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Development of a Mechanisms Kit for hands-on learning for Mechanical Design Engineering Courses

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Abstract—*This work introduces an easy-to-fabricate, versatile, and affordable mechanisms kit developed as complementary material for mechanical engineering courses. This kit allows easy physical assembly of different mechanisms that enable deeper comprehension of mechanical concepts, validation of results, and easy visualization of mechanisms through an iterative, exploratory, and reflective process. The kit contains an acrylic base with perforations, acrylic and 3D printed mechanical components, M3 screws, and measuring elements. Its design is based on the hands-on learning approach proposed by constructivist Jean Piaget and principles of the didactic materials introduced by Maria Montessori. The article presents a detailed description of the kit and implementation examples.*

Keywords—*learning kit, mechanisms, rapid prototyping, hands-on learning, educational innovation.*

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***Abstract*—This work introduces an easy-to-fabricate, versatile, and affordable mechanisms kit developed as complementary material for mechanical engineering courses. This kit allows easy physical assembly of different mechanisms that enable deeper comprehension of mechanical concepts, validation of results, and easy visualization of mechanisms through an iterative, exploratory, and reflective process. The kit contains an acrylic base with perforations, acrylic and 3D printed mechanical components, M3 screws, and measuring elements. Its design is based on the hands-on learning approach proposed by constructivist Jean Piaget and principles of the didactic materials introduced by Maria Montessori. The article presents a detailed description of the kit and implementation examples.**

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I. Introduction

The new challenges in mechanical engineering practice demand a continuous evolution in the learning methods for higher education. Traditionally, engineering education has taken an analytical approach. The aim of the Mechanisms Design courses is that the learner gains an understanding of the motion of mechanical devices, visualizing relationships between components and accurately predicting their behavior. Lectures are the standard way to introduce mechanical concepts to present theoretical problems and the analytical approaches to solve them later.

Simultaneously, students use software to design and conduct simulation experiments that can provide information to analyze different mechanisms. However, during lectures, or labs with software, students hardly experience the mechanical behavior of the issues given to them, which separates the theory from understanding how mechanisms work. In addition, the problems are presented on a board or screen, using bi-dimensional diagrams or images, which can be challenging to visualize and understand the motion of three-dimensional objects.

Universities and professors are actively exploring innovative teaching techniques to equip students with the necessary skills to become highly qualified professionals and navigate a complex and ever-changing world. With this purpose, methods as gamification [2,3], use of mobiles in the classroom (i.e., augmented reality) [4,5], Capstone and Project-based learning [6], use of remote and virtual laboratories [7], activities at hands-on environments (i.e., Makerspaces) [8], among others, have been applied in Mechanical Engineering Courses to produce improvements in the learning outcomes. Many of these hands-on techniques and methods require specialized equipment or software with limited specific content, while others entail extended hours of class preparation, and its use applies for a single mechanism design. Nevertheless, these approaches share a common positive aspect: they offer students an active role in the learning process, which is the defining feature of Experiential Learning. Experiential Learning methods in which students actively participate in hands-on activities have been demonstrated to be effective for better understanding technical concepts and acquiring high order thinking skills [9], helping develop non-technical skills such as critical thinking, communication skills, problem-solving, and team building [10], and increasing motivation [11,12].

To address these challenges, we have developed an

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affordable and versatile physical kit to complement the learning process in the classroom. This kit enables students to experience mechanical phenomena using components such as bars, gears, cams, screws, spacers, bearings, and measurement elements. The parts are easily assembled to visualize the mechanism and rapidly understand how different arrangements behave. By comparing the physical mechanism constructed with the kit from the analytical results, students are expected to think deeply about the theoretical formulas of mechanism analysis and use the kit as a tool for mechanism synthesis. Examples of the benefits of having the opportunity to experiment with a physical kit are that the student can understand first-hand the restrictions in movement that a mechanism can have or that not all the combinations in the length of the links can allow its assembly. This work is based on the hands-on learning approach considered in the constructivist theory introduced by Jean Piaget and the didactic materials developed by Maria Montessori. The implementation used the intervention model.

In the initial section of this paper, we present the research literature focused on concepts of hands-on learning, as well as the utilization of learning materials. We then emphasize the importance of employing this type of material in mechanical courses and proceed to detail the design process and development of the kit components, providing and explanation of its practical utilization. We briefly compare similar kits available in academia or commercially. Lastly, we propose an implementation scheme and two examples that highlight the potential classroom application of the kit. In conclusion, we acknowledge how the application of this kit fosters the student's motivation, sense of achievement and better understanding of mechanical concepts. We finally discuss areas of improvement and future work.

