Work In Progress: Torque, Engineering Students, and the Conceptual Shift from External to Internal Forces

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Abstract

This work-in-progress paper explores how students express their understanding of torque. Typically introduced in first semester physics, torque is a fundamental concept across many engineering disciplines. However, the transition from physics to engineering mechanics (i.e., statics) appears to be a hurdle for students. Specifics on why students struggle with torque are sparse. Both quantitative and qualitative studies have investigated how students learn torque, but to our knowledge, no study has yet investigated how students conceptualize torque. To address this gap, this qualitative study investigated the research question: What themes emerge when students express their conceptualization of torque? To address the research question, this study adopts a qualitative methodology based on phenomenography. Semi-structured interviews were conducted with 13 students from the engineering technology program at Metropolitan State University of Denver (MSU Denver). Students were questioned about torque in different contexts. Data analysis was performed using content analysis techniques, and descriptive coding was used. Topics covered in the interviews included students' prior knowledge on torque, their perception of torque in proportion to other variables (force, distance, and angle), their ability to estimate the magnitude of torque, and their conceptualization of torque in other formats. Academic experience of each student was tracked by the highest-level class taken: physics, statics, or mechanics of materials. In this work-in-progress paper, we focus on one particularly intriguing result: A rich theme is how students understand torque through one of two forms. In the first form, based on entry-level courses in physics, torque results from external forces applied to an object of interest. In the second form, based on the advanced-level course of statics, torque (sometimes called moment) results from internal forces within the object of interest. Students with less academic experience generally conceptualized torque as an external force, as presented in first-semester physics, corresponding to a dynamic point of view. In contrast, students with more academic experience more often conceptualized torque as internal forces corresponding to a static equilibrium point of view. This work-in-progress paper shows that, in the context of learning torque, the transition from physics to engineering mechanics is not trivial. Focus on the classroom transition between torque with external forces and internal forces should foster improved curricula and pedagogy for improved student learning.

Keywords: Higher Education (4.c), Undergraduate (4.f), Engineering Curriculum (5.a), Conceptual Learning (7.a), Interviews (12.a.iii), Phenomenography (12.d.v.7).

1. Introduction

Torque, the rotational analog of force, is defined as follows:

$$\tau = r \times F, \tag{1}$$

$$|\tau| = |r|\ |F| \sin(\theta), \tag{2}$$

$$\tau = I\ \alpha\ , \tag{3}$$

where τ is the torque vector, r is the position vector (to the point where the force is applied), F is the force vector, θ is the angle between r and F, I is the moment of inertia, and α is the angular acceleration. Torque, which for the purposes of this study is synonymous with moment, has been seen as a hurdle for engineering students (Litzinger et al., 2010):

> "From the comparison of written work of the weak and strong (statics) students, we learned that the weaker students were poorer performers in creating free-body diagrams and formulating the equilibrium equations, with one caveat. The two groups were about equally likely to forget to use a moment … balance equation."

This hurdle is important, because it is part of a decades-long challenge for engineering programs to recruit, retain, and graduate students (Steenkamp et al., 2017). For example, Andriani et al. (2020) has shown the lack of motivation of students in trying to learn torque and static equilibrium. Several researchers have stated that students have difficulty in learning statics (Yoonsoo, 2015; Kontra et al., 2015); we posit that understanding students' conceptions of torque could help in this regard. A search of the literature has found several quantitative studies and a smaller number of qualitative studies on students' conceptions of components of torque or similar physics concepts.

Beginning with quantitative studies, Kontra et al. (2015) covered angular momentum, which is related to torque via equation (3). They worked with students by introducing them to angular momentum through tactile feedback provided by a joystick, which provided a physical connection to the student, and then assessed student understanding through quizzes and brain scans. Several quantitative studies (Kontra et al., 2015; Zacharia, 2012) dealt with a sport related activity through brain magnetic resonance imaging (MRI) and cognitive tests. Other quantitative studies include Rimoldini and Singh (2005), who studied student understanding of rotational motion and rolling. Two studies focused on cross products (Deprez et al., 2019; Kustusch, 2016), which relate to torque via equation (1).

