Available online at http://journal.um.ac.id/index.php/jps
P-ISSN: 2338-9117 E-ISSN: 2442-3904
DOAJ-SHERPA/RoMEO-Google Scholar

**Jurnal Pendidikan Sains**
*Volume 11, Number 4, December 2023, pp. 123–134*

# IDENTIFYING STUDENTS' INCORRECT COMMON-SENSE KNOWLEDGE IN FORCES AND MOTION: RECOMMENDATIONS FOR DEVELOPING COMPUTER-BASED LEARNING MEDIA

**Ahmad Ridlotul Adha[1], Sutopo[2,*], Nasikhudin[3]**

*Department of Physics, Faculty of Mathematics and Natural Sciences, State University of Malang, Jl. Semarang 5, Malang, 65145, Indonesia*

[1] *ahmad.ridlotul.2203218@students.um.ac.id*; [2] *sutopo.fisika@um.ac.id**, [3] *nasikhudin.fmipa@um.ac.id*
*Corresponding author

**DOI:** 10.17977/jps.v11i42023p123

**ARTICLE INFO**

**Article History:**
Received 08/11/2023
Revised 27/11/2023
Approved 05/12/2023
Published 08/12/2023

**Keywords:**
Force and motion
Literature review
Common sense knowledge
Impetus
Active force

**ABSTRACT**

Conceptual understanding is a crucial area in physics education research, focusing on students' comprehension of fundamental principles. Force and motion, integral topics within this field, are inherently linked to students' daily experiences. Numerous studies have identified the persistence of common sense knowledge among students. This research presents a literature review aimed at identifying such consistently held misconceptions. We analyzed 17 papers sourced from Publish or Perish 8, Google Scholar, and Scopus. Our analysis revealed that the concepts of impetus and active force are the most persistent forms of common sense knowledge, influenced by real-life experiences. Additionally, students' difficulties with kinematics tend to diminish over time. With advancements in technology and educational methodologies, it is anticipated that these incorrect common sense understandings can be progressively reduced and eventually eliminated.

**How to Cite:** Adha, A. R., Sutopo, S., & Nasikhudin, N. (2023). Identifying students' incorrect common-sense knowledge in forces and motion: Recommendations for developing computer-based learning media. *Jurnal Pendidikan Sains, 11*(4), 123–134. https://doi.org/10.17977/jps.v11i42023p123

## INTRODUCTION

Conceptual understanding is a crucial area of study in physics education research, focusing on students' learning difficulties. This field has been evolving since the 1970s, when physics instructors began emphasizing the challenges students face in grasping fundamental concepts (Docktor & Mestre, 2014). Conceptual understanding plays a vital role in physics, particularly in developing essential competencies such as problem-solving abilities and scientific reasoning (Affriyenni et al., 2020; Diyana et al., 2020; Docktor & Mestre, 2014; Kattayat & Josey, 2019; Sutopo, 2021). Therefore, it is essential to prioritize conceptual understanding in fundamental topics within physics education. A strong grasp of these concepts helps students build a solid foundation for problem-solving and scientific thinking.

One of the fundamental topics in physics education where common sense knowledge frequently arises is forces and motion. This topic is closely related to daily life, leading many learners to develop their understanding through personal experiences (Adha et al., 2023). However, discrepancies often exist between learners' knowledge and the scientific community's understanding. Addressing this issue requires implementing diagnostic tests to assess students' prior knowledge (Fazio & Battaglia, 2019; Martin-Blas et al., 2010; Savinainen & Scott, 2002). With this information, instructors can take effective measures in the teaching process.

This article synthesizes the findings of physics education research utilizing the Force Concept Inventory (FCI) instrument. The objective is to identify common sense knowledge consistently maintained by students. Previous studies have highlighted the need for FCI surveys across various cultures and student backgrounds (Bayraktar, 2009; Luangrath et al., 2011; Martín-Blas et al., 2010; Rebello & Zollman, 2004). Our article focuses on the results of students' responses to the FCI conducted in several different countries. As an initial step, we formulated a research question to guide our analysis: "What are the most common sense knowledge regarding forces and motion?". This research question will serve as a foundation for deepening our understanding of common sense knowledge in the context of forces and motion based on previous studies.

### Force Concept Inventory (FCI)

The Force Concept Inventory (FCI) is a highly valuable diagnostic instrument in physics education research. Developed by Hestenes et al. (1992) in the early 1990s, the FCI consists of 29 multiple-choice questions designed to assess students' understanding of forces and motion. In 1998, the FCI underwent a revision by Hake (1998), resulting in a total of 30 items. This revision aimed to address the considerable potential for false positives and ambiguity present in the first version. False positives occur when students provide correct answers without truly understanding the underlying concepts.

Over time, several researchers have evaluated and modified the FCI. For instance, in 2015, Han et al. (2015) divided the FCI into two shorter versions to save time and mitigate the memorization effects among students. Additionally, in 2018, Yasuda et al. (2018) conducted an analysis of items 5, 6, 7, and 17. Their findings indicated that questions 6, 7, and 17 contained significant false positives. However, they did not recommend altering the existing FCI questions but suggested addressing the issue by adjusting the scores of students experiencing false positives. To this day, the second version of the FCI is widely used by researchers, primarily to assess students' prior knowledge in the areas of forces and motion.

