifting plate design. The testing procedure involved grasping an object, lifting the end-effector to show stable grasping, and releasing the object. The testing procedure was repeated for three configurations of the end-effector for all objects: using two extended fingers and the base lifting plate; using two extended fingers, two standard fingers, and the base lifting plate; and using just two extended fingers without the base lifting plate. Ideally the end-effector can grasp objects with no assistance, but this can be problematic for heavy objects and the low strength motors used, as the base lifting plate can struggle to slide underneath the object while it is flat on a surface. All target objects were first tested without any assistance, but for any objects that encountered this problem the object was manually lifted slightly while the base lifting plate rotated underneath ("assisted grasp"), to test the ability of the end-effector to stably grasp even if acquiring the grasp without assistance was unsuccessful. 31 target objects were tested and are listed in Section 3. The results of the grasp tests can also be used to determine the quality of the 3D printed components of the end-effector. To evaluate cost and time of fabrication and assembly, the material cost of and time taken to print every 3D printed component was recorded during fabrication, and the time taken to assemble the end-effector was measured.

3 Results and Discussion

3.1 Grasp Tests

The testing procedure described in Section 2.6 was performed for all objects and repeated for the configurations described. The results are shown in Table 1, and some objects successfully grasped in the two finger configuration are shown in Figure 12.

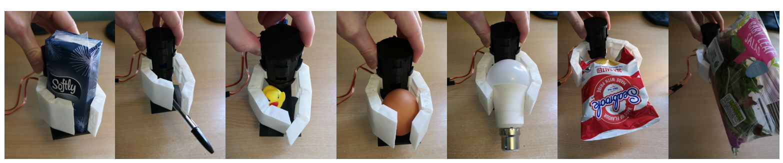

Fig. 12: Some objects successfully grasped with two fingers unassisted

Table 1 shows that 20 of the 31 objects tested were successfully grasped in the two finger configuration. These objects varied in shape, size, weight, and material. Furthermore, most (16 out of 20) of the objects successfully grasped using the base lifting plate could not be grasped without it (two fingers only), proving that the base lifting plate improves grasping capability. The objects successfully grasped without the base lifting plate were among the lightest tested, supporting the expectation that the base lifting plate would allow heavier objects to be grasped. Some of the most interesting successfully grasped objects are: the small rubber duck, which could not be grasped by the fingers alone due to its small size but was easily grasped using the base lifting plate; the spray bottle, which was too heavy for the fingers alone to grasp and larger than the base

Object	Two fingers	Four fingers	Two fingers only	Assisted grasp
Glass pepper grinder	✓	✗	✗	–
Packet of tissues	✓	✓	✓	–
Bicycle light	✓	✗	✗	–
Torch	✗	✗	✗	✓
Set of keys	✓	✗	✗	–
Wallet	✗	✗	✗	✓
Aerosol can	✓	✗	✗	–
Kiwi fruit	✓	✗	✗	–
Pen	✓	✓	✓	–
Large plastic box (16x10cm)	✗	✗	✗	✗
Small plastic box (8x8cm)	✓	✓	✗	–
Compact disc	✗	✗	✗	✓
Small rubber duck	✓	✓	✗	–
Spray bottle	✓	✗	✗	–
Plastic bottle (empty)	✓	✓	✓	–
Plastic bottle (250ml water)	✓	✗	✗	–
Plastic bottle (500ml water)	✗	✗	✗	✓
Egg holder	✗	✗	✗	✓
Drinking glass	✓	✗	✗	–
Large potato (250g)	✗	✗	✗	✓
Small potato (100g)	✓	✗	✗	–
Mango	✗	✗	✗	✓
Small tomato	✓	✓	✗	–
Raw egg	✓	✗	✗	–
Light bulb	✓	✗	✗	–
Paper cup (empty)	✓	✓	✓	–
Paper cup (half full of water)	✗	✗	✗	✓
Paper cup (full of water)	✗	✗	✗	✓
Packet of crisps	✓	✗	✗	–
Bottle of golden syrup	✗	✗	✗	✓
Bag of salad	✓	✗	✗	–

Table 1: Test results for all objects and all configurations

lifting plate but could be grasped by the combination of the two; and the bag of salad, which must be handled gently and was much larger than the base lifting plate but could be grasped without causing damage.

Despite the idea that more fingers would provide a more supported grasp, four fingers successfully grasped only 7 of the 31 objects. During testing the reason for this was clear; adding more fingers increases strain on the motor, and the small motor used was unable to pull the tendon cables as much, resulting in reduced bending in the fingers and providing a weaker grasp. It is expected that with a stronger motor, four fingers would perform similarly to two fingers. However, the results obtained show no advantage to using four fingers; taller objects such as the plastic bottle could be grasped using two fingers. Further investigation using a stronger motor is needed to establish any benefits of using extra fingers.

