

# Development of a soft gripper for replicating human grasps in forest nursery tasks

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## ABSTRACT

This research aims to automate labour-intensive tasks in forest nurseries by developing a soft gripper that mimics human workers' grasps to perform the singulation and sorting of tree saplings. By analysing human workers and conducting experimental investigations, the required grasp types and grip forces were identified. The Fin Ray Effect (FRE) structure, noted for its adaptability to asymmetric shapes, was chosen as the gripper's basis. However, modifications were necessary to achieve the required power and pinch grasp types and to provide the desired grip forces. Simulation analysis explored various beam configurations and boundary conditions of FRE fingers, resulting in a proposed modified design. Experimental investigations confirmed that the proposed gripper effectively delivered required grasps and grip forces. The new design enabled three additional grasp types for FRE grippers and increased grip forces by over 200 %. This gripper design is suitable for industrial pick-and-place applications where precise pinching grasp and various power grasps with sufficient payload capacity are needed.

## 1. Introduction

Humans employ a diverse range of grasps in their daily lives to perform personal tasks or fulfil job responsibilities [1]. To automate repetitive and physically demanding tasks in industries using robotic manipulators, robots need to replicate various grasp types used by humans. Numerous studies on grasping taxonomies have categorised and leveraged the functions of the human hand [2,3]. These studies have identified several distinctive grasp types, broadly categorised into power and precision grasps. Power grasps prioritise stability, usually by enveloping the object, often establishing multiple points of contact between the object and the surfaces of the fingers and palm. Precision grasps, such as fingertip or pinch grasps, emphasise applying small forces and enabling capabilities like dexterous manipulation.

This research aims to automate the labour-intensive task of singulation of developing trees, reducing the Forest Nursery sector's dependence on seasonal human labour for crop processing by introducing a practical robotics solution. Analysing the grasping and separating actions through observing human workers revealed that several types of power grasps to adapt the asymmetric shape of a bunch of trees, as well as precision pinching grasp to grip individual trees are needed to

perform this task.

To mimic the human grasps, human-like robotic hands have already been developed by increasing the number of actuated degrees of freedom and employing complex control strategies [4–6]. Despite their high dexterity, these hands often incorporate expensive mechanisms and sensors, as well as requiring intricate motion planning. These factors hinder their widespread use in practical applications and further commercialization.

Power grasping can be achieved with less anthropomorphic designs, involving multiple points of contact between each finger and the target object, resulting in an enveloping grasp. Various power grasping approaches with under-actuated finger structures have been proposed [7–10], which reduces mechanical complexity and the number of required actuators. For precise grasping, the SARAH hand was developed based on the coupling between different fingers and utilized a parallelogram linkage for precise parallel pinch [11]. The ROBOTIQ gripper (adaptive family) employs an elegant mechanism with a single actuator, allowing it to switch between precision and power grasps [12].

In the past decade, there has been a significant surge in the exploration of soft and elastic materials to build robotic systems [13–15]. Soft robotic hands, designed to interact safely and gently with delicate

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Fig. 1. Grasp types used by skilled operators.

environments, have recently garnered attention [16–21]. These hands utilise soft materials to reduce the risk of damage, and their passive compliance simplifies control complexity for secure object grasping. However, this enhanced adaptability in soft grippers often comes at the cost of payload capacity and precision. Fin ray effect (FRE) grippers, inspired by the natural movement of fish fins, are a well-known family of soft grippers that can adapt to various object shapes and sizes [22–25]. The biomimetic design of these grippers allows for improved grasping performance, especially when dealing with irregularly shaped objects. The fin-like structures can conform to the object's contours, enhancing grip stability. Moreover, the lightweight and compact nature of these grippers reduces the overall weight of robotic systems and allows for easier integration into various platforms. Also, FRE fingers can be easily customised for different purposes by adjusting the shape, size, and arrangement of the fins [26–28]. This flexibility allows for modifying the gripper to specific tasks or object types.

In this study, leveraging the benefits of soft FRE structures, this pattern is utilised to implement the required grasps for the tree separation task. However, the conventional design of FRE grippers proved insufficient in providing all required grasp types and necessary grip forces. Therefore, through mathematical analysis and simulations, a modified design was achieved, aimed at accurately replicating the capabilities of human hands, ensuring safe contact with delicate tree saplings, and providing the required grip forces for successful separation tasks. With the modified design, the FRE fingers can envelop irregularly shaped objects like a human grasp and grip small objects at the fingertip like a human pinch. Experimental results verified that more stable grasps can be achieved with the modified design.

By addressing limitations in both grasp diversity and grip force, this work sets a new benchmark for the design and application of soft grippers. It demonstrates how biomimetic principles, coupled with task-specific engineering, can solve real-world challenges while expanding the applicability of soft robotics in industrial and agricultural domains. To the best of our knowledge, this study is the first to introduce a FRE gripper design that achieves both power grasps and precision pinching grasps, specifically tailored for grasping of delicate tree saplings. While previous works have explored the FRE mechanism for adaptive grasping, they have been limited in their ability to handle a wide range of object

geometries and forces simultaneously. The proposed modifications to the FRE gripper, including optimized structural enhancements and novel boundary conditions, represent a significant step forward in addressing these limitations. This unique approach not only fills a critical gap in the existing literature but also sets a new benchmark for soft robotic grippers in industrial and agricultural applications.

## 2. Materials and methods

Analysis of skilled operators' actions in the forest nursery revealed that for the singulation and sorting of tree saplings, operators use five different grasp types, based on the grasp taxonomy in [3]. As shown in Fig. 1, the grasps include:

- Power-Palm Large Diameter (PPLD),
- Power-Palm Small Diameter (PPSD),
- Power-Palm Medium Wrap (PPMW),
- Precision-Parallel Extension (PPE),
- and Precision-Pad Prismatic (PPP).

Moreover, measurement of the required forces to separate the tree saplings, as detailed in the Results and Discussion section, revealed that the robotic gripper replicating the human workers' grasps was expected to provide the following functions:

- The fingertip pinching (PPP) of individual trees with applying over 10 N grip force
- The shape-adaptive power grasping of small (PPSD), medium (PPMW), and large size (PPLD) bunch of trees with asymmetric shapes, as well as parallel grasp of a flat bunch (PPE), with applying over 30 N grip force

To achieve the desired grasp requirements, the FRE structure was identified as a suitable candidate because the available gripper design based on this pattern [29] could provide PPLD and PPE grasps. Moreover, this structure has the potential to be customised for different applications. In the following sections, the arrangement of these grippers is investigated in detail.