### FCI's Conceptual Dimension

The FCI is an instrument encompassing essential dimensions for understanding Newtonian mechanics. Hestenes et al. (1992) identified six conceptual dimensions within the FCI: (1) Kinematics, represented in items 20, 21, 23, 24, and 25; (2) Newton's First Law, as reflected in items 4, 6, 8, 10, 18, 26, 27, and 28; (3) Newton's Second Law, found in items 6, 7, 24, and 25; (4) Newton's Third Law, relevant to items 2, 11, 13, and 14; (5) Types of Forces, covering items 1, 3, 5, 9, 12, 15, 16, 17, 18, 22, 23, 29, and 30; and (6) Superposition, evident in items 9, 18, and 19. It is important to note that some FCI items may encompass more than one conceptual dimension, resulting in the same item appearing in multiple different conceptual dimensions.

**Table 1.** FCI common sense knowledge taxonomy 1995 (second version) (Adha et al., 2023).

| Common Sense Knowledge | | Inventory Item |
|---|---|---|
| **0.** | **Kinematics** | |
| K1. | Position-velocity undiscriminated | 19 (B, C, D) |
| K2. | Velocity-acceleration undiscriminated | 19 (A); 20 (B, C) |
| K3. | Nonvectorial velocity compsition | 9 (C) |
| **1.** | **Impetus** | |
| I1. | Impetus supplied by hit | 11 (B, C); 27 (D); 30 (B, D, E) |
| I2. | Loss/recovery of original impetus | 7 (D); 8 (C, E); 21 (A); 23 (A, D, E) |
| I3. | Impetus dissipation | 10 (C); 12 (C, D); 13 (A, B, C); 14 (E); 24 (B, C, E); 27 (B) |
| I4. | Gradual/delayed impetus build-up | 9 (D); 10 (B, D); 21 (D); 26 (C); 27 (E) |
| I5. | Circular impetus | 6 (A); 7 (A, D) |
| **2.** | **Active Force** | |
| AF1. | Only active agents exert forces | 15 (D); 16 (D); 17 (D); 18 (A); 28 (B); 29 (B); 30 (A) |
| AF2. | Motion implies active force | 5 (C, D); 18 (C); 27 (A) |
| AF3. | No motion implies no force | 29 (E) |
| AF4. | Velocity proportional to applied force | 22 (A); 25 (A); 26 (A, B) |
| AF5. | Acceleration implies increasing force | 3 (B) |
| AF6. | Force causes acceleration to terminal velocity | 3 (A); 22 (D); 26 (D) |
| AF7. | Active force wears out | 22 (C, E) |
| **3.** | **Action/Reaction Pairs** | |
| AR1. | Greater mass implies greater force | 4 (A, D); 15 (B); 16 (B); 28 (D) |
| AR2. | Most active agent produces greatest force | 15 (C); 16 (C); 28 (D) |
| **4.** | **Concatenation of Influences** | |
| CI1. | Leargest force determines motion | 17 (A, E) |
| CI2. | Force compromise determines motion | 6 (D); 7 (C); 12 (A); 14 (C); 21 (C) |
| CI3. | Last force to act determines motion | 8 (A); 9 (B); 21 (B); 23 (C) |
| **5.** | **Other Influences on Motion** | |
| CF. | CF. Centrifugal force | 5 (E); 6 (C, D, E); 7 (C, D, E); 18 (E) |
| OB. | OB. Obstacles exert no force | 4 (C); 5 (A); 11 (A, B); 15 (E); 16 (E); 29 (A) |
| R1. | Resistance: Mass makes things to stop | 14 (A, B); 27 (A, B) |
| R2. | Resistance: Motion when force overcomes resistance | 25 (B, D) |
| R3. | Resistance: Resistance oppose force/impetus | 25 (E) |
| G1. | Gravity: Air pressured-assisted gravity | 3 (E); 11 (A); 17 (E); 29 (C) |
| G2. | Gravity: Gravity intrinsic to mass | 3 (D); 11 (E); 13 (E) |
| G3. | Gravity: Heavier object fall faster | 1 (A); 2 (B, D) |
| G4. | Gravity: Gravity increases as objects fall | 3 (D); 13 (B) |
| G5. | Gravity: Gravity acts after impetus wears down | 12 (D); 13(B); 14(E) |

### Common Sense Knowledge in the FCI Taxonomy

Although the FCI has undergone revisions, interestingly, there have been no significant changes in the taxonomy of common sense knowledge it contains. The changes made mostly concern the content of the questions, question numbers, and answer choices, while the dimensions and taxonomy remain the same. There are six groups of common sense knowledge: (0) Kinematics, which includes confusions such as mistaking position for velocity, velocity for acceleration, and considering velocity as a scalar quantity (Hestenes et al., 1992); (1) Impetus, the idea that explains why an object continues to move even in the absence of any external force, with this impetus diminishing due to air resistance (Hestenes et al., 1992; Suprapto et al., 2016; Wells et al., 2019); (2) Active Force, the notion that every moving object has an actively acting force upon it (Hestenes et al., 1992; Wells et al., 2019); (3) Action/Reaction Pairs, where students mistakenly believe that a larger object exerts a larger (more dominant) force (Wells et al., 2019); (4) Concatenation of Influences, where students incorrectly assume that in cases involving multiple forces, one force always "wins" over the others, leading to only one force affecting the object (Hestenes et al., 1992; Wells et al., 2019); and (5) Other Influences on Motion, a catch-all category for distractors that can't be specifically categorized. This group encompasses many naive thoughts found in students, such as the belief that mass hampers active forces, motion only occurs when active forces overcome opposing forces, and the notion that heavier objects fall faster than lighter ones (Hestenes et al., 1992). These common sense knowledge dimensions highlight a variety of misconceptions frequently held by students, including the belief that mass impedes active forces, that motion occurs only when active forces overcome opposing forces, or that heavier objects fall faster than lighter ones. Table 1 provides a more detailed overview of these common sense knowledge dimensions.

