

## Article

# Development of a Dynamic Hands-Free Door Opener to Prevent COVID-19 Pandemic Spreading

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**Abstract:** The situation caused by COVID-19 has shown several vulnerabilities in the attitudes and habits of modern society, inducing the need to adopt new behaviors that will directly impact daily activities. The quickly spreading virus contaminates the surfaces of handles and objects, and subsequent contact with the eyes, nose, or mouth is one of the main contagion factors. There is an urgent need to rethink how we interact with the most-touched surfaces, such as door handles in public places with a high flux of people. A revision was performed of the most-used door handles to develop a proposal that could be applied to already existing models, thus avoiding the need for their total replacement. Through interaction between engineering, design, and ergonomics, an auxiliary hands-free door opener device was developed, following iteration improvement from an initial static geometry and culminating in a dynamic system aiming to provide greater ergonomic comfort in its use. The development followed a methodology using 3D modelling supported by 3D printing of the various components to accurately understand their functioning. In addition, the finite element method supported the prediction of the structural behavior of the developed systems. The final models were produced through CNC machining and submitted to functional validation tests with volunteers. The developed HFDO demonstrated relevant differentiation from the existing models on the market: for its geometry and material, but mainly for its strong emphasis on the interaction between the object and the user, resulting from the dynamic component in its use/manipulation.

**Keywords:** COVID-19; handle; industrial design; ergonomics; doors openers



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## 1. Introduction

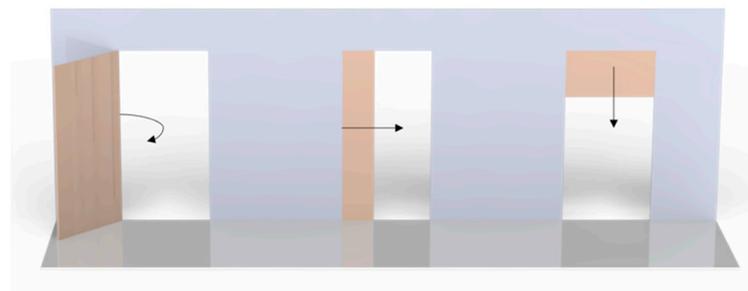
Considering the current pandemic and the future challenges to global health, the need to develop and implement solutions that mitigate or eliminate the various means of contamination with viruses and bacteria, especially COVID-19, in daily activities becomes evident. In this sense, door handles, being among the most varied architectural elements, characterized by high human interaction, have been identified as one of the main contagion points. According to the Portuguese Standard EN 1906, from 2017, door handles are defined either lever or round handles with a mirror or rosette intended to activate locks. According to the *Human Factors Design Handbook* by Woodson et al., the most common door handles are L-shaped or lever systems, knob handles, and fixed D-shaped pieces, with closed or open ends [1].

### 1.1. Handles in the Spread of Viruses and Bacteria

Handles in public places are significant factors in contagion, since they are potential agents in the spread of viruses and bacteria. In this sense, their role in contamination, especially in the hospital context, has been a target of analysis for a long time. However, this problem has gained even more significance in the current pandemic situation. Wojgani et al. [2] developed a study in two intensive care units and a long-term care unit to determine whether the microbial contamination of door handles was related to their design, location, or/and use. They found a significant correlation between the frequency of movements through a door and the degree of contamination. The handles, when compared the push plates, revealed, on average, a level of contamination that was five times higher. The study by Wojgani et al. [2] also showed that door handles applied in clinical environments, in their daily use, were contaminated with bacteria, and the design, location, mode, and frequency of operation had a direct impact on the number of bacteria found. An identical analysis was described in the study by Odigie et al. [3], where the microbiological examination of samples from several hospital units revealed that handles in different sections of a hospital environment are contaminated by a variety of pathogenic and non-pathogenic microorganisms. It was also shown that the location of the doors had a significant role in the distribution of the microorganisms. These authors also found that the samples from the bathroom door handle registered the highest bacterial load, which can be attributed to the increased exposure rates to the bacteria disseminated by users who enter and leave without proper hand hygiene. Additionally, the surfaces of the internal handles could act as potential transmitters in the spread of diseases. These two studies reported situations in the hospital context. However, identical conditions can be found in schools, universities, and public buildings with a substantial inflow of people. Thus, it is imperative to find strategies that prevent users from becoming infected via their hands.

### 1.2. Door Opening Systems

The various door opening systems, handrails, and switches are, perhaps, the most used interfaces in the experience of people in different types of buildings. This relationship, decisive in humans' interactions with architecture, dates back to its appearance in ancient Egypt. Throughout the history of mankind, doors and their opening systems also assumed a decorative role. A door is akin to an extension of the wall that moves to allow the isolation and the penetration of spaces, as quoted in Carvalho, 2012 [4], calling it an "operable wall". Chang and Drury, as cited in Carvalho, 2012 [4], classified doors according to their interaction with humans, dividing them into three types, as shown in Figure 1: (1) normal force on the door—includes doors with a rotation axis, "pull/push" or swivel, reciprocating and through-throttle suspensions (e.g., ribbons, beads); (2) horizontal force parallel to the door plane—sliding or folding doors; and (3) vertical force parallel to the door plane—garage doors and similar.



**Figure 1.** Types of door and their interaction with the user: normal force (left); horizontal force (middle); vertical force (right).

The current door opening mechanisms are configured so that the user's hand carries out the different operations: apprehending, pulling, and pushing. Various situations are

evident, whether for hygiene reasons or for fear of contamination, where the user strives to find strategies to interact with the door without holding its handle. One of the most vulnerable places where such situations happen is hospitals, in which cross-transmission of various pathogens occurs despite the demanding hygienic and aseptic standards. Carvalho, 2012 [4], compared the norms for this type of device defined in Australia, the United Kingdom, the United States, and Portugal. It was verified that the general characteristics for the operation of doors, such as handles and locks, are similar and can be identified as: being easy to grip; being easy to operate with a single closed hand; not requiring a firm grip or wrist rotation; offering minimal resistance to performance; having non-slip properties; and having chromatic contrast identification concerning the door surface for easy visual detection. The author also mentioned that fixed D-shaped handles are identified in the four norms as being suitable for people with strength and manual dexterity difficulties. Knob handles, however, are contraindicated in all studied standards. Additionally, it is important to mention that the English norm advises lever movements (e.g., lever puller) for solutions regarding devices with mobile characteristics.

Although most users can manage all types of systems correctly, children and people with reduced mobility have difficulties with most types of openings. In this sense, L-shaped (with a lever) can be considered the best handles, since they do not have to be tightened, and their appearance offers the quick perception of their use [1].

### 1.3. Auxiliary Devices for Door Opening Systems

Several projects for auxiliary door opening devices have been developed to reduce direct contact between users' hands and different types of handles. These include arm/forearm opening systems for direct fixation to the door, systems for fitting or fixing to the handle, and opening systems with the foot.

With regard to opening systems activated by the arm with direct fixation to the door, three systems can be referred to: (1) Sanitgrasp [5], manufactured in stainless steel and developed according to the standards of the Americans with Disabilities Act (ADA); (2) Toepener [6], also compatible with ADA and made of stainless steel, with easy and safe assembly through four screws; (3) Sanitary Door Opener Device [7], in aluminum, with rounded curves and anodized coating, in a shape that seeks to avoid the risk of trapping the user's arm in the handle, even when the door is pushed abruptly and forcefully by a person on the other side.

From the systems that are being fixed to already existing handles, the functional solution that this project seeks to follow can be highlighted [8], which seeks to eliminate direct contact with devices such as handles, elevator buttons, telephones, computer mice and keyboards. The proposed system is produced in acrylonitrile-butadiene-styrene (ABS). The Intulon System [9] is a circular handle adapter with a diameter of less than 18 mm. The Materialize company [10] offers free models for fastening with screws, whose geometry and assembly instructions can be downloaded online in order for each user to produce the model autonomously through additive manufacturing.

Still, within the scope of devices to be fixed to the handle, the Shaftmodule system is composed of a shell-type metallic piece and is fixed with the use of screws [11]. A particular system for round handles, to be printed in 3D, was proposed by Adapta [12].