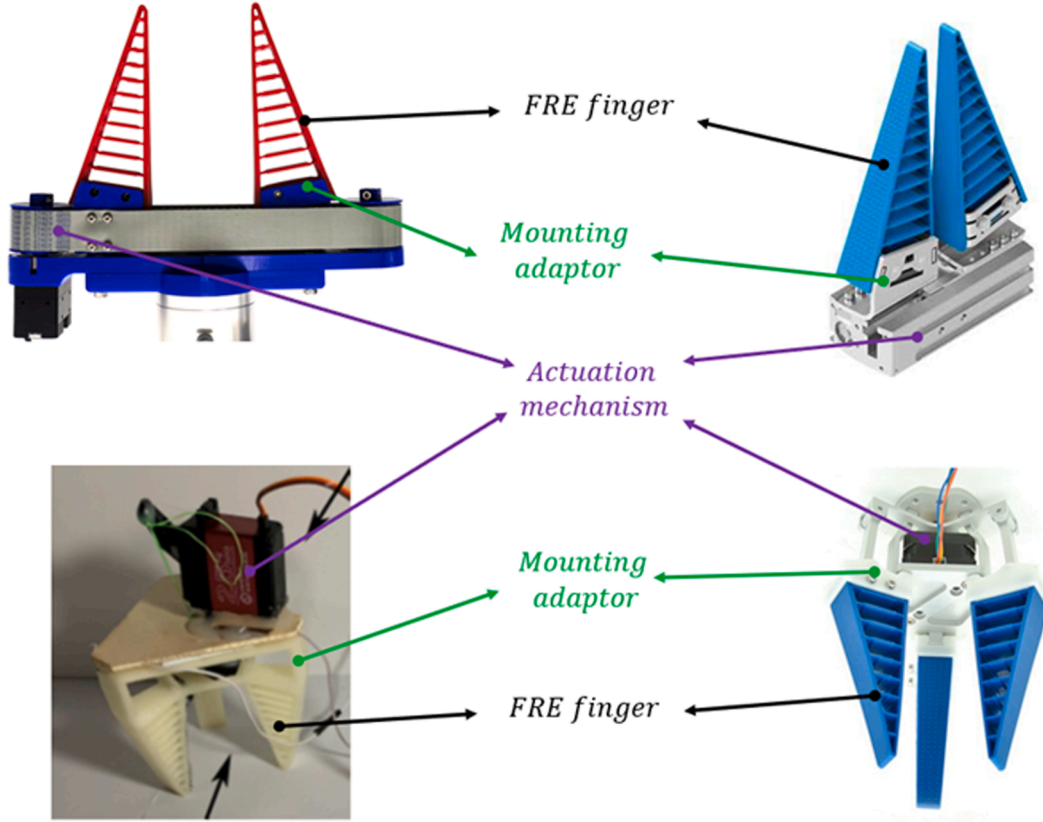


Fig. 2. The FRE gripper arrangement [29,30].

### 2.1. FRE grippers

The FRE gripper arrangement, as depicted in Fig. 2, comprises three main components:

The soft FRE finger, that makes direct contact with the object, adapting to its shape in response to contact force. These fingers possess a soft and triangular design, featuring multiple crossbeams that undergo buckling during deformation. The Festo structure is the most famous FRE finger design [29].

The actuation mechanism is responsible for movements of the fingers using external actuators, enabling rotational or parallel movements of the grasping fingers. Typically, this mechanism incorporates pneumatic actuators or electric motors, coupled with an appropriate power transmission system.

The Mounting Adaptor (MA) is a component, typically rigid, that establishes a connection between the FRE finger and the actuation mechanism. This part influences the boundary conditions of the FRE finger and consequently affects its adaptive shape and grasping forces. Various designs for MA have been proposed, depending on the round or in-line configuration of the fingers and their sizes. Nevertheless, in all cases, the MA clamps the FRE finger from the bottom.

The FRE fingers are mostly used with round or in-line configurations, as shown in Fig. 2. With the round configuration [30], the Power-Palm Sphere, Power-Palm Disk, and Power-Pad Sphere grasps can be provided (Fig. 3a). With the in-line configuration, the PPLD, Power-Pad Ring, and PPE grasps can be provided (Fig. 3b). However, these grippers are unable to fully wrap around objects to securely hold them and provide PPMW and PPSD grasps. They also cannot perform precise pinching with their fingertips to achieve PPP grasps. The available design, in addition to being unable to provide the necessary grasp types, also failed to deliver the required grip forces as later investigated in the ‘Results and discussion’ section. Utilizing soft bodies often comes at the expense of reduced carrying payload and limited performance in high-force

applications. The analysis and the modified design to achieve the desired specifications are discussed in the following sections.

### 2.2. Simulation analysis

Each FRE finger includes two main beams (front- and back-beams) and several crossbeams. To analyse the FRE structure, each beam is independently described by the system of differential equations based on Cosserat rod theory [31,32], considering their coupled boundary conditions. In this model, the shape of the beams can be described by their centreline curve, the Cartesian position in space  $P(s) \in \mathbb{R}^3$ , and the rotation matrix of their material orientation  $R(s) \in \text{SO}(3)$ , as functions of the arc-length of the beam  $s \in [0, L]$  ( $L$  is the length of the undeformed beam). This model, in static form, is described by the following ordinary differential equations:

$$\begin{aligned} \dot{P} &= R(K_{se}^{-1}R^T n + v^*), \\ \dot{R} &= R(K_{bt}^{-1}R^T m)^\wedge, \\ \dot{n} &= -\rho, \\ \dot{m} &= -\dot{P} \times n - \mu, \end{aligned} \quad (1)$$

where the dot denotes a derivative with respect to  $s$ , and  $(\cdot)^\wedge$  represents the mapping from  $\mathbb{R}^3$  to  $\mathfrak{so}(3)$  [33].  $n(s)$  and  $m(s)$  are the internal force and moment vectors in the global coordinate frame, respectively.  $K_{se}$  is the stiffness matrix for shear and extension, and  $K_{bt}$  represent the stiffness matrix for bending and twisting [31].  $\rho$  and  $\mu$  correspond to the force and moment variations along the beams.  $v^*$  is the kinematic variable of the beam in a stress-free reference state. Each beam in the FRE finger was described by the system of differential equations (1). However, the boundary conditions of the system of equations are coupled because of the physical constraints inherent in the finger structure. The ends of the main beams are clamped together, and so the following boundary condition equations for the end pose and the static

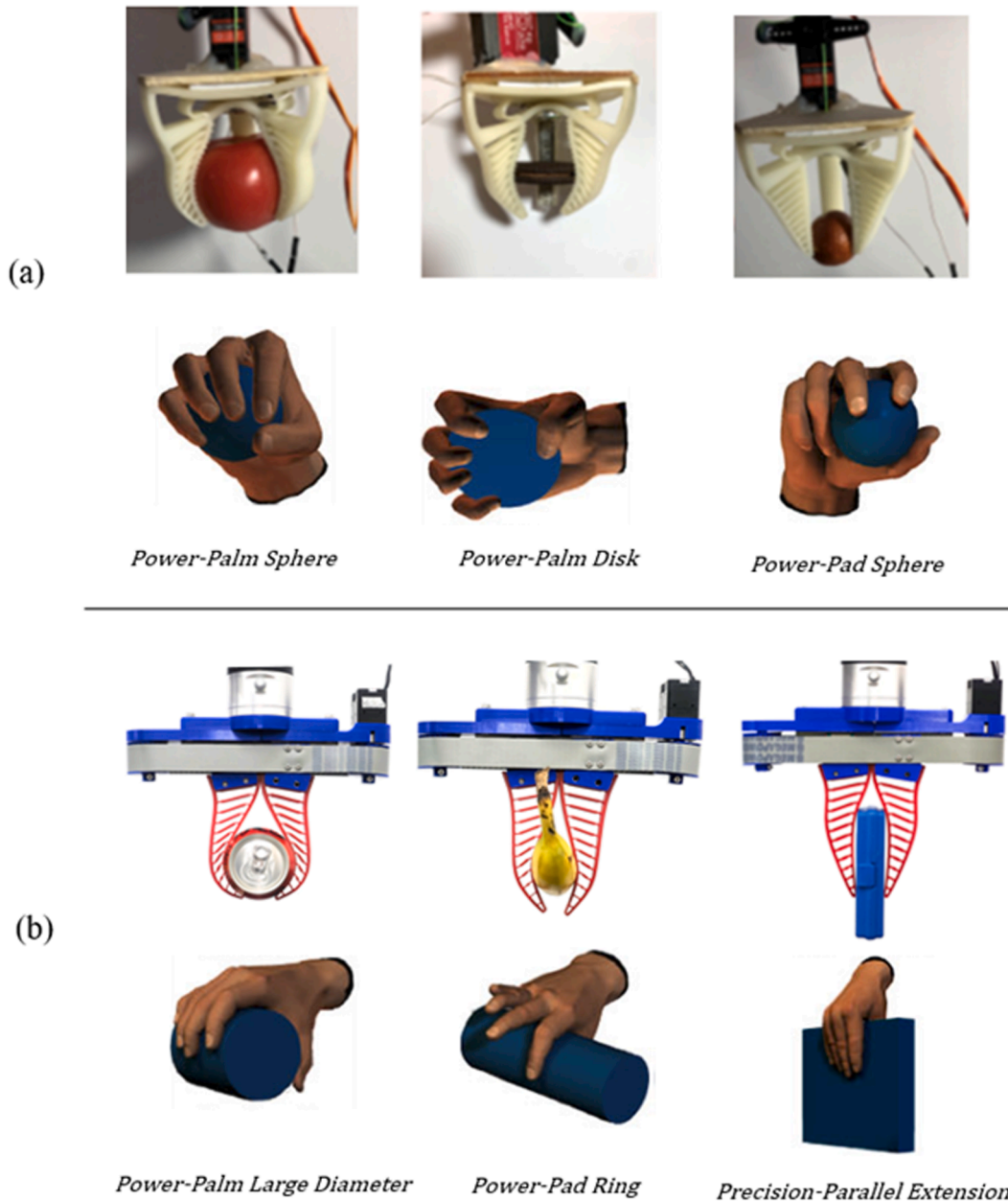


Fig. 3. Grasp types can be provided with (a) the round configuration [30] and (b) the in-line configuration of the FRE fingers.

