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Work-In-Progress: Incorporating Open-Ended Modeling Problems into Undergraduate Introductory Dynamics Courses

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Work-In-Progress: Incorporating Open-Ended Modeling Problems into Undergraduate Introductory Dynamics Courses

Abstract

This work-in-progress paper aims to document the process of incorporating open-ended modeling problems (OEMPs) into introductory undergraduate dynamics courses. Content in engineering science courses is historically challenging for students to understand and transfer to new, unfamiliar contexts. These challenges likely arise in part from pervasive traditional teaching methods that emphasize solving “textbook problems” which are not truly representative of the complex, ill-defined problems professional engineers usually engage. Subsequently and unsurprisingly, engineering education researchers and industry stakeholders alike have long lamented engineering graduates’ inability to independently and creatively solve new problems. Practicing engineers exercise what Gainsburg (2007) identifies as *engineering judgment* to make assumptions, discretize elements, decide how to model qualitative factors, and evaluate the reasonableness of the end result stemming from these decisions. In most engineering classes, instructors (or the textbook) usually simplify systems so much that these activities are circumvented entirely. However, our research team has previously demonstrated how OEMPs, which ask students to apply mathematical models learned in class (e.g., rigid body acceleration analysis) to real-world systems, can inspire the productive beginnings of engineering judgment in undergraduate students.

Our research team has primarily implemented and studied OEMPs in undergraduate introductory statics and mechanics of materials courses. For this current work, we formed a multi-institutional, cross-disciplinary faculty learning community with two engineering education researchers and four faculty members teaching dynamics. This paper documents the process of expanding on lessons learned from implementation of OEMPs in statics courses—as well as one instructor’s experiences with OEMPs in a dynamics courses—to more fully investigate the transferability of OEMPs into undergraduate introductory dynamics courses at multiple institutions.

This paper first describes our process for collaboratively creating new dynamics OEMPs based on formalizing guidelines and sharing lessons learned from statics OEMPs development. We discuss reflections from the faculty members about the value and challenges of designing a dynamics OEMP. We then describe how initial observational feedback was collected from undergraduates at multiple institutions who assessed the new OEMPs from a student perspective. Next, we present the OEMP assignments we created. The paper concludes by describing our plan for qualitatively analyzing interviews with students to understand how students engaged in the productive beginnings of engineering judgment while completing the dynamics OEMPs.

Implications include insights on how students approach and solve complex, ill-defined problems, develop engineering judgment, and build mathematical models. This investigation also provides the future opportunity to compare how students engage in these activities across multiple engineering science courses, institutions (including Carnegie classifications), and engineering subdisciplines. Lastly, this work will help to advance our development of general guidelines for creating and scaffolding an OEMP in any discipline.

Introduction

Following a meta-analysis of 255 studies on active learning in STEM education, Freeman et al. concluded, "If the experiments analyzed here had been conducted as randomized controlled trials of medical interventions, they may have been stopped for benefit—meaning that enrolling patients in the control condition might be discontinued because the treatment being tested was clearly more beneficial" [1, p. 8413]. Despite the notable educational gains associated with active learning instructional techniques, the pervasiveness of these approaches remains limited. From observations of over 2,000 STEM classrooms, Stains et al. note that "didactic" instructional practices (i.e., passive lecturing requiring little to no student engagement) dominated about 55% of the classrooms [2]. In a related 2010 study, Borrego, Froyd, and Hall note that while over 80% of engineering educators are aware of the benefits of active learning techniques, their adoption rates were just shy of 50% [3]. Henderson and Dancy also observed that achieving sustainable adoption of research-based instructional practices has proved to be extremely difficult [4].

The literature also reveals why fewer faculty adopt and retain these techniques than might be expected given their largely positive influence on educational experiences. At an institutional level, most faculty (particularly those on a research tenure track) are not rewarded or recognized for superior teaching performance, which unfortunately but understandably leads to prioritizing time and effort spent elsewhere [5]. In addition, and at an individual level, faculty are also wary of adopting these instructional techniques given insufficient class time, lack of preparation time, class size, and inexperience with implementing these techniques [6-13]. As a result, instructors tend to implement more traditional instructional techniques that have been shown to be less effective in achieving important student outcomes [14-15].