There are also systems that involve activation with the foot. These systems work by means of mechanical parts fixed at the door's bottom, connected to the handle by a cable, such as the Planet NoHandler [13]. In this context, we highlight the StepNpull<sup>®</sup> system [14], an anodized aluminum device, which allows for opening a door hands-free by using a foot, a cane, or a crutch. This system consists of a metal plate with a serrated edge that is screwed to the bottom of the door, allowing the user to step on it and, in this manner, open the door. With features similar to StepNpull [14], there are the HandsFreeDoorPull [15], with rounded geometry, and the Metiba System [16], which is also fixed to the bottom of the door but is retractable.

#### 1.4. Proposed Dynamic Hands-Free Door Opener

This work presents an innovative door opening system to be implemented and used without the hands, designed as a hands-free door opener (HFDO), focusing on its potential application in hospitals, health units, and other public areas with a high inflow of people. For this purpose, design and engineering disciplines created synergies, developing the opening system as a solution to help mitigate the problems mentioned. A consortium of two companies and two non-business entities from the Portuguese national R&D system was created, supported by the Research Incentive System and Technological Development promoted by the National Innovation Agency.

The objective was to design and develop a simple product from scratch with high aesthetic and functional value, characterized by great usability, versatility, affordable cost, easy installation, and low maintenance. In this sense, the developed product has a strong incorporation of design and mechanical design methodologies, emphasizing the ergonomic aspects in its cognitive, physical, and anthropometric dimensions, with respect for the current rules in terms of safety and procedures.

The solution presented and described in this work enables its adaptation to different handle geometries. The description is based on the L-shaped geometry and the “bar” category systems, with both a horizontal and a vertical assembly. This proposal provides the option of opening the door using an arm, or even a foot, by incorporating different mechanisms and/or handles while guaranteeing the fundamental biomechanical characteristics, emphasizing their strength and mechanical rigidity, associated with a geometry that can be easily decontaminated.

## 2. Materials and Methods

In this project, an attempt was made to develop an opening system that works without the use of the hands, adaptable to doors with a “pull/push” axis of rotation, which is the most common in the majority of buildings. These systems, commonly referred to as handles, are usually pieces of wood, metal, or porcelain pulled to open drawers and doors.

### 2.1. Ergonomics, Interaction Concepts and Design

Ergonomics can be considered a decisive factor in each product design project, and can be involved in three complementary approaches [17]: (1) developing new techniques and strategies that can allow an unaided person to perform better on the spot at work, at home or in the community; (2) developing specialized tools or assisted technologies that can maximize the use of residual skills and compensate for missing skills; (3) changing the design of the world to make it more usable and to offer a broader range of skills and abilities.

The domain of interaction, where ergonomics is central, influences the symbiotic relationship between humans and the product, allowing the user to understand what to do and then evaluate the results to determine the following action [18]. In this way, we identified 4 of the 6 Norman principles, affordance, signifiers, constraints, and feedback, as important concepts in the development of this project:

- “Affordance” is probably the principle that could have the most significant impact on this project and can be defined as the relationship between a physical object and a person (or any agent: animal, human, or even machine and robot). The quality of an object allows the user to identify its functionality without previous explanation, which can happen intuitively (e.g., doorknob) or based on previous experiences (e.g., white colour can mean peace). The greater the “affordance”, the better the identification of its use. It is important to note that “affordances” of physical objects are based on their size, format, and weight, while those of virtual object (web, app, etc.) happen through graphic representations and metaphors;
- “Signifiers” refer to any mark, sound, or any perceptible indicator that communicates the appropriate behavior to a person. These signs can be deliberate and intentional, but also accidental and unintentional;

- “Constraints” are powerful clues limiting the set of possible actions, which can be of physical, cultural, semantic, and logical order. The deliberate use of design restrictions allows people to readily determine the appropriate course of action, even in a new situation;
- “Feedback” concerns the communication of the results of an action and contributes decisively to reducing the user’s frustration and stress.

Another characteristic intrinsic to the objectives of this project is attractiveness, which, as highlighted by Norman [19], is a consequence of aesthetic quality that can function as a valuable attribute.

HFDOs’ basic operative concepts show that for a correct interaction between the user and a hands-free opening device, the device needs to allow the user to easily place the forearm in a vertical position behind the front part of the handle and pull (1). This way, the hands never touch the handle and remain clean and hygienic (2). The user rotates and moves away when the door opens, naturally releasing the arm (3). The ends of the handle must be rounded to prevent injuries (4). For the correct performance of these actions, the Americans with Disabilities Act (ADA) standards guide [20] states that the operable parts must be usable with one hand, must not require gripping, pinching, or twisting of the wrist, and must require no more than 22.3 N of force to operate.

The guiding principles of this project follow the premises of universal design that can be defined as strategies to create environments suitable for use by anyone, regardless of age, size, or capacity [21]. Universal design can be considered the practice of designing products or environments that can be used effectively and efficiently, both by people without limitations and by those who operate with functional limitations, for example, due to physical-motor handicaps [17]. In this sense, the design of the proposed system was developed to be attractive, easy to learn, and effective in being easily operated by the user. The project’s technical specifications involved two complementary domains, namely the scientific aspects presented in the previous point and the definition of technical requirements and performance variables. To identify technical specifications, visits were made to a number of Portuguese hospitals, duly accompanied by technicians from the maintenance sector, and it was concluded that the vast majority of doors were equipped with handles of the lever type with a circular profile or a blade profile. Complimentary visits were made to other locations with a high flow of people, such as shopping centers and public service institutions, emphasizing schools and banking entities, showing that the most commonly used handles were those with circular and square tubular sections. Based on these visits, oral discussions, questions, and answers from stakeholders and through the observation of existing equipment, the technical requirements and design were produced for a device with modular characteristics, which is easy to assemble, with a base for a lever handle with a circular profile (identified as being the predominant type) and with simple adaptation to other types of handles by changing the device’s accessories. The creation of this system device resulted from a continuous iterative process, reaching the following objectives:

- Creating a system appropriate for various handle geometries, ensuring its versatility;
- Manufacturing using an easy-to-clean material and geometry, enabling its decontamination;
- Guaranteeing fundamental characteristics/properties for intensive use, considering mechanical resistance, stiffness, and resistance to fatigue;
- Designing for intuitive use.

The research previously presented in the introductory section showed the existence of solutions on the market that, despite being partially effective, were not efficient. As static devices, without any dynamic component, they do not allow a continuous movement between the rotation of the door around its axis of connection to the wall and the passage of the user in front of it, who is obliged to remain behind it. Because of that, users often need to resort to the foot to immobilize the door and thus overcome it. This difficulty is mostly evident in doors with an automatic closing spring, present in most educational and health institutions.

Thus, the addition of dynamism to the device was considered, assuming that it would result in greater functional efficiency, aiming to help the user to understand the existence of the original handle, promoting the notion that this device is an auxiliary to the existing handle, helping in the perception of its correct use.

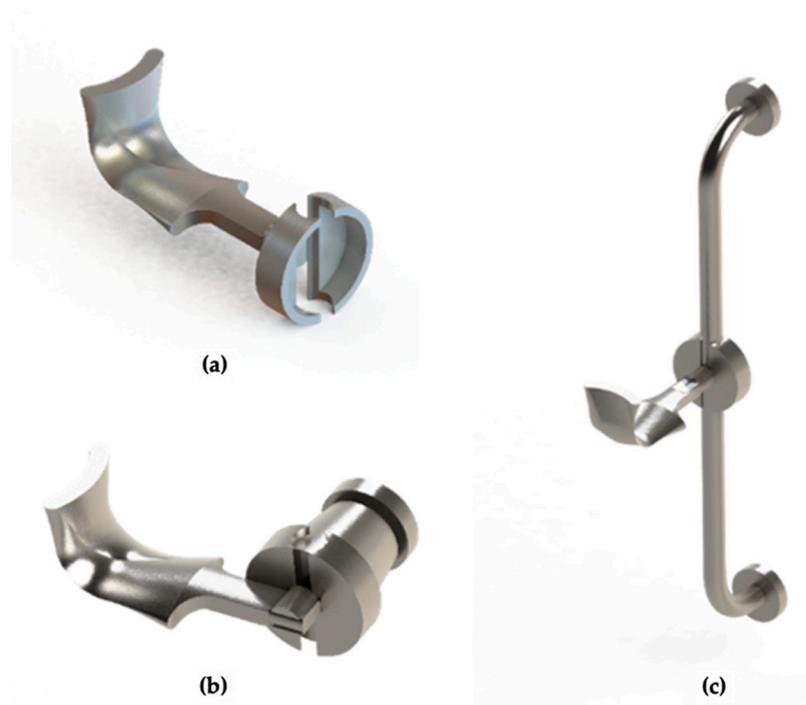
2.2. Geometrical Models—Description of the Project Evolution

The three-dimensional geometry of the models was created using modelling software (Solidworks® 2019, Dassault Systèmes SOLIDWORKS Corp., Waltham, MA, USA). Table 1 presents a summary of the Auxiliary Door Opening Device’s (ADOD) evolution. The description of the project’s evolution is described.