## METHOD

In conducting the literature review for this paper, we began by searching through online library resources (Publish or Perish 8, Google Scholar, and Scopus) using the keywords: "force and motion", "Force Concept Inventory", and "FCI answers". This search yielded publications including journal articles and conference proceedings. We subsequently selected only those articles published in reputable scientific journals (Munfaridah et al., 2021). The selection criteria for the articles were (1) the article was published within the last 39 years (1984-2023) and (2) the article described the state of students' conceptual understanding as measured by the FCI. The time interval selection was based on the relevance of research during these years to the FCI. Using these criteria, we selected 17 articles, as presented in Figure 1. The selected articles were then categorized by their publication year in Table 2.

We acknowledge three limitations related to the papers analyzed in this research, both in terms of database usage and the specific time range. First, although the online libraries we utilized are commonly employed in physics education research, we may have missed significant contributions not included in the database platforms we used. Second, the selected time range may exclude important research published before 1984. Third, this systematic review focuses exclusively on undergraduate-level research, and thus does not provide a comprehensive synthesis of the knowledge base involving various age groups and educational levels.

## RESULTS

The scope of this research problem is focused on the topics of forces and motion, with an emphasis on the use of the Force Concept Inventory (FCI), a tool widely employed by previous researchers. Our investigation spanned the period from 1984 to 2023, aiming to understand the development of students' understanding over time. Specifically, we reviewed research papers that addressed students' common sense knowledge as assessed by FCI responses, which were obtained through various data collection and processing methods.

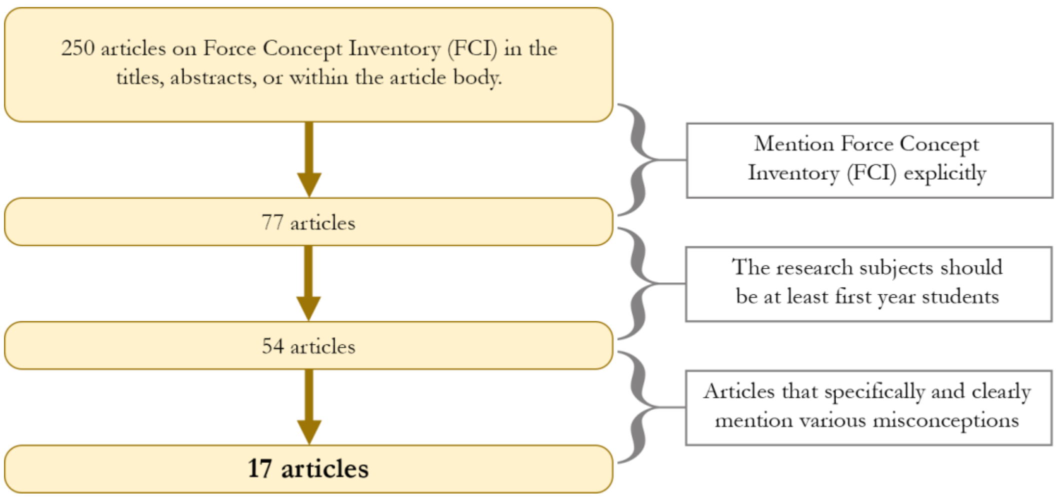


**Figure 1.** The article selection process (Munfaridah et al., 2021).

**Table 2.** List of reviewed articles.

| No | Title | Authors |
|---|---|---|
| 1. | Research on conceptual understanding in mechanics | McDermott (1984) |
| 2. | Force Concept Inventory | Hestenes et al. (1992) |
| 3. | The effect of distracters on student performance on the Force Concept Inventory | Rebello and Zollman (2004) |
| 4. | Misconceptions of Turkish pre-service teachers about force and motion | Bayraktar (2009) |
| 5. | Enhancing Force Concept Inventory diagnostics to identify dominant misconceptions in first-year engineering physics | Martin-Blas et al. (2010) |
| 6. | On the use of two versions of the Force Concept Inventory to test conceptual understanding of mechanics in Lao PDR | Luangrath et al. (2011) |
| 7. | An item response curves analysis of the Force Concept Inventory | Morris et al. (2012) |
| 8. | Exploration of students' misconceptions in mechanics using the FCI | Poutot and Blandin (2015) |
| 9. | Using module analysis for multiple choice responses: A new method applied to Force Concept Inventory data | Brewe et al. (2016) |
| 10. | Conceptual coherence of non-Newtonian worldviews in Force Concept Inventory data | Scott and Schumayer (2017) |
| 11. | Central distractors in Force Concept Inventory data | Scott and Schumayer (2018) |
| 12. | Exploring the structure of misconceptions in the Force Concept Inventory with modified module analysis | Wells et al. (2019) |
| 13. | Jordanian pre-service physics teacher's misconceptions about force and motion | Al-Rsa'i et al. (2020) |
| 14. | Force Concept Inventory: More than just conceptual understanding | Stoen et al. (2020) |
| 15. | Network analysis of misconceptions in FCI data | Scott and Schumayer (2021) |
| 16. | Visualizing depth of student conceptual understanding using subquestions and alluvial diagrams | Yasuda et al. (2023) |
| 17. | Exploring student's misconception in force and motion using the FCI | Adha et al., 2023 |