As of 2020, the Accreditation Board of Engineering and Technology (ABET) defines student outcomes as "what students are expected to know and be able to do by the time of graduation. These relate to the knowledge, skills, and behaviors that students acquire as they progress through the program" [16]. Ideally, engineering science courses (i.e., non-lab and non-design courses) prepare students to apply the theoretical concepts in subsequent design and/or lab courses, on project teams, and as practicing engineers. However, engineering science courses are often taught like applied mathematics courses with little connection to engineering practice [17]. Decontextualizing a course in this manner distances students from the processes that help them engage in developing engineering judgment [18]. An instructional approach that helps students connect engineering science content with engineering practice is to frame the content as mathematical models describing natural phenomena under certain simplifying assumptions [17].

Research shows that students best learn modeling practices through their explicit inclusion in the curriculum [3]. One such approach to incorporate mathematical modeling into undergraduate engineering education is through open-ended modeling problems (OEMPs) in which students work either individually or in groups to develop mathematical models that describe a real-world scenario [17]. OEMPs are similar to Model-Eliciting Activities (MEAs) [19] in that students make and substantiate assumptions throughout the process of establishing their mathematical models. **A key difference between MEAs and OEMPs is that OEMPs prompt students to consider multiple alternatives to determine the first-principles model that best represents the engineering system in question, which uniquely requires students to exercise their engineering judgement**, whereas MEAs ask students to fit models to data. Engineering judgement is exercised and developed in design/lab courses, but OEMPs provide opportunities to hone this judgement **while** applying course content and justifying the related underlying assumptions in engineering science courses.

Active learning is inherently part of the curriculum for design and lab courses, and many of lessons learned in those contexts can be applied to OEMPs. For example, these kinds of courses rely on project-based learning and/or problem-based learning that provide ample opportunities for students to engage in mathematical modeling. Though similar, there are a few differences between project- and problem-based learning. Project-based learning is more geared towards the *application* of knowledge. The associated tasks are usually designed to mimic as closely as possible the conditions in the engineering profession, which means they span a longer period of time (i.e., a semester-long project). On the other hand, problem-based learning is more geared towards the *acquisition* of knowledge. Project-based learning is usually employed in subject courses (e.g., math courses, physics etc. in engineering), whereas problem-based learning is not. Finally, self-direction is stronger in project-based learning compared to problem-based learning because the learning process is less directed by the problem statement [20]. Note that OEMPs can fall into either category depending on the scope of the activity (i.e., OEMPs can manifest as an active learning activity conducted in a single discussion section or as a semester-long project).

It is important to note that OEMPs are a form of active learning—regardless of the scope of the activity—while simultaneously satisfying multiple ABET student outcomes. This work aims to describe how to create an appropriate OEMP in a manner that an instructor with little to no engineering education research experience could follow. A synergistic aim (to be reported in future work) is to extend work previously completed in largely statics courses to dynamics courses in order to illustrate the transferability of OEMPs to other contexts. This paper opens with a brief description of the different elements that define an OEMP, the process for creating an OEMP, and a description of the OEMPs that the co-authors created for this work. Then, the synthesized results from the faculty and undergraduate feedback are presented and discussed, followed by conclusions and future work.

Methods

Background of OEMPs

An OEMP consists of the following four elements: 1) a real-world scenario, 2) the application of 1+ mathematical models (e.g., rigid body acceleration analyses) that students are currently learning in class, 3) opportunities for students to practice exercising engineering judgment, and 4) the absence of one "correct" answer [17]. As alluded to in the Introduction, OEMPs can range from a singular problem on a homework assignment to a semester-long project that sequentially builds on what the students are learning. For example, one of the first OEMPs provided students with a simplified, statistically determinant model of a bridge that students were asked to design the suspension cables using their mathematical model [17]. This OEMP, like all those that followed, utilized scaffolding, which is the purposeful design and structure of the assignment such that the instructor supports students as they progress.

