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Student Misconceptions about Force and Acceleration in Physics and Engineering Mechanics Education*

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Conceptual misunderstanding, also known as misconception, is common among many learners, especially novice learners, and often results in learners' poor academic performance in many disciplines. The present study focuses on two fundamental and critical concepts in physics and engineering mechanics education: force and acceleration. The present study pieces together scattered literature information on student misconceptions about force and acceleration, and develops a comprehensive list of all possible categories (or types, or "symptoms") of student misconceptions: 38 misconceptions (in two categories with nine sub-categories) about force and 15 misconceptions (in three categories) about acceleration. The most commonly reported misconception about force is "motion implies force" for both K-12 (kindergarten to grade 12) and college students. The most commonly reported misconception about acceleration is "acceleration is always in the direction of motion." The present study further examines the reasons reported in the existing literature for why students have various misconceptions about force and acceleration. These reasons are grouped into four categories: (1) preconceived misunderstanding; (2) incomplete or partial understanding; (3) wrong interpretations and comprehensions; and (4) vernacular misunderstanding. Methods of how to correct student misconceptions are also suggested and discussed in this paper.

Keywords: student misconceptions; force; acceleration; physics; engineering mechanics

1. Introduction

1.1 Student misconceptions

As concepts are fundamental building blocks of knowledge in all academic disciplines, a solid understanding and comprehension of concepts plays a critical role in helping learners develop their knowledge base and structure, apply correct concepts to problem solving, and thus develop expertise and competence in their professions [1]. However, conceptual misunderstanding—also known as misconception—is very common among many learners, especially novice learners, and often results in poor or wrong knowledge base and structure. Misconceptions have been reported as one of the main reasons for poor academic performance or poor problem-solving skills in many disciplines, particularly in science, technology, engineering, and mathematics (STEM) disciplines [2]. For example, failure in critical courses during college was reported as one of the primary reasons that students drop out of engineering. With the decreasing number of engineering graduates, the attrition rate of engineering undergraduates remains high. Ohland et al. [3] reported that only about 57% of engineering undergraduates in the United States of America completed their degrees in engineering across many institutions of higher learning involved in their study.

Research further shows that student conceptual misunderstandings can be robust and difficult to correct [4]. Some misconceptions stem from students' previous experiences, tracing back to high school or early college. Students come into the classroom not as blank slates, but with durable and robust preconceptions associated with their prior experiences. Some student preconceptions even violate the fundamental mathematical and scientific principles the instructor taught in the classroom [5].

1.2 Student learning challenges in understanding physics and engineering mechanics concepts

As two closely-related courses, physics (at both high school and college levels) and engineering mechanics (i.e., statics and dynamics courses taught in the first or second year of undergraduate study) share many common concepts, including displacement, velocity, force, acceleration, energy, impulse, and momentum, as well as a variety of laws and principles such as Newton's First, Second, and Third Laws of motion. Inherently, students in these courses share many common misconceptions, which negatively affect their academic performance not only in these courses but also in many subsequent courses such as machine structure and design as well as advanced dynamics.

A student's perception about a concept reflects his or her level of understanding of course materials. In physics and engineering mechanics education,

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some misconceptions such as "friction always hinders the motion," are not difficult to correct [6]. The instructor can demonstrate to students that in a case in which an absolutely frictionless occasion exists, one cannot even walk a step. Friction is obviously the driving force for motion in this case. However, some student misconceptions are subtle and may go unaddressed; for example, some students mistakenly think that "objects in outer space have no weight, because they are 'weightless'" [7, 8].

Compared to physics, engineering mechanics (i.e., statics and dynamics) focuses more on in-depth analysis of concepts (such as force, work, energy, velocity, and acceleration) in either linear or curvilinear motion. Typically, engineering undergraduates must complete college physics before they are allowed to take engineering mechanics courses, which have been widely regarded as the most difficult undergraduate courses for students to succeed in [9, 10]. Students are often confused about the complicated relationships among the variety of difficult concepts in engineering mechanics [11]. Fang [12] investigated student perceptions of a set of concept pairs (i.e., two concepts closely related but significantly different) in engineering mechanics as well as the correlation between student perceptions and student problem-solving performance. He found that students have many misconceptions about lower-level concept pairs in engineering dynamics, and that statistically correlation exists between student perceptions and student problem-solving performance.