### McDermott Study in 1984

The first study we examined was conducted by McDermott (1984). Although there is no clear information about the number of research subjects, this study provides a detailed description of how the research was conducted. It involved a series of individual interviews with students, classroom observations, and discussions with physics teachers. The researcher also used structured questions and tasks that involved equipment manipulation and experimental observations. The data collected included transcripts of individual interviews, classroom observations, teacher-student dialogues, homework assignments, and test results. The researcher also used computer simulations to facilitate the observation of the effects of parameter variations in experiments.

The results of the study showed that both students and physics teachers experienced some common sense knowledge misconceptions, such as, (1) heavier objects fall faster, (2) every moving object has a force acting on it, or to keep an object moving, a force must always act on it, (3) inability to distinguish between position and velocity, and (4) inability to distinguish velocity from acceleration. Based on the research findings, McDermott (1984) recommended the development of instructional materials that connect physics concepts with mathematical representations and the physical world. Furthermore, it is important to emphasize learning that focuses on mastering concepts rather than rote memorization.

### Hestenes et al. Study in 1992

A similar study conducted by Hestenes et al. (1992) also found many common sense knowledge misconceptions in the topic of mechanics. Several students were involved in this research, coming from different universities, including Arizona State University and Harvard University. This research marked the first implementation of the FCI. The research began with the identification of common sense knowledge held by students in the topic of force and motion through diagnostic tests (FCI) and interviews. The researchers then developed and implemented new teaching methods to enhance student understanding. The teaching methods involved the use of computers, laboratory activities, classroom discussions, and specific techniques to stimulate discussions.

The results of the study showed incorrect common sense knowledge, including (1) heavier objects fall faster, (2) linear and angular momentum misconceptions, (3) inability to distinguish between position and velocity, and (4) inability to distinguish velocity from acceleration. Based on their research findings, Hestenes et al. (1992) recommended the development of more effective teaching methods to address students' incorrect common sense knowledge in force and motion.

### Rebello and Zollman Study in 2004

The next study we reviewed is the research conducted by Rebello and Zollman (2004). There were 238 students taking algebra-based introductory physics courses actively involved in this study. The research aimed to explore the effectiveness of the distractors used in the FCI and whether alternative distractors would be more effective than the current ones. The phenomenographic approach was used to address the issues in this research. This approach allowed the researchers to categorize and analyze students' incorrect common sense knowledge that were not revealed in the multiple-choice format. Through this method, the researchers could identify more effective distractors in revealing students' incorrect common sense knowledge. Several were found, namely, (1) motion indicates the presence of force, so when the force is removed, the object will stop immediately, (2) resistance (mass makes an object stop), (3) larger objects exert more force, and (4) heavier objects exert more force. The research results indicated that alternative distractors based on open-ended answers were effective in revealing alternative student understandings and could replace some of the existing distractors in the FCI. Therefore, the Rebello and Zollman (2004) recommendation for future research is to conduct studies involving larger and more diverse samples, including students with different backgrounds and educational levels.

### Bayraktar Study in 2009

The next literature we reviewed is Bayraktar (2009) research, which identified several incorrect common sense knowledge on the topic of force and motion. The study involved 79 prospective physics teachers at a university in Turkey. The research design used was a quantitative cross-sectional design, employing the FCI as the data collection instrument. The results of the study revealed students' incorrect common sense knowledge, including, (1) heavier or more active objects exert greater force, (2) impetus, and (3) every moving object experiences a force in the same direction as its motion. Based on these findings, the Bayraktar (2009) recommended conducting similar studies in different cultures and backgrounds.

### Martin-Blas et al. Study in 2010

Similar research was also conducted by Martin-Blas et al. (2010) at the Universidad Politécnica de Madrid. The study involved 143 students, with 110 students enrolling in ETSII (Escuela Técnica Superior de Ingeniería Informática) as Group 1 and 30 students enrolling in EUITF (Escuela Universitaria de Ingeniería Técnica Forestal) as Group 2. Data collection was done using the FCI in both groups. The obtained data was then compared for the number of correct and incorrect answers in both groups, and conceptual errors that consistently triggered incorrect answers were identified.

The research results revealed students' incorrect common sense knowledge, namely, (1) when an object is in motion, there must always be a force acting in the direction of motion, and (2) heavier or more active objects exert greater force in action-reaction pairs. Based on these findings, the Martin-Blas et al. (2010) recommended the development of computer-based learning media that enable students to simulate and visualize concepts related to force and motion.

### Luanglarth et al. Study in 2011

Another similar study was conducted by Luanglarth et al. (2011) at different universities in Laos. This survey involved 485 students, with 264 students surveyed using FCI and 221 students surveyed using Lao version of FCI (LFCI). After the survey, some students were interviewed to obtain qualitative data about the questions they found easy or difficult and their motivation while working on the questions. The analysis methods used were qualitative and quantitative descriptive analysis to identify patterns of students' incorrect common sense knowledge and describe their understanding of the topics of force and motion.