II. Research Literature

Recognizing the need for supplementary material to enhance the understanding of mechanisms in the classroom, this work considers the fundaments of constructivist learning for creating hands-on environments, merged with the principles of the Montessori method to design a physical kit for auto-learning, understanding mechanical concepts, and pursuing engagement.

A. Hands-on learning

Constructivism is a learning theory that proposes that knowledge results from reflection and gradual building within the brain [13]. Piaget suggests that individuals must build their knowledge. When new information is presented, it is compared with past experiences or previously acquired data, either adjusting the previous beliefs or reassuring that the once-constructed knowledge is correct [14]. To address the constructivist method Piaget's theory *encourages* the "learning-by-doing" approach suggesting that involvement is critical in the learning process. This approach includes 'hands-on' interactions with objects rather than transmitting information alone.

The experiential learning theory introduced by David Kolb suggests that knowledge is created through experience transformation [15]. According to Kolb, through experiential learning, students can reflect on their experiences and integrate their observations into logical concepts that will then be used to solve problems [16]. According to Kolb, effective learning requires to engage in a cyclical process of learning and reflection, organized in four stages:

A. Concrete learning experience based on observation.

B. Reflection.

C. Abstract conceptualization of the situation and information.

D. Application of the learned concepts by active experimentation.

Another author who emphasized the importance of experiential learning is Carl Rogers. He believed that learning is a process of personal growth and development that occurs through direct, first-hand experience, by creating a learning environment that encourages learners to engage in self-directed exploration and discovery through real-life situations [17]. Other authors, such as Colin B. & Wilson J., created a handbook that deepens this theory and explains how it can be applied in the classroom [18].

B. Learning Materials and Kits

Montessori is a method of education based on auto-directed activity, hands-on learning, and collaborative work. Dr. Maria Montessori insisted that the professor should not intervene in the student's work to allow them to learn at their own pace and interest [19]. To support her method, Montessori developed a collection of manipulable objects designed to self-learn different concepts, including science and mathematics [20]. This work considers ideas for creating learning materials based on the Montessori Method, such as the control of error, isolation of concepts, structure and order, and the principles recommended for a fundamental lesson.

Introducing new material to the child is called the Fundamental Lesson, defined as a determinate impression of contact with the external world [21]. Montessori suggested that materials should be presented orderly and straightforwardly, focusing on introducing one topic at a time. In addition, the materials are designed to allow error control so that the student receives instant feedback on his progress. Working with self-correcting resources helps students notice, understand, adjust, and learn from mistakes rapidly and intuitively [22].

Other authors acknowledged the importance of using tools that allow iteration. Resnick et al. argue that designing interactive tools enhances the user's cognitive process [23]. Petrich et al. proposed that having an artifact that motivates the process of iteration pushes the student to find and solve a problem bringing participants into close contact with the moment and connecting new learning with previous knowledge [24]. On their part, Morris and McCarthy developed a range or learning materials such as games, simulations and other interactive tools that support the four stages of her learning model called 4MAT (experiencing, processing, generalizing, and applying). These tools promote hands-on experiences that allow iteration, making mistakes and correcting errors as part of the learning process [25].

III. Materials and Methods

One of the key learning outcomes in mechanical engineering is the ability to solve complex engineering problems by applying scientific principles. Developing this type of competence requires understanding and applying math and physics principles to study machines' motion while emphasizing the application of kinematic theories to real-world problems [24].

A. Courses in Analysis and Design of Mechanisms

A mechanism is a device where joints link an interaction of rigid parts to transmit, control, constrain, or translate motion from one component to another. Mechanisms can be used as a stand-alone solution or combined with other mechanisms or elements into a machine that can achieve a specific function.

Courses on mechanisms commonly cover kinematic analysis, which involves studying position, velocity, and acceleration. Four bar linkages, slider cranks, cams, gears, and other typical mechanisms are examined. Courses combine analytical and simulation experiments that can help students develop design skills.