1.3 Scientific contributions of the present study

In the present study, we have conducted an extensive literature review using popular literature databases including Web of Science, Pro-Quest Digital Dissertation, Science Direct, IEEE Xplore Digital Library, Google Scholar, and our university's library search engines that include a number of literature databases. Particular attention has been paid to the following journals and conference proceedings that focus on either physics education or engineering education: Journal of Engineering Education, International Journal of Engineering Education, European Journal of Engineering Education, Advances in Engineering Education, Physics Education, Cognitive Science, and American Society for Engineering Education (ASEE) annual conference proceedings, to name a few.

The results of our literature review show that many studies have been conducted in the past to address student misconceptions in either physics or engineering mechanics education. If we use a medical term, these categories (or types) can also be called "symptoms" as in the case in which a patient having a particular disease develops various forms of symptoms including fever, headache, vomiting, and so on. Individually, the vast majority of relevant published studies typically deal with no more than three symptoms of student misconceptions. For example, Goenen [7] investigated misconceptions among 267 science and physics student teachers. The four testing items he used in his study covered only one sub-category of misconceptions about force (specifically "gravitational force"). Rosenblatt et al. [13, 14] studied student conceptual understandings of directional relationships among vector force, velocity, and acceleration. Temiz and Yavuz [15] studied student misconceptions about Newton's Second Law and found that students were hesitant to apply Newton's Second Law when given the context of outer space. Their study results show that students misunderstood the concept of gravitational force executed upon objects in outer space.

As the starting point of our systematic research, the present study focuses on two fundamental and critical concepts in physics and engineering mechanics education: force and acceleration. The scientific contributions of the present study include: (1) piecing together of scattered literature information on student misconceptions about force and acceleration, and development of a comprehensive list of all possible categories (or types, or "symptoms") of student misconceptions about force and acceleration based on extensive literature review and analysis; and (2) examination of the reasons reported in the existing literature for why students have various misconceptions about force and acceleration. The examination will help explore effective methods to correct student misconceptions.

1.4 Research questions of the present study

Because students have different backgrounds, experiences, and prior knowledge, it might be easy for one student to understand one concept, but challenging or even difficult for another student to understand the same concept. Therefore, the present study aims to answer the following two fundamental research questions:

1. Based on the existing literature, *what* are all possible categories of student misconceptions about force and acceleration in physics and engineering mechanics education?
2. What are the reasons reported in the existing literature for *why* students have these misconceptions about force and acceleration?

The first research question addresses various forms of "symptoms" of student misconceptions about force and acceleration. The second research question addresses the reasons behind those symptoms. In the remaining sections of this paper, the detailed research method employed in the present study is described first, including the keywords and inclusion and exclusion criteria used in the literature search. Then, all possible categories and associated sub-categories of student misconceptions about force and acceleration are presented, followed by an examination of reported reasons why students have these misconceptions. Methods for correcting student misconceptions are also suggested and discussed. Conclusions are made at the end of the paper.

2. Research method

2.1 Key words, inclusion and exclusion criteria

The above Introduction section has provided a brief description of a set of literature databases employed in the present study, including the journals and conference proceedings examined. The following keywords, including their combinations, were used in the literature search: misconception, conceptual misunderstanding, preconception, alternative conception, force, tension, acceleration, speeding-up, velocity, speed, movement, and motion.

The following criteria were used to evaluate whether a published study was relevant and therefore should be included in the present research. These criteria, also called inclusion criteria, include:

1. Time period when studies were published: 1970–2015
2. Publication categories: journals (print and/or online versions), conference proceedings, and degree theses and dissertations
3. Topics addressed: physics, engineering mechanics, engineering statics, engineering dynamics
4. Relevant concepts addressed: motion, velocity, speed, acceleration, frictional force, gravitational force, mass, and inertia.

Note that the No. 4 criterion listed above also includes several concepts (such as motion, velocity, speed, and displacement) beyond force and acceleration because those concepts are most closely related to force and acceleration.