The analysis results indicated incorrect common sense knowledge, including, (1) heavier objects fall faster, (2) heavier or more active objects exert greater force in action-reaction pairs, (3) when an object is in motion, there must always be a force acting in the direction of motion, and (4) position and velocity are not differentiated. Based on these findings, the Luanglarth et al. (2011)recommended conducting similar survey research involving a larger number of research subjects with diverse backgrounds, various universities, and greater consideration of learning experiences in data analysis.

### Morris et al. Study in 2012

The next scholarly article we reviewed is the result of Morris et al. (2012) research on the effectiveness of using Item Response Curves (IRC). The analysis using IRC was compared with Item Response Theory (IRT) analysis, both of which analyze the responses of students in the FCI. There is no clear information about the number of subjects and the specific location where the research was conducted, but this study was carried out in the United States. The main result of this study is that IRC analysis is more suitable for evaluating the performance of questions and answer choices in the FCI than IRT analysis. IRC provides more detailed information about the functionality of distractors and can be used to identify incorrect common sense knowledge.

In addition, the study also identified some students' incorrect common sense knowledge, including, (1) in the case of an object moving upwards, the force applied must be greater than the object's weight, and (2) the understanding that to maintain constant velocity, the force applied must remain constant. Based on these findings, the Morris et al. (2012) recommend using IRC to analyze students' FCI responses and paying attention to students' incorrect common sense knowledge when designing questions and answer choices in the force concept test.

### Poutot and Blandin Study in 2015

Another study conducted by Poutot and Blandin (2015) over three years at CESI, France, successfully identified students' incorrect common sense knowledge. This research used the FCI to assess the progress of first-year engineering students in understanding Newtonian physics concepts and compared the effectiveness of two teaching methods: traditional instruction and exercises versus Problem-based Learning (PBL). The results of this study showed that both teaching methods produced similar outcomes in terms of improving the understanding of Newtonian physics concepts. However, the researchers identified several incorrect common sense knowledge, including, (1) heavier objects fall faster, (2) heavier objects exert greater force, (3) there is always a force in the direction of motion, (4) there is a greater force in the direction of motion, and (5) inability to differentiate between acceleration and velocity (Poutot & Blandin, 2015). Based on these findings, Poutot and Blandin (2015) suggest identifying and understanding the incorrect common sense knowledge held by students regarding Newtonian mechanics and implementing project-based learning to overcome epistemological barriers.

### Brewe et al. Study in 2016

The research conducted by Brewe et al. (2016) focuses on the use of Module Analysis for Multiple Choice Responses (MAMCR) to analyze responses in multiple-choice assessments, specifically the FCI. This method is used to identify non-normative responses that can be interpreted as alternatives for factor analysis. MAMCR allows for the identification of specific conceptual responses from students. The results of using MAMCR revealed several incorrect common sense knowledge, including, (1) impetus, (2) larger force results in a larger impact, and (3) students' inability to differentiate between velocity and acceleration. Brewe et al. (2016) recommend using MAMCR to analyze student responses in the context of FCI.

### Scott and Schumayer Study in 2017

The two-year survey conducted by Scott and Schumayer (2017) in calculus-based physics courses yielded interesting results for discussion. Over 1500 first-year students participated in this research. Student responses were then analyzed using factor analysis to identify correlations among students' answers to different FCI questions and determine common incorrect knowledge. The results of the survey revealed several incorrect common sense knowledge, including, (1) larger force results in a larger impact, (2) larger mass indicates greater force, (3) resistance (mass makes an object stop), and (4) there is always a force in the direction of motion. Based on these results, Scott and Schumayer (2017) recommended repeating similar surveys in different countries and contexts, conducting interviews to identify other factors that may influence incorrect common sense knowledge, and developing instructional strategies to address this issue.

### Scott and Schumayer Study in 2018

In 2018, Scott and Schumayer published a related paper aiming to understand and identify students' incorrect common sense knowledge about Newtonian mechanics (Scott & Schumayer, 2018). The research results showed the existence of distractor groups in the FCI that reflected different non-Newtonian worldviews. Factor 1 in the factor analysis depicted the impetus worldview, while factor 2 portrayed a circular impetus worldview. In factor 1, item 11C was identified as the most critical item rejecting Newton's First Law and affirming the impetus worldview, with item 10D also significant to a lesser degree. For factor 2, item 7D was the most important item related to circular impetus, implying beliefs about the effects of circular impetus over time. This analysis indicated that the rejection of Newton's First Law is central to the impetus worldview, while circular impetus is a derived concept (Scott & Schumayer, 2018). Based on these findings, Scott and Schumayer (2018) proposed a new approach to teaching Newtonian mechanics that addresses the impetus worldview. This teaching method includes clarifying the concept of motion, introducing Newton's First Law, explaining friction, and then introducing Newton's Second and Third Laws. Further research is needed to validate this teaching approach.

### Wells et al. Study in 2019

Wells et al. (2019) conducted a study at a major university in the southern United States using Modified Module Analysis (MMA) and network analysis. The data were obtained from pretest and post-test FCI responses of over 4,500 first-year students. Network analysis examined the structure of students' incorrect common sense knowledge, identifying communities representing different misconceptions. The results revealed misconceptions such as, (1) the assumption that motion characterizes the presence of a force on an object, (2) centrifugal force, (3) circular impetus or impetus in circular motion, and (4) the assumption that the largest force determines motion. Wells et al. (2019) suggested two things. First, instructors should use confusing questions or experiments that contradict these misconceptions. Second, instructors and researchers should avoid using blocking items in physics education research instruments, favoring MMA for understanding misconceptions.

