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Statics You Can Feel: Using Modular Manipulatives to Make Abstract Concepts Tangible

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Abstract:

Statics is often a student's first encounter with engineering mechanics, yet many topics feel abstract to students and its highly visual nature can make concepts difficult to grasp without tangible reference points. While prior studies have introduced physical manipulatives, few have detailed how they are used in practice or what students are expected to gain. This paper addresses the gap by presenting a set of low-cost, modular manipulatives that allow students not only to see but also to feel the effects of fundamental statics principles. Drawing on experiential and constructivist learning theories, this work emphasizes tactile interaction as a means for students to construct understanding through hands-on, sensory engagement. Through physical interactions, such as pulling on ropes to apply loads, sensing reactions at supports, and experiencing the resistance and rotation associated with moments, students receive kinesthetic feedback that cannot be replicated through lecture, diagrams, or digital tools alone.

The manipulatives, constructed from PVC members with 3D-printed connectors, were developed for select modules in statics (e.g., support reactions, two-force members, trusses, etc.), but their modular design allows reconfiguration to support additional topics across the course. Their pedagogical strength lies in the tactile experiences they create – students directly feel how equilibrium is maintained, how forces are applied, or how a moment about a point causes an object to want to rotate.

This paper provides detailed classroom procedures for each manipulative, including step-by-step implementation, guiding prompts, and strategies for connecting physical experiences to analytical problem solving. Qualitative data gained from student surveys is also described for each manipulative activity to gain information on which activities students felt were most engaging and helped with their understanding. By emphasizing the tangible learning benefits for students, this work positions manipulatives as adaptable, scalable tools for integrating tactile and multimodal learning into statics instruction.

Introduction:

Manipulatives are tangible or virtual objects designed to represent abstract concepts and have long been used to support learning in STEM education. In mathematics and science education, especially at the K–12 level, manipulatives are recognized for improving conceptual understanding by engaging learners visually and kinesthetically [1] These tools allow students to interact with content in a tactile way, making abstract relationships more concrete and accessible. Theoretical models suggest that manipulatives serve as cognitive bridges, helping students build mental models that integrate symbolic representations with physical experiences [2]. As a result, their adoption has steadily grown in postsecondary STEM fields, including engineering, where many concepts involve significant spatial or physical reasoning.

Within engineering education, manipulatives have been introduced across a range of disciplines. Studies have shown that student engagement, comprehension, and problem-solving skills can improve when learners are provided with hands-on opportunities to explore system behavior and physical relationships. The same rationale underlies their use in statics, a gateway engineering course that requires students to master spatial reasoning, vector analysis, and the concept of equilibrium. Given the high cognitive demands of statics, manipulatives offer a promising pedagogical strategy to support students who struggle with visualizing forces and predicting structural behavior [3].

Several types of manipulatives have been developed and deployed for engineering statics education. Steif and Dollár [4] designed physical tools and different activities to help students understand vector decomposition, free-body diagrams, and support reactions. Their approach involved classroom demonstrations where students could physically manipulate systems and observe how force directions changed under equilibrium constraints. Similarly, Mejia et al. [5] created truss models that allowed students to explore internal member forces and identify zero-force members by physically loading different joints. Other studies have extended this concept by introducing 3D-printed kits, where modular components are assembled to replicate key statics concepts such as moments and force transmission [6], [7].

The documented ways in which these manipulatives are used vary considerably. In some implementations, students are encouraged to touch, rotate, and manipulate components themselves, enabling full physical interaction [8]. In others, the demonstrations are primarily visual, with instructors manipulating the tools for students to observe. Some studies describe collaborative group work centered around manipulatives, where students engage in guided inquiry or structured problem-solving [9]. Most commonly, manipulatives are used as instructor-led tools within a classroom or laboratory setting, although the extent of facilitation can differ. For example, Coller [10] questioned whether unguided interaction offered sufficient instructional value, finding no significant gains in student outcomes without structured support in mechanical engineering students.

Modularity is another key design consideration for manipulatives in statics. Many kits are intentionally designed with interchangeable components so that the same set of parts can be configured to illustrate multiple concepts—such as equilibrium in 2D and 3D, moment arms, or two-force members. This modularity not only increases the pedagogical flexibility of the tools but also improves their cost-effectiveness. Reported costs vary, but most kits used in university settings are low-cost, with 3D-printed kits typically ranging from $20–$100 per set, depending on size and materials. Simpler models using PVC piping, string, and force gauges can often be assembled for under $50, making them an accessible option for many engineering programs [6], [7].

A growing body of work has explored manipulatives in statics, yet the literature provides limited insight into how instructors actually implement these tools, what students are expected to learn from them, and how students interact with them. This paper addresses that practical gap by documenting the design and use of modular, low-cost statics manipulatives across several course topics. Additionally, it describes the materials, construction, and implementation of the manipulative statics kit and outlines each instructional module in which the manipulatives were integrated, including the learning goals associated with each activity. The purpose of this work is to provide a practical resource that instructors can use to adopt or adapt similar hands-on tools in their own classrooms and to support broader, evidence-informed integration of manipulatives in statics instruction.

Statics Manipulative Kit Description:

The manipulative statics kit described in this paper has several things in common with many other hands-on statics kits referenced in the literature. This kit is modular and can be reassembled in different configurations to demonstrate different topics and different problems within the same topic. Although, unlike many of the 3D printed kits, this design utilizes threaded PVC pipes (pipe nipple) as the main structure members for improved durability and eliminating the difficulty and fragility of 3D printing long slender objects. The 3D printed components are primarily reserved for connector pieces to be able to customize configurations. The complete Statics Manipulative Kit is shown in Figure 1 with a bill of materials described in Table 1. The prices shown in Table 1 are reflective of 2024 prices from Grainger resulting in a total kit cost of $63.74. Many parts of this kit, specifically the force gauge and PETG filament, are able to be purchased at a lower cost from other suppliers.

The 3D printed parts are made from PETG and use 4 wall perimeters and gyroid infill for improved strength. All connector pieces are threaded to match the threads of the purchased PVC. This also makes for quick and easy reassembly of the components. The pins are designed for quick connections and have two locations for locking the pins in place – one location at the depth of attaching two members together and one location for the depth of attaching three members together. The wheel has a groove integrated into the design to allow a PVC pipe to track in the groove. It also doubles as a pulley and allows a rope to sit within the groove.