Creating an OEMP (DIY OEMP)

The first step is to choose a **context** (preferably one that the students can personally relate to and may have interest in) that will serve as the backdrop for the OEMP. The next step is to identify what **learning objectives** the students should be able to accomplish in working through the mathematical modeling portion of the OEMP. In parallel, one should consider the **scope** of the problem. For example, a problem intended for a single class meeting (whether it be discussion, lab, or lecture) will by necessity have considerably fewer parts (and less open-endedness) than a problem to be completed as part of a homework assignment covering several weeks or as a final course project. The **timing** of the OEMP, particularly if it is intended to span more than a single class/assignment, is important as well. The learning objectives for a part of the OEMP should align with what content is covered in lecture that week. Next, it is important to bear in mind how much **scaffolding** is necessary to reduce student anxiety and frustration with the open-endedness [21-22]. One should also consider what **resources** could or should be made available to the students such that they can complete the OEMP in the allotted time frame. Many students would likely spend a lot of time attempting to identify a "good" source of necessary information (e.g., data for making assumptions) as well as deciding what criteria constitutes a good source. These resources can range from providing specific values or equations needed to complete the problem to providing website links or articles that students can access and decide which values or information to use. Providing resources also has the benefit of restricting the students' solution space, which can expedite grading. Finally, students can work on parts **individually** and/or as part of a **group**. If the latter, one may need to consider group dynamics. Transitioning from individual work to group work can be beneficial for students to interactively engage in the material (i.e., mutual sense-making [23]) by providing them with the opportunity to justify their assumptions to their group members and coming to a consensus moving forward with the problem.

On a finer grain level, the aforementioned learning objectives will inform the creation of a **draft** where each question or part should support or achieve the learning objective. It is imperative at this point for the instructor to **work through a complete initial draft**. It has been the experience of all co-authors who have created OEMPs that inevitably additional steps are identified that were not originally scaffolded into the initial draft. For example, one might need to estimate a mass moment of inertia to utilize in subsequent moment equations. This exercise also helps identify the possible solution space and which assumptions narrow that space. The draft should then be **revised** to ensure that the steps needed to achieve the learning objectives are not so elusive that students will not know what procedure to follow. Next, it is recommended to **send the OEMP and the solution to another person** (a fellow faculty member or graduate student) to work through the problem themselves. During this process, similarities and differences between the solutions will reveal the degree to which the problem achieves the learning objectives and whether the scaffolding is sufficient. It is also common during this phase to identify the degree to which different parts of the OEMP are open- or closed-ended. It is helpful to consider the order and interdependence of open- and closed-ended parts. Closed-ended parts can be beneficial, particularly as it relates to developing engineering judgment ("Is your answer reasonable? Why or why not?") as well as for ease of grading. It is also recommended that the **draft be sent to undergraduate students** familiar with the course content. This final step is optional but very useful to understand the pitfalls and roadblocks that may be encountered by future undergraduate students, particularly as it relates to scaffolding. Finally, many students may encounter design paralysis whereby they are unable to decide on an assumption or way to model a component in fear of losing points. Providing **rubrics** to the students and graders can be very helpful to alleviate some of this anxiety, as can reminding students verbally that the goal is to make and justify decisions, not necessarily to arrive at a "correct" solution.

Examples of Two OEMPs

Two faculty members at two public universities created OEMPs to be used in their Spring semester courses. Neither faculty member had prior experience creating an OEMP. The Washing Machine OEMP was created for an introductory dynamics course required for largely second-year undergraduate students majoring in mechanical engineering, civil and environmental engineering, and certain biomedical engineering tracks. A total of 86 students were enrolled at the beginning of the semester. The Figure Skating OEMP was created for an introductory dynamics class required of largely second-year undergraduate students majoring in biomedical engineering. A total of 13 students were enrolled at the beginning of the semester. Feedback was elicited from all faculty co-authors as well as 5 students at 3 public universities, none of who have completed more than one OEMP and all who have taken an introductory dynamics course.