### Al-Rsa'i et al. Study in 2020

Al-Rsa'i et al. (2020) conducted research at two universities in Jordan to identify students' misconceptions in understanding conceptual physics. Methods included open-ended questions, two-tier diagnostic tests, concept mapping, and various interactive teaching methods. FCI was used to measure students' understanding of force and motion concepts, analyzed using ANOVA. The misconceptions identified included, (1) the belief that force only occurs with motion or is a visible or tangible strength, (2) the belief that motion requires a force, or that uniform motion is always constant, (3) misunderstanding Newton's laws, believing they only apply under certain conditions, (4) the belief that stationary objects lack inertia, or inertia only occurs during speed changes, and (5) misconceptions about friction and gravity. Al-Rsa'i et al. (2020) recommended using interactive and motivating teaching methods to address these misconceptions.

### Stoen et al. Study in 2020

Stoen et al. (2020) research at Washington University examined the relationship between conceptual understanding and problem-solving skills in physics. The study involved 370 students in a Calculus-based Introductory Physics course, identifying the relationship between structural knowledge, attitudes, concept-based problem-solving skills, and FCI performance. Key misconceptions included, (1) the perception that force and velocity are proportional or directly related, and (2) the misunderstanding that force and velocity are not related at all. Stoen et al. (2020) recommended teaching strategies that directly confront misconceptions, such as confusing questions or experiments.

### Scott and Schumayer Study in 2021

Scott and Schumayer (2021) study at one university involved FCI response surveys from first-year students, using exploratory factor analysis and network analysis to study correlation structures. The study identified an impetus-based understanding, where students believe motion is caused by an object's inherent property, contrary to the Newtonian view of external interactions causing motion (Scott & Schumayer, 2021).

### Yasuda et al. Study in 2023

Yasuda et al. (2023) conducted a study at a Japanese university involving 359 students in an online FCI survey. Using visualization approaches, alluvial diagrams, and think-aloud interviews, the study identified misconceptions such as, (1) the belief that motion only occurs if a force is acting, (2) misconceptions about mass, weight, and gravitational forces, and (3) misunderstandings about the normal force and centripetal force. Yasuda et al. (2023) recommended enhancing students' understanding of Newton's Laws explicitly and using active, computer-based learning methods.

### Adha et al. Study in 2023

Adha et al. (2023) conducted an FCI survey involving 81 first-year physics education students in Indonesia. The analysis revealed misconceptions such as, (1) acceleration indicating increasing force, (2) motion implying the presence of a force, (3) the last force acting determining motion, and (4) misconceptions about impulse, mass, and velocity. Adha et al. (2023) suggested using computer-based interactive learning media outside of regular class hours.

## DISCUSSION

Our literature review reveals that the concept of "impetus" frequently emerges as a misconception in responses to the Force Concept Inventory (FCI). Analyzing 17 literature sources, we observed that "impetus" appeared 14 times, while misconceptions related to "active force" and "other influences on motion" each appeared 10 times. Additionally, misconceptions about "action/reaction pairs" were identified 6 times, and those regarding "kinematics" and "concatenation of influences" each appeared 5 times. These findings corroborate the prevalence of incorrect common sense knowledge about impetus among learners (Bani-Salameh, 2016a, Bani-Salameh, 2016b; Bani-Salameh et al., 2017; Bogdanov & Viiri, 1999; Scott & Schumayer, 2018; Scott & Schumayer, 2021; Suprapto et al., 2016; Tawil & Said, 2022). Moreover, other studies have similarly identified misconceptions related to "impetus" and "active force" (Cahyadi, 2004; Trumper & Gorsky, 1996; Viiri, 1996), with the latter predominantly characterized by the AF2 misunderstanding. The detailed distribution of these misconceptions is presented in Table 3.

Table 3 demonstrates that "impetus" has persisted as a prevalent misconception from before the development of the FCI to the present. This suggests that efforts by experts to address these misconceptions have had limited success in improving learning outcomes. Additionally, "impetus" is more closely aligned with common sense knowledge derived from real-life experiences than with scientific concepts (Pertiwi & Setyarsih, 2015). Therefore, cultural factors may significantly contribute to the persistence of these misconceptions, particularly in the context of mechanics. Misconceptions about impetus negatively impact the understanding of Newton's First Law (Scott & Schumayer, 2018; Scott & Schumayer, 2021). Hammer (1996) proposes several steps to address this issue, such as (1) recognizing the existence of incorrect knowledge, (2) exploring students' knowledge and reasoning, (3) addressing incorrect knowledge and p-prims through targeted instruction, and (4) balancing support and challenge. These strategies aim to induce cognitive conflicts that lead to conceptual change (Hadjiachilleos et al., 2013; Limón, 2001; Linn, 2006).

Our literature review also indicates that "active force" has been a persistent misconception since 2012, existing even before the FCI was developed (Clement, 1982; Gilbert & Zylbersztajn, 1985; Sadanand & Kess, 1990). The limited use of the FCI in the late 1990s and early 2000s is one possible contributing factor. Common triggers for misconceptions include textbooks, culture related to geographic location, and intuition (Fadllan, 2011). Comparing our findings with previous research, we found that the "active force" misconception is not significantly influenced by geographical factors or outdated textbooks at the college level. Therefore, intuition appears to be the primary factor, supported by several studies (Adha et al., 2023; Scott & Schumayer, 2017; Scott & Schumayer, 2018).