Figure 1. Statics Manipulative Kit

Table 1. Bill of materials

Item	Price	Quantity	Price per Quantity
Force Gauge	$17.25	1 unit	$17.25
Pipe nipple 8-inch length	$4.64	3 unit	$13.92
PETG filament (1 kg roll)	$27.94	~0.4 kg	$11.18
Pipe nipple 12-inch length	$4.87	2 piece	$9.74
Pipe nipple 3-inch length	$2.28	2 unit	$4.56
Bucket (1 gal)	$3.87	1 unit	$3.87
Rope (50 ft)	$14.80	~7.5 ft	$2.22
Ruler (optional)	$1.00	1 unit	$1.00
Total			**$63.74**

This kit used Schedule 80 PVC pipe which has thicker walls for improved strength. The diameter of the PVC and scale of the models was important to consider to ensure that students were able to achieve the feeling and learning objectives necessary. Having them too small would be difficult to see interactions, difficult to apply large loads, and hard to feel appropriate forces if the applied loads were small. Too large of models would make transportation and modularity difficult, difficult for students to hold onto the models due to limited strength, and much more expensive to produce. A nominal diameter of ¾" was used (outside diameter: 1- 1/16").

Modules used with Manipulatives:

This section describes each of the modules in which a hands-on manipulative activity was introduced. Manipulatives were introduced in small-group recitations consisting of approximately 10-15 students. Recitations were 50 minutes, but each manipulative activity only used the first 5-10 minutes of that time. All activities were guided by the instructor and had visual and verbal instructions and prompts displayed on the overhead screen. All students were asked to form groups of 2-4 in which to interact with each Statics Manipulative Kit. Each activity is listed in Table 2 and described in the following subsections.

Table 2. List of manipulative activities

Module	Time Implemented	Number of Students
2D Particle Equilibrium	Week 3	54
Moment of a Force	Week 4	37
Support Reactions	Week 6	44
Two-Force Members	Week 7	37
Planar Trusses	Week 9	43
Belt Friction	Week 14	30

Two-dimensional (2D) Particle Equilibrium

This activity was designed so students would think about equilibrium in a simple 3-force particle equilibrium system. The primary goal was for students to see and feel what is happening in the ropes and relate this to the calculations that they are performing through equilibrium. Intuitively, most students understand what will happen with changing the tension or angle of one rope and how it affects other ropes in the system, but seeing and feeling it while discussing the principle of equilibrium helps conceptually understand how they relate.

This activity aimed at eliminating the common misconception that if two ropes are used to support a weight, then the tension in each of those ropes will be one-half of the weight regardless of the angle. This activity proves to students that this idea is not correct, and the angle of the rope plays a critical role in the tension of the rope. Appendix Figure A details the process for this activity along with the associated steps of the activity.

Learning Objectives:

1. Use the condition for equilibrium of a particle to solve a system of concurrent forces by summing the forces to zero
2. Use the condition for equilibrium of a particle to recognize how reaction forces change based on the angle of application
3. Recognize that tension is uniform throughout a single rope segment (neglecting friction effects)

Moment of a Force

Students often struggle with a scalar approach to moments in 3D – both in understanding which forces cause a moment about which axes and the directions of moments. One of the main goals of this activity was for students to see and feel moments being produced. In both 2D and 3D, seeing that the member does not rotate when a force is applied directly through the pivot point confirms that no moment is produced about that point. In 3D, students are able to feel moment developed in the axis and are able to see the system rotate about specific axes. The activity steps can be seen in Appendix Figure B.

This activity hoped to eliminate several misconceptions about the moment of a force. The first misconception students have is understanding that the sign associated with the moment is based on the direction of the tendency of rotation (the right-hand rule sign convention) rather than the sign of the force. A second misconception students have about moments is that horizontal force components are automatically disqualified when considering the moment about a point in 2D. The reason for this thought is believed to come from starting this topic with simple examples that involve horizontal members in which case, the horizontal components run through the point of the moment and do not cause a moment. Further, when discussing a scalar approach to moments in 3D, it is explained that force components parallel to an axis do not cause rotation about that axis. Students often misinterpret this statement when returning to 2D problems, incorrectly assuming that horizontal force components are inherently parallel to an axis and therefore cannot produce a moment, even though moments in a 2D x-y system act about the z-axis.

Learning Objectives:

1. Identify clockwise and counter-clockwise moments of forces
2. Recognize that a force running through a point or axis causes no moment about that point or axis
3. Identify which forces produce a moment about specified axes in three-dimension (3D)

Support Reactions

Support reactions can cause quite a few misconceptions with students. When discussing basic supports in 2D (pins, rollers, and fixed connections), students often just memorize the reactions from these supports without much thought on where they come from even though a detailed explanation of their origin is presented in lecture and the textbook. For a pin, students memorize this as two orthogonal force components without understanding this comes from a single force at a contact point as some unknown angle. For a roller, students memorize this as a single reaction force – often incorrectly memorizing this as a single vertical force even if the roller is not on a horizontal surface. Fixed connections are also memorized as their components being two orthogonal force components and a couple-moment. Some students can grasp the idea of why the couple-moment is present, but many do not understand what is causing the couple-moment based on the type of support.

This activity on support reactions is designed to allow students to see how reactions change based on the type of support and the orientation of the support. In this way, students can begin to realize why we represent the supports with standard reactions and where these reactions come from. These activities are shown in Appendix Figure C along with the associated activity process steps.

Learning Objectives:

1. Recognize that an object in contact with a body will cause a force normal to a tangential line at that point on the body
2. Justify why a pin is represented by two orthogonal force components
3. Justify why a fixed support is represented by two orthogonal force components and a couple-moment

Two-Force Members

While the name "two-force member" indicates that only two forces act on that member, students are not as sure how those forces act on the member and what qualifies a member as a two-force member. Often, lectures or textbook idealize a two-force member as a member pinned at both ends with no forces acting on the member itself. This typically allows students to quickly identify two-force members in a frame or machine, but are often mishandled with the direction of the reactions if the member is something other than a straight member.

This activity helps to address that if two forces are applied on a member, those two forces must have equal and opposite magnitudes and must be colinear. To minimize the effect that the member's mass has, this demonstration was done on a horizontal surface rather than suspended in the air. It is important for students to understand what kind of effect self-weight has and whether this could be neglected if appropriate, however, introducing this with this activity may cause more misconception and might deter from the primary learning objectives. Process steps and figures are shown in the appendix.