The Washing Machine OEMP consisted of 4 parts, each of which was to be completed in a 50-minute discussion section. The goal for the assignment was to analyze the dynamics of a simplified washing machine (Fig. 1a) and use that analysis as a design tool. The first part was closed-ended to familiarize the students with the context of the problem and apply a concept covered recently in lecture (particle kinematics in normal/tangential coordinates). The second part was moderately open-ended and again provided students with the opportunity to apply concepts recently covered in class (Euler's equation and parallel axis theorem). This portion of the assignment is largely scaffolding to set up the third part, which was uncovered while working through the initial draft. The third part of the problem represents the complete dynamic analysis of the system as well as provides scaffolding for the final part of the OEMP. In the final part, students are asked to use their analysis from the third part as a design tool to improve the design of the (simplified) washing machine, which purposefully drew inspiration from the actual model's design. A draft of the problem is offered in Appendix A.

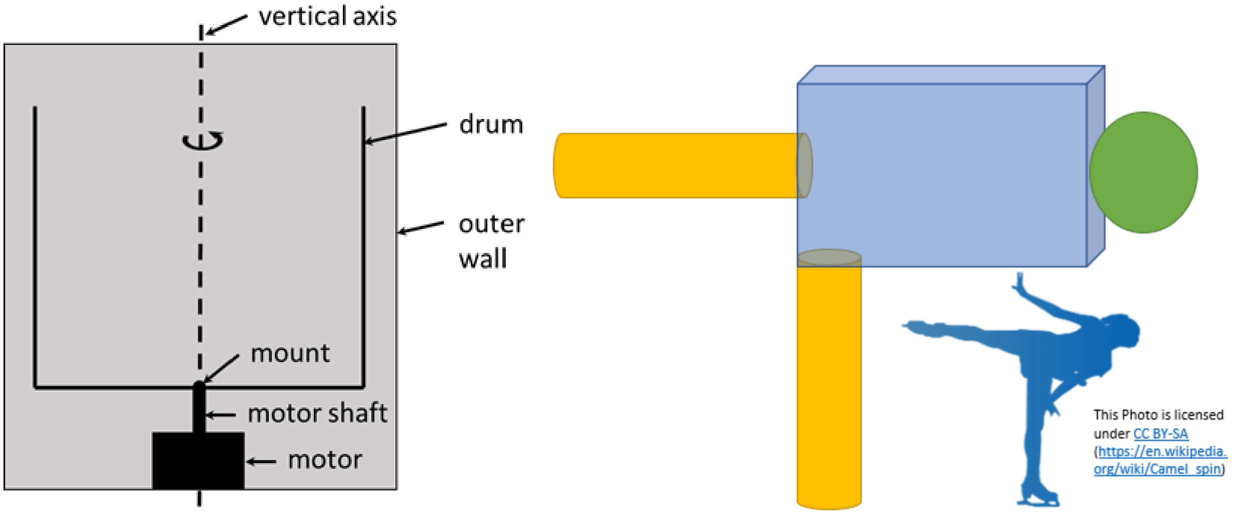

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Figure 1: *(a) Simplified schematic of the washing machine. (b) One possible modeling choice for the ice skater in a camel spin position.*