equilibrium of the main beams can be obtained:

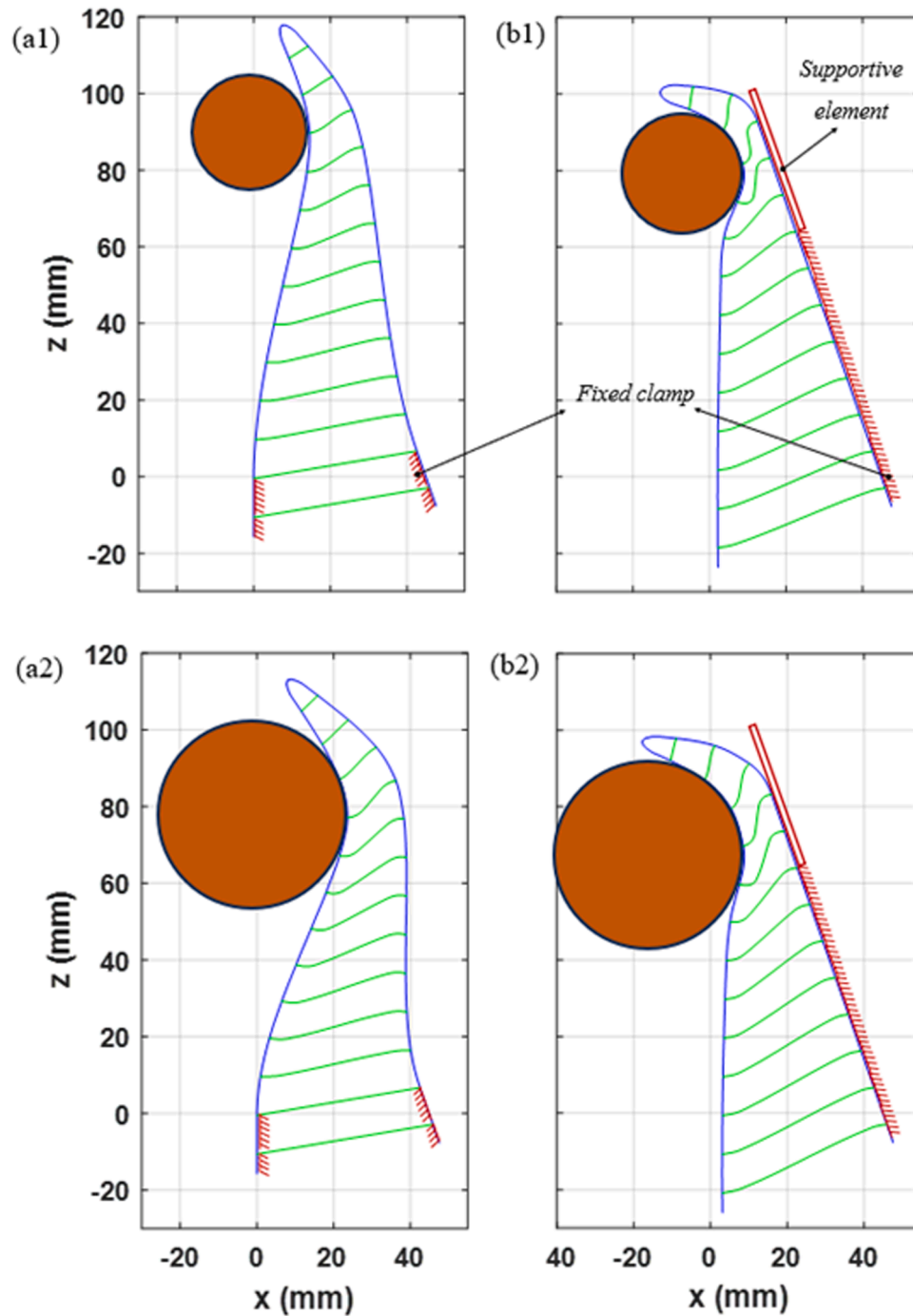
$$\begin{aligned}
 \mathbf{P}_f(L_f) &= \mathbf{P}_b(L_b) \\
 [\log(\mathbf{R}_f(L_f)\mathbf{R}_b(L_b))]^\vee &= \mathbf{0} \\
 \mathbf{n}_f(L_f) &= \mathbf{n}_b(L_b), \\
 \mathbf{m}_f(L_f) &= \mathbf{m}_b(L_b),
 \end{aligned} \tag{2}$$

where where  $\log$  is the matrix natural logarithm which maps  $SO(3)$  to  $\mathfrak{so}(3)$ , and  $(\cdot)^\vee$  represents the mapping from  $\mathfrak{so}(3)$  to  $\mathbb{R}^3$ . The suffix  $f$  is for the front-beam,  $b$  for the back-beam, and  $i$  for the  $i$ th crossbeam, where  $i = 1$  to  $n$ . The base of the  $i$ th crossbeam is clamped to the front-beam at the arclength  $l_i$ , and the end of each crossbeam ( $s = l_i$ ) is clamped to the back-beam. So, for the base and end pose of all the crossbeams one can obtain:

$$\begin{aligned}
 \mathbf{P}_i(0) &= \mathbf{P}_f(l_i), \\
 [\log(\mathbf{R}_i(0)\mathbf{R}_f(l_i))]^\vee &= \mathbf{0}, \\
 \mathbf{P}_i(l_i) &= \mathbf{P}_b(l_i) \\
 [\log(\mathbf{R}_i(l_i)\mathbf{R}_b(l_i))]^\vee &= \mathbf{0} \text{ for } i = 1 \dots n.
 \end{aligned} \tag{3}$$

The developed model is simulated in MATLAB.

To have the PPMW and PPSD grasps, it was needed that the gripper's fingers completely wrap around the object. Therefore, the bending of fingers in reaction to the contact force must significantly increase to provide the required wrapping configuration. To have the desired wrapping properties, initially various beam patterns were explored in simulation analysis of FRE fingers. However, the results showed that changing the beam patterns did not have a significant effect on the desired properties. So, different MA designs, by changing the boundary conditions of the finger, were investigated in simulations. To cause the finger to bend more around the object, greater internal forces in the opposite direction of the contact force must be applied from the crossbeams to the front-beam. Therefore, the back-beam needs to exert more force on the crossbeams, which in turn, apply more forces to the front-beam. However, since the back-beam is flexible, it moves backward in response to the internal forces, and its reaction forces are limited. Preventing the backward movement of the back-beam with a supportive element can significantly increase its reaction forces. Additionally,



**Fig. 4.** Simulated finger shape after gripping a circular object with diameter of 30 mm with (a1) the original gripper and (a2) the modified gripper, and a circular object with diameter of 50 mm with (b1) the original gripper and (b2) the modified gripper.

releasing the base of the front-beam from the mounting adapter allows this beam to bend more easily around the grasped object.

Figs. 4(a1) and 4(b1) show the simulation results for an FRE finger with the original mounting adapter after gripping circular objects with diameters of 30 mm and 50 mm. Similar results, after applying the new boundary conditions, are shown in Figs. 4(a2) and 4(b2). To restrict the deformation of the back-beam under the new boundary conditions, the beam is clamped in some parts, and a supportive element limits the backward movement in other parts. A comparison of the two finger shapes indicates that with the new boundary conditions, the FRE fingers can better envelop the grasped objects. Therefore, by restricting the deformation of the back-beam and releasing the base of the front-beam,

it is expected that the enveloping capability needed for the PPMW and PPSD grasps will be achieved.