Learning Objectives:

1. Explain how when only two forces are acting on a body, those forces must be equal, opposite, and colinear
2. Evaluate different loading scenarios on a member and determine whether the member is classified as a two-force member or a multi-force member

Planar Trusses

There are many studies that have involved planar truss demonstrations and activities in statics. Many of these use creative ways of visualizing the internal forces such as LED lights [11] or replacing members with rope [12]. However, none of these demonstrations have allowed students to feel these internal forces. This activity makes a real internal cut in a member (Figure 2) and allows students to bridge this cut with their own hand. By keeping a small gap between the members when it is grasped, it allows students to feel the internal pushing and pulling effects. The entire process for identifying zero-force members and feeling the axial load in the truss members is detailed in Appendix Figure E.

Figure 2. Truss showing the internal cut

Learning Objectives:

1. Quickly identify (without calculations) zero-force members in a truss
2. Identify which members are in tension or compression in a simple truss

Belt Friction

The primary misconception with belt friction for students is which tension is larger. This activity helped to show students that the tension on one side could be smaller or larger depending on the direction of impending motion. In this way, students could understand that a range of tensions could be applied to maintain equilibrium. Additionally, students had the opportunity to feel this tension for three different contact angles. These contact angles and configurations are shown in the appendix in Figure F.

Learning Objectives:

1. Determine the contact angle, β, for use in the belt friction equation,
2. Recognize the direction of impending motion
3. Discover a range of tensions that can be applied to keep a system involving belt friction in equilibrium

Results and Discussion:

The study was guided by the research question: *How do students' reported enjoyment, engagement, and perceived understanding differ across various manipulative-based instructional activities?* The participants consisted of 95 unique undergraduate students enrolled Engineering Statics. Each week, 5 out of the 10 recitation sections participated in the manipulative activity.

All students who completed the manipulative activities were invited to participate in the survey, and participation was voluntary. For this reason, the number of students exposed to each manipulative activity (summarized in Table 2) does not reflect the number of survey responses in the subsequent data. Surveys were administered immediately following completion of each manipulative activity to capture students' perceptions while the experience was still recent. Data were collected across six distinct manipulative activities implemented throughout the course. Student responses were collected anonymously to encourage candid feedback, and no identifying information was linked to survey responses. The following subsections discuss the results of these surveys as well as observations the instructor made during the activity.

Two-dimensional (2D) Particle Equilibrium

Engagement was relatively low with this activity and some students were observed not to participate. Some potential reasons for the low engagement may be due to the activity being early in the semester when students are not as comfortable with their peers in recitation. Additionally, this activity involved students standing up, but it appeared that many students wanted to remain sitting and therefore did not get as much out of the activity.

Some friction between the ring and the rope affected the symmetry of the angle in the rope (Appendix Figure A, step 4). This was briefly discussed with students, although not in depth since friction is discussed later in the semester.

Figure 3 shows the results of the survey on particle equilibrium. Most students indicated that they at least felt a moderate amount of enjoyment and engagement from the activity. Students reported that the activity helped with their understanding of particle equilibrium, however, these results were not as strong as the enjoyment and engagement. This also mirrored some of the comments made by students that they had already learned these concepts so the demonstration itself was not a big factor in helping to understand particle equilibrium.

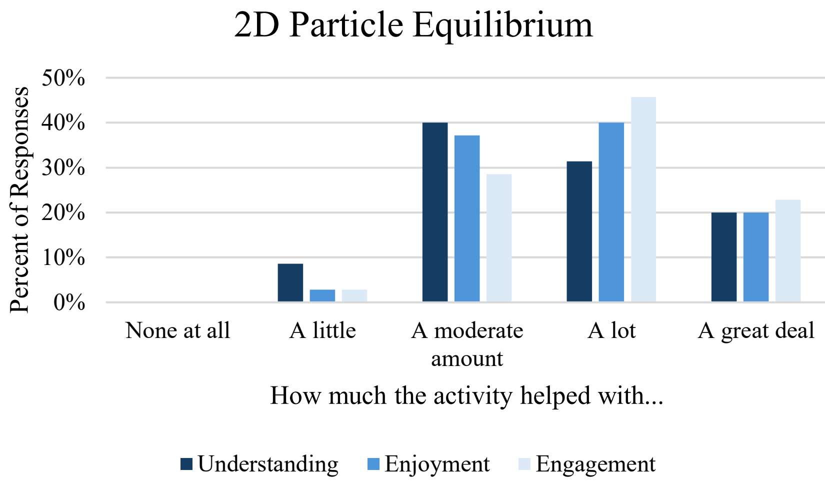

Figure 3. 2D particle equilibrium qualitative results (n = 35)

Moment of a Force

There was not a lot of engagement among groups as the instructor facilitated the activity. There also was not a lot of willingness to explore different force directions and axis rotations when students were asked to in the 3D system. Despite this, most comments provided by students indicated that the activity helped with their ability to visualize the moment of a force in 3D about each respective axis. This is also supported by a higher percentage of students indicating that it helped a lot with their understanding as shown in Figure 4.

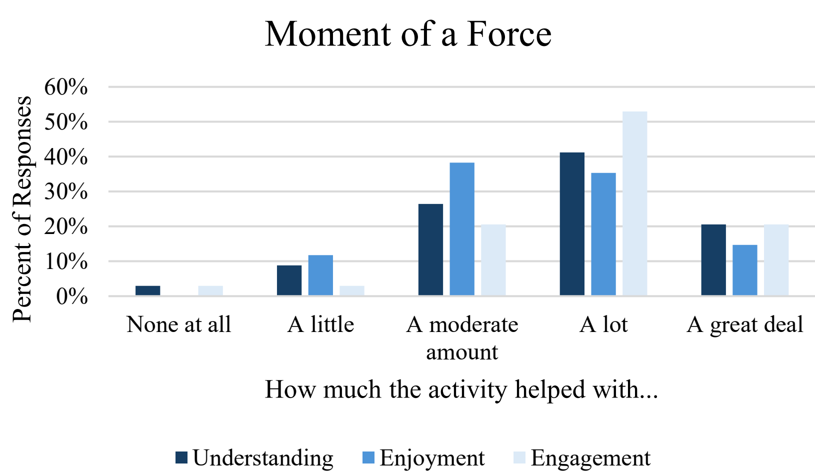

Figure 4. Moment of a force qualitative results (n = 34)

Support Reactions

The assumption of smooth contacts (negligible friction) worked very well in this example due to the low coefficient of static friction between the two PVC pieces. In fact, it made the activity challenging, but also fun for students to try and balance the beam. Many students were observed to be smiling as students' beam collapsed from lack of stability which led them to have conversations about why that happened and how they could reorient their support to make it stable. This activity had one of the highest levels of enjoyment as shown in the results in Figure 5. Additionally, students felt it helped a lot with their understanding of support reactions and all students felt at least a moderate amount of engagement in the activity. Only positive comments were received for this activity with most mentioning that seeing and feeling the reaction forces helped their understanding of either support reactions or force-couples (as related to the fixed support).