Turning now to qualitative studies, Litzinger and others (2010) explored the cognitive ability of students to solve statics problems, finding that students mostly solved problems by memorizing how to solve for reaction forces, which may indicate a loss of a tangible link and intuition. Thompson and Saldanha (2003) used torque to illustrate the process by which students can conceive of the possibility of measuring different attributes (e.g., torque as an amount of twisting force). Zacharia et al. (2012) investigated physicality in kindergarten students and their understanding of a balance beam. The study did not cover torque per se, but equation (2) is often used to find the balance point of a balance beam.

Although both quantitative and qualitative studies have investigated how students learn torque, to our knowledge, no study has yet investigated how students conceptualize torque. This gap in the literature leads to our research question: What themes emerge when students express their conceptualization of torque?

2. Methods

Our theoretical framework is knowledge in pieces (diSessa, 1993). From this perspective, a person's conception of some construct, such as torque, comprises a collection of knowledge elements. Our methodology is phenomenography, which we chose because we wanted to study the individual experiences of students learning torque. Phenomenography is a guide that helps to focus on the different ways people think about phenomena. Following Miles and Huberman (1994), samples were stratified by academic experience, which was tracked by the highest-level class taken: physics, statics, or mechanics of materials. These four strata (including those who had not yet taken physics) each had about the same number of interviewees. Students were recruited through Metropolitan State University of Denver (MSU Denver) class lists by the first author and colleagues at MSU Denver. Most of these students were in Civil Engineering Technology or similar programs. The 13 students interviewed spanned from students taking their first introduction to engineering class to students who were about to graduate. Interview protocols were approved by the Colorado Multiple Institutional Review Board IRB (COMIRB) protocol #19-3090 with review and consent from the MSU Denver human subjects review board. These human subjects reviews limited recruitment to students unlikely to be in the interviewer's future classes in order to avoid the power dynamics that result when students speak to their current or likely future professors.

Semi-structured interviews were conducted using Microsoft Teams in May-June 2022, following the questions given in the Appendix, which prompted think-aloud responses. Topics included prior knowledge on torque, perception of torque in proportion to other variables (force, distance, and angle), estimating the magnitude of torque, and conceptualization of torque in other formats. The interviewer sometimes gave prompts such as units. The interviews took 20 minutes on average. Transcription from the Microsoft Teams meeting recordings was typed manually with help from closed captions. Visual drawings from the students were also added to the transcripts. Occasionally, body language was also noted.

Coding followed common procedures with specifics from Bryman (2016) using codes in several categories. Saldaña (2013) was also used for emergent codes, categories, and themes. Coding was performed entirely by the lead author so inter-rater reliability has not yet been attempted. We used Microsoft Excel to perform coding, student assessment memos, and theme creation for the qualitative data transcribed from the students. For this work-in-progress paper, we focus on three particular codes: (1) class experience, (2) conceptualization as external forces versus internal forces, and (3) how students adjusted between the forms of internal and external forces.

3. Results

Through interviews and analysis of the responses, we found that students express their understanding of torque mostly through two forms. The two forms are torque with *external* forces and torque with *internal* forces. As students advance through the curriculum, from entry-level courses in physics to advanced-level courses in engineering mechanics, the form in which torque is presented changes from predominantly external forces to predominantly internal forces.

Overall, the students' expressions were varied, sometimes spontaneous, and often were not expected from the student's class level experience. We often saw a shift from external force expressions of torque from early class level students to more conceptual themes expressed in internal force expressions of torque from advanced level students. Analysis of student expressions shows that the transition between external forces, usually dynamic, and internal forces, usually static, is often tricky. Student expressions often differed when discussing torque in the two different forms.