Moreover, student difficulties related to kinematics seem to be decreasing, which is an encouraging trend. According to the FCI common sense knowledge taxonomy in Table 1, kinematics misconceptions are classified into three types: K1, K2, and K3. Our review identified only K1 and K2. The shift from teacher-centered to student-centered teaching approaches likely contributes to the reduction of these misconceptions.

Effective teaching strategies identified in the literature include: (1) Multi-representation learning, resulting in an N-gain improvement of 0.35 (Sutopo et al., 2020); (2) Student-centered teaching that connects practical laboratory observations with real-world concepts, uses visual aids, and promotes peer-to-peer learning (Cashman & O'Mahony, 2022); and (3) Computer-based recitation programs providing automatic, customized feedback based on students' initial understanding, resulting in an N-gain improvement of 0.31 (Sutopo et al., 2017). Implementing these strategies significantly enhances students' conceptual understanding.

**Table 3.** Students' incorrect common sense knowledge recorded in FCI over more than two decades (*out of FCI's taxonomy).

| Year | Students' Incorrect Common Sense Knowledge | Code | Group |
|---|---|---|---|
| 1984 | • Heavier object fall faster. | G3 | Other influences on motion |
| | • Every moving object is subject to a force acting upon it, or to maintain an object's motion, a force must constantly act upon it. | Impetus | Impetus |
| | • Inability to differentiate between position and velocity. | K1 | Kinematics |
| | • Inability to differentiate between velocity and acceleration. | K2 | Kinematics |
| 1992 | • Heavier object fall faster. | G3 | Other influences on motion |
| | • Linear impetus and circular impetus. | Impetus dan I5 | Impetus |
| | • Inability to differentiate between position and velocity. | K1 | Kinematics |
| | • Inability to differentiate between velocity and acceleration. | K2 | Kinematics |
| 2004 | • The belief that motion indicates the presence of a force, so when the force is removed, the object will immediately come to a stop. | AF2 | Active force |
| | • Resistance: Mass causes an object to stop. | R1 | Other influences on motion |
| | • A larger object exerts a greater force. | AR1 | Action/reaction pairs |
| | • A heavier object exerts a greater force. | G3 | Other influences on motion |
| 2009 | • Heavier object fall faster. | AR1 | Action/reaction pairs |
| | • An object that is more active exerts a greater force. | AR2 | Action/reaction pairs |
| | • Impetus; | Impetus | Impetus |
| | • Every moving object experiences a force in the same direction as its motion. | Impetus | Impetus |
| 2010 | • A force must always act in the direction of motion when an object is moving. | Impetus | Impetus |
| | • Objects that are heavier or more active exert greater force in action-reaction pairs. | AR1 | Action/reaction pairs |
| 2011 | • Heavier object fall faster. | G3 | Other influences on motion |
| | • Heavier or more active objects exert a greater force in action-reaction pairs. | AR1 dan AR2 | Action/reaction pairs |
| | • When an object is in motion, there must always be a force acting in the same direction as the velocity. | Impetus | Impetus |
| | • Inability to differentiate between position and velocity. | K1 | Kinematics |
| 2012 | • In the case of an object moving upward, the force applied must be greater than the weight of the object. | CI1 | Concatenation of influences |
| | • The understanding that to maintain constant velocity, the applied force must remain constant. | AF4 | Active force |
| 2015 | • Heavier object fall faster. | G3 | Other influences on motion |
| | • A larger object exerts a greater force. | AR1 | Action/reaction pairs |
| | • There is always a force in the direction of motion. | Impetus | Impetus |
| | • There is a greater force in the direction of motion. | CI1 | Concatenation on influences |
| | • Inability to differentiate between velocity and acceleration. | K2 | Kinematics |
| 2016 | • Impetus; | Impetus | Impetus |
| | • A greater force results in a greater impact. | CI2 | Concatenation of influences |
| | • Inability to differentiate between velocity and acceleration. | K2 | Kinematics |
| 2017 | • The force that causes an object to move must have the same direction as the object's motion. | Impetus | Impetus |
| 2018 | • Impetus | Impetus | Impetus |
| | • Circular impetus | I5 | Impetus |
| 2019 | • The assumption that motion implies the presence of a force acting on an object. | AF2 | Active force |
| | • Centrifugal force. | CF | Other influences on motion |
| | • Circular impetus | I5 | Impetus |
| | • The assumption that the largest force determines motion. | CI1 | Concatenation of influences |