The internal forces of the front-beam for this simulation, shown in Fig. 5, reveal that with the new boundary conditions, the front-beam experiences more internal forces due to increased contact forces from the grasped object. Thus, with the increased contact forces, it is expected that the new boundary conditions also result in greater grip forces.

On the other hand, to achieve the PPP grasp, the fingertip must be able to enclose very small diameter objects to provide a firm pinch. However, the original form of the beams cannot conform to the surface of very small shapes for precise firm pinching. Therefore, the tip structure was modified to achieve this property. Through iterative

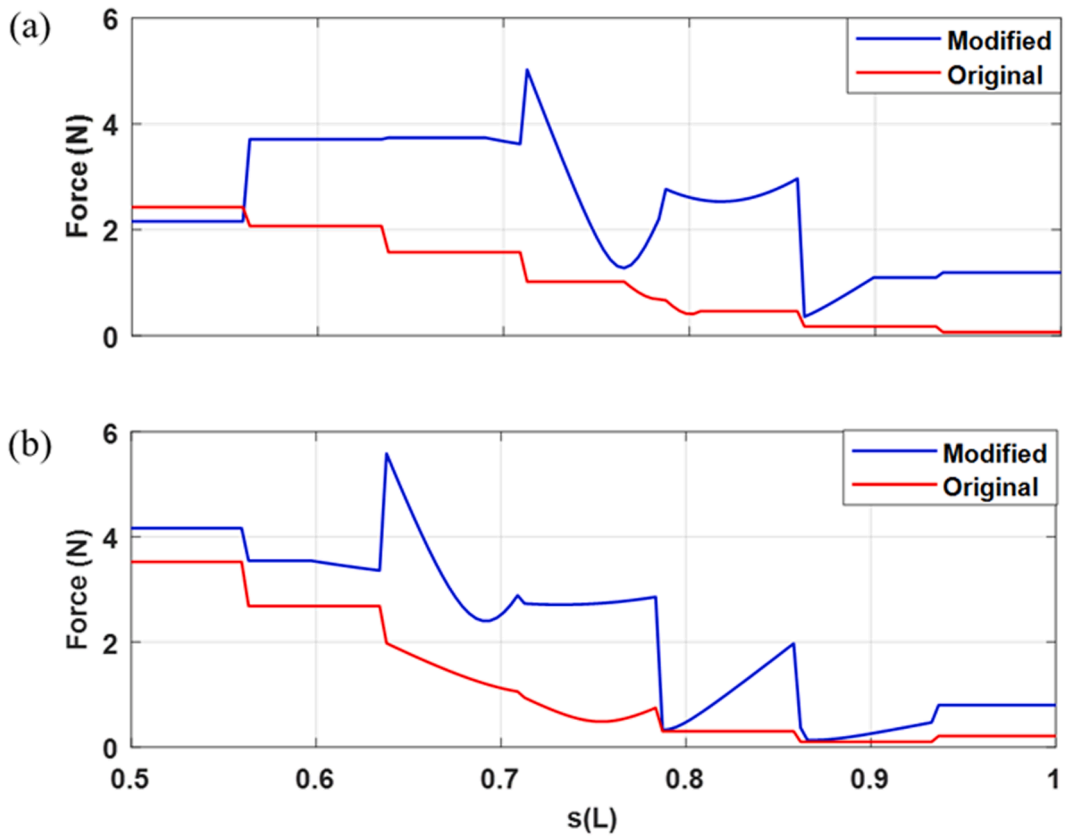


Fig. 5. The internal forces of the front-beam after gripping the circular object with (a) diameter of 30 mm, and (b) diameter of 50 mm.

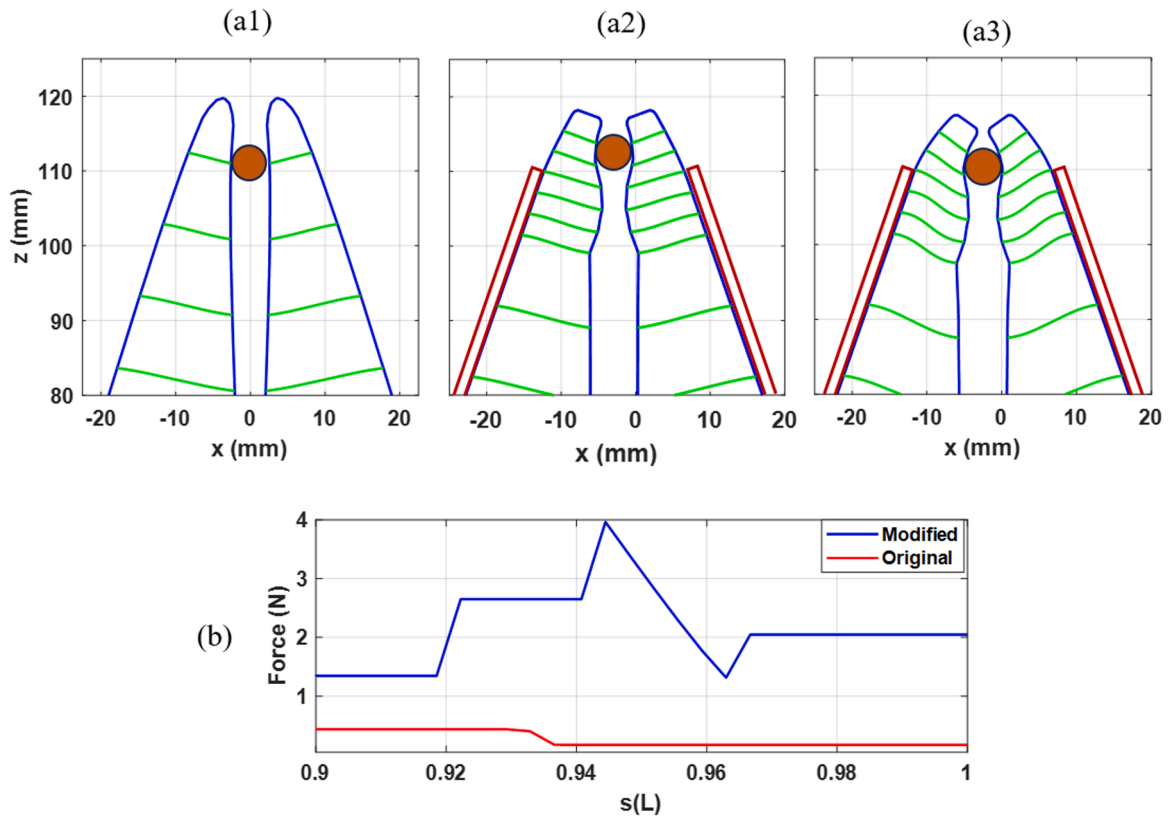


Fig. 6. Comparison of the simulated finger shape after gripping a small circular object at the tip; (a1) The original FRE finger, (a2) the finger with modified fingertip pattern, (a3) the finger with both modified fingertip pattern and altered beam thicknesses. (b) The internal forces of the front-beams.