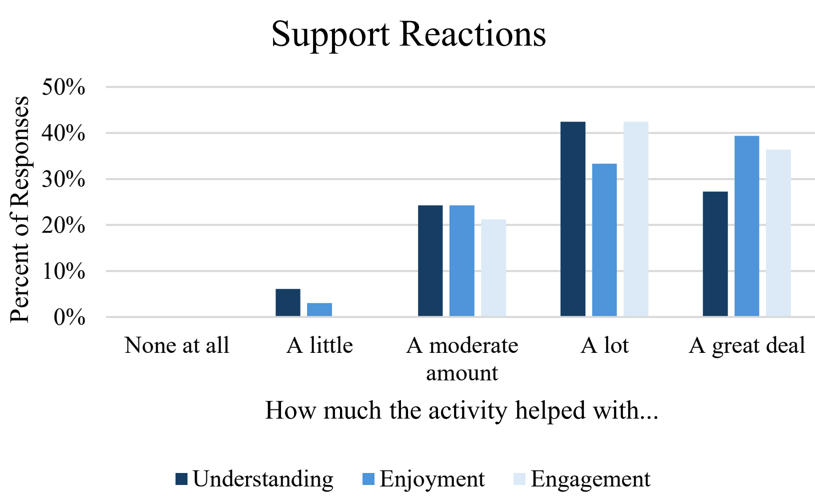

Figure 5. Support reactions qualitative results (n = 33)

Two-force members

This activity was specifically designed to place the member on a tabletop to avoid any confusion with the weight of the member. Even with this, many students wanted to hold the members in the air and then caused some confusion with the two forces not needing to be colinear. This was addressed and provided discussion among the group about how weight may not be negligible if the applied forces are small in comparison.

Feedback provided by students was very limited for this activity and was mixed. Many described the activity as being helpful, but two comments were less positive with one reporting their group was not very enthusiastic, and another mentioned not understanding two-force members or the importance in the context of statics. The results in Figure 6 match this with many students still finding the activity enjoyable, but not as many felt it helped with their understanding of two-force members in comparison to some of the other activities.

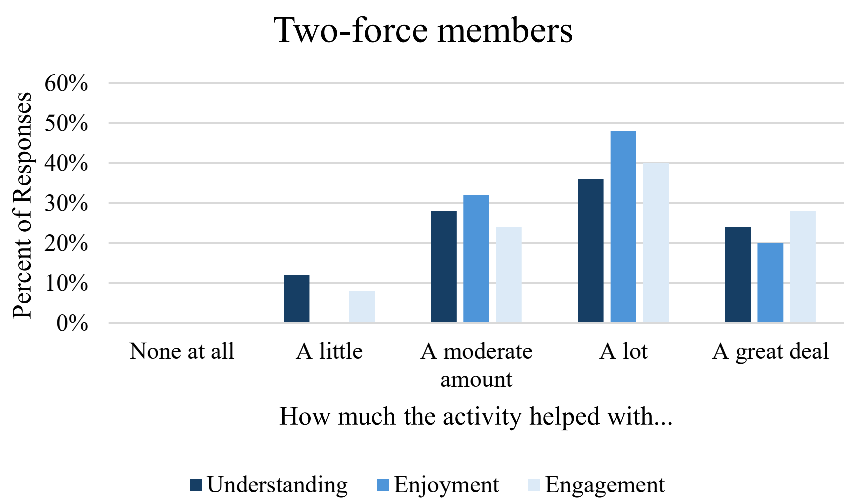

Figure 6. Two-force members qualitative results (n = 25)

Planar Trusses

Students seemed genuinely engaged with this activity. The connections of the pinned members made things easy for students to quickly change configurations. There was some confusion about how to support the truss by hand since holding at the pins is necessary to ensure forces are transferred properly. When groups were prompted about the internal forces in members after they had a chance to feel them, all groups answered them correctly. The only exception was on some of the ZFM configurations some students felt a small force. This was addressed and discussed due to some of the members not being perfectly aligned.

Figure 7 details the qualitative results of this activity which had the most enjoyment and engagement of any activity. The level of understanding was split into two different questions to isolate both zero-force members and understanding which members were in tension or compression. From this, most students felt like their understanding for tension and compression was helped a lot as well as their understanding of ZFMs.

In addition to the composite qualitative results, comments provided by students were overwhelmingly positive for this activity with every student’s comments mentioning that they enjoyed the activity or that it greatly helped them feel the internal loading of a truss.

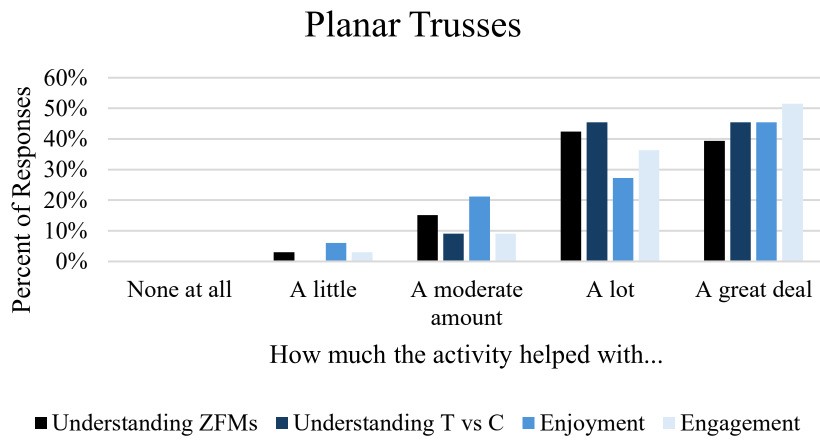

Figure 7. Planar trusses qualitative results (n = 33)

Belt Friction

This activity was very quick and simple which helped to keep students' attention. Progressing through larger contact angles helped students understand that the friction could either help (if they were preventing the bucket from falling) or hinder (if they were trying to lift the bucket). A contact angle of 5π provided a fun experience for most students because they had an opportunity to show off their strength to try to lift the bucket.

This activity showed one of the highest responses of helping with understanding (Figure 8). The enjoyment and engagement were also higher than most of the other activities. Feedback was more limited with some indicating that they knew or understood this before the activity, while others mentioned this was a nice way to help visualize and understand the impending motion of belt friction.