The following are example conversations where students mentioned the difficulty of thinking in the different forms. Participant 6 described confusion between torque and moment (where quotations have been edited to remove filler words such as *like* and trimmed for clarity and brevity marked with an ellipsis):

> "I always had a hard time distinguishing it between moment. I think they're vaguely the same thing, but basically just like a rotational force. The rotational force by a motor… in a vehicle or something. What causes things to rotate."

Participant 1, who had not yet taken physics, stated that they participated in self-learning. The student had a beginning understanding of canceling torque in statics, which the student calls static torque:

> "I would say static torque would almost be like trying to push open a door or open a lever and it not opening like you're not utilizing the hinges on it … I would just say the torque is essentially zero … because you're not able to push on it, move it."

Several students spontaneously commented on how confusing it is when torque is presented in terms of a static internal forces when they often studied torque in terms of a dynamic external forces in physics. Students also used nontraditional or self-taught concepts to try to understand the difference between these forms. Many students looked for movement, deformation, physical feelings, or physical actuation put upon an object due to torque.

Multiple students used unique approaches to harmonize the dissonance between the forms of external and internal forces. We do not have a comparison of these approaches with other mechanical subject conceptualizations, but it is suspected that these approaches are in response to the hurdles found in students' transitions in their conceptions of torque.

4. Discussion and Conclusions

Many students struggle to express torque when shifting from an external force form to an internal force form. There is often a tangible cause and effect in the external forces creating torque. The forces creating torque, the actions of the torque, and the results of torque are almost always visible and tangible in an external force form. Students then progress to the internal force form, often in statics. Although internal forces can certainly generate visible deformation of highly elastic solids, in many engineering applications (*e.g.*, steel beams) the deformations are small enough to be invisible. In these applications, internal force forms are almost completely devoid of visible and tangible torque. This transition can create a large challenge in how students see torque concepts. Recognizing this challenge is the first step toward creating more effective pedagogy.

There are several limitations in the current study. During the interviews, we generally used the term *torque*, only occasionally using the equivalent term *moment*. Because torque is the common terminology in external force forms, this language may have led to more students to respond with external force expressions. Several of those expressions were surprising; upon reflection, some opportunities for follow-up questions were missed.

In conclusion, this study brought into focus the conceptual confusion between the external and internal force forms in which torque (or moment) is expressed and measured. Students express frustration with the transition between the two forms. When asked to describe torque or describe examples, most students express torque in a tangible external force form. Students who had not taken statics had difficulty describing equations in an internal force form without added information from the interviewer. However, this is likely evidence of why many of these students are frustrated when they transfer to internal force forms. The form in which torque is expressed matters. Tangible results from torque are easier for many students to comprehend, and prior experience and intuition may play a part in the attractiveness of the external force form. Exploring how we may be able to bridge the two forms could be worthy future work. More generally, the methods presented here, aimed at understanding how students conceptualize technical concepts, lays a groundwork for future work addressing other challenges in engineering education.

Appendix

This appendix lists the semi-structured interview questions:

1. What do you think of when you hear the term “torque”? Can you give an example?
2. A wrench is a common application of torque, also known as a "twisting force" make you think about? Can you give an example of when you have felt something like that?
3. Find a reasonably heavy book and hold it out at arm’s length. Think of what you feel. What keeps the book still? Hold it at half length, your arm will probably have a “V” shape. How do the feelings change? Hold it at your side down the length of your body. How does it feel? What keeps it still?
4. What things might be important to measure with the book activity? When is the book harder or easier to lift? Why?
5. This equation defines torque. Have you seen this equation before? In what context? How do you make sense of it?
6. How do you see the radius, force, and angle in the book activity? Can you show me, give an example?
7. Sometimes Nat has trouble when trying to twist open a jar. When this happens, Nat puts the jar at a lower height or stands on a step stool. Nat says both of these things help. How could torque explain this?

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