If a published study particularly focused on the following concepts, that study was excluded from the present study. In other words, the following concepts were used as exclusion criteria:

1. Rigid body
2. Mass momentum inertia
3. Impact
4. Angular velocity
5. Angular acceleration

2.2 Categorizing the findings of relevant studies

Based on the results of the literature review described above, student misconceptions about force and acceleration were categorized into different categories and sub-categories. These categories and sub-categories were discussed and agreed on by the two researchers of the present study. Both researchers have mechanical engineering backgrounds and are content experts of this research. One researcher (the second author of this paper) has been an instructor for engineering dynamics courses for nearly ten years and has taught nearly 2,000 students in his engineering dynamics courses over the past ten years.

3. Categories and sub-categories of student misconceptions

3.1 Number of relevant studies and a representative list of journals examined

Using the research method described above, a total of 135 studies were found from more than 30 journals and numerous conference proceedings. Among these 135 studies, 31 studies focused on student misconceptions about force, and only 8 studies focused on student misconceptions about acceleration. A representative list of journals that have published studies on student misconceptions about force and/or acceleration are provided below. This list is not intended to be all-inclusive, and is used for illustration purposes only:

- Journal of Engineering Education
- International Journal of Engineering Education
- European Journal of Engineering Education
- International Journal of Science Education
- Cognitive Science
- European Journal of Physics
- Cognition and Instruction
- Instructional Science
- American Journal of Physics
- International Journal of Theoretical Physics
- Physics Education
- Journal of Computer Assisted Learning
- Journal of Counseling & Development
- Journal of Research in Science Teaching
- International Journal of Science and Mathematics Education

3.2 Assessment instruments employed in the existing research

Various assessment instruments have been developed to identify various categories and sub-categories of student misconceptions about force and acceleration. For example, Hestenes et al. [16] and Hestenes and Halloun [17] developed the well-known Force Concept Inventory (FCI) to identify some intuitive preconceptions of students, involving such relationships as those between motion and force, or between acceleration and force. Built upon the FCI, Hestenes and Wells [18] developed a Mechanics Baseline Test (MBT) to provide a comprehensive assessment of student understanding of mechanics concepts.

Student misconceptions about dynamics concepts were evaluated in the Dynamics Concept Inventory (DCI) [19, 20], which has been widely adopted by many engineering educators and researchers. Steif and Hansen [21] and Steif and Dantzler [22] employed 27 multiple-choice questions from the Statics Concept Inventory (SCI) to study student misconceptions of force in statics by involving 245 college students from 5 universities. His research results show that the SCI offers a valid evaluation of student conceptual understanding in statics.

Rosenblatt et al. [13, 14] developed an assessment instrument called FVA (Force, Velocity and Acceleration) to assess student conceptual understanding of the relationships among the directions of force, velocity and acceleration. Thornton and Sokoloff [23] used their own developed Force-Motion Concept Evaluation (FMCE) to assess student conceptual understanding of the relationship between force and motion.

All six assessment instruments described above were reported to be reliable for assessing student misconceptions about force and acceleration. Table 1 shows the number and percentage of technical questions assessing student understanding of force and acceleration in six primary instruments. From Table 1, it is also clear that force and acceleration play a foundational and critical role in physics and engineering mechanics education. It is also for this reason that we selected these two concepts as the starting point of our systematic study on student misconceptions.

3.3 Student misconceptions about force

Tables 2 and 3 summarize the categories and subcategories of student misconceptions about force and acceleration, respectively. The most commonly reported misconception about force is "motion implies force" for both K-12 (kindergarten to grade 12) and college students. The most commonly reported misconception about acceleration is "acceleration is always in the direction of motion."

As shown in Table 2, student misconceptions about force consist of two categories and nine subcategories. Although these misconceptions were described differently in different papers, they all share some common features. For the following paragraphs, we only selected representative papers in each sub-category to elaborate student misconceptions. We did not cite all relevant papers we found; otherwise, this paper would be tedious.

Force itself: Misconceptions are associated with misunderstandings of Newton's laws of motion, incomplete understandings of physics and mechanics concepts, and student learning difficulties in comprehending the properties of force itself. Demirci [24] investigated student misconceptions about active force, summarized as "only active agents exert force" and "passive force does not exist." Students commonly think that only active objects can exert force on a passive object. Research also shows that many high school physics teachers could not even recognize the passive force that a table exerts upon an object placed on it [25].