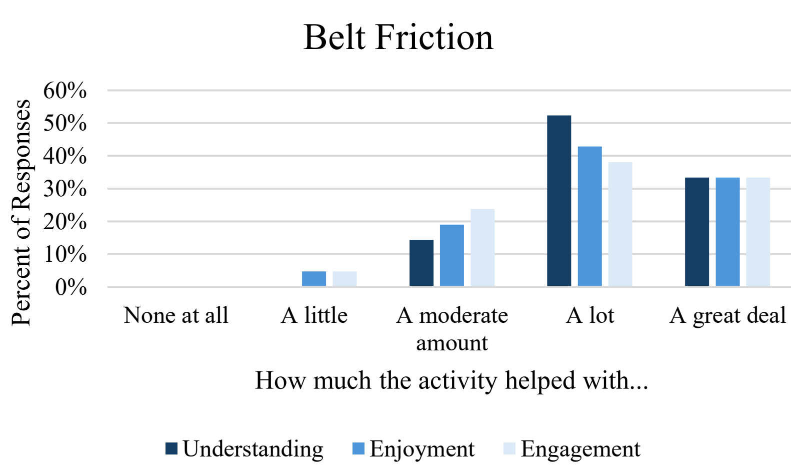

Figure 8. Belt friction qualitative results (n = 21)

Discussion and Future Work:

This paper has outlined the development and classroom use of modular manipulatives designed to make foundational statics concepts physically tangible for students. The focus of this paper is on describing the educational purpose, structure, and potential benefits of each activity. Across activities, students were able to see, feel, and physically explore ideas that are typically taught through worked-out example problems and described in theory. Survey results indicate that the manipulatives helped students visualize support reactions, understand moment behavior, identify tension and compression in trusses, and recognize the physical meaning behind equilibrium concepts. These findings reinforce the value of tactile engagement as a complement to traditional instruction, particularly for topics where students commonly struggle with spatial reasoning or misconceptions.

Beyond their pedagogical impact, the manipulatives offer practical advantages for implementation. The PVC and 3D-printed construction allowed for low-cost, durable, and reconfigurable tools that can support a wide range of statics concepts without extensive fabrication effort. Because the kits are modular, instructors can adopt individual activities, integrate the full sequence, or modify the configurations to suit different course structures. The step-by-step activity guides provided here are intended to help educators replicate these experiences while preserving instructional alignment and conceptual clarity.

The majority of students responded that the manipulative activities helped a lot with their understanding of the respective topic. Comparing all the manipulatives, planar trusses and belt friction topics were reported as providing the most amount of help with students' understanding. Similarly, those activities showed that most enjoyment and engagement among students' survey results with support reactions also having high levels of enjoyment and engagement.

Future work will focus on refining connector designs, expanding the scope of manipulatives to additional support types and three-dimensional systems, and incorporating student feedback into more robust versions of each activity. Longer-term studies will also explore how repeated exposure to tactile demonstrations influences conceptual understanding, course performance, retention, and student confidence across an entire statics curriculum. Ultimately, this work positions manipulatives as a scalable and adaptable means of helping students bridge the gap between physical intuition and analytical problem solving, supporting a more engaging and experiential approach to engineering mechanics.

References:

[1] K. Carbonneau, S. Marley, and J. Selig, “A meta-analysis of the efficacy of teaching mathematics with concrete manipulatives,” *J. Educ. Psychol.*, vol. 105, no. 2, 2013.

[2] D. H. Uttal, K. V Scudder, and J. S. Deloache, “Manipulatives as Symbols: A New Perspective on the Use of Concrete Objects to Teach Mathematics,” *J. Appl. Dev. Psychol.*, vol. 18, pp. 37–54, 1997.

[3] P. S. Steif and J. A. Dantzler, “A statics concept inventory: Development and psychometric analysis,” *Journal of Engineering Education*, vol. 94, no. 4, pp. 363–371, 2005, doi: 10.1002/j.2168-9830.2005.tb00864.x.

[4] P. S. Steif and A. Dollar, “Reinventing the Teaching of Statics,” *International Journal of Engineering Education*, vol. 21, no. 4, 2005.

[5] J. Mejia, W. Goodridge, B. Call, and S. Wood, “Manipulatives in Engineering Statics: Supplementing Analytical Techniques with Physical Models,” in *ASEE Annual Conference & Exposition*, 2016.

[6] S. M. S. Ardakani and J. Ellis, “Dynamic 3D-Printed Statics Modeling Kit and In-Class Activities,” in *ASEE Annual Conference & Exposition*, 2022.

[7] E. Davishahl, T. Haskell, and L. Singleton, “Feel the force! An inquiry-based approach to teaching free-body diagrams for rigid body analysis,” in *ASEE Annual Conference & Exposition*, 2020.

[8] E. Justo, A. Delgado, C. Llorente-Cejudo, R. Aguilar, and J. Cabero-Almenara, “The effectiveness of physical and virtual manipulatives on learning and motivation in structural engineering,” *Journal of Engineering Education*, vol. 111, no. 4, pp. 813–851, Oct. 2022, doi: 10.1002/jee.20482.

[9] E. Danahy, E. Wang, J. Brockman, A. Carberry, B. Shapiro, and C. B. Rogers, “LEGO-based robotics in higher education: 15 years of student creativity,” *Int. J. Adv. Robot. Syst.*, vol. 11, no. 1, Feb. 2014, doi: 10.5772/58249.

[10] B. D. Coller, “An Experiment in Hands-On Learning in Engineering Mechanics: Statics,” *International Journal of Engineering Education*, vol. 24, no. 3, 2008.

[11] K. Sadowski and S. Jankowski, “Learning statics by visualizing forces on the example of a physical model of a truss,” *Buildings*, vol. 11, no. 9, Sep. 2021, doi: 10.3390/buildings11090395.

[12] J. Lesko, J. Duke, S. Holzer, and F. Auchey, “Hands-on-Statics Integration into an Engineering Mechanics-Statics Course: Development and Scaling,” in *1999 Annual Conference*, 1999. doi: 10.18260/1-2--7705.

Appendix:

2D Particle Equilibrium:

Materials Needed:

- (1) Bucket with approximately 10N of weight
- (1) Force gauge
- (1) Connecting ring
- (3) 18-inch ropes
- (1) 36-inch rope

Guided Process:

The guided process steps below correspond to the numbered steps in Figure A.