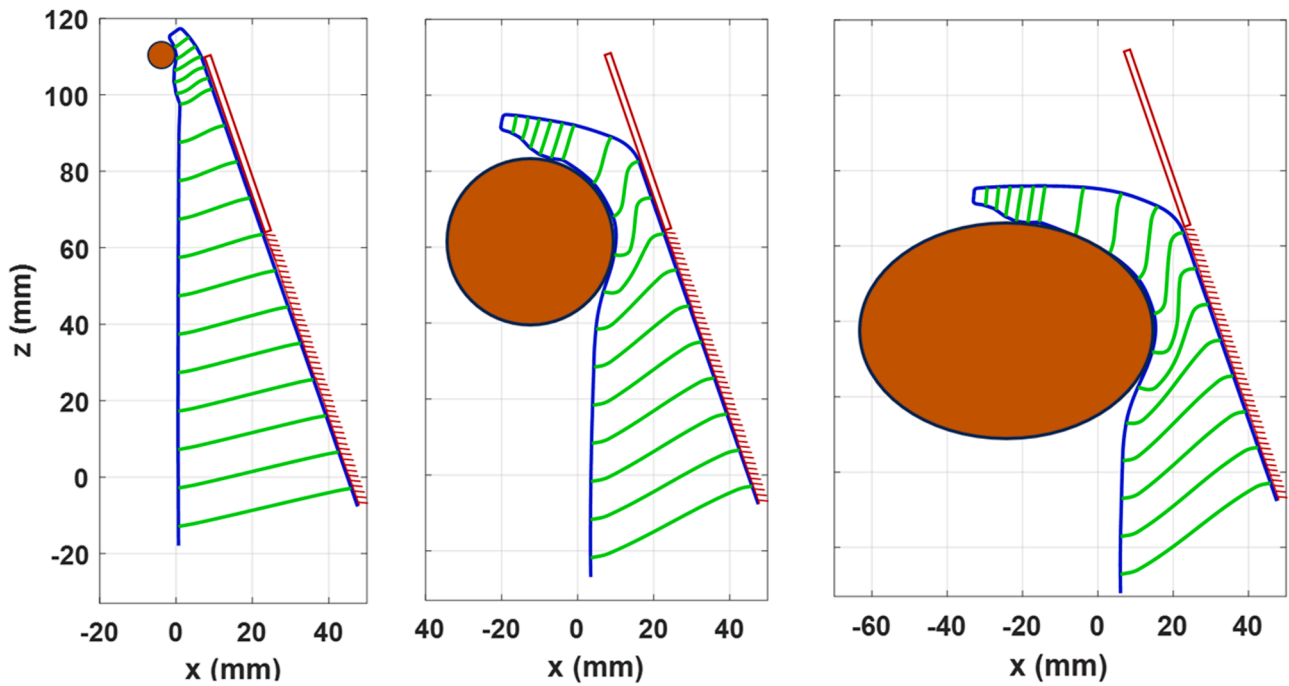


Fig. 7. Simulated finger shape after gripping different objects.

simulations, we observed that a curved beam shape near the tip considerably increased the contact area upon grasping, thereby providing enhanced stability. Consequently, the no-load shape of the front-beam was modified from a straight to a curved configuration, introducing a bump near the tip. Moreover, simulation analyses revealed that increasing the number of crossbeams and adjusting both the crossbeam and front-beam thicknesses at the fingertip allow the FRE structure to better conform to the contours of small objects, thereby improving the contact surface area. Additionally, the fingertip size was chosen based on the dimensions of the trees used in our experiments to ensure compatibility and optimal performance. This design was

optimized empirically, leveraging simulation-based trials to maximize performance for small object grasping. While not derived through formal optimization criteria, this process highlights the potential for further development of objective-function-driven design methodologies in future work.

In Fig. 6, the simulation results for grasping a small circular object ( $\varnothing = 5 \text{ mm}$ ) are presented. Fig. 6(a1) shows the result for the original FRE finger, and Fig. 6(a2) shows the result for the finger with a modified fingertip shape and added back support. From the results, the new beam pattern better encloses the object. Fig. 6(a3) shows the proposed design, where the thickness of the crossbeams at the fingertip was also reduced

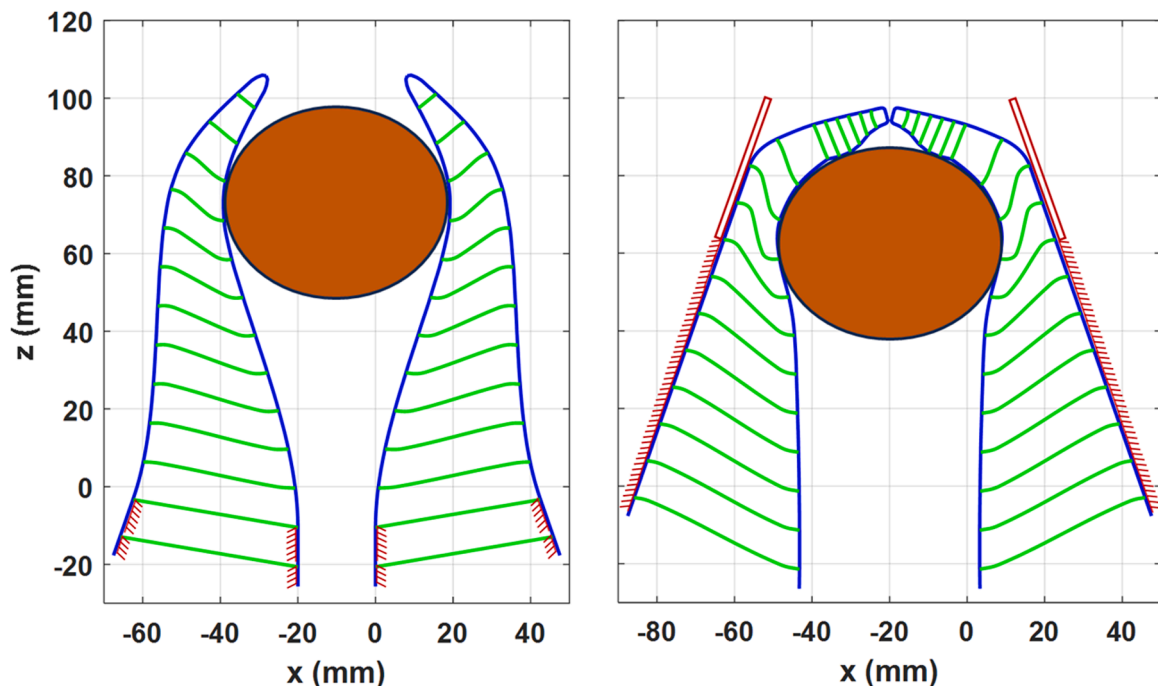


Fig. 8. Comparison of the simulated finger shapes after power grasping an elliptical object.

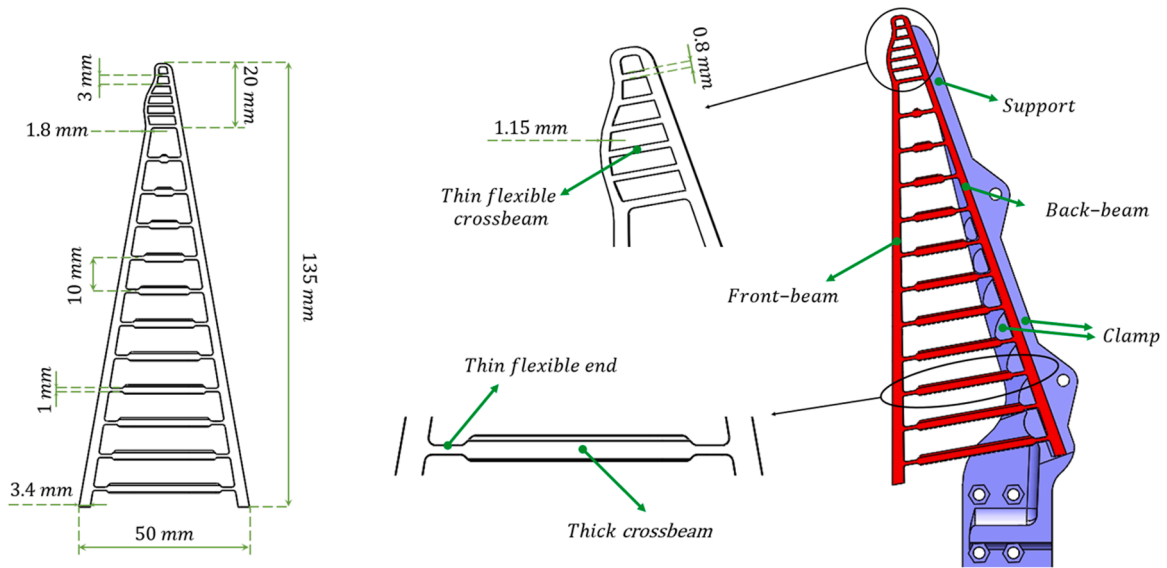


Fig. 9. The modified FRE gripper design.

by 20 %, and the thickness of the front-beam was reduced by 35 %. The results indicate that decreasing the beam thickness at the tip further improved the ability to enclose the small object due to increased flexibility and better deformation. The original design maintained a smooth profile with minimal deformation at the fingertip post-grasping and in contrast, the proposed design exhibited a more pronounced deformation. Fig. 6(b) also illustrates greater internal forces in the front-beam with the modified structure, resulting from the back support provided by the modified mounting adaptor. Therefore, more stable pinching is expected from the new beam configuration by providing more contact force and contact surface. These design adjustments highlight the potential for further optimization through detailed parameter exploration in simulations.