**Table 1.** The predisposition of the participants to the use of devices.

Model	Procedures and Implementation
ADOD-V1	The first approach to adapt to different geometries. Identification of improvements to be implemented in the leaf. Relevance to the implementation of the dynamism.
ADOD-V2	Development of a leaf with ergonomic language. Identification of improvements in the clamp system and dimensions. Definition of the L and D shapes as a priority to match the system.
ADOD-V3	The first approach to a dynamic component. Inclusion of a planar spring. Identification of the improvements in the leaf’s dimensions, the clamp system and the type of spring.
ADOD-V4	Implementation of a simple torsional spring. Addition of a simple clamp, allowing four positions of the leaf.
ADOD-V5	Addition of a second torsional spring to allow the rotation of the leaf in both directions.
ADOD-V6 ADOD-V7	Implementation of improvements in the clamp system with two components to allow its implementation in closed handles: tested with a planar spring (V6) and two torsional springs (V7).
ADOD-V8	Implementation of an angular discrete coupled system to allow different initial positions of the leaf (based on V7).
Final Model Dynamic	Implementation of a torsional spring with a double effect, allowing better performance and more compact geometry. Evolution of the geometry transition between the leaf and flat hinge components. Adjustments in the final dimensions of the components.
Final Model Static	Based on the same language of the dynamic model, but without the rotation component. A simplified version with the possibility of leaf position adjustments.

Based on the models mentioned above, the first geometric model resulted from an attempt to adapt to different handle geometries, namely cylindrical and “L” type shapes. Ergonomics was also considered, mainly in the contact region between the forearm and the device, to make the door opening experience as pleasant as possible. This prototype also tried to guide the user towards correct use, demonstrating that its geometry is intuitive to manipulate. Figure 2 illustrates the result of this first approach, purely technical and functional, designed as Auxiliary Door Opening Device, version 1 (ADOD-V1).



**Figure 2.** Auxiliary Door Opening Device—ADOD-V1: (a) 3D model; (b) representation of system coupled to a cylindrical handle; (c) representation of the system coupled to a D type handle.

The research previously presented in the introduction showed the existence of solutions on the market that, despite being partially effective, were not efficient, being static devices. Based on the identified difficulties associated with the static systems, the addition of dynamism to the device was considered as a project reference for development. Assuming that the dynamic component would result in greater functional efficiency, the next focus was to transmit to the prototype a language that would simultaneously translate the mentioned dynamism associated with ergonomics and integration in the door. In this context, it was hoped that the formal language would result in a simple and attractive piece without sharp edges, which would induce its correct form of use.

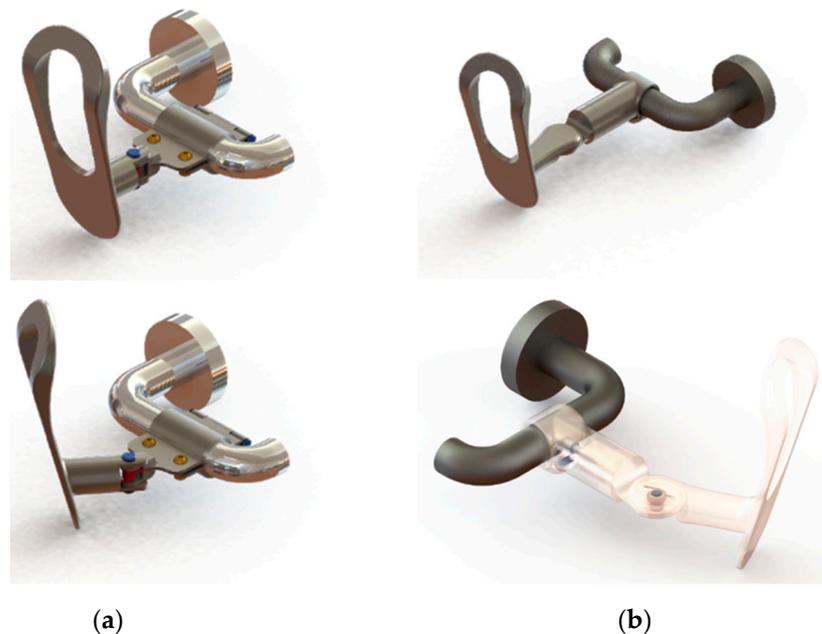
This piece, in its initial version, was a compact block of material. Still, for aesthetic, hygiene, and weight reasons (visually and physically), an opening in the vertical piece was designed, thus reducing the surface available for contamination. This opening was also intended to help the user understand the original handle's existence, promoting the notion that this device is an auxiliary to the existing handle, helping in the perception of its correct use. Figure 3 show this new language (ADOD-V2).

Although the device's compatibility with different door handles is a critical component, the identification of doors for which the product is intended mainly includes two types of handle: "L" and "D" shaped. This assumption, identified by the consortium, as described above, led to the development of a requirement to prioritize this type of handle. Thus, this project considers these two types of handles, resulting in a simpler geometry. At this stage, an approach to a mechanism for fixing the prototype to the handle has already been developed. The part was divided into two components, the fixation to the handle and the vertical element. This will allow greater versatility in future situations, since it will permit keeping the vertical component while only producing new fixing parts, according to the different existing handles' geometry.



**Figure 3.** Three-dimensional visualization of the ADOD-V2 system with a vertical leaf: (a) without opening; (b) with opening.

In addition, a spring was included in this model that would allow the dynamic component to be put into effect. Initially, we considered using a spring since it does not affect the product’s geometry in an evident way. Additionally, some dimensional adjustments were made to the height of the vertical element (leaf) so that the dynamic movement can be accompanied by a comfortable contact surface, with the arm or forearm, that effectively adapts to the dynamism of the opening movement. Figure 4a shows the first developments of the model ADOD-V3, including the dynamic component with a spring. The high number of components in the system for fixing the device to the handle is evident, in addition to the presence of holes and geometric details that could promote the accumulation of pathogens, so the next iteration considered the elimination of these critical areas. Thus, a further evolution of the model (Figure 4b) reveals a smaller number of components and a geometry that facilitates cleaning and decontamination and transmits a language of continuity between the vertical leaf and the connection to the handle. This language was achieved by replacing the spring with a torsion spring.



**Figure 4.** ADOD-V3 system: (a) simple version; (b) refined version.

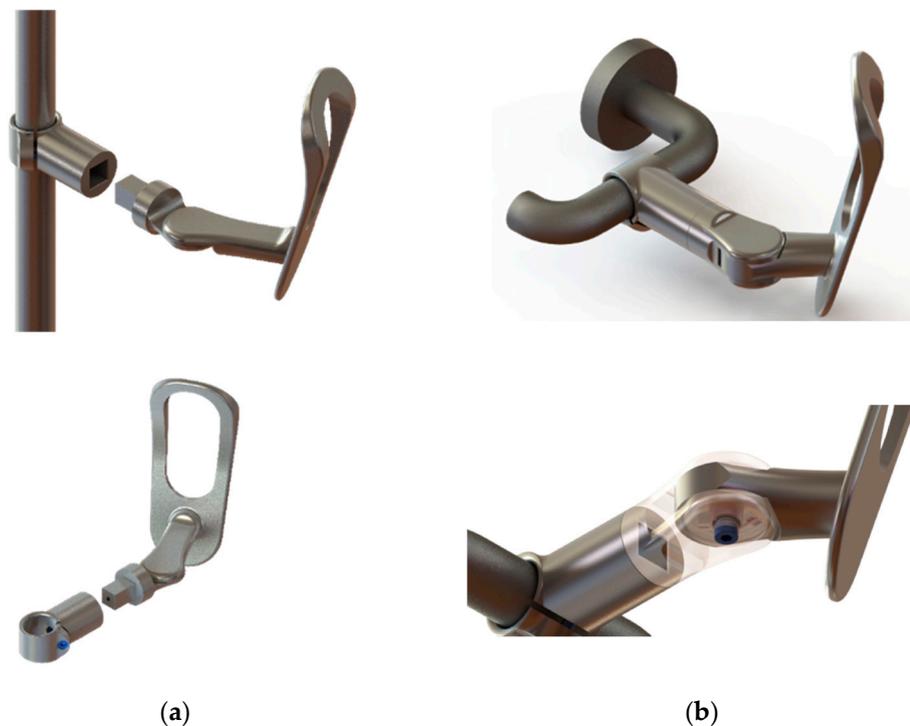
To guarantee the coupling to different types of handle geometry, an evolution of the system, with a simple clamp and a simple spring (ADOD-V4), was defined (Figure 5a). The previous model fulfils its function, but only if the rotation is carried out in one direction, as only a single torsion spring was applied, which only allows this type of movement.