Force vs. motion: Despite Newton's First Law of Motion, many students mistakenly believe that a moving object has a continuous force acting upon it, and that if an object is not moving, there is no net force acting upon it [24, 26, 27]. This particular misconception reflects a lack of skill to apply what has been learned in the classroom to real-world situations.

Force vs. velocity: A heavier object has more gravitational force acting on it. However, many students mistakenly believe that a heavier object has a greater gravitational acceleration and thus reaches the ground at a higher speed even though students already know about the famous of Galileo's experiment at the Leaning Tower of Pisa [26].

Table 1. Number and percentage of technical questions assessing student understanding of force and acceleration in six primary instruments

Concept	DCI	FCI	MBT	FMCE	SCI	FVA
Total	29	30	26	47	27	17
Force (F)	9 (31.0%)	19 (63.3%)	13 (50.0%)	24 (51.1%)	N/A	N/A
Acceleration (A)	9 (31.0%)	16 (53.3%)	15 (57.7%)	8 (17.0%)	N/A	N/A
Intersection (F&A)	4 (13.8%)	11 (36.7%)	11 (42.3%)	N/A	N/A	N/A
Union (F+A)	14 (48.8%)	24 (80.0%)	17 (65.4%)	32 (68.1%)	15 (55.6%)	10 (58.8%)

DCI: Dynamics Concept Inventory [19, 20];
FCI: Force Concept Inventory [16, 17];
MBT: Mechanics Baseline Test [18];
FMCE: Force-Motion Concept Evaluation [23];
SCI: Statics Concept Inventory [21, 22];
FVA: Force, Velocity and Acceleration [13, 14].

Table 2. Student misconceptions about force

Category	Sub-category	Student misconceptions	Example studies
General Force	Force itself	1. Force must be active.	[24]
		2. Passive forces don't exist.	[25, 26]
		3. Two forces in an action-reaction pair can cancel or "balance."	[22, 26]
	Force vs. Motion	4. Motion implies force. (No motion implies no force)	[24, 26–28]
		5. Objects will continue along that path, linear or curvilinear, even after all the forces are removed.	[24]
		6. The net force must be in the direction of motion, so objects will travel along a line in that direction.	[28, 29]
		7. An object will slow down if there is no net force.	[24]
		8. Rocket propulsion is due to exhaust gases pushing on something behind the rocket.	[30]
		9. Freely falling bodies can only move downward.	[31]
		10. Being at rest is the "natural" state of motion of all objects.	[24, 26, 27]
	Force vs. Velocity/ Speed	11. Constant velocity means no force acting on the object.	[32]
		12. Force parallel to velocity vector.	[24, 26, 27]
		13. An object moving at a constant velocity has no forces acting upon it.	[32]
		14. Faster moving objects have larger force acting on them.	[26]
		15. Heavier objects fall faster than lighter ones.	[1, 26]
	Force vs. Acceleration	16. Acceleration implies increasing force.	[24]
		17. Acceleration equals to the force divided by mass. (Newton's Second Law).	[24-26, 32]
	Force vs. Mass	18. A big object is hard to push because it is heavy.	[22, 26]
		19. Large objects exert a greater force than small objects.	[26]
	Force vs. Energy	20. Force is energy.	[1]
		21. A constant force accelerates a body, until the body uses up all the power of the force.	[24]
Particular Force	Gravitational force	22. Mass and weight are same.	[33]
		23. Weightlessness means there is no gravity.	[7]
		24. There is no gravity (gravitational force) in outer space.	[7, 29]
		25. Only gravity works on the people standing on the ground.	[7, 10]
		26. Moon stays in orbit because the gravitational force on it is balanced by the centrifugal force acting on it.	[7, 8]
		27. Constant gravity does not imply constant acceleration	[7, 8, 32]
		28. Gravity is selective; it acts differently or not at all on some matter.	[15]
		29. Gravity increases with height.	[8]
		30. Gravity requires a medium (air) to act through.	[34]
	Frictional force	31. Friction always hinders motion.	[6]
		32. Friction is constant and equals to $f = \mu N$ (normal force).	[6, 7, 21]
	Other forces and items	33. Contact force on object always equals object weight.	[35]
		34. Contact forces won't exceed the object weight.	[6]
		35. Force must happen when two or more objects contact with each other.	[6, 7, 21]
		36. The tension in a string is the sum of the forces acting on each end.	[36]
		37. Inertia is force.	[35]
		38. Impetus is a force.	[32]