The clamped region of the back-beam was determined after several simulations, identifying the segment that does not bend when gripping objects of various sizes within the context of our application. From simulations, for gripping larger objects, a shorter length of the back-beam must be fixed as shown in Fig. 7. The length of the back support was also adjusted to ensure proper pinching grasp at the fingertip. We acknowledge that this is an empirical method, showcasing the capacity of the model. Indeed, depending on the application or the size and shape of the object, the fixed portion can be adjusted after simulation analysis for different scenarios, thanks to the proposed modelling method.

Fig. 8 compares the enveloping capability of the grippers after power grasping an elliptical object ( $\varnothing_{\text{major}} = 58 \text{ mm}$  and  $\varnothing_{\text{minor}} = 50 \text{ mm}$ ). In this simulation, the applied contact force to the object from each finger

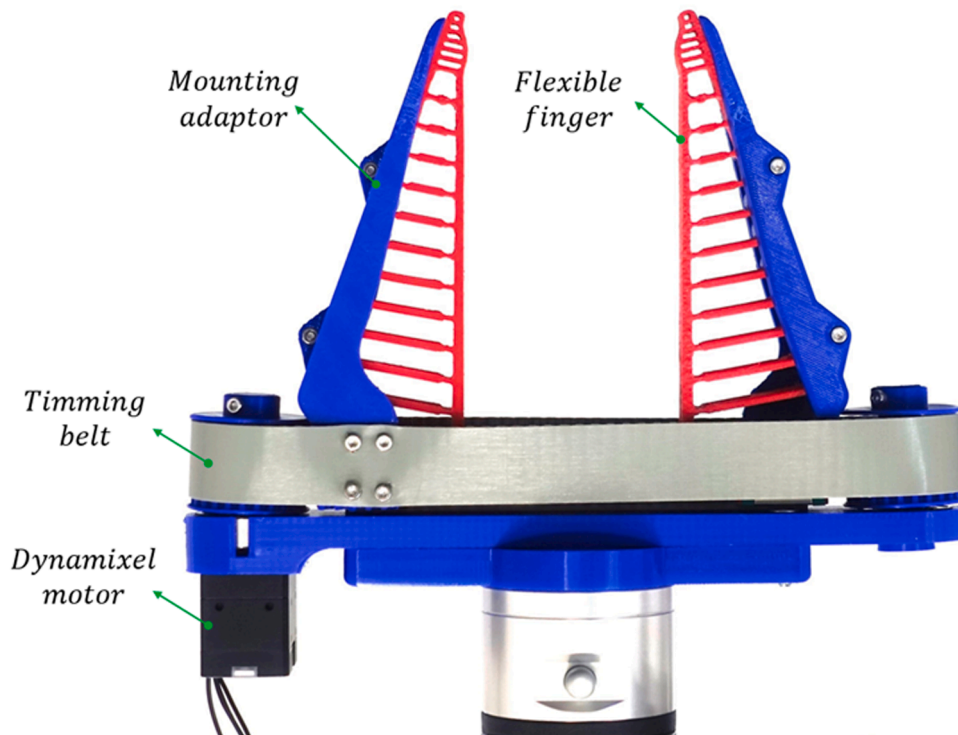


Fig. 10. The fabricated modified FRE gripper.

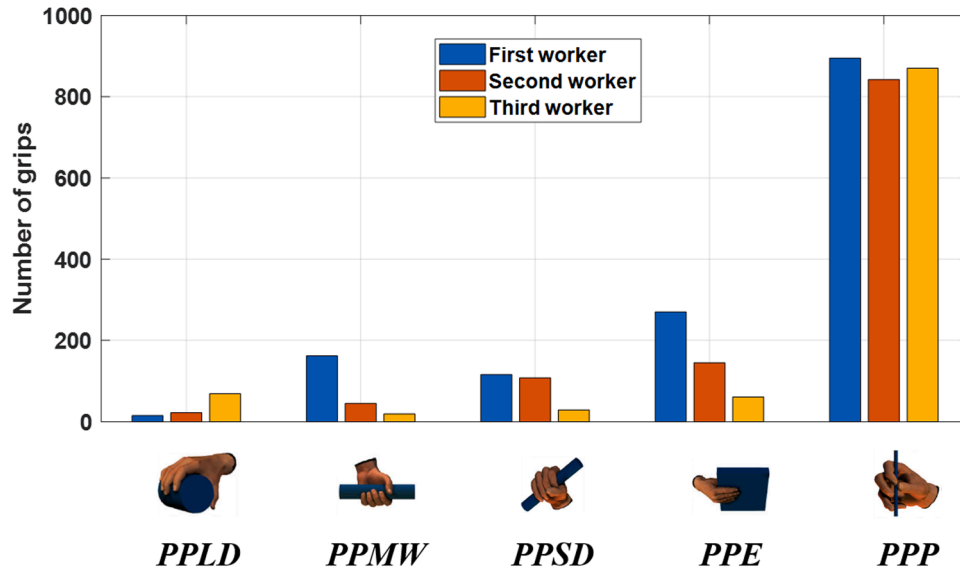


Fig. 11. Number of each grasp used by skilled operators.

in the original gripper is 2.6 N. However, this force for the modified gripper is 8.4 N, representing a 223 % increase. The contact surface with the modified gripper is also increased by over 150 %. Thus, with a larger contact surface resulting from better enveloping the object and increased contact forces, it is expected that the new FRE structure provides more stable power grasps in addition to offering the required human-like grasps. In the next section, the 3D design of the modified FRE gripper is described.

### 2.3. Proposed design

The proposed design based on the mentioned analysis is given in

Fig. 9. In this design, the MA supports the finger from the back instead of the bottom to provide more lateral forces toward the grasped object. The MA in the lowest parts clamps the back beam of the finger, while the highest parts serve as a supportive element, allowing this beam to bend easily toward the grasped object. The flexible finger structure consists of two main parts, including the body and the tip. The finger's body is based on the Festo FRE structure [29] and includes horizontal crossbeams that connect the main beams. The crossbeams in this part are thick bars acting as rigid elements with thin flexible ends. However, the tip structure contains thin flexible crossbeams with constant thickness. In the tip structure, the number of crossbeams is increased, and the thickness of the front-beam is decreased. The shape of the front-beam in



Fig. 12. The experimental setup for measuring the separation forces.

**Table 1**  
Separation forces.

	Min	Avr	Max
Individual tree (N)	0.95	4.2	9.2
Bunch of trees (N)	3.5	18.7	28.5

the tip structure is changed and a bump is included to provide the PPP grasp.