Only one object that was tested using the assisted grasp failed. The large plastic box could not be grasped as too much weight extended too far beyond the base lifting plate. Using a larger base lifting plate may yield a successful grasp – this could be investigated in future work. This potential solution highlights the strength of the modular design; a larger base lifting plate could easily be fabricated and installed. All other objects that could not be grasped in the two finger configuration were grasped using the assisted grasp, most of which were the larger, heavier objects. These could not be grasped unassisted as the base lifting plate was unable to slide underneath the object without pushing it out of the fingers' grasp, due to the weight and shape of the base of the object. The strength of the motors is again a likely contributor; stronger motors should provide a stronger stable grasp from the fingers and rotate the base lifting plate under heavier objects. However, the success of the assisted grasps demonstrates the capability of the end-effector to hold larger and heavier objects, even if it struggles to acquire the grasp, and showcases the ability of the base lifting plate design to hold objects that could not be held by the fingers alone.

Direct comparisons can be made for objects also tested on previous gripper designs. The gripper designed in [13], which inspired the fingers designed here, grasped a cylinder, box, and egg, similar to the aerosol can and egg grasped here. However, the gripper in [13] was only capable of an assisted grasp, whereas the end-effector designed here grasped many objects unassisted. The grippers here and in [12] both grasped a pen, compact disc, raw egg, and keys. The gripper in [12] grasped a large plastic box where the one designed here could not. On the other hand, it is unclear how much assistance was provided to achieve the grasps in [12] – the compact disc at least suggests assistance as it could not stand up by itself for unassisted grasping. These comparisons suggest that the end-effector designed here is similarly capable to previous designs, and more capable at unassisted grasping. The wider range of objects tested here also increases confidence in its capability and versatility.

The success of the end-effector in the two finger and assisted grasp configurations proves the strength of the design, the suitability of 3D printing to fabricate both hard and soft components for robotic grippers, and the quality of the fabricated components. The hard PLA components provide strength and rigidity and the flexible fingers and tendon cables grasp delicate objects gently and passively adapt to different shapes and sizes. However, there is room for improvement. Figure 13 shows the stages of grasping and releasing and it can be seen that the fingers do not always fully open when cable tension is released. The reason for this could be due to a number of factors; friction between the tendon cable and finger, angle at which the tendon cable is wound on the spool, and/or lack of cable tension when unwinding the spool. Further investigation is needed to improve this mechanism, but apart from this, the components all work well.

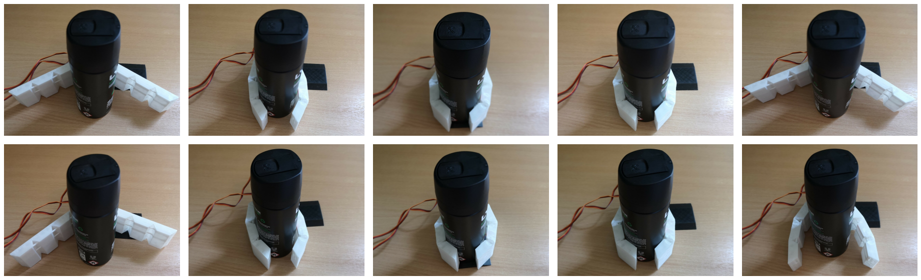

Fig. 13: Stages of grasping and releasing, performed twice. Sometimes the fingers do not fully open when the object is released.

This work did not aim to incorporate sensing or feedback control, however, sensing could be integrated in future work so that the performance of the end-effector during grasping could be characterised quantitatively. Application of the approach used in [7] to the design presented in this work would be particularly interesting, further utilising 3D printing to also integrate sensing directly into the fabricated components.

3.2 Fabrication and Assembly

All components can be fabricated for £4.44 and in 22 hours (four-finger configuration) or for £3.12 and in 16 hours (two-finger configuration). Assembly of either configuration takes 5 minutes or less. This low cost design makes the end-effector economical, and fast fabrication and assembly allow for rapid prototyping of new design ideas. Optimisations for faster printing were made but more optimisation is possible to further reduce fabrication times. Also, no components depend on any other being fabricated first, so components can be fabricated simultaneously using multiple 3D printers.

Material cost and fabrication/assembly time is difficult to compare to previous designs as these factors are rarely reported. However, for their simplified gripper, [8] reported a cost of approximately $10 (£7.85) per student for a classroom of 30. Similarly, the end-effector designed in this work could be simplified, removing the cost of the motors and microcontroller, making the total cost (excluding the one-time overhead of a 3D printer) the material cost as detailed above. The full system with the motors and microcontroller adds around £20, still low-cost for an electronically actuated system. Fabrication of the gripper in [8] may be faster than the one here (though print time of 3D molds is not given), but the silicone curing process is inherently serial, whereas the components used in this work could be fabricated simultaneously with multiple 3D printers.