In this way, a second torsion spring was added to increase the versatility of the device and make it possible to be mounted on any door, whatever the direction of its opening. This characteristic required geometric modifications that resulted in the ADOD-V5 model (Figure 5b). With a quadrangular connection, both systems provide four different positions, allowing them to be implemented on different handles.

This project is a typical example of how the creation of a product develops. Initial assumptions are considered that change or consolidate throughout the various iterations. Sometimes it is questioned whether all of the decisions and paths taken were the correct ones, and, in most cases, the solution to this type of challenge lies in simplicity. In this sense, the team decided to develop a model based on simplicity while maintaining the main requirements.

In previous models, the possibility of mounting on the “L” and “D” handles was an objective that was only partially fulfilled, since the geometry of the connection between the handle and the device only allowed for fixing on open handles, as is the case of the “L” handles. The “D” handles, being closed, do not allow the device to be anchored. Thus, the connection geometry was changed and now consists of two components that make it possible to mount the device on both “L” and “D” handles (Figure 6a,b).

These changes led to the realization that, although its functionality was not compromised, ergonomics and language coherence, considered as being important requirements in this project, were included. In this sense, there was a need to rethink the type of spring used, since the formal and dynamic component that characterizes the device is dependent on mechanical components that allow dynamism. The mechanical components that particularly allow the type of movement desired—that is, rotation after load application and subsequent return to the initial position—are the springs. For this reason, different geometric approaches were carried out, considering the diversity of solutions that the said mechanical component offers.



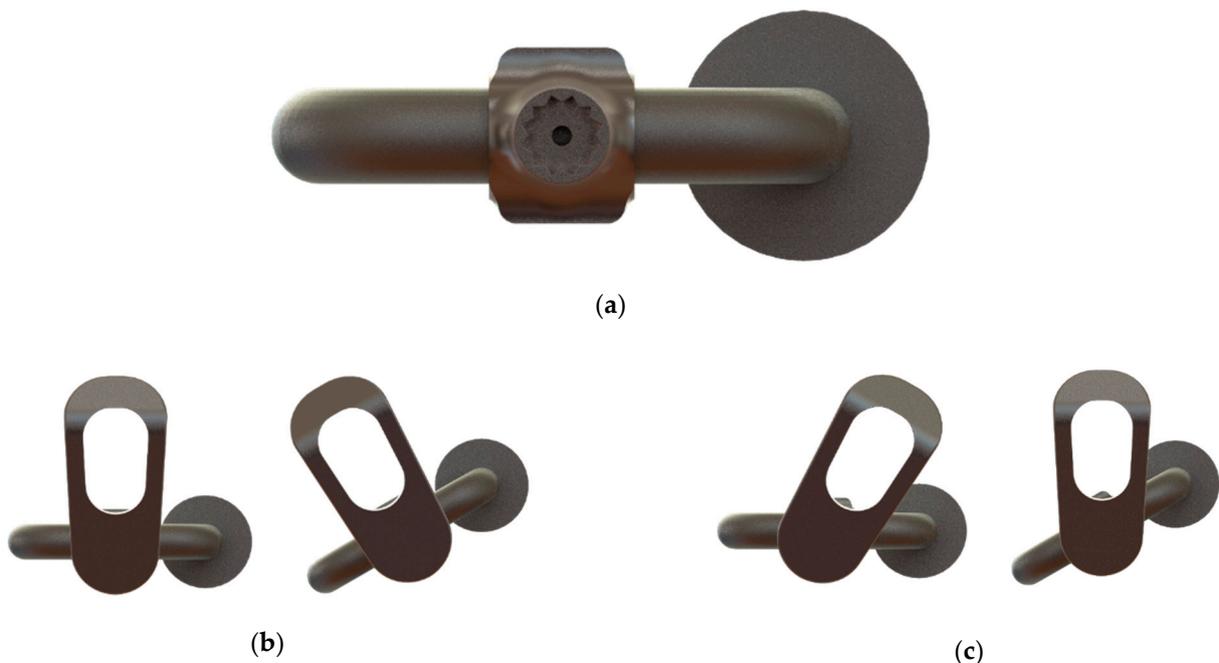
**Figure 5.** Three-dimensional visualization: (a) ADOD-V4 system with a simple clamp and spring; (b) ADOD-V5 system with a double clamp and a double spring.



**Figure 6.** Three-dimensional visualization: (a) ADOD-V6 system; (b) ADOD-V7 system.

At this stage, it was also considered essential to study the influence that two parameters could have on the functioning and performance of the device under development: the distance from the vertical component to the center of rotation of the prototype and the vertical dimensions of the forearm’s contact zone with the device. All of the evolutionary prototypes developed were also produced through additive manufacturing, using 3D printers, to observe preliminary functional tests, and these dimensions were adjusted based on experimental tests.

Through this functional analysis based on produced components, combined with the 3D modelling implemented, it was found that during the opening movement, the axis of rotation of the device was gradually tilting. This fact led us to implement a solution based on coupling with angular discretization ( $30^\circ$ ), as represented in Figure 7. The image on the left (Figure 7b) shows a vertical starting position of the leaf, with a final inclination. The image on the right (Figure 7c) shows an initial inclination position, leading to the final vertical position of the leaf.



**Figure 7.** Leaf positioning system: (a) angular discrete coupled system; (b) initial vertical position of the leaf with a final inclination; (c) inclination initial position of the leaf with a final vertical position.

As the different models were being developed, prototypes were produced to test several aspects of their functionality, such as ergonomics and design. Figure 8a shows an example of 3D prototyping, with a Prusa mk3s+ equipment, producing the mechanical components in polyethylene glycol terephthalate with carbon fiber (PETG-CF), a material with good mechanical properties. Figure 8b shows an example of a brass prototype produced with a CNC machine.

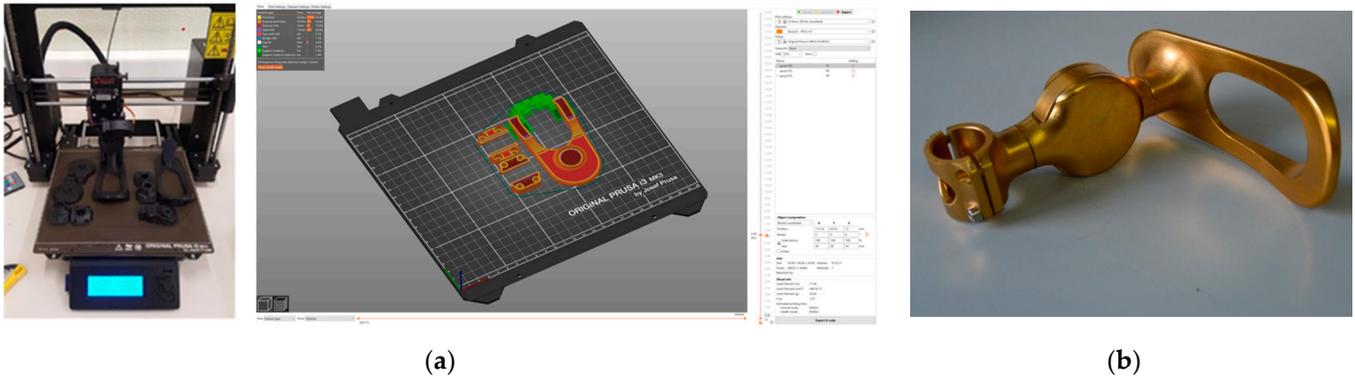


Figure 8. (a) Visualization of 3D printing in PETG-CF material; (b) brass prototype produced with CNC machining.