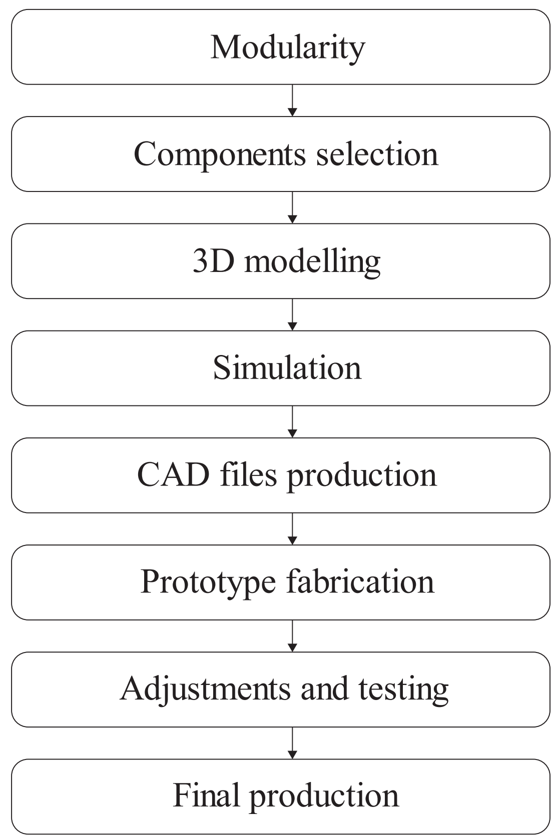

Fig. 1 Design Process of the Mechanisms Kit

B. Courses in Analysis and Design of Mechanisms

A mechanism is a device where joints link an interaction of rigid parts to transmit, control, constrain, or translate motion from one component to another. Mechanisms can be used as a stand-alone solution or combined with other mechanisms or elements into a machine that can achieve a specific function.

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C. Design of a mechanism Kit

Equipment available in the market is used for practical lessons in mechanisms courses. For instance, TecEquipment [26], PA Hilton [27], and Edibon [28] afford manipulation of the components to experiment with mechanical assembly. However, these products are either too specialized, expensive, or inaccessible.

In recent publications, researchers have put forth the idea of utilizing kits for hands-on learning. For instance, Arimoto, K. et al introduced and experiential-learning based kit to facilitate the observation of the buckling phenomena in slender elements [29]. Li, S. et al created a reconfigurable compliant kit consisting of flexure beams and rigid plates to teach the concept of freedom and constrains in compliant mechanisms [30]. In a similar vein, Limaye et al. proposed a kit for compliant mechanism design involving rigid connectors with flexible beams [31]. Furthermore, Morimoto et al. provided a kit comprising pre-manufactured components, craft materials, electronics, and tools for mechanism construction. The DIY kit was distributed to first-undergraduate students during the pandemic [32].

Although these kits demonstrate valuable contribution towards understanding specific mechanical concepts, they present challenges when it comes to replication and widespread use. On its part, Morimoto's kit requires students to manually construct most of the parts, resulting in significant time consumption for testing an individual mechanism.

Given the lack of attainable alternatives, an easy-to-fabricate, versatile, affordable mechanism Kit was developed. The Mechanism Kit facilitates the rapid construction of mechanisms, enabling the modification of parameters and the comparison of mechanical behavior in an intuitive manner. The design process (Fig. 1) began by determining the modularity of the base or working area, which defined the grid's size, shape, and position. We then decided on using commercial screws as pin joints due to their simple assembly and accessibility. The next step was to select, and 3D model a range of standard mechanical components that fit the dimensions of the base and screws. Simulations of the components were run in the software SOLIDWORKS® 2021 (Dassault Syst`emes, V`elizy, France) to verify assemblies. Then, fabrication files were generated for laser cutting and 3D printing. Two prototypes made of MDF were fabricated to ensure the kit was functional and met the design requirements. The final kit is described here:

This kit consists of 25cm. by 25cm. base made of 3mm. transparent cast acrylic (Acrylite®), graduated through laser engraving in both axes at each centimeter. A slot to insert acrylic legs and elevate the base is close to each corner. It has circular perforations and slots in strategic positions to place different mechanical components, such as bars of different lengths, cams, gears, and flexure hinges. These parts are made of solid color acrylic and also contain perforations. In addition, the kit includes acrylic spacers, a bearing, M3 screws of different lengths, bolts, and other graduated and labeled elements to measure position and displacement. All parts were fabricated in an STM-L1390 CO2 CNC laser cutter, except for the flexure hinges manufactured in eSun® 2.85mm. Polylactid Acid (PLA) filament using an Ultimaker 2 Fused Deposition Modeling (FDM) 3D printer. Figure 2 shows all the components of the Mechanisms Kit.