Table 3. Student misconceptions about acceleration

Category	Student misconceptions	Example studies
Acceleration vs. Force	1. Acceleration implies increasing force.	[37, 38]
	2. Acceleration equals to the force divided by mass.	[1]
Acceleration vs. Velocity/Speed	3. The maximum acceleration happens when the object reaches the maximum velocity/ speed.	[39]
	4. Velocity is constant when acceleration is also constant.	[39]
	5. Acceleration equals zero when speed equals zero (even instantaneously).	[40]
	6. Larger (smaller) velocity means larger (smaller) acceleration.	[41]
	7. Same velocity means same acceleration for two objects.	[24, 41]
	8. Acceleration equals zero when the speed (magnitude of the velocity) keeps constant.	[42]
	9. An object moving in circle with constant speed has no acceleration.	[43]
	10. Acceleration is the change of the speed (without direction).	[42]
Direction of Acceleration	11. The motion of an object is always in the direction of the net force/acceleration applied to the object.	[13, 14, 38]
	12. Acceleration always occurs in the same direction as motion.	[5, 13, 14]
	13. Acceleration is always in a straight line.	[44]
	14. An increase in speed directly proportional to an increase in acceleration.	[41]
	15. Acceleration is a scalar (with magnitude, but no direction).	[45]

Force vs. acceleration: Many students strongly believe that acceleration implies increasing force. This misconception might be associated with student confusion of velocity and acceleration [32].

Force vs. mass: Both the Force Concept Inventory [16, 17] and the Dynamics Concept Inventory [19, 20] address student misconceptions about the action-reaction force pair. Much research [22] has shown that both K-12 and college students have the common misconception that "Large objects exert a greater force than small objects."

Force vs. energy: According to the understanding of some students, a moving object moves because it has potential energy caused by gravitational force, whilst the same object in outer space would have no potential energy because it would be weightless [17]. This particular misconception can be corrected relatively easily if correction is made at an early stage in a student's high school study. Otherwise, students may carry this misconception to their college studies, where it is much harder to correct.

Gravitational force: Young students think that the objects in the outer space are weightless because there is no gravitational force acting upon them. Older students think that the gravitational force changes drastically with various altitudes [7]. Research shows that these misconceptions are common even among some preschool teachers [8]. A questionnaire survey administrated among 116 undergraduate students revealed that students were not confident applying Newton's Second Law of motion in outer space where there is no friction or contact medium between two objects [15].

Frictional force: "Friction always hinders motion" is a common misconception among many students [6]. The well-known Dynamics Concept Inventory addresses this particular misconception in its Questions 27 and 29 [19, 20]. This misconception is associated with some real-world experiences of students. For example, friction slows down a moving object. This misconception about frictional force is very common among K-12 teachers and senior physics students in college.

Other forces and items: Many students are confused about impetus. They confuse impetus with force by introducing an imaginative force working on a moving object, and insisting that the motion of the object ceases when impetus wears down [32].

3.4 Student misconception about acceleration

Studies on student misconceptions about acceleration are much fewer than studies on student misconceptions about force. A possible reason is that acceleration is more abstract than force, and the correction of student misconceptions about acceleration is therefore harder. Table 3 has summarized the categories of student misconceptions about acceleration. As seen from Table 3, students have 15 common misconceptions about acceleration. Compared to student misconceptions about force at both K-12 and college levels, student misconceptions about acceleration were more often reported in college-level engineering mechanics courses, particularly in engineering dynamics courses. This is because acceleration is a central concept in these college-level engineering dynamics courses. For the following paragraphs, we selected representative papers (rather than all relevant papers) in each sub-category to elaborate student misconceptions.

Acceleration vs. force: Rowlands et al. [37] administered a semi-structured interview to study student misconceptions about acceleration. His interview records show that students did not understand the relationship between acceleration and force. The common misconception is described as "acceleration implies increasing force." Another study showed that students easily neglect acceleration when the direction of velocity changes or when an object moves in a curved trajectory that causes normal acceleration [38].

Acceleration vs. velocity: Students were often confused about the velocity and acceleration of an object. Many students thought that if two objects had the same velocity, those two objects must also have the same acceleration or vice versa [41]. Some students even thought that there existed a linear relationship between force and velocity [45].