Adjusting 3D printing parameters is an essential procedure to obtain components with the desired precision and mechanical characteristics. After a process of adjustment and optimization, the parameters considered are presented in Table 2.

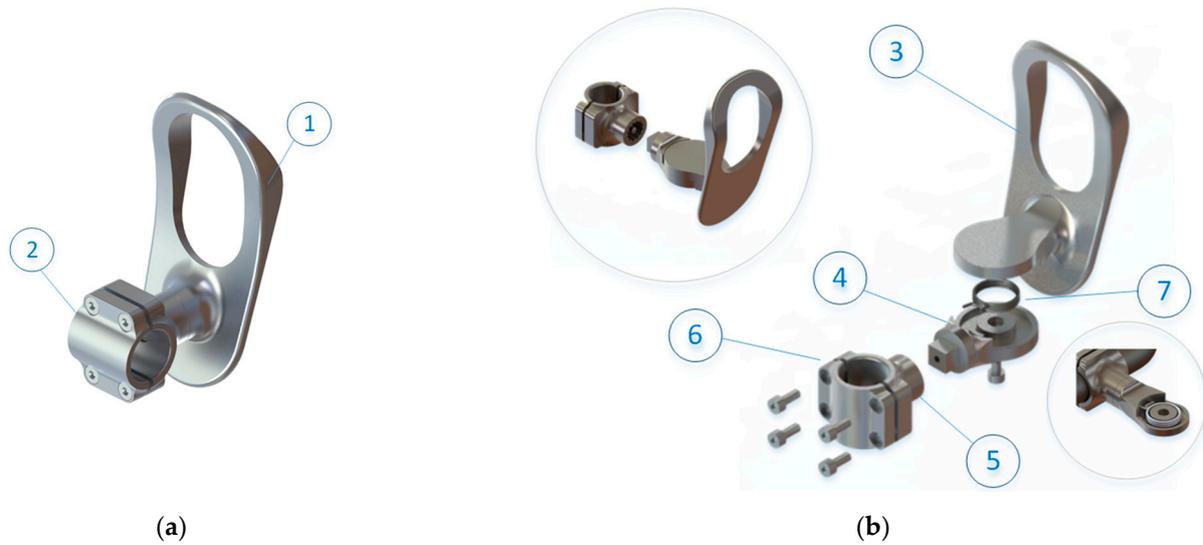
Table 2. Three-dimensional printing parameters used for printing with the PETG-CF.

Parameter	Units
Temperature	260 °C
Heated bed Temperature	90 °C
Layer Height	0.1 mm
Extrusion Width	0.5 mm
Number of Perimeters	4
Type of Filling	Gyroid
Filling Density	25%
Part Cooling	0%
Speed	45 mm/s

### 2.3. Final Models

For experimental validation and proof of concept, two final devices were defined, based on all sequential developments—one short-fixed (without dynamism) and the other dynamic (with dynamism).

Figure 9 presents a 3D visualization of the short-fixed device (Figure 9a), and the dynamic system represented with an exploded view (Figure 9b). The short-fixed system has two main components, a leaf (1) and a clamped system (2) with two components for leaf positioning. The main dimensions of this device are: L = 68 mm; W = 58 mm; H = 114 mm. The representation of the figure corresponds to a circular-type handle, but, as explained, this geometry can be prepared to fit other types of handle section. The dynamic system has four main structural components: the leaf with a geometric transition (3), the flat hinge component (4), the clamp system to match the handle (5, 6), and a torsional spring to allow the rotation of the leaf during the use. The main dimensions of the mounted device are: L = 92 mm; W = 58 mm; H = 114 mm. Figure 10 shows, as an example, the visualization of both systems clamped in a D-type handle.



**Figure 9.** Three-dimensional model visualization: (a) short-fixed system with a leaf (1) and a clamped system (2); (b) dynamic system with a leaf (3), a flat hinge component (4), a handle clamp system with two components (5,6) and a torsional spring (7).



**Figure 10.** Visualization of the systems clamped to a D-type handle: (a) short-fixed; (b) dynamic.

2.4. Material

The production of the final prototypes was performed using aluminum alloy 7075 T6 through CNC machining. This material was chosen for the devices due to its excellent mechanical properties, good ductility, high strength, toughness, good fatigue resistance, and the easiness of its machining. The mechanical properties of the alloy are presented in Table 3. With this material, the short-fixed prototype weighed 190 g and the dynamic prototype weighed 255 g.

**Table 3.** Mechanical properties of the aluminum alloy 7075 T6.

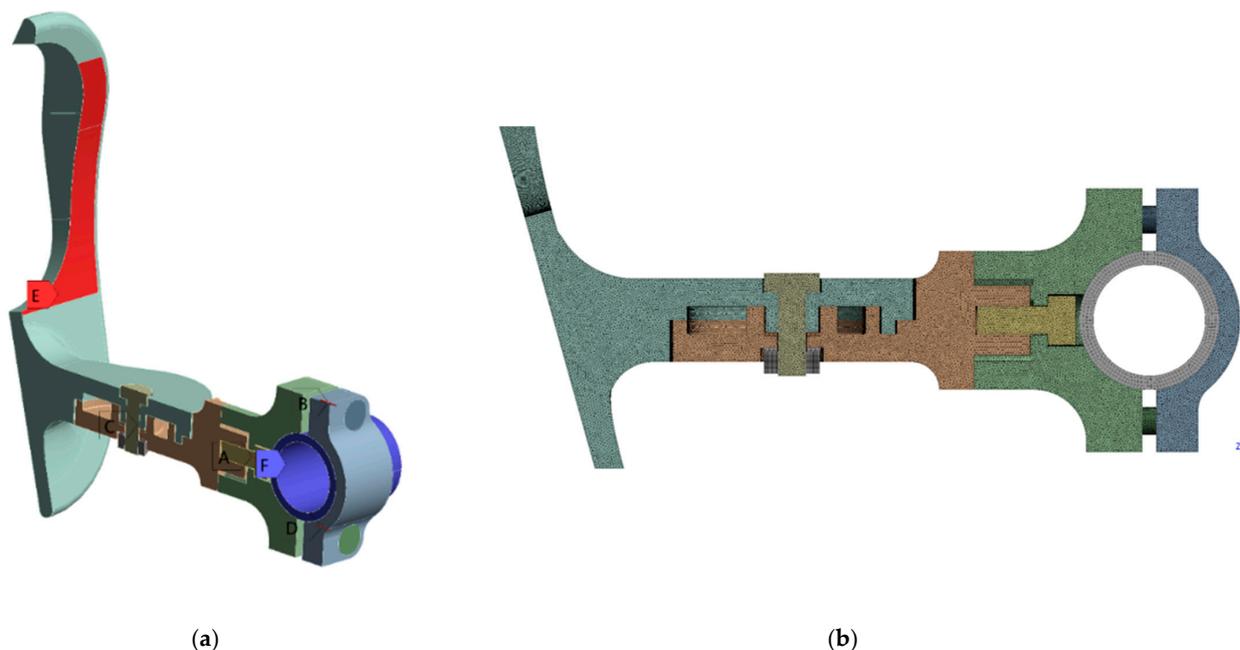
Property	
Young’s Modulus	71.70 GPa
Poisson’s Ratio	0.33
Yield Strength	503 MPa
Tensile Strength	572 MPa
Elongation at break	11%

### 2.5. Numerical Models

The models were numerically studied using Ansys® Mechanical, Release 2020 R2 for finite element analysis. The defined models for the studies assumed isotropic properties with a bilinear elastoplastic hardening for all of the components. The force condition was based on the standard EN 1906: 2012 for the handles, considering 200 N of force applied onto surface E, as represented in Figure 11, considering extreme use situations.