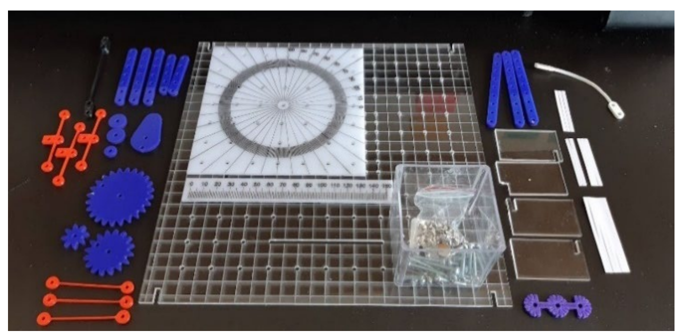


Fig. 2. Image of all the components of the Mechanisms Kit

As shown in Figure 3, the components are joined with commercial M3 screws that act as pivots of the mechanisms. The spacers determine the position of the components in the *Z* axis to avoid collisions with the bolts. Figure 4 shows different types of assemblies that can be tested using the kit. The Fabrication files of the board, components and, measuring elements can be found in the

Supplementary Material Section at the end of the manuscript.

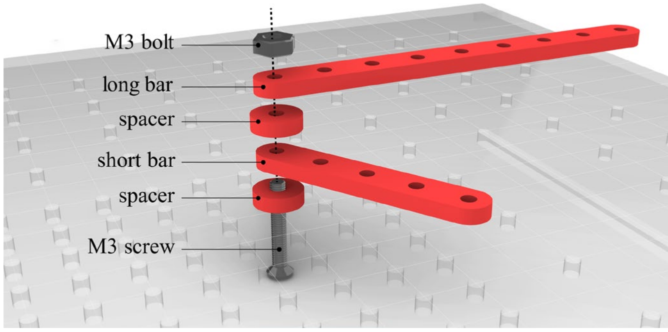


Fig. 3. Diagram of the assembly of components through a M3 screw.

The method used for implementing the mechanisms kit in the classroom is similar to what Resnik and Rosebum describe as *Tinkerability*: a compelling work style characterized by an exploratory, iterative style of engaging with a problem [33]. This way, the student goes back and forth between the kit and the analytical approach, configuring mechanical assembly components to investigate their behavior through reflective conversation. An example of this process is described in the following section.