The Figure Skating OEMP also consisted of 4 parts but was intended to be completed primarily as an individual homework assignment. The context of this OEMP was the dynamic analysis of figure skating spins, a topic relevant to the 2022 Winter Olympics (Fig. 1b). The first part was the main open-ended modeling step where students were asked to use between 4 and 6 homogeneous 3D solids to create a composite-body model of a specific figure skater in 2 common spin positions. Based on faculty feedback, the resources provided to the students to approximate the dimension and mass of each solid was narrowed and clarified. The goal of the second part was to calculate the skater's mass moment of inertia in each position based on the values determined in the first part, which involves closed-ended application of mass-moment of inertia equations and the parallel-axis theorem. The third part of the problem asked students to calculate angular velocity and work. The final part asked students to describe how they would adjust their models to analyze pairs skaters, a male and female, using their knowledge of dynamics. Based on their work in previous parts of the OEMP, they are asked to predict which skater would need to slow down their spin to match the rate of their partner and suggest ways to do so. A draft of the problem is also offered in Appendix B.

Solicited Feedback on the OEMPs

We collected feedback on the OEMPs from two separate and sequential groups. First, faculty members of our research team read both OEMPs and offered suggestions and edits based on their experience. Beyond the two instructors who designed the dynamics OEMPs presented in this paper, our research team includes a researcher who has also implemented OEMPs in their courses since 2018, a researcher who has studied OEMPs since 2018, and two instructors who have implemented OEMPs in their courses since 2019. One of the most significant outcomes of this feedback was an emphasis on the value of working through the problem before giving it to students. For example, while working through the initial Figure Skating OEMP draft, it was discovered that the calculated angular velocity for one of the spins was unreasonably large regardless of choices for part 1 (a result of the simplification of homogeneous solids misrepresenting the center of mass location). This discovery created a teachable moment that could be expanded upon for future iterations of the OEMP (e.g., analysis of moment at the ankle to remain upright in the camel spin position). The members of the research team were able to identify additional scaffolds and uncover steps where the students will need to make assumptions about aspects of the problem that they may not be able to explicitly realize on their own. This process also aided in designing the rubrics for grading different parts of the OEMP.

Feedback from the members of the research team emphasized that one needs to maintain realistic expectations of how much time it will take the students to complete the OEMPs. Because students are busy with all their classes, they only have a limited amount of time to devote to any one assignment, OEMPs included. Therefore, it is important to ensure that students are spending time where the instructors intend for them to focus. For example, if finding and assessing the trustworthiness of a reference is not a learning objective of a particular OEMP, it is better to provide students with that reference so they can focus their attention on the other learning objectives. It is also good practice to have the students explicitly document their assumptions and justifications in their assignment as well as any information they gathered from any resources they used. This requirement prompts students to make assumptions and defend them, which encourages the development of engineering judgment as opposed to arbitrary guessing. For the graders, it makes the assumptions easier to find when grading.

With this feedback, the 2 instructors who designed the OEMPs each made revised drafts of their problem. These revised OEMPs were then given to 5 undergraduate students at 3 different universities. Two of the undergraduates had both completed OEMPs in their courses and served as research assistants on this project at a first university. Another 2 of the undergraduates had served as research assistants at a second university and the fifth undergraduate, at a third university, had no experience with OEMPs. These students all worked through the OEMPs as if they were students in the dynamics course; however, they did not perform all of the closed-ended calculations. In the interest of time, they focused on making assumptions, modeling the real-world system, and identifying equations they would use. Each student spent between 45 - 75 minutes solving each OEMP.

The undergraduate feedback was largely positive with some useful suggestions that were incorporated into the final versions of the OEMPs before they were assigned. Both OEMPs were perceived as having open- and closed-ended parts. The Washing Machine OEMP has increasing amounts of open-endedness as students progress from part to part, whereas the Figure Skating OEMP has decreasing amounts of open-endedness. The students perceived that both problems were appropriately difficult, though they suggested some clarifications that could better guide students. For example, it was (incorrectly) assumed that students would remember an equation for motor torque that was presented in a previous class for Part I of the Washing Machine OEMP. Finally, students were able to articulate some assumptions, but others were seemingly implicit based on how they had previously solved problems in their own dynamics classes.