1) Zero the force gauge and determine the weight of the bucket (neglecting the weight of the connecting ring and rope can be optionally discussed here).
    a. What is the tension in the rope above the connecting ring (rope A)?
    b. What is the tension in the rope below the connecting ring (rope B)?
2) Add a third rope to the ring and have someone apply a small horizontal force to this rope (rope C).
    a. Is it possible for ropes A and B to remain vertical?
3) Apply a larger force to rope C.
    a. What happens to the tension in rope A?
    b. What happens to the tension in rope B?
    c. Why does the angle of rope A change?
4) Remove ropes A and C and replace these with one continuous rope (rope DE)
    a. What is true about the tension on both sides of rope DE?
    b. Can the angle on each side of the rope be different?
5) If the angle relative to horizontal decreases, what will happen to the tension in rope DE?
6) If the angle relative to horizontal is 90°, determine the tension in rope DE.

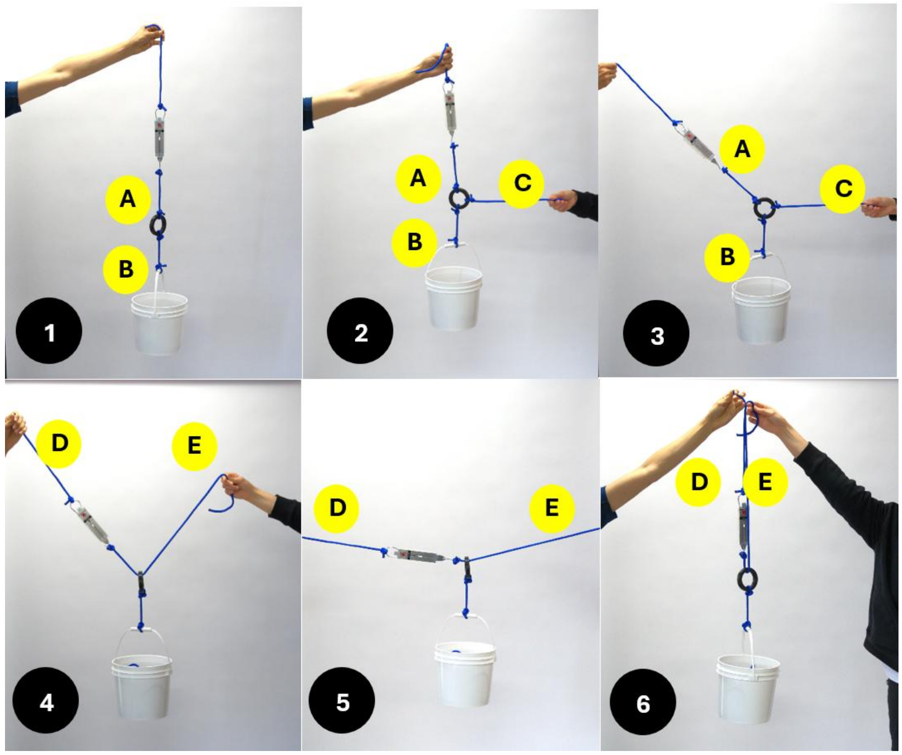

Figure A. 2D Particle Equilibrium

Moment of a Force:

Materials Needed:

- (1) pin
- (2) 18-inch rope
- (1) 12-inch PVC pipe
- (2) 8-inch PVC pipe
- (1) 3-inch PVC pipe
- (1) 90° connector
- (1) 3-way connector
- (3) end connector

Guided Process:

The guided process steps below correspond to the numbered steps in Figure B.

1. Have one student hold the pin at the origin to act as the pivot point while another student applied a horizontal and vertical force to the ends of the member
    a. Which force causes a moment about point A?
    b. Based on each student's perspective, is the vertical force positive or negative?
    c. What is the direction of the moment caused by the vertical force about point A?

2. Apply a single force to the end of the member and vary the angle to see the effect of the moment about point A.
3. Are there any angles that don't cause any moments about point A?
4. Configure the system as a 3D system and repeat steps 1-3.
    a. Which axis is the force causing a moment about while keeping the force in the x-y plane?
    b. Is any rotation caused about the x and y axis?
5. Apply a vertical force at the end of the member
    a. Hold all three axes – one at a time – to feel which axis the force is causing a moment about
6. Move the rope to the elbow of the member (on the x-axis)
    a. Hold all three axes – one at a time – to feel which axis the force is causing a moment about

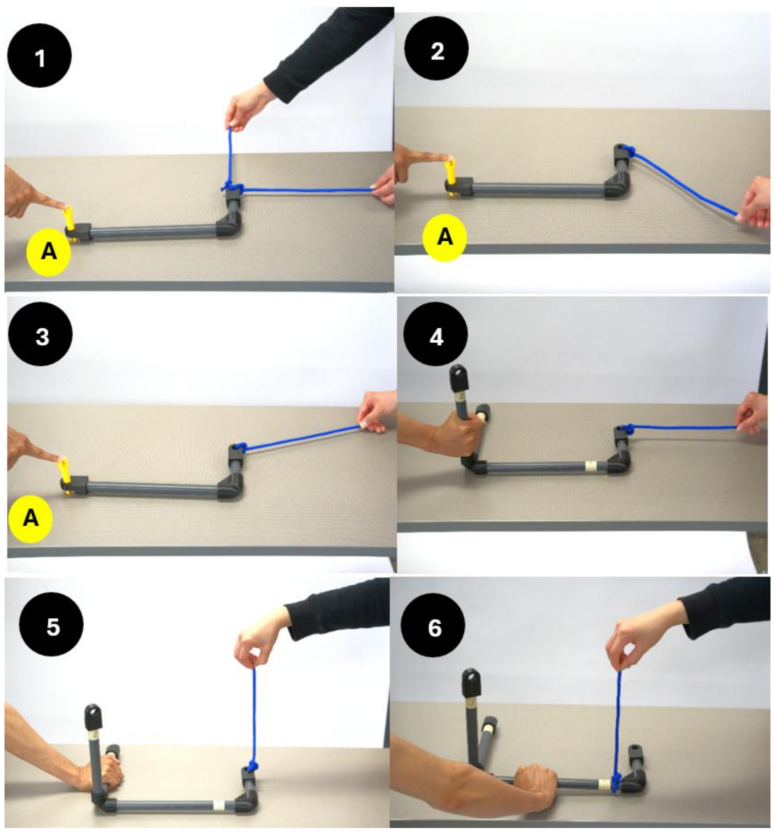

Figure B. Moment of a force

Support Reactions:

Materials Needed:

- (2) 8-inch PVC pipe
- (2) 12-inch PVC pipe

- (4) end connector
- (2) pin
- (2) 18-inch rope
- (1) T-connector
- (1) bucket (with various added weight if desired)
- (1) wheel

Guided Process:

The guided process steps below correspond to the numbered steps in Figure C.