Direction of acceleration: Macabebe et al. [40] found that most college students did not clearly understand the concept of negative acceleration, and only about 3% of students could correctly answer relevant questions. The root cause of student misconceptions about the direction of acceleration is related to students' real-world experiences where friction plays an important role. Rosenblatt et al. [13, 14] assessed students' understanding of the relationships among the directions of force, velocity, and acceleration of a moving object. She found that "partially correct" concepts were common among 800 college students involved in her study. She suggested that the correction of student misconceptions should start from correcting these "partially correct" concepts.

4. Reasons why students have misconceptions

Compared to extensive research on identifying what misconceptions students have about force and acceleration, the research on why students have these misconceptions is still limited. For example, much research has identified that the most common misconception of students about force is the relationship between motion and force, because most students mistakenly believe motion implies force. However, limited research was conducted to reveal the reason why students have this particular misconception.

In spite of the above-described reality, we made efforts in the present study to categorize the limited research into different types. Based on our analysis, student misconceptions can be generally grouped into the following four types:

1. Preconceived misunderstanding, i.e., the misunderstanding carried over from a student's previous experiences.
2. Incomplete or partial understanding.
3. Wrong interpretations and comprehensions.
4. Vernacular misunderstanding, i.e., misunderstanding due to a student's insufficient or even deficient reading skills, or due to the lack of clarity in textbooks and other reading materials.

Most often, these four types of misunderstanding overlap, and the boundaries among them are not absolutely distinct. For example, a student may develop a conceptual misunderstanding from his or her prior experience that was related to his or her low level of reading skills. In other words, the same student can develop one, two, three, or all four types of misunderstanding about the same concept. The following paragraphs elaborate each of these four types of misunderstanding.

4.1 Preconceived misunderstanding

Student misconceptions about force and acceleration are often associated with student pre-existing understanding of physics and engineering phenomena. Clement [27] found that student conceptual misunderstanding of force and acceleration could be traced back to deep-seated preconceptions that make a complete understanding of Newton's First and Second Laws of motion very difficult. In some cases, real life experience even provides students with incorrect preconceptions that can negatively influence their understanding of concepts [15]. A typical example of misleading life experience is how a car stops when the driver firmly pushes the car's brake. By observing or experiencing this phenomenon, students often think that the direction of friction is *always* opposite to the direction of motion [32]. This misunderstanding can be corrected by exposing students to different sorts of real life experiences. For example, ask students to compare the direction of friction with the direction of motion when a person walks on foot. In the latter case, the direction of friction is in the same direction as the motion; otherwise, the person cannot walk. Hands-on experiments, video demonstrations, and computer simulation and animation, are among the useful tools to help correct this type of misconception.

Not only students but also teachers can have preconceived misunderstanding. Researchers such as Bayraktar [26], Goenen [7], and Timur [8] have investigated the conceptual understandings of force and acceleration among K-12 teachers. Their results show that preconceived misconceptions were also common among teachers. Inevitably, teachers pass on their misconceptions to their students. Bayraktar [26] studied K-12 teachers' preconceptions and demonstrated that teacher's educational experiences significantly influence their students' understanding of concepts. As teachers make difference, quality teacher education, not only on pedagogy but also on scientific content, always plays a critical role in ensuring high quality student education at both K-12 and college levels.

4.2 Incomplete or partial understanding

Incomplete or partial understanding often occurs when a student does not fully understand or comprehend key concepts. Misunderstandings may involve the accurate definition of a particular concept, associated math, the pre-conditions in which to apply the concept, and the similarities and differences between two closely related concepts [11, 12]. For example, in physics and engineering dynamics, the "Principle of Work and Energy" and "Conservation of Energy" are two closely-related but significantly different concepts. When there is a friction force, only the "Principle of Work and Energy" can be used for problem solving. However, students may mistakenly select "Conservation of Energy" to solve problems without realizing that friction reduces energy.

In another example, Halim et al. [28] indicated that many students developed a tendency to memorize course contents without truly understanding them, thus students had difficulty applying what they learned to new situations. Lopez [43] had similar findings when studying student misconceptions about angular and linear acceleration in the rigid rolling body without slipping, and concluded that student misconceptions were correlated with student priority on getting the right answer for textbook homework problems, rather than on fully understanding course materials. Montfort et al. [46] showed that some engineering students who graduated from a university with an engineering degree did not truly master fundamental physics and engineering concepts.