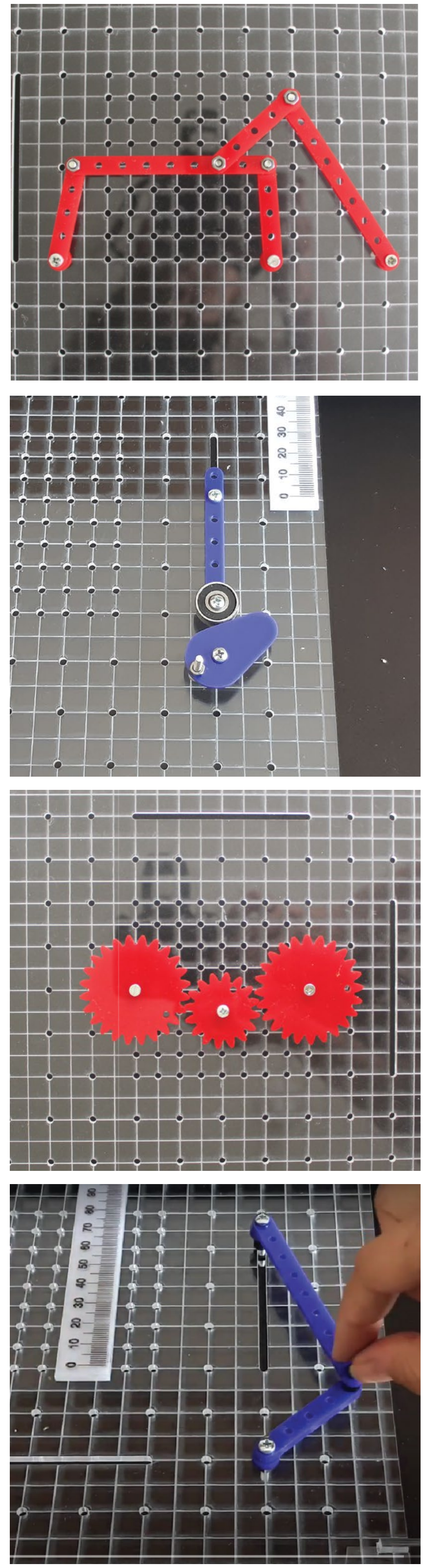
IV. Implementation Example

This project intends to provide students and faculty with a complementary tool for mechanisms learning. This Kit is designed to facilitate the assembly of mechanisms intuitively and fast, allowing to experiment with their functionality. Although the Kit is designed to be used individually or in a small group in auto-directed activities, the professor's guidance becomes a key element to guarantee success in the classroom. The professor should lead the conversation to promote reflection, analysis, and the introduction of mechanical concepts of different levels of complexity. Before using the Mechanisms Kit, it is suggested to spare time for the students to familiarize themselves with the materials. A proposed scheme for practice using the Kit is presented below:

1. Solve a problem analytically on the board.

2. Provide a kit for a small group of students and ask them to replicate the mechanism.

3. Ask them to verify the results (promote observation, analysis, and reflection).



(a)

(b)

(c)

(d)

Fig. 4. Different mechanisms can be constructed with the kit. (a) Six-bar linkage mechanisms. (b) Cam and follower mechanism with a bearing. (c) Slider-crank mechanism. (d) Gear system.

4. Open the discussion of how the behavior of the mechanism could change if some parameters are changed.

5. Integrate exploratory activity with the theoretical concept (for example, ask what kind of application the mechanism could have or how the mechanism could be powered).

Once the learners have developed a solid understanding of the mechanical concepts, together with the professor they will look for opportunities to apply the learnt concepts in new context or, more complex systems.

Given that validation test of the kits with students are in process, quantitative results are not available at this stage. Nevertheless, here we provide two implementation examples for teaching fundamental concepts in mechanical design. These examples serve to provide insights into the practical application and pedagogical value of the kit, offering a glimpse into its potential effectiveness in the educational context.

A. Grashof Law

The first example addresses the *Grashof Law*, an essential concept in four-bar mechanisms, which states that, for a planar four-bar linkage system to move, *the sum of the shortest (s) and longest (l) link lengths cannot be greater than the sum of the* other two link lengths ($s + l \leq p + q$) [34]. The mechanisms kit is an excellent tool for introducing this theorem. The students can rapidly construct a four-bar mechanism because it has links of different lengths with perforations at other positions. Following the control of error strategy introduced by Montessori, the students can change the length of the links by replacing the bar with a longer or shorter one or by joining two links at different positions defined by the perforations as many times as they consider necessary. This exercise initiates the understanding that modifying local parameters impacts the whole movement. By manipulating the components and exploring different combinations, they learn, for example, that if $s + l > p + q$, no continuous relative motion is possible, and no link will make a complete revolution relative to another. Then, the student can use the 360 degrees protractor to measure the rotational movement of a chosen link to introduce the new concept of position analysis. Figure 5 shows different four-bar mechanism configurations. In all examples, the protractor measures the angular displacement of the crank.

B. Range for a slider-crank mechanism

The second example is the study of the traditional slider-crank mechanism, which converts rotational motion into linear motion. Its analysis includes determining the initial and final position of the slider to obtain its stroke (the maximum linear distance the slider may travel between the two points). As most engineering students arrive with good mathematical skills, they can do a position analysis of a given mechanism using trigonometry. Then, they can use the kit to build the slider-crack mechanism. First, exploring the physical mechanism lets them clearly visualize the abstract diagram presented in the problem, and then it helps them validate their results. As the constructivist method suggests, a new concept can be introduced as they explore the mechanism behavior with the kit. The professor can encourage the students to find a relationship between the length of the crank arm and the slider stroke to introduce the analytical approach, which states that the stroke ($(\Delta R_4)_{max}$) is twice the length of the crank arm (L_2). This relationship is represented as $L_2 = (\Delta R_4)_{max} \div 2.$ and can be easily understood with the mechanism kit by measuring the slider displacement given by a certain crank arm length.