1. Have one student hold the pin leaves while another student holds the rope support
    a. Change the angle of the rope support. How does this affect the pin support?
2. Replace the rope support with a roller and incline the beam. Mimic the “ground” for the roller by two PVC pipes.
    a. What must be true about the “ground” incline and the incline of the beam to maintain equilibrium?
    b. What happens if you make the “ground” horizontal while the beam is inclined and why does this happen?
3. Replace the roller with a pinned wheel. Mimic the “ground” for the wheel by a single PVC pipe.
4. Change the angle of the “ground” while the beam is inclined.
    a. How is this possible with the pinned wheel, but not with the roller?
5. Hold one end of the cantilever beam to simulate a fixed connection.
    a. What does your hand feel?
    b. Is it harder to hold in this position compared to directly holding the end with the rope/applied force? Why?
6. Simulate the fixed support with just two smooth contact points via two PVC pipes.
    a. What happens when the distance between the two contact points decreases and why?

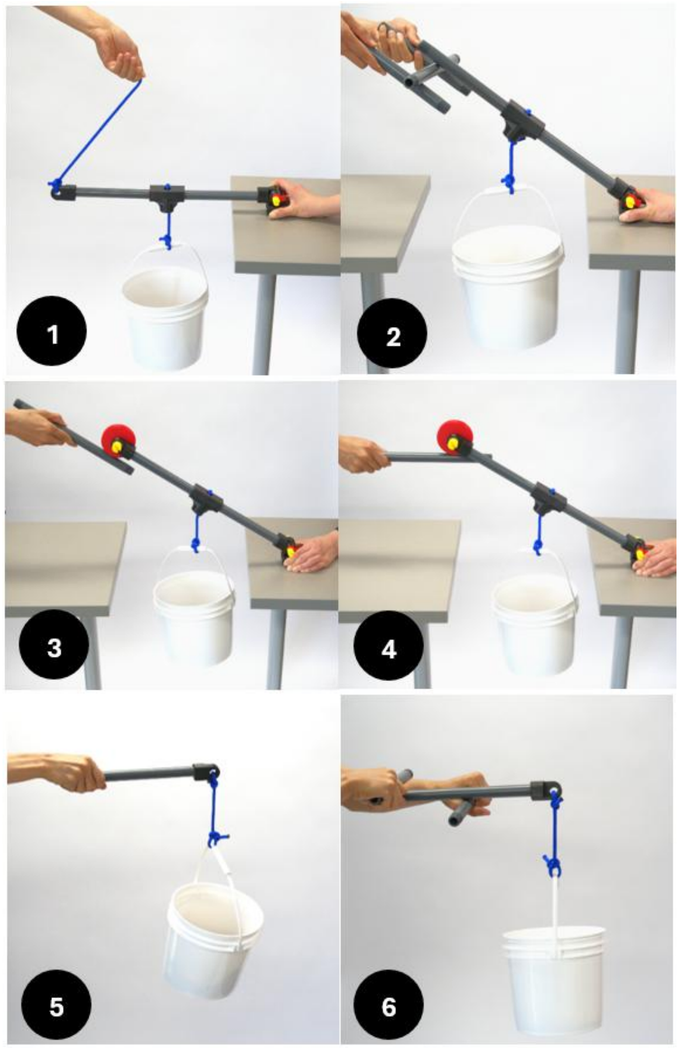

Figure C. Support reactions

Two-force members*:*

Materials Needed:

- (1) 12-inch PVC pipe
- (2) 8-inch PVC pipe
- (2) 3-inch PVC pipe
- (6) end connector
- (2) 18-inch rope
- (1) 90° connector
- (1) T-connector
- (2) pin

Guided Process:

The guided process steps below correspond to the numbered steps in Figure D.

1. Apply a force to each rope of the straight member at various directions
2. Recognize that the only way for the member to be in static equilibrium is for the forces to be colinear
3. Apply a force to each rope of the L-member at various directions
4. Recognize that the only way for the member to be in static equilibrium is for the forces to be colinear
5. Add a member pinned to the T-connector and simulated as a fixed connection at the opposite end via someone's hand
    a. Identify two-force members in this system
    b. How do you know there are no two-force members?
6. Change the fixed connection to a pinned connection and have someone hold the leaves of the pin
    a. Identify two-force members in this system

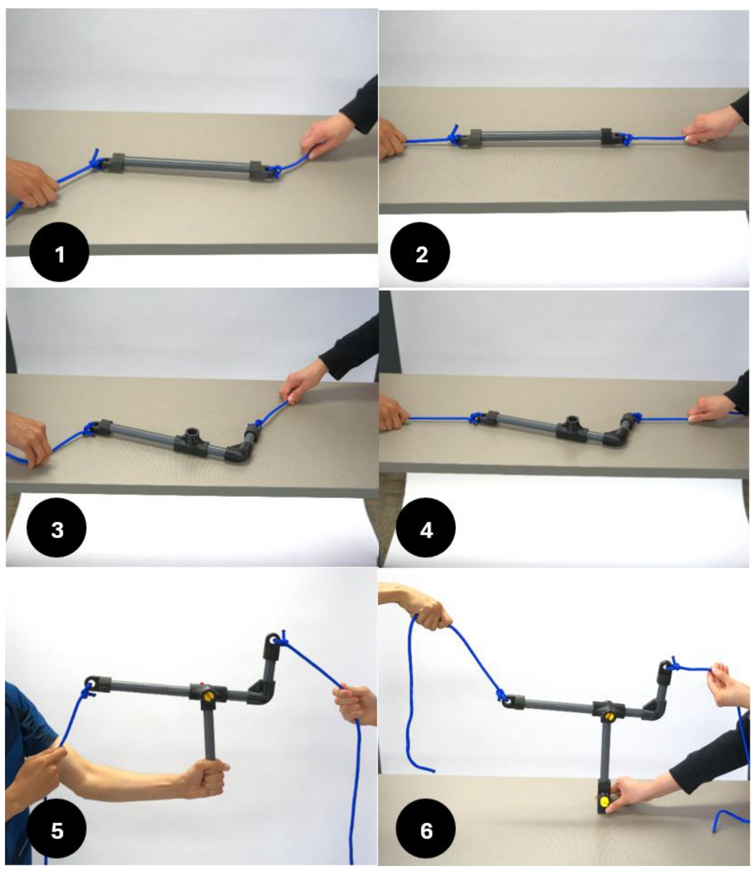

Figure D. Two-force members

Planar Trusses:

Materials Needed:

- (2) 12-inch PVC pipe
- (3) 8-inch PVC pipe
- (2) 3-inch PVC pipe
- (12) end connector
- (2) end caps (optional)
- (4) pin
- (1) 18-inch rope
- (1) bucket

Guided Process:

The guided process steps below correspond to the numbered steps in Figure E.