Incomplete or partial understanding can be corrected by exposing students to a variety of problem-solving activities, so that students can develop solid critical thinking and reasoning skills and have a full mastery of key concepts. For example, the instructor can develop two sets of different problems. One set of problems involves friction, and another set does not involve friction. The instructor can then ask students to work on each problem, and finally show students the correct concepts (such as the "Principle of Work and Energy" or "Conservation of Energy") students should use to solve different problems.

4.3 Wrong interpretations and comprehensions

Wrong interpretations and comprehensions are the discrepancies between a student's own understanding and the correct meaning of a concept. College students have complained about poor academic performance due to underprepared skills and knowledge of mathematics, which hindered their understanding of the concepts they have met [47]. Lopez [43] explored common misconceptions of acceleration among first-year engineering students, and results indicated that many students tended to use scalar instead of vector when considering velocity and acceleration. Many students reported that they generally understood concepts such as impulse and momentum, but still didn't know where and when to apply the concepts they learned [48].

Wrong interpretations and comprehensions can also be caused by students' poor mathematics knowledge and skills [45]. Students coming into the of physics or engineering mechanics classroom are supposed to have a solid foundation of mathematics, while research shows that students' inadequacies in mathematics play an important role in their poor academic performance when learning some higher level concepts, such as acceleration.

Visual interventions (concept maps, video demonstrations, interactive programs, computer-based simulations and/or animations, etc.) are among the most effective methods to correct wrong interpretations and comprehensions of students, especially for difficult concepts [49, 50]. Taylor et al. [51] reported the positive impact of the instructional sequence on non-engineering students' conceptual understanding of basic engineering mechanical concepts, such as normal force, tension, compression, and vector components.

4.4 Vernacular misunderstanding

Vernacular misunderstanding is often associated with either a student's insufficient or even deficient reading skills, or the lack of clarity in textbooks and other reading materials. Generally, this type of misconception arises from using terms that mean different things in daily life and the scientific context. Students meet the concepts of location, distance, displacement, speed, velocity, and acceleration in physics and engineering mechanics classrooms, with some of them vague and undifferentiated [41]. Science curricula and textbooks are responsible for perpetuating misconceptions, and some contain blatantly false information [52]. Some of these misconceptions come from inappropriate teaching methods and materials. Students indicated that a concept would be more difficult for them to understand if it involved other concepts, especially rotational-related or angular-related concepts [48].

The quality of textbooks and other reading materials can also contribute to vernacular misunderstandings of students. For example, some textbooks do not explain well, or do not even mention the difference between velocity and speed (two concepts closely related to the concept of acceleration) and use these two concepts interchangeably throughout the text. Therefore, some students mistakenly think that velocity and speed are the same concept. In fact, velocity is a vector, and speed is a scalar.

The most effective method of preventing vernacular misunderstanding is to improve students' reading skills by teaching students how to read before teaching them how to learn. This means improving the quality of some textbooks. Research has shown that reading plays a significant role in learning. Due to limited lecture time in the classroom, most reading occurs outside the classroom. Therefore, both K-12 schools and institutions of higher learning should explore ways to encourage student reading in extra-curricular activities.

5. Discussions

The purpose of identifying student misconceptions and finding out reasons behind them is to explore effective ways of correcting student misconceptions. In the above section, we have suggested a variety of methods to correct each of these four types of student misconceptions. In this section, we discuss other methods reported in the literature on how to correct student misconceptions of force and acceleration. We group these reported methods into "thinking-oriented" methods and "doing-oriented" methods. The "thinking-oriented" methods focus on improving student thinking (brain training) skills. The "doing-oriented" methods emphasize involving students in a variety of hands-on active learning (hands training) processes.

5.1 "Thinking-oriented" methods

Student preconceptions can be robust and difficult to correct unless significant proof or evidence are given [53, 54]. In the extreme situation, facts can change but students do not, as students still argue about the change of facts. Posner et al. [55] stated that four conditions are necessary in order to achieve a conceptual change: (1) students must feel dissatisfied with the existing concepts; (2) a new concept has been provided; (3) the new concept has been proved or demonstrated; and (4) students see that the new concept is useful and available.