Conclusions and Future Work

This work aims to advance the development of general guidelines for creating an open-ended modeling problem (OEMP) for any discipline. Here, we present the work of two dynamics instructors as they create their first OEMPs following examples, advice, and feedback from other members of the research team who have experience implementing OEMPs in largely statics courses. In this paper, we have aimed to capture these practical guidelines for creating an OEMP. While these guidelines are specific to OEMPs, we also believe they can be generally applied to many open-ended problems in engineering education. In addition to the research team feedback that guided the development of the OEMPs presented here, undergraduate feedback on draft problems provided useful suggestions for scaffolding.

Future work includes qualitatively analyzing interviews with students to understand exactly how students engaged in the productive beginnings of engineering judgment while completing these dynamics OEMPs. In addition to investigating the transferability of the learning experiences elicited by OEMPs to another engineering science context, insights include how students approach and solve complex, ill-defined problems, develop engineering judgment, and build mathematical models. This investigation provides the opportunity to compare how students engage in these activities across multiple engineering science courses, institutions (including Carnegie classifications), and engineering subdisciplines.

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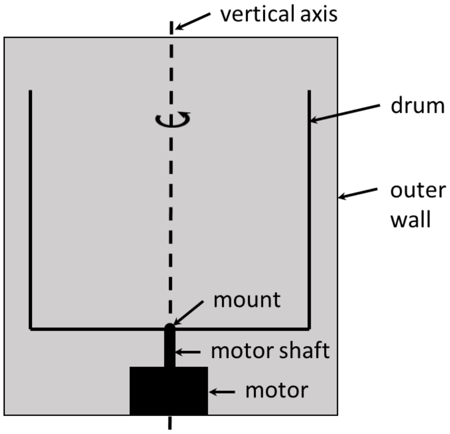
Appendix A: Washing Machine Open-Ended Modeling Problem

Directions: You will work on different parts of this activity in your Discussion groups. For this open-ended modeling problem activity, we will be considering a top-loaded washing machine (example pictured below). The make and model you will focus on is the Whirlpool top load impeller washer (https://www.bestbuy.com/site/whirlpool-4-6-cu-ft-top-load-impeller-washer-with-built-in-faucet-white/6468663.p?skuId=6468663).

Note that the diagram on the right is an oversimplification of the actual washing machine. In reality, the drum is actually two components: 1) a spinning basket that holds the clothes and 2) a stationary tub that keeps the water contained.



Part I – Particle Kinematics

For this part, the answers are close-ended, meaning there is one correct answer. ***Convert to metric units!***

Learning objectives: Perform a velocity and acceleration analysis for a particle

- Calculate the maximum torque that the motor can produce when the washing machine is completely empty (i.e., no items or water) using the following equation:
  $$Power = P = torque * angular\ velocity = \tau\omega$$
  Note that all of the information you need to answer this question is on the site listed above (hint: pay special attention to the "From the Manufacturer" section). Include in your answer what information you gathered from the website.

- For some arbitrary point A attached to the spinning drum, what is the velocity and acceleration in normal/tangential coordinates when the drum is spinning at its (constant) maximum angular speed? Assume the diameter of the washing machine drum is 21.25" (0.54 m).

Part II – Rigid Body Kinematics

Learning objectives: Use Euler's equation for the drum and utilize parallel axis theorem

For this part and the ones to follow, you will need to make a number of assumptions about to solve for the requested parameters. **There is no single right answer for each assumption; however, you do need to justify each assumption that you make.** For each question, please write and justify any assumptions that you made that ultimately led to your answer.

- For the case when the washing machine is completely empty, let's say you observe the machine requires 13.4 seconds to reach its maximum angular speed after starting from rest. What is the mass moment of inertia for the drum about its vertical axis?

- Now assume the drum is filled to capacity with clothes and water. If you model the clothes and water together as a cylinder, estimate the mass moment of inertia of the drum and load together (note the density of water is 62.43 lbs/cu ft = 997 kg/m^3). It is recommended that you consider either looking through the Location Requirements on page 5 in the owner's manual (https://content.syndigo.com/asset/e46746d1-be12-42b3-b768-39caf7c9920c/original.pdf) and/or looking through this link (https://www.consumerreports.org/washing-machines/top-large-capacity-washing-machines-a9447685306/).