1. Have one student support the truss in various orientations and apply the load at various locations.
    a. What are the zero-force members in the truss?
2. Replace the center member with the 2 3-inch members
    a. Have one student hold the ends of the 3-inch members with one hand
    b. Is your hand being pulled apart, pushed together, or no feeling on your hand?
    c. Does this mean the member is in tension, compression, or a ZFM?
3. Change the truss orientation and repeat step 2
4. Change the load position and repeat step 2
5. Change the truss orientation and repeat step 2
6. Change the load position and repeat step 2

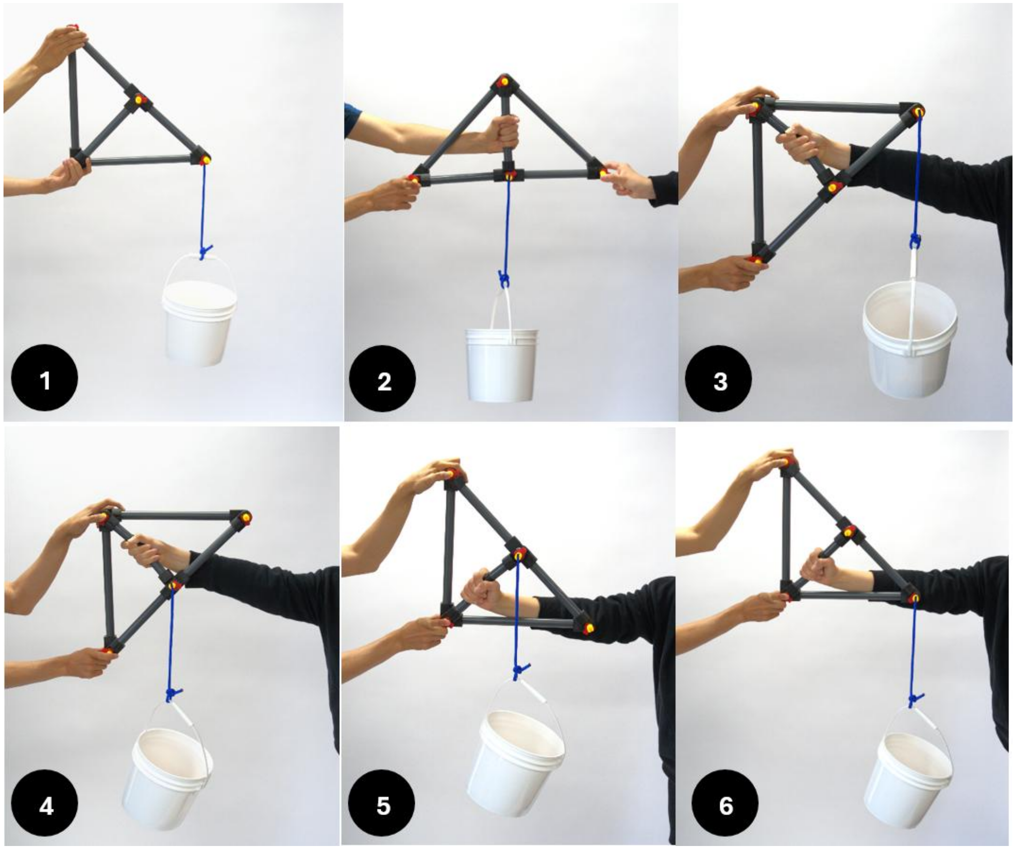

Figure E. Planar trusses

Belt Friction:

Materials Needed:

- (1) force gauge
- (1) 36-inch rope
- (1) 18-inch rope
- (1) 12-inch PVC pipe
- (1) bucket with various added weight

Guided Process:

The guided process steps below correspond to the numbered steps in Figure F.

1. Weigh the bucket
2. Wrap the rope one-half time around the PVC pipe
    a. What is the contact angle β?
    b. What is the minimum force needed to keep the bucket from falling?
    c. What is the minimum force needed to lift the bucket?
3. Repeat step 2 with wrapping the rope another time around the bucket
4. Repeat step 3 with wrapping the rope another time around the bucket

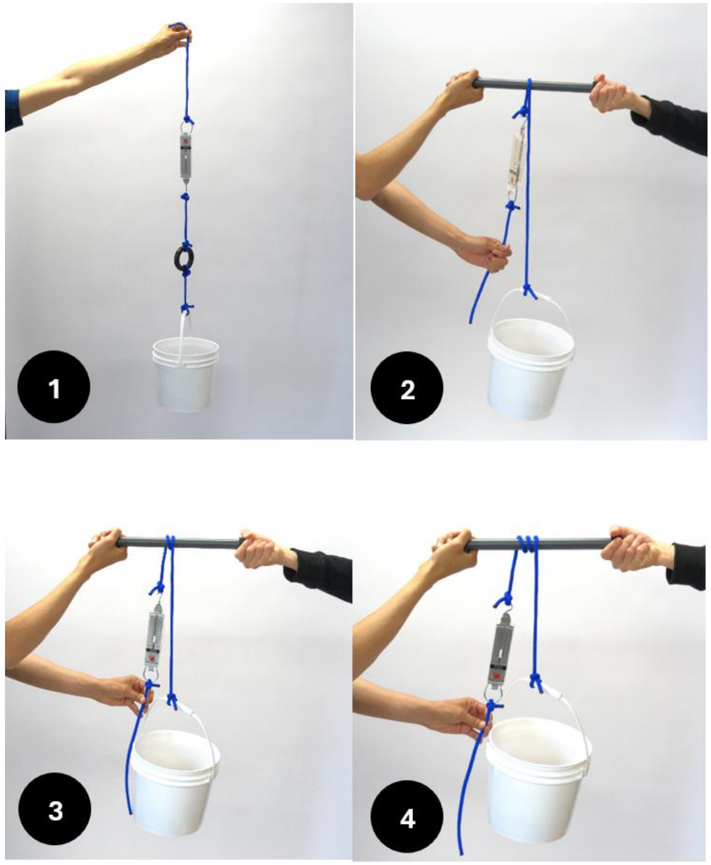

Figure F. Belt friction