To correct student misconceptions based on a "thinking-oriented" method, Streveler et al. [11] suggested that students need more accurate mental models or training models to help them better understand critical fundamental concepts. Based on a Delphi methodology, Streveler et al. [11] found that the students involved in their study did not fully understand many fundamental concepts, including those concepts that were rated as important and well-understood by the engineering faculty experts involved in the Delphi survey. Halim et al. [28] used a module called "Cognitive Acceleration through Science Education (CASE)" to improve the students' formal thinking in learning processes and reported that the CASE helped students develop a better understanding of the nature of force and thus students could draw correct free-body diagrams. The teaching intervention created by Halim et al. [28] included student activities in the classroom and emphasized students' thinking levels for understanding the basic characteristics of the force arrow (i.e., the direction, magnitude, labeling and starting point of force). Broek and Kendeou [56] employed a computational model and an empirical think-aloud method to study the role of misconceptions in cognitive processes. He showed that the concurrent activation of misconceptions and correct information plays a critical role in the process of conceptual change. Students do not correct their misconceptions unless misconceptions are activated with correct information that strongly conflicts with student perceptions.

5.2 *"Doing-oriented" methods*

For a "doing-oriented" method, a variety of instructional interventions have been developed to provide students with hands-on active learning experiences, so students can correct their misconceptions. For example, Constanzo and Gray [57] implemented an approach called Interactive Mechanics in the classroom. After an introductory lecture, students conducted a series of project activities to find the solution to a difficult problem through teamwork, analysis, and use of computer tools. Emphasizing project-based collaborative learning, the project exposed students to many concepts and ideas that a traditional dynamics class did not address. Rueda and Gilchrist [58] also employed project-based learning to improve students' learning outcomes by helping students understand course materials including key concepts. Ellis and Turner [59] used concept maps to improve student conceptual understanding in engineering mechanics. Concept maps are a graphical tool for knowledge organization, representation, and elicitation. With a concept map, students can see the relationships among different concepts, thus helping students see the "big picture" of learning topics. Steele et al. [60] employed in-class worksheets to improve student learning of the Statics Concept Inventory (SCI). They reported that by providing feedback on conceptual topics through in-class multiple-choice worksheets and discussion, student performance on relevant topics addressed by the SCI significantly improved.

6. Conclusions

Student misconceptions often result in poor or wrong knowledge base and structure. The present study has focused on a critical review and analysis of two fundamental and critical concepts in physics and engineering mechanics education: force and acceleration. The present study makes two scientific contributions by 1) developing a comprehensive list of all possible categories (or types, or "symptoms") of student misconceptions about force and acceleration, and 2) examining the reasons reported in the existing literature for why students have various misconceptions about force and acceleration. The answers to the two research questions are summarized in the following paragraphs.

Research Question 1: Based on the existing literature, what are all possible categories of student misconceptions about force and acceleration in physics and engineering mechanics education?

Answer: Based on 135 closely-related papers reviewed in the present study, students have 38 misconceptions (in two categories with nine subcategories) about force and 15 misconceptions (in three categories) about acceleration. The nine subcategories about force include: force itself, force vs. motion, force vs. velocity/speed, force vs. acceleration, force vs. mass, force vs. energy, gravitational force, frictional force, and other forces and items. The three categories about acceleration include: acceleration vs. force, acceleration vs. velocity/speed, and the direction of acceleration. The most commonly reported misconception about force, among both K-12 and college students, is "motion implies force". The most commonly reported misconception about acceleration is "acceleration is always in the direction of motion."

Research Question 2: What are the reasons reported in the existing literature for why students have these misconceptions about force and acceleration?

Answer: Based on our analysis, student misconceptions about force and acceleration are associated with one or more of the following reasons: (1) preconceived misunderstanding, i.e., the misunderstanding carried over from a student's previous experiences; (2) incomplete or partial understanding; (3) wrong interpretations and comprehensions; and (4) vernacular misunderstanding, i.e., misunderstanding due to a student's insufficient or even deficient reading skills, or due to the lack of clarity of textbooks and other reading materials. We have suggested various methods to correct student misconceptions associated with each reason. The correction methods reported in the literature are also divided into "thinking-oriented" methods that focus on brain training and "doing-oriented" methods that focus on a variety of hands-on learning activities.

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