The fabricated modified gripper is shown in Fig. 10. The flexible FRE fingers were made of NinjaFlex filament, while the rigid elements of the MA and the actuation mechanism were made of PLA. All elements were printed using a RAISE3D Pro2 printer. All elements were printed using a RAISE3D Pro2 printer. The AM utilises a Dynamixel XH430-W350-R motor as actuator and T5 timing belt and pulley as power transmission system. The performance of the proposed gripper is investigated

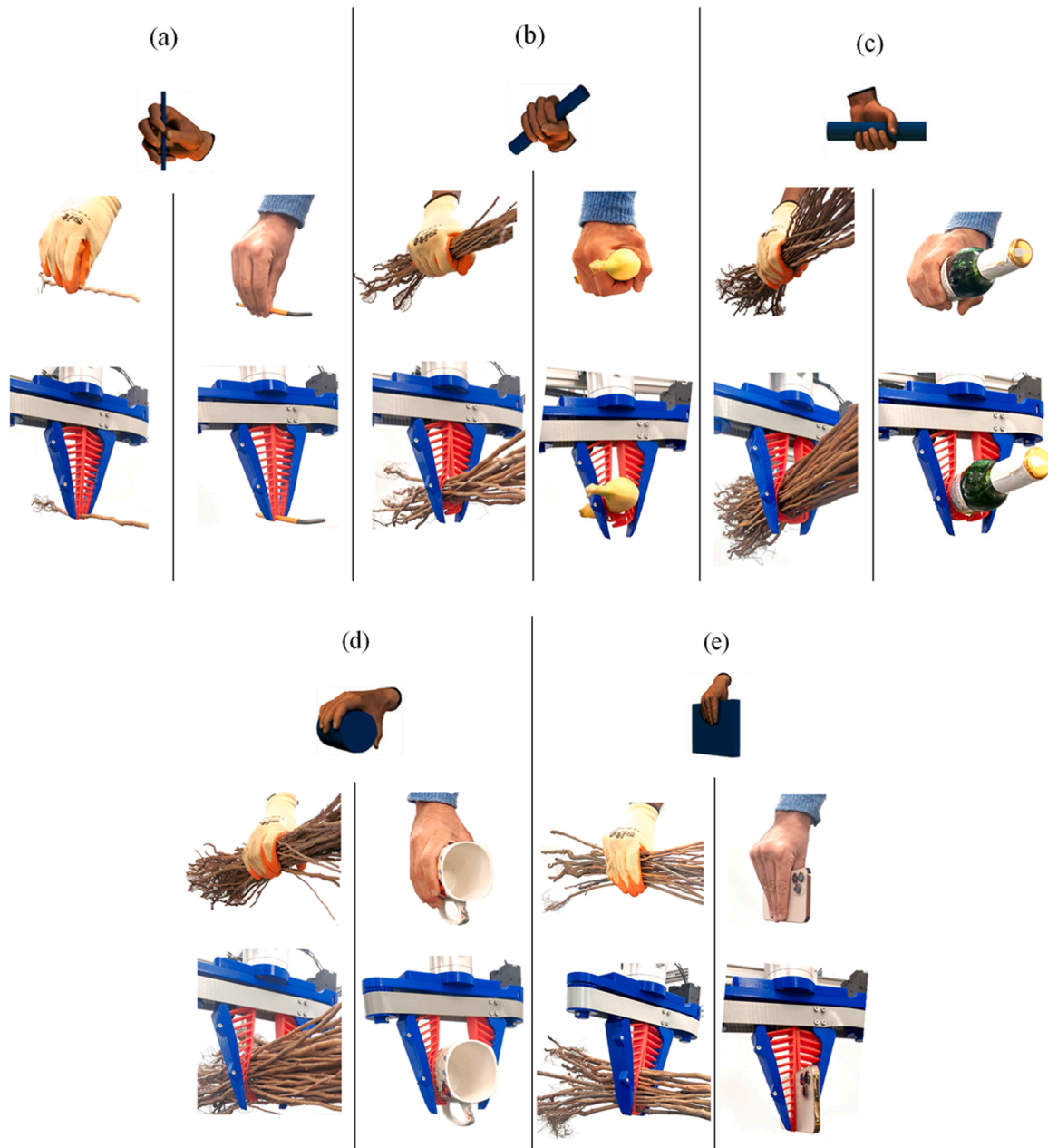
in the next section.

### 3. Results and discussion

In this section, the details of worker analysis, the separation force measurement, and the tests performed to validate the performance of the proposed gripper in providing the desired grasp types, necessary grip forces, and grasp stability are described.

#### 3.1. Analysis of workers

Three different workers in the forest nursery were analysed to replicate their grasp performance. Fig. 11 illustrates the frequency of each grasp used by each worker during the 15-minute separation process. From the results, the PPP grasp is the most frequent, and the number of other grasps varies significantly among different workers.



**Fig. 13.** The provided grasp types by the proposed gripper, along with a comparison to human grasps used for holding trees and various objects encountered in daily life, include: (a) PPP, (b) PPSD, (c) PPMW, (d) PPLD, and (e) PPE grasps.



Fig. 14. The experimental setup for measuring the grip forces.

However, all grasp types were necessary for the process for all workers.

Additionally, the required force to separate an individual tree from a bunch, or to split bunches of different sizes, was measured. The trees were secured to the table as a bundle, with the bunch section or individual tree to be separated affixed to the force sensor (PCE-PFG-50). The sensor was then moved upward using a gantry robot, causing the section or single tree to separate from the bundle, with the sensor registering the maximum force during this test. The experimental setup is depicted in Fig. 12. The tests for separating individual trees and splitting the bunches were repeated 30 times, and Table 1 presents the minimum, maximum, and average required separation forces. From the results, it can be concluded that the gripper must provide up to 9.2 N of grasp force for pinching an individual tree and up to 28.5 N of grasp force for gripping a bunch of trees.

### 3.2. Evaluation of provided grasp types

The first test investigates the performance of the proposed gripper in providing the required grasp types. Fig. 13 presents the results of this test. Grasping a single tree and bunches of trees of different sizes, as well as other objects of various shapes, is shown in this figure and compared with human hands. From this figure, it is evident that the gripper can successfully provide the desired grasp forms. The gripper fingers can properly wrap around the objects to provide the PPSD and PPMW grasps, similar to human hands. The fingers can also pinch small objects at the tip, mimicking the human PPP grasp. The PPLD and PPE grasps are also achievable with this gripper, similar to the original FRE gripper, but with significantly more grip forces necessary for many industrial applications requiring sufficient payload, such as the singulation of tree saplings. The grip forces and grasp stability are investigated in the subsequent tests.

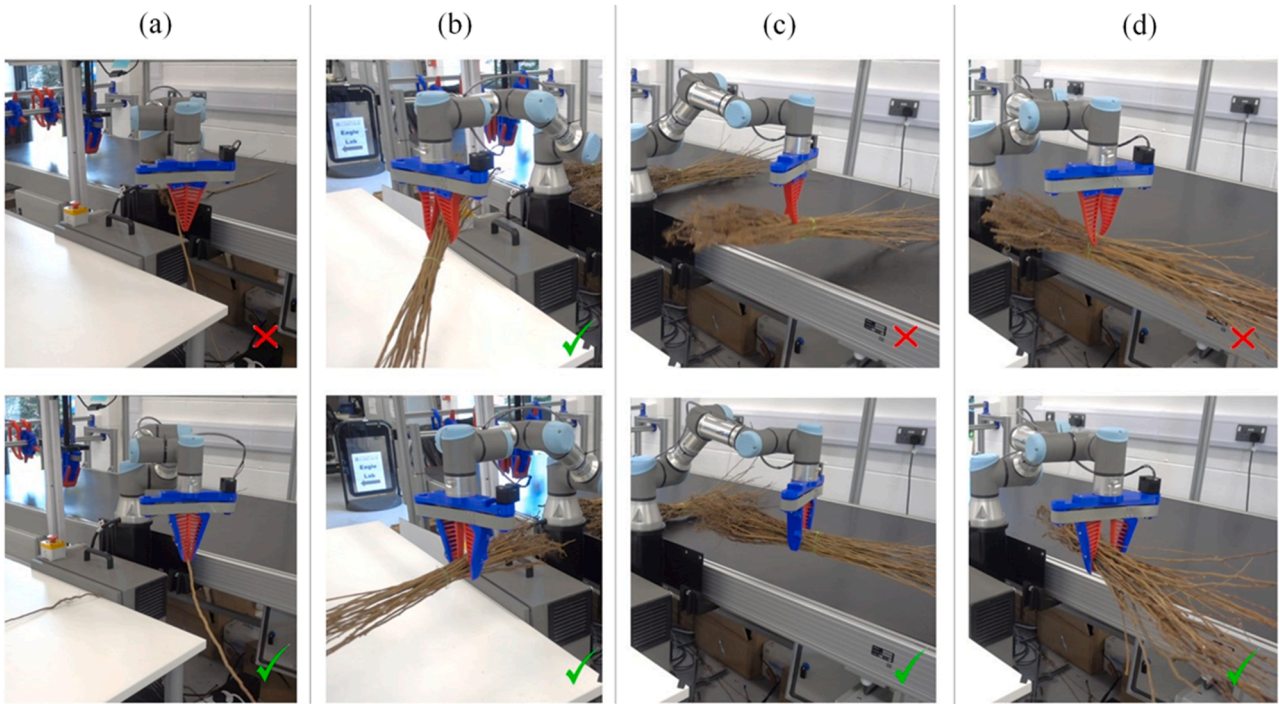
Table 2  
Grasp force results.