The rigid PLA components are consistently fabricated to a very high standard. Throughout development, PLA components never failed due to a flaw in their fabrication, and components always fit together accurately. The 3D printing process is therefore a suitable fabrication technique for rigid components.

The soft NinjaFlex components are generally fabricated slightly less consistently and to a lower standard. This is due to the additional challenges of printing with a flexible material, such as reduced structural integrity, longer time to set, and increased stringing. Stringing in particular was an issue in all fingers produced, requiring some manual cleanup after printing. The lower quality of the fingers may be partially due to design and print parameters; they must be compliant and flexible, and parameters that achieve this, such as reduced wall thickness, also reduce the quality. Nevertheless, despite lower quality than the PLA components, the quality of the NinjaFlex components was still good and did not affect their operation. Further experimentation with tuning print parameters may also further improve quality.

3D printing the components does not require any manual involvement except starting prints, removing printed components, and cleaning up the stringing on the NinjaFlex fingers. Components could be combined into one print, reducing the number of times that prints must be started and components removed, and as mentioned above it may be possible to reduce stringing. Compared to the silicone curing process used in most other soft robotic designs, a manual process which can produce inconsistent and even non-functional results if not performed correctly and carefully, 3D printing requires little manual involvement and produces mostly consistent, high quality, and functional components.

4 Conclusion

This work aimed to evaluate a novel design of robotic end-effector, inspired by two-handed human grasping, comprised of rigid and soft materials, and fabricated using 3D printing. Grasp tests were performed on a wide range of objects to evaluate grasping capability, and results were discussed and compared to previous soft robotic gripper designs. The grasp tests show that the base lifting plate design allows the end-effector to successfully grasp many target objects that could not be grasped using only the fingers. All but one of the objects tested could be held by the end-effector, for many of which the grasp could be acquired without any assistance. The material costs and fabrication/assembly time of the 3D printed components were also discussed. Strengths and limitations of the design, as well as advantages of the fabrication process and opportunities for improvement, were highlighted, and avenues for further related work have been identified. The benefits of the novel design presented, and the successful application of 3D printing to a hybrid hard/soft robotic gripper, create new opportunities for this field, presenting innovative ideas that can be further explored and applied in future research.

References

1. Bartlett, N.W., Tolley, M.T., Overvelde, J.T., Weaver, J.C., Mosadegh, B., Bertoldi, K., Whitesides, G.M., Wood, R.J.: A 3d-printed, functionally graded soft robot powered by combustion. Science **349**(6244), 161–165 (2015). https://doi.org/10.1126/science.aab0129