Only the finite element model for the dynamic system is presented, which corresponds to the worst case. The finite element model was defined with tetrahedral parabolic solid elements (Solid187 element from Ansys library), with 3 degrees of freedom per node, representing the translations in the three orthogonal directions. The model was considered when clamped onto a tubular L-type handle, and the boundary conditions assumed the restraint of all the nodes in the internal face of the handle. Considering the symmetry of the system and for computational purposes, only half of the model was considered, as shown in Figure 4. The contacts between components were modelled using a frictionless-type formulation. The bolt connections for clamping the components of the system and the system to the handle were virtually modelled considering the Bolt Pretension tool of the software, with 1000 N of force.

A mesh convergence study was performed, leading to 1,275,990 elements with a size of 0.2 mm.



**Figure 11.** Representation of the finite element model for the dynamic system: (a) E—surface for applied force; F—boundary surface; A—bolt connection between the components for; B—bolt connection for clamping the system to the handle; C—rotational pin; (b) visualization of the mesh.

### 2.6. Manufacturing

The manufacturing of the components was performed by means of MAS CNC machining (MAS MCV 800), and all the preparations were made with Mastercam software, 2019 version.

### 2.7. Usability Testing Protocol

A protocol with a set of usability tests was prepared to identify the results obtained with the developed system. Usability testing is a technique used in user-centered interaction design to evaluate a product by testing it on users. It provides direct input on how real

users use the system [22]. As a result of usability testing, a measure of a human-made product's capacity to meet its intended purpose will become available.

There are several scale usability scores (SUS) available. A SUS allows for evaluating a wide variety of products, becoming a reference in the industry [23]. These scale use a list of questions, and for each of them, a Likert scale is used to provide an answer. Some of the questions have a positive emphasis, while the others have a negative one. To analyze the results, a score must be created. An average score of 68 points, on a 0–100 scale, means there are no usability problems with the product.

The usability tests were performed within a university campus context (Polytechnic of Coimbra, School of Engineering) in a building with several equal doors and handles. Three doors were prepared with one of the different kinds of devices on each:

- Short-fixed, referred to as "A". The simplest device, without dynamic rotation and with a short distance to the handle;
- Long-fixed, referred to as "B". The same as dynamic, but with dynamic rotation blocked;
- Dynamic, referred to as "C". The developed device, with dynamic rotation to follow the arm.

The tests were performed for several days, and a total of 52 volunteers participated in the usability study. Before participation in the usability test, the volunteers were informed about the objectives and methodology and gave informed consent. As a criterion for inclusion in the sample, being a member of the university was the only criterion considered. As an exclusion criterion, the inability to perceive informed consent was considered. The protocol for usability tests with the volunteers was prepared to follow the Declaration of Helsinki and was approved by the Polytechnic of Coimbra Ethical Committee (Reference No. 110\_CEPC2/2020). The protocol involved opening 4 doors, and the volunteer had to open and transpose the door without using their hands, in a random order, following the intuition to use the system. One of the doors did not have any device clamped to the handle, and the other three doors each had one of the devices clamped onto it. All the doors opened to the same side. Figure 12 shows a volunteer opening the door "C", prepared with the dynamic system clamped onto the handle.

### 2.8. Experimental Tests

To identify the experimental behavior of the two models, dynamic and static, two sets of test equipment were developed and built, based on the NP EN 19106:2017 standard, also taking into account the numerical model. This standard is applicable to lever- and round-type handles, which activate locks and other devices, thus representing an experimental test solution for extreme conditions, given that these devices were designed to adapt to these types of handles. Although this new device does not completely fit into the scope of this standard, it was understood that these tests should be based on what is described therein.

Uniaxial traction (Figure 12a) and durability tests (Figure 12b, indicated by the standard) were chosen for implementation. This equipment can be visualized in Figure 12—(a) uniaxial traction and (b) durability.

For the uniaxial traction, 1000 N was applied and maintained for a few seconds. For durability, forces  $P = 50$  N and  $R = 10$  N were used. The motor, which generated the knob's rotational movement, was made to rotate at a frequency of one cycle every 2 s. The equipment was kept in continuous rotation for 111 h—that is, 4.5 days—to complete 200,000 processes. Five devices of each type were tested.

Figure 13 shows an example of the two models after the tests. On the left, in Figure 13a, the area where a very slight gap due to wear was identified can be observed. On the right, the static device can be seen without any identification of problems.

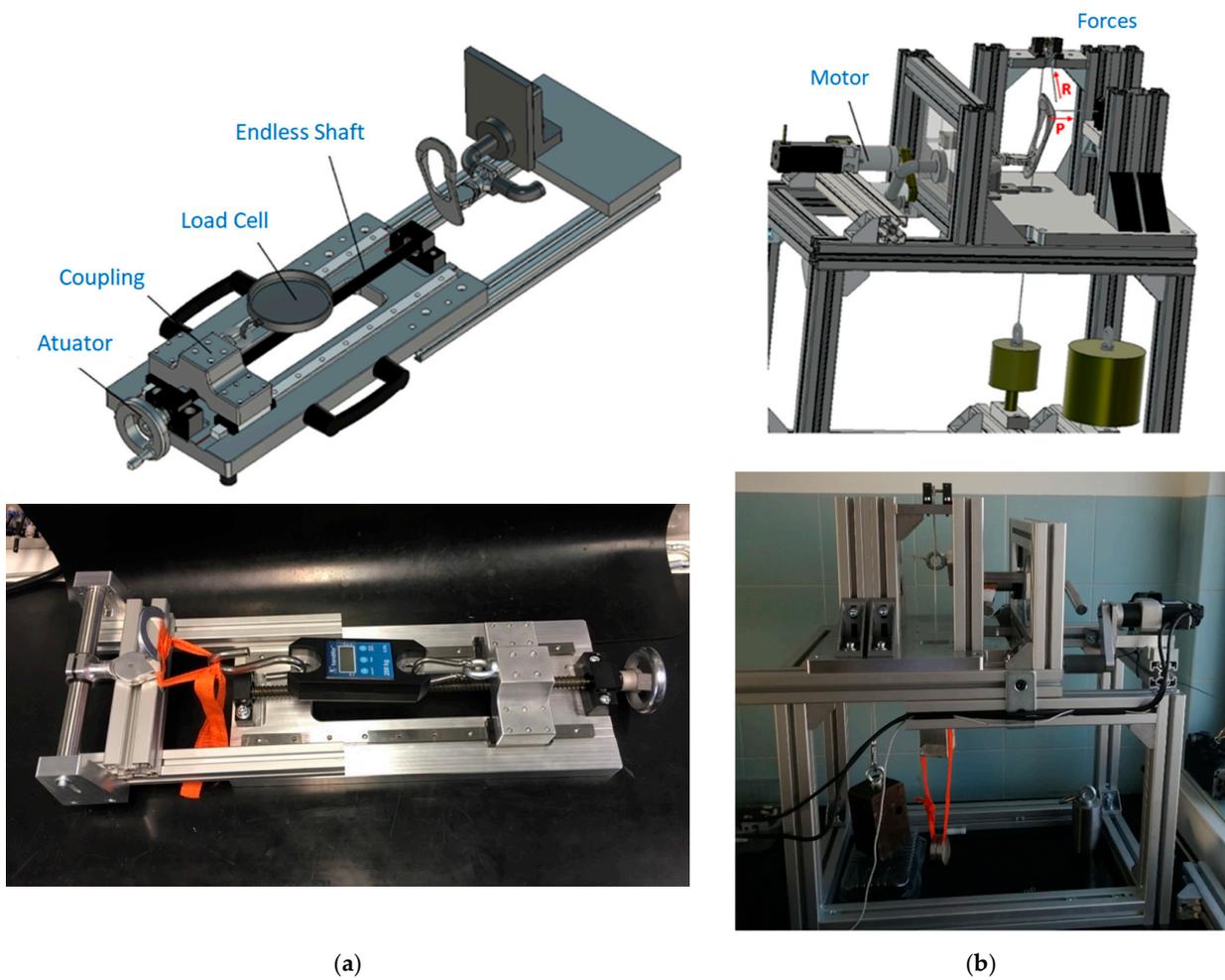


Figure 12. Equipment developed for experimental tests: (a) uniaxial traction; (b) durability.



Figure 13. Examples of the models after experimental tests: (a) dynamic Model; (b) static Model.