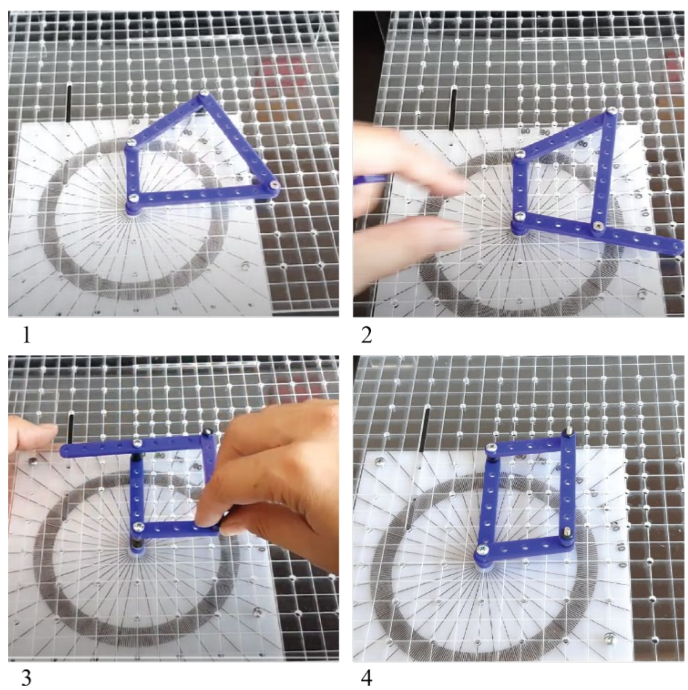


Fig. 5. Different four-bar mechanisms to explore the Grashof Law.

Further exploration will bring a deeper understanding of the mechanism's behavior. For example, if the students change the position of the crank to the sides, they will discover that the relationship is only valid when the crank and the slider are aligned. Figures 6a and b show the in-line slider-crank mechanisms with two different crank lengths by moving the position of the pin joint through the perforations of the bar. The total stroke changes according to the length.

V. Conclusions

This project aims to provide a hands-on kit to complement the learning of mechanisms in engineering courses. The kit allows exploring multiple mechanism topologies quickly and intuitively to motivate self-learning and improve comprehension of mechanical concepts. The correct application of this kit can foster the student's motivation and sense of achievement. Feedback from test users shows that this kit is a helpful tool that assists students in understanding the motion and behavior of mechanisms.

The kit has certain limitations that need to be addressed. Firstly, the length of the components and joint position are restricted by the location of the perforations which imposes limitations on the construction of mechanisms with specific lineal and angular dimensions. Additionally, an area of improvement lies in replacing the commercial M3 screws with snapping pivot elements to mitigate variations in friction caused by the pressure exerted on the bolts during screwing. Besides addressing these improvements, the following step in this study is to validate the equipment through a pilot test on a reduced number of lab practices with students. Future work includes integrating components for measuring and visualization, such as a digital scale, sensors, and a digital display.

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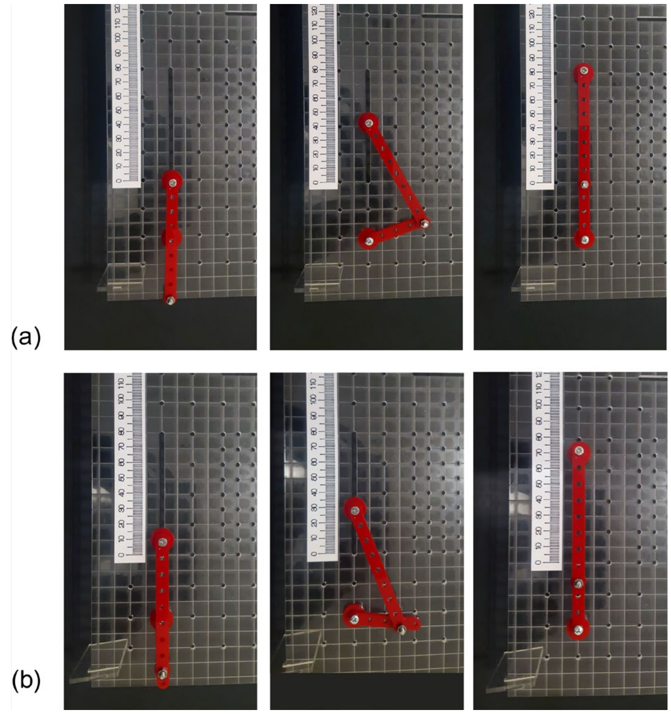

Fig. 6. Explorations of the in-line crank–slider mechanisms. (a) A 4cm. crank bar length displaces 8cm. (b) A 2cm. crank bar length displaces 4cm.

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SUPPLEMENTARY MATERIAL

DWG files for laser cutting can be found in this link: **t.ly/4yaO**

The name of the file specifies the type of component, type of material and thickness of material.