2. Billard, A., Kragic, D.: Trends and challenges in robot manipulation. Science **364**(6446) (2019). https://doi.org/10.1126/science.aat8414
3. Calisti, M., Giorelli, M., Levy, G., Mazzolai, B., Hochner, B., Laschi, C., Dario, P.: An octopus-bioinspired solution to movement and manipulation for soft robots. Bioinspiration & biomimetics **6**(3), 036002 (2011). https://doi.org/10.1088/1748-3182/6/3/036002
4. Carrozza, M.C., Cappiello, G., Stellin, G., Zaccone, F., Vecchi, F., Micera, S., Dario, P.: A cosmetic prosthetic hand with tendon driven under-actuated mechanism and compliant joints: ongoing research and preliminary results. In: Proceedings of the 2005 IEEE International Conference on Robotics and Automation. pp. 2661–2666. IEEE (2005). https://doi.org/10.1109/ROBOT.2005.1570515
5. Deimel, R., Brock, O.: A novel type of compliant and underactuated robotic hand for dexterous grasping. The International Journal of Robotics Research **35**(1-3), 161–185 (2016). https://doi.org/10.1177/0278364915592961
6. Dollar, A.M., Howe, R.D.: A robust compliant grasper via shape deposition manufacturing. IEEE/ASME transactions on mechatronics **11**(2), 154–161 (2006). https://doi.org/10.1109/TMECH.2006.871090
7. Elgeneidy, K., Liu, P., Pearson, S., Lohse, N., Neumann, G., et al.: Printable soft grippers with integrated bend sensing for handling of crops. In: 19th Annual Conference Towards Autonomous Robotic Systems. vol. 10965, pp. 479–480 (2018). https://doi.org/10.1007/978-3-319-96728-8
8. Finio, B., Shepherd, R., Lipson, H.: Air-powered soft robots for k-12 classrooms. In: 2013 IEEE Integrated STEM Education Conference (ISEC). pp. 1–6. IEEE (2013). https://doi.org/10.1109/ISECon.2013.6525198
9. Firouzeh, A., Paik, J.: An under-actuated origami gripper with adjustable stiffness joints for multiple grasp modes. Smart Materials and Structures **26**(5), 055035 (2017). https://doi.org/10.1088/1361-665X/aa67fd
10. Glick, P.E., Van Crey, N., Tolley, M.T., Ruffatto, D.: Robust capture of unknown objects with a highly under-actuated gripper. In: 2020 IEEE International Conference on Robotics and Automation (ICRA). pp. 3996–4002. IEEE (2020). https://doi.org/10.1109/ICRA40945.2020.9197100
11. Hannan, M.W., Walker, I.D.: Analysis and experiments with an elephant's trunk robot. Advanced Robotics **15**(8), 847–858 (2001). https://doi.org/10.1163/156855301317198160
12. Hao, Y., Gong, Z., Xie, Z., Guan, S., Yang, X., Ren, Z., Wang, T., Wen, L.: Universal soft pneumatic robotic gripper with variable effective length. In: 2016 35th Chinese control conference (CCC). pp. 6109–6114. IEEE (2016). https://doi.org/10.1109/ChiCC.2016.7554316
13. Hassan, T., Manti, M., Passetti, G., d'Elia, N., Cianchetti, M., Laschi, C.: Design and development of a bio-inspired, under-actuated soft gripper. In: 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). pp. 3619–3622. IEEE (2015). https://doi.org/10.1109/EMBC.2015.7319176
14. Ilievski, F., Mazzeo, A.D., Shepherd, R.F., Chen, X., Whitesides, G.M.: Soft robotics for chemists. Angewandte Chemie **123**(8), 1930–1935 (2011). https://doi.org/10.1002/ange.201006464
15. In, H., Jeong, U., Lee, H., Cho, K.J.: A novel slack-enabling tendon drive that improves efficiency, size, and safety in soft wearable robots. IEEE/ASME Transactions on Mechatronics **22**(1), 59–70 (2016). https://doi.org/10.1109/TMECH.2016.2606574

16. In, H., Kang, B.B., Sin, M., Cho, K.J.: Exo-glove: A wearable robot for the hand with a soft tendon routing system. IEEE Robotics & Automation Magazine **22**(1), 97–105 (2015). https://doi.org/10.1109/MRA.2014.2362863
17. Jeong, U., Kim, K., Kim, S.H., Choi, H., Youn, B.D., Cho, K.J.: Reliability analysis of a tendon-driven actuation for soft robots. The International Journal of Robotics Research **40**(1), 494–511 (2021). https://doi.org/10.1177/0278364920907151
18. Kim, S., Laschi, C., Trimmer, B.: Soft robotics: a bioinspired evolution in robotics. Trends in biotechnology **31**(5), 287–294 (2013). https://doi.org/10.1016/j.tibtech.2013.03.002
19. Laschi, C., Cianchetti, M., Mazzolai, B., Margheri, L., Follador, M., Dario, P.: Soft robot arm inspired by the octopus. Advanced robotics **26**(7), 709–727 (2012). https://doi.org/10.1163/156855312X626343
20. Lipson, H.: Challenges and opportunities for design, simulation, and fabrication of soft robots. Soft Robotics **1**(1), 21–27 (2014). https://doi.org/10.1089/soro.2013.0007
21. McKenzie, R.M., Barraclough, T.W., Stokes, A.A.: Integrating soft robotics with the robot operating system: A hybrid pick and place arm. Frontiers in Robotics and AI **4**, 39 (2017). https://doi.org/10.3389/frobt.2017.00039, https://www.frontiersin.org/article/10.3389/frobt.2017.00039
22. Rus, D., Tolley, M.T.: Design, fabrication and control of soft robots. Nature **521**(7553), 467–475 (2015). https://doi.org/10.1038/nature14543
23. Schumacher, C., Bickel, B., Rys, J., Marschner, S., Daraio, C., Gross, M.: Microstructures to control elasticity in 3d printing. ACM Transactions on Graphics (TOG) **34**(4), 1–13 (2015). https://doi.org/10.1145/2766926
24. Trivedi, D., Rahn, C.D., Kier, W.M., Walker, I.D.: Soft robotics: Biological inspiration, state of the art, and future research. Applied bionics and biomechanics **5**(3), 99–117 (2008). https://doi.org/10.1080/11762320802557865
25. Vamsi, P.B., Rao, V.R.: Design and fabrication of soft gripper using 3d printer. In: IOP Conference Series: Materials Science and Engineering. vol. 402, p. 012026. IOP Publishing (2018). https://doi.org/10.1088/1757-899X/402/1/012026