### 3. Results

#### 3.1. Numerical Results

The stress field obtained is presented in Figure 6. All the regions of the component show stress values lower than the yield strength of the material, demonstrating an adequate strength. Figure 14b shows the details of the bolts' connection, where peak stress is obtained corresponding to stress hotspots that arise due to geometric discontinuities. It should also be mentioned that the 200 N load applied corresponds to a limited case (for instance, in the case of an emergency), and that this load is significantly higher than the normal operating conditions of the door opening. Considering the rigidity of the system, a maximum value of 34.692 mm for the equivalent displacement was obtained (Figure 14a), which can be considered adequate for the force conditions of the model. A fatigue study (Figure 15b) was also performed, taking into account the results obtained with the static analysis and the S–N curve of the material [24]. This analysis shows that at least  $10^5$  cycles can be achieved for the considered conditions.

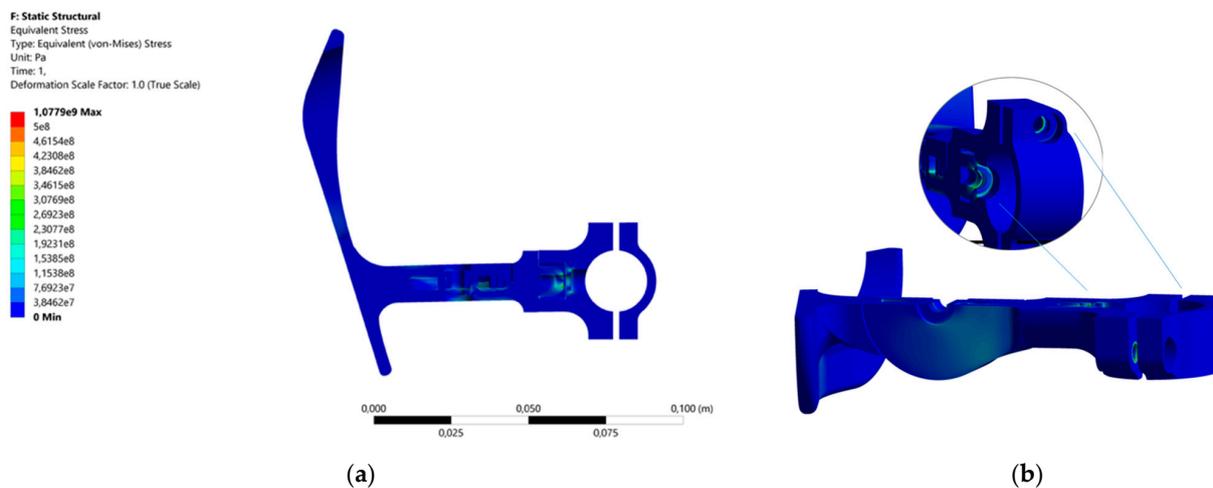


Figure 14. Representation of the results obtained with the finite element model: (a) Von Mises equivalent stress distribution; (b) Von Mises stress distribution with hotspot details due to geometric discontinuities of the model.

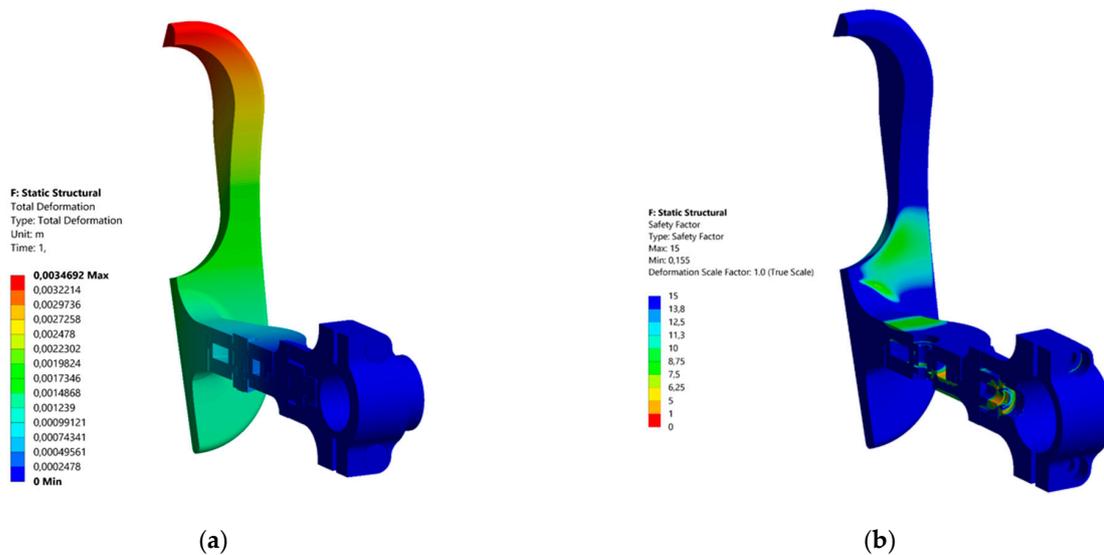


Figure 15. Representation of the results obtained with the finite element model: (a) visualization of the distribution of the total displacement; (b) visualization of the distribution of the fatigue safety factor for  $10^5$  cycles.

### 3.2. Usability Results

#### 3.2.1. Participants

A total of 52 volunteers were included in the study. Participants were randomly selected to participate, including 12 females and 40 males. As this test was performed at a university campus, 38 participants were students, 9 were teachers, and 5 were staff. Participants' ages ranged from 18 to 58 years old, with a mean age of 26.4 years and a standard deviation of 9.8 years.

Participants opened and transposed the four doors designated for the study, with the first one having no handle to serve as a reference (Figure 16). After performing this task, participants received the private link to access and answer the questionnaire, in which they expressed their agreement with the sentences in it. Answers were recorded for each of the three devices, enabling the calculation of the usability score concerning each device.



**Figure 16.** Dynamic system: (a) visualization of the system clamped in the handle and the hand position for opening; (b) sequence of opening performed by a volunteer.

#### 3.2.2. Habits/Easiness of Door Opening

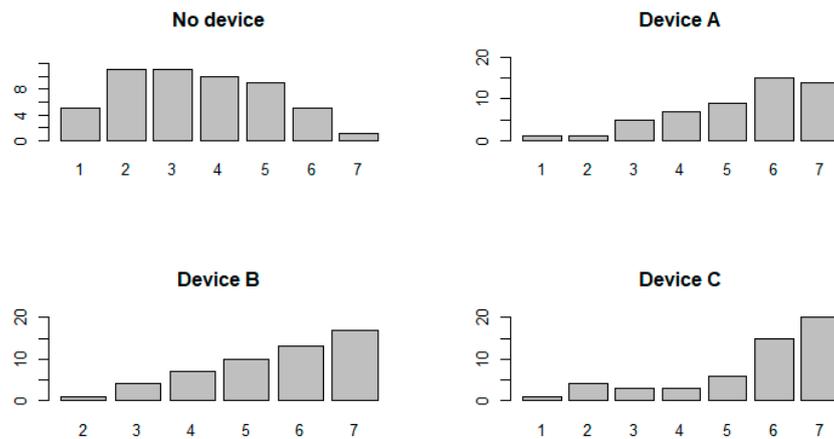
When participants were asked about their habits regarding door opening during the current SARS-COV-2 pandemic, 26 of them mentioned using their elbow/forearm, 21 mentioned using their hand, and four mentioned using their wrist.

Table 4 presents the answers about how often each participant would use each device. We observed that most participants are willing to use these devices, although the dynamic option (Device C) demonstrates more preferences in the Always option.

**Table 4.** The participants' predisposition towards the use of the devices (each cell indicates the number of participants choosing each level of the answer).

Device	Always	Frequently	Neutral	Rarely	Never
Short-Fixed (A)	21	23	4	2	2
Long-Fixed (B)	24	21	3	2	2
Dynamic (C)	25	21	2	2	2

The analysis of the questionnaire answer concerning the easiness of door opening shows that most participants found it more complex to open the door with no device. In contrast, most participants chose Device C as the device giving more support to opening the door without hand use. Figure 17 shows the results concerning the ease of use.



**Figure 17.** Distribution of the number of answers to each level in the Likert scale for the question about the easiness of door opening with no device or with devices A, B or C.