- Let's also say you observe the full machine now requires 20.2 seconds to reach its new (different) maximum angular speed. How fast is the drum spinning now? Does your answer make sense?

- Now let's consider one possible worst-case scenario. Let's say the item in the washing machine is a comforter that is very water absorbent, and it concentrates the mass near a point that is offset from the center of the drum. What is the new mass moment of inertia of the system? How different is your answer from the mass moment of inertia of the distributed load? Does it make sense?

Part III – Rigid Body Kinetics

Learning objectives: Perform force analysis using Newton's 2nd law and Euler's law of motion

This part is continuing from the worst-case scenario from the previous part where the only item in the washing machine is the comforter.

- Start with the free body diagram of the drum that includes any loads on the drum and the mount between the drum and the rest of the washing machine. You should choose how to

model the mount, but make sure your system is solvable and not over- or under-constrained!
- What are the magnitudes of the reaction forces at the mount between the drum and the motor?
- What are the magnitudes of the reaction moments at the mount between the drum and the motor?

Part IV – Rigid Body Kinetics (continued)

Learning objectives: Perform force analysis using Newton's 2nd law and Euler's law of motion

This part is again continuing from the worst-case scenario from the previous part where the only item in the washing machine is the comforter.

One conclusion you should reach from your answer to the previous part is that having the drum solely supported by the mount is not a great design. Let's say you are asked to improve upon the design such that the reaction forces and moments at the mount are reduced. Drawing inspiration from the design of the actual washing machine, let's say you add a suspension system consisting of identical springs (same unstretched length, same spring stiffness constants, etc.) around the circumference of the drum. Note that the clearance between the drum and the outer walls of the washing machine is 3.25" (0.08 m) on either side and the total height of the drum is 22.5" (0.57 m). Update your analysis from the previous part to recommend design improvements.

- Start by drawing the updated free body diagram of the drum that includes any loads on the drum and the mount between the drum and the rest of the washing machine.
- What are the magnitudes of the reaction forces and moments at the mount between the drum and the motor now?
- Based on your results, why might you want to iterate on your design to add additional components?

Appendix B: Figure Skating Open-Ended Modeling Problem

Winter Olympics events are full of examples of science and engineering, including dynamics. For this assignment, you will use your knowledge of rigid body angular kinetics to model the spins of figure skater Nathan Chen. Nathan Chen is a three-time World Champion, five-time U.S. National Champion ice skater, and favorite for a 2022 Olympic individual medal. He is 22-years-old and stands 1.66 meters tall.

Spins are a required element in figure skating competitions where the skater rotates at a single point on the ice while holding a specific position. The two spins (and associated positions) you will analyze for this assignment are the camel or parallel spin and the scratch or blur spin. The camel spin is the ice skating version of a ballet arabesque with the skater leaning forward on one leg with the other leg extended behind them forming a T-shape (Figure 1). This spin typically occurs at the beginning of a spin sequence. The scratch or blur spin is an upright spin where the legs are crossed together and the arms are either held tightly against the chest or extended above the head with the hands together (Figure 2).

Figure 1. Camel Spin

Figure 2. Scratch Spin

Show all appropriate steps as you work through the following parts.

Part I: Modeling of Composite Rigid Body

The first step in your analysis is to determine how to model Nathan Chen (1.66 meters tall) in each position as a composite body of homogenous, simple solids. You are required to use three to six 3D solids in your model of each position.