Gripper	Object	Releasing force (N)		
		Min	Avr	Max
Original	Single tree	1.06	1.28	1.59
	Small bunch	4.80	5.62	6.07
	Medium bunch	6.96	7.58	8.10
	Large bunch	9.11	11.17	12.98
Modified	Single tree	12.84	13.76	15.28
	Small bunch	47.36	49.68	51.42
	Medium bunch	32.77	34.15	35.76
	Large bunch	31.66	33.02	34.46

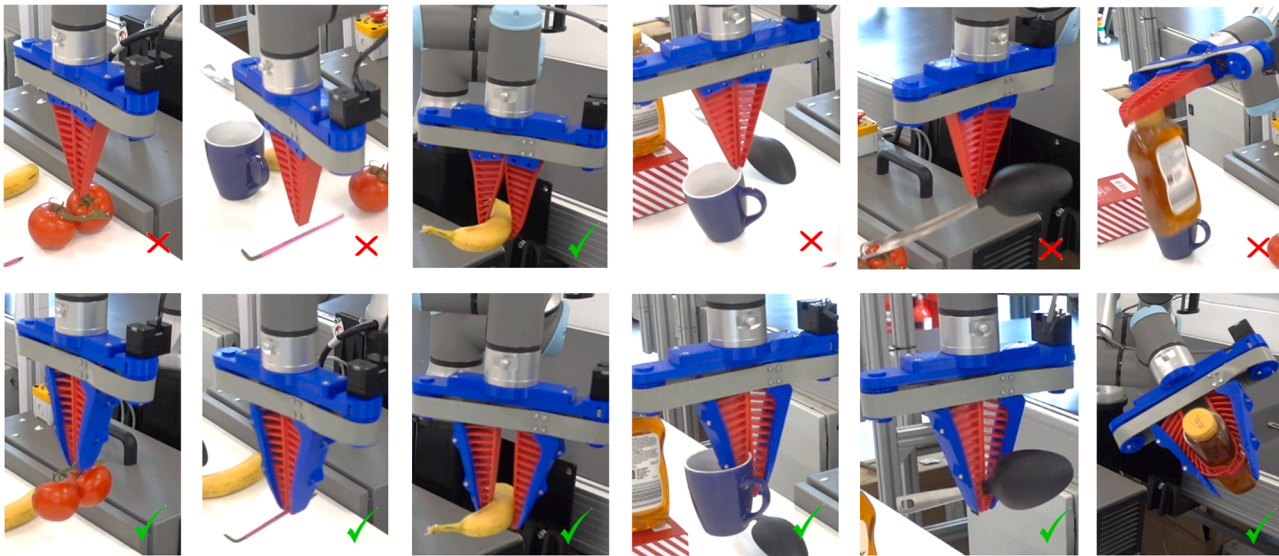
### 3.3. Evaluation of grip forces

The second test examines the grip force of the gripper and compares it with the conventional FRE gripper. For this test, the grippers were mounted on a UR3 arm in a vertical configuration, as shown in Fig. 14. An individual tree, as well as different sizes of tree bunches, were grasped with both grippers while the trees were fixed to the force sensor (PCE-PFG-50) from below. The robot then moved upward, and since the trees were fixed to the force sensor, the gripper released them during this movement. The sensor registered the maximum force during each test. This test was repeated 5 times for an individual tree ( $\varnothing = 5 \text{ mm}$ ), a small bunch ( $\varnothing = 30 \text{ mm}$ ), a medium bunch ( $\varnothing = 45 \text{ mm}$ ), and a large bunch of trees ( $\varnothing = 70 \text{ mm}$ ). The accompanying video (Video\_1) demonstrates this test, and Table 2 summarises the maximum, minimum, and average values for the measured forces.

From the results, it is observed that in the original design, the releasing force decreases with the decreasing bunch size due to the reduced contact surface. However, in the modified design, since the fingers envelop the object and apply more contact forces, the releasing force significantly increases. The maximum releasing force belongs to



**Fig. 15.** Comparison of the grasp stability of the grippers for picking and lifting (a) a single tree, (b) a small bunch ( $\varnothing = 30\text{ mm}$ ), (c) a medium bunch ( $\varnothing = 45\text{ mm}$ ), and (d) a large bunch of trees ( $\varnothing = 70\text{ mm}$ ).



**Fig. 16.** Comparison of the grasp stability of the grippers for picking and lifting various objects.

the small bunch, as the fingers perfectly wrap around the bunch like the PPSD grasp of human hands. The releasing force for the large bunch is increased threefold, while for a small bunch, it is about eight times greater, and for a single tree, it is more than ten times greater. It can be concluded that the new design significantly increases the releasing force, with a more considerable improvement for smaller objects. The results indicate that the releasing force of the gripper satisfies the required forces for each grasp type for the forest nursery tasks.

### 3.4. Evaluation of grasp stability

In the third test, to examine the grasp stability, the gripper was used to pick-and-place individual trees as well as bunches of trees with

different sizes. The UR3 arm moved at its maximum speed (1 m/s) during this test and the performance was compared with the conventional FRE gripper. This test was performed twice, and the accompanying video (Video 2) demonstrates it. Fig. 15 compares the provided grasps by both modified and conventional grippers. As the video\_2 demonstrates, the proposed gripper successfully picked up and stably moved all trees both times. In contrast, the conventional gripper was unable to pick up and stably move the trees in >80 % of the cases, with the objects falling from the gripper during movement.

To assess the gripper's performance for general pick-and-place applications, the final test involved using the gripper to handle objects of various shapes and sizes, as shown in Fig. 16. This test was repeated twice and as illustrated in Video\_3, the original gripper was unable to

pick up small objects with a pinching grasp and lift heavy objects. However, the proposed gripper successfully pinched the small objects and lifted the heavy ones by providing more contact surface (wrapping the object) and more contact forces. It successfully picked up and stably moved all six objects both times, whereas the conventional gripper could only pick up and stably move one object in both repetitions. These results demonstrate that the proposed method can significantly enhance the grasp stability of FRE grippers for pick-and-place scenarios commonly encountered in industrial applications.

#### 4. Conclusions

To mimic human workers' hands, modifications were applied to the Fin Ray Effect (FRE) grippers in this research. Utilizing a mathematical model based on the Cosserat rod theory, the shape and internal forces of the FRE structures were analysed in simulations. By changing the boundary conditions and the tip shape, the finger could better envelop the objects and apply more contact forces in simulations. Additionally, the fingertip could pinch small objects. Experimental results revealed that with the proposed design, FRE grippers could provide three additional grasps, and the grip forces significantly increased. The developed gripper can be utilised for various applications requiring reliable movement of delicate objects with sufficient payload. In addition to tree sorting in forest nurseries, other examples include sorting, packaging, and palletizing various goods in warehouses or retail automation, as well as harvesting or handling crops in agricultural settings.

#### CRedit authorship contribution statement

**Mohammad Sheikh Sofla:** Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Hanita Golshanian:** Validation. **Elizabeth I. Sklar:** Supervision, Methodology. **Marcello Calisti:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization, Methodology.

#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Mohammad Sheikh Sofla, Hanita Golshanian, Elizabeth Sklar and Marcello Calisti report financial support was provided by Forestry Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Data availability

No data was used for the research described in the article.

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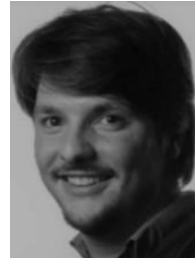
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