### 3.3. Statistical Results

Statistical analysis of the data was performed using the open-source software R version 4.0.3, together with R-Studio version 1.3.1093.

A usability comparison was performed, and the usability means index was determined for each of the three devices. The questionnaire used to run the usability test consisted of 12 questions, each of which allowing answers in a Likert scale with seven levels, ranging from strongly disagree (1) to strongly agree (7). Eight of these questions exhibited a positive emphasis, and the remaining four exhibited a negative emphasis.

For each question with a positive emphasis, the contribution to the final score was the value chosen in the Likert scale minus 1, while for the questions with a negative emphasis, the contribution to the final score was seven minus the value chosen in the Likert scale. To obtain a score ranging from 0 to 100, the final score in the usability test was multiplied by 1.388.

Overall, answers regarding device C collected the majority of preferences for questions with a positive emphasis compared with answers for devices A and B.

The usability means index was determined for each of the three devices. Device A presented a mean value of 80.16, while this value was 81.20 for device B and 81.33 for device C. The standard deviations were 12.00, 12.06 and 11.22, respectively, for devices A, B, and C (Table 2 and Figure 18). Each participant graded each device with a score larger than the reference value of 68 for the usability score, reflecting the absence of usability problems.

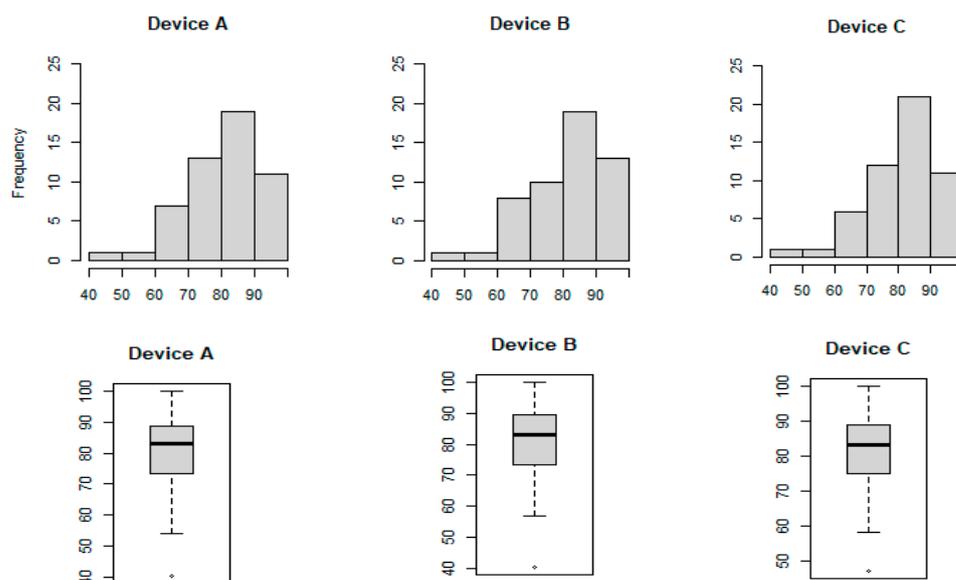
The Shapiro–Wilk test for the normality of index distributions returned *p*-values of 0.0288, 0.02216 and 0.04482, respectively, for devices A, B, and C, allowing us to not reject the assumption of normality for a significance level of  $\alpha = 0.01$ .

Bartlett’s test for homogeneity of variances presented a value of 0.8503. With the same level of significance, distributions were assumed to have equal variances.

Although no statistically significant differences in means we observed (ANOVA test to compare means presented a *p*-value of 0.856 (Table 5)), it was device C, the dynamic one, that exhibited the largest mean index.

**Table 5.** One-way ANOVA table for comparison of mean indexes.

Source	Degrees of Freedom	Sum Sq.	Mean Sq.	F Value	<i>p</i> -Value
Device	2	43	21.5	0.155	0.856
Residuals	153	21.171	138.4		



**Figure 18.** Histograms (top row) and boxplots (bottom row) of usability indexes—devices A, B, and C.

### 3.4. Experimental Results

The results of the uniaxial traction show that none of the tested models feature any deformation and abnormality.

Regarding the durability tests, after the stipulated load cycles, the devices were removed and observed. In the case of the static model, no anomalies or deformation were observed. In the dynamic model, a slight slack was observed without compromising the system's proper functioning.

## 4. Discussion

The impact of COVID-19 in day-to-day life has raised the sensation of insecurity in the population, but simultaneously has made people much more open to trying and adopting solutions that can mitigate the spread of the virus.

Through this study, it was possible to realize that even without HFDO devices applied to normal doors, many people already try to develop strategies by using the forearm or elbow so as not to touch the handle with their hand.

The results show that the static devices, without any dynamic component, are less appreciated by users, precisely because the ergonomic comfort of the movement to operate the door is not fluid and requires elaborate body movements. In the questionnaire used to find the usability score, the Cronbach's alpha concerning the questions related to the devices was 0.743, revealing an acceptable internal consistency. Additionally, the mean usability score for each device was larger than 68, meaning that participants found no problem with usability with the proposed devices. The results also suggest that universal dimensions, proper contact surface, aesthetics, ergonomics, and affordances, defined as the quality of an object that allows the user to identify its functionality without previous explanation [18], were the main characteristics that contributed to the success of this product.

In this sense, this study aimed to find new strategies that help in the interaction and ergonomics between users and HFDO. The developed dynamic HFDO adopts ergonomics, considered a major aspect of product design, mainly through the dynamic approach and suitable shape for adequate interaction with the human body, making the door opening experience as pleasant as possible.

In this context, the formal language of HFDO results in a simple and attractive piece without sharp edges. An opening in the vertical piece was designed to reduce weight, the

surface available for contamination by the virus, and adding aesthetic value, hygiene, and visual and physical lightness.

This hole was also intended to help the user to understand the existence of the original handle, promoting the notion that this device is auxiliary and, at the same time, allowing the perception of its correct use.

The experimental results obtained from the tests carried out show that the devices have a high structural strength and performance level, even with the introduction of a double-effect spring.

From the perspective of scale economy, the system presented was divided into two components—the fixation to the handle and the vertical element. This solution will allow greater versatility in future situations, since it will permit keeping the vertical component while only producing new fixing parts, according to the different geometries of existing handles. This is one of the differences from existing products manufactured as a single piece or, at least, without the possibility of adapting one of the parts to different diameters and geometries without manufacturing a new HFDO. Another differentiating factor is the incorporation of dynamics in a piece that, instead of fixing directly to the door, fixes to the existing handle, generating potential economic gains, since it will be possible to mitigate the transmission of the virus without having to replace the original handles on existing doors.

From the beginning of this study, the working premise was to develop a product that could be CNC machined. This constraint, which determined the development of the project and its final result, namely the prototypes, is directly related to the technical capabilities of one of the partners promoting the project. This option influenced the production cost of the final system, as one of its present limitations, with all the mechanical components produced with CNC machining. However, other economic manufacturing processes can be considered for the implementation of the product on the market, for example, through casting moulds with subsequent finishing. This will be a work to be taken into account shortly, in the implementation phase of the device on the market.

## 5. Conclusions

In the present work, an innovative device that allows for opening doors without using one's hands was proposed. The system allows dynamic movement that provides higher comfort to the user when opening doors.

This device was designed for various handle geometries, using an easy-to-clean material that enables its correct decontamination. The geometric aspects do not affect its hygiene and guarantee the design for intuitive use. They also ensure intensive use, mechanical resistance, stiffness, and fatigue resistance.

This solution will also contribute to improving the accessibility of handles to individuals with limited joint mobility of the hands (neurological patients, trauma sequelae, etc.) or those with occupied upper limbs who have various difficulties in opening doors.

In the future, the team intends to develop a system connected to the handle, which would enable opening the door with a pedal. Designed in harmony with the characteristics of the already developed handle, it should form a homogeneous set. In addition, it is envisaged to create fasteners for different handle geometries, thereby extending the scope of application of this project.

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**Institutional Review Board Statement:** The usability test study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Ethics Committee of POLYTECHNIC OF COIMBRA (Reference No. 110\_CEPC2/2020, 11 December 2020).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study of usability.

**Data Availability Statement:** Not applicable.

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