A. Draw a sketch of the collection of solids you choose to model the body in each position; also indicate the axis of rotation in your sketches
B. Complete the following table with the solid geometries in your sketch (e.g., cylinder) and the dimensions needed to define the size and location of these solids (e.g., cylinder radius and height)

Position	Body Part(s)	Solid	Dimensions Needed	Dimension (cm)	Perpendicular Distance (cm)	Mass (kg)
Example	*Lifted Leg*	*Cylinder*	*Radius* *Height*	*Radius = 5.71* *Height = 88.3*	*44.15*	*9.64*
Camel						
Scratch						

C. Use the information presented in section 3.3.1.3-1 of this NASA report on anthropometry to estimate each of the dimensions included in your table if your goal is to model Nathan Chen's spins. Add these estimates to the fifth column.
   a. **The resources appendix contains copies of the NASA Figures containing "Anthropometric Dimensional Data for American Male". It may be easier to first determine the number label of the dimension that you want to use based on the Resources Appendix figures, then Ctrl+F in the NASA website to find the value.**

D. Based on the orientation of your solids and their dimensions, estimate the perpendicular distance between the solid's center of gravity and the skater's axis of rotation (think about what *r* you need for the parallel axis theorem). Add these estimates to the sixth column.

E. Use the information presented in Figure 3.3.7.3.1.2-1 of the same NASA report to estimate the mass of each of the solids included in your table if your goal is to model Nathan Chen's spins. Add these estimates to the final (seventh) column.

F. **Clearly state any and all assumptions you made to complete Part I**

Part II: Calculation of Mass Moment of Inertia

Your next step is to calculate the mass moment of inertia (I) of your modeled body about its rotational axis.

A. Predict which position (Camel or Scratch) has the larger I value

B. Calculate the mass moment of inertia of each solid about an axis that is parallel to the rotational axis and passes through the solid's center of gravity

C. Determine I of the entire body about the rotational axis *in units of kgm^2* (**assume the rotational axis is fixed**)

   a. If needed, use the parallel-axis theorem to determine the mass moment of inertia of each solid about the axis of rotation

   b. Once the mass moment of inertia of each solid is determined relative to the rotational axis, I of the total body is the algebraic sum of individual solids' mass moments of inertia

D. State if your calculated results match your prediction

E. **Clearly state any and all assumptions you made to complete Part II**

Part III: Calculation of Angular Velocity & Work

A. Based on Dr. Ramo's analysis of a video of Nathan Chen, he completes one rotation in the camel position every 0.5 seconds. Using this information, calculate his final angular speed after he has completed a transition to a scratch spin position. *Express your answer in rad/s and RPM (revolutions per minute).*

B. **Clearly state any and all assumptions you made to complete Part III(A)**

C. Based on this change in angular velocity, calculate the amount of work done by Nathan in changing his position.

D. **Clearly state any and all assumptions you made to complete Part III(B)**

E. According to the Guinness World Record, the fastest scratch spin was 342 RPM. How does this value compare to your value calculated in Part A? **State which assumption(s) you have made thus far that you think most affected your calculation in Part A.**

F. If you were to re-do your model and/or make different assumptions describe at least one change you would make.

Part IV: Gender Comparison

Side-by-side camel spins and scratch spins are also required elements in pairs skating (a man and a woman skating together). Points are awarded, in part, based on how synchronized their spins are (meaning they rotate at the same speed). The United States' top pair team is Alexa Knierim (1.57m, age 30) and Brandon Frazier (1.89m, age 29).

A. Describe how you would adjust the composite rigid-body models you created for Nathan Chen to model Brandon Frazier. Based on these changes, would the mass moment of inertia increase, decrease, or not change? *You should explain your answer, but you **do not** need to calculate Brandon's I values.*

B. Describe how you would adjust the composite rigid-body models you created for Nathan Chen to model Alexa Knierim. Based on these changes, would the mass moment of inertia increase, decrease, or not change? *You should explain your answer, but you **do not** need to calculate Alexa's I values.*

C. Based on your analysis, which skater of the pair spins faster than the other, on average? In other words, which skater will have to slow their spin rotation to match that of their partner? **Explain the dynamics basis of your prediction.**

D. If you were the pairs skating coach, how would you recommend this skater slow their spins?