**Table 3.** (*Continued*).

| Year | Students' Incorrect Common Sense Knowledge | Code | Group |
|---|---|---|---|
| 2020 | • The assumption that force only occurs when there is motion. | AF2 | Active force |
| | • The belief that motion only occurs when a force is applied. | AF2 | Active force |
| | • The belief that Newton's first law only applies when a force is acting, or assuming that Newton's third law only applies when there is direct contact between two objects. | xxx* | xxx* |
| | • The belief that a stationary object has no inertia or that inertia only occurs when there is a change in velocity. | xxx* | xxx* |
| | • Frictional force always hinders motion or the belief that frictional force only occurs on rough surfaces. | xxx* | xxx* |
| | • Gravity only occurs on Earth or the belief that gravity only acts on falling objects. | xxx* | xxx* |
| 2020 | • The belief that force and velocity are proportional or directly related. | AF4 | Active force |
| 2021 | • Impetus-based understanding. | Impetus | Impetus |
| 2023 | • The belief that motion only occurs if there is a force acting on it. | AF2 | Active force |
| | • The belief that mass and weight are the same thing. | G2 | Other influences on motion |
| | • The belief that the normal force is always parallel to the surface or that the normal force only occurs on stationary objects. | xxx* | xxx* |
| | • The belief that the centripetal force is a force that pulls objects toward the center of the circle or that centripetal force only occurs in circular motion. | xxx* | xxx* |
| | • The belief that Newton's laws only apply to linear motion or that Newton's laws only apply to objects moving at a constant velocity. | xxx* | xxx* |
| 2023 | • Acceleration indicates a increasing force. | AF5 | Active force |
| | • Motion implies the presence of force. | AF2 | Active force |
| | • The last force acting determines the motion. | CI1 | Concatenation of influences |
| | • Impetus by hit | I1 | Impetus |
| | • Mass makes an object stop. | R1 | Other influences on motion |
| | • Velocity is proportional to the force applied. | AF4 | Active force |
| | • Impetus dissipation; | I3 | Impetus |
| | • Motion only occurs when force overcomes resistance. | R2 | Other influences on motion |

## CONCLUSION

Based on the literature review conducted, it can be concluded that the common sense notion of impetus is the most consistent misconception. Analysis of 17 papers revealed that the impetus misconception was identified 14 times. Additionally, the active force misconception was also frequently encountered, appearing in 10 of the same papers. Both the impetus and active force misconceptions are rooted in common sense knowledge driven by real-life experiences. Furthermore, students' difficulties related to kinematics tend to decrease over time. With advancements in technology and educational systems, it is hoped that incorrect common sense knowledge can be gradually minimized and eventually eliminated.

## ACKNOWLEDGMENTS

I extend my deepest appreciation to Prof. Sutopo and Dr. Nasikhudin for their exemplary mentorship, scholarly insights, and dedicated involvement in every stage of our research. Their unwavering guidance, constructive feedback, and scholarly wisdom have been instrumental in shaping this article. I am profoundly grateful for their mentorship and the knowledge they imparted, which significantly enriched our academic journey.

## FUNDING AGENCIES

The authors no received financial support for the research, authorship, and/or publication of this article.

## AUTHOR CONTRIBUTIONS

ARA was involved in designing the methodology, conducting formal analysis, and drafting the original manuscript. S, an expert in fundamental physics concepts, contributed by conceptualizing the study and providing guidance on the theoretical framework. N guided the execution of the literature review, offering direction and support throughout the study.

## CONFLICT OF INTEREST STATEMENT

The author declares that there are no conflicts of interest regarding the publication of this paper. The guidance and support provided by supervisors were part of their professional responsibilities, and no financial, personal, or other relationships have influenced the research and findings presented in this study. All efforts have been made to ensure that the research is conducted and presented with the highest standards of integrity and transparency.

## REFERENCES


Adha, A. R., Nasikhuddin, N., & Sutopo, S. (2023, August). Exploring student's misconception in force and motion using the FCI. In F. Huriawati et al. (Eds.), *Cybergogi dan masa depan pendidikan fisika di Indonesia*. Proceedings of the SNPF (Seminar Nasional Pendidikan Fisika) IX 2023. Retrieved from https://prosiding.unipma.ac.id/index.php/SNPF/article/view/3950

Affriyenni, Y., Susanti, N. E., & Swalaganata, G. (2020, April). The effect of hybrid-learning on students' conceptual understanding of electricity in short-term fundamental physics course. In *AIP Conference Proceedings* (Vol. 2215, No. 1, p. 040001). AIP Publishing. https://doi.org/10.1063/5.0000508

Al-Rsa'i, M. S., Khoshman, J. M., & Tayeh, K. A. (2020). Jordanian pre-service physics teacher's misconceptions about force and motion. *Journal of Turkish Science Education*, *17*(4), 528–543. https://doi.org/10.36681/tused.2020.43

Bani-Salameh, H. N. (2016a). How persistent are the misconceptions about force and motion held by college students?. *Physics Education*, *52*(1), 014003. https://doi.org/10.1088/1361-6552/52/1/014003

Bani-Salameh, H. N. (2016b). Using the method of dominant incorrect answers with the FCI test to diagnose misconceptions held by first year college students. *Physics Education*, *52*(1), 015006. https://doi.org/10.1088/1361-6552/52/1/015006

Bani-Salameh, H., Nuseirat, M., & Alkofahi, K. A. (2017). Do first year college female and male students hold different misconceptions about force and motion. *IOSR Journal of Applied Physics*, *9*(2), 14–18. https://doi.org/10.9790/4861-0902021418

Bayraktar, S. (2009). Misconceptions of Turkish pre-service teachers about force and motion. *International Journal of Science and Mathematics Education*, *7*, 273–291. https://doi.org/10.1007/s10763-007-9120-9

Bogdanov, S., & Viiri, J. (1999, August). Students' understanding of the force concept in Russia and Finland. In *Proceedings of the 2nd International Conference of the European Science Education Research Association (ESERA), Kiel*. Retrieved from https://archiv.leibniz-ipn.de/projekte/esera/book/b111-bog.pdf

Brewe, E., Bruun, J., & Bearden, I. G. (2016). Using module analysis for multiple choice responses: A new method applied to Force Concept Inventory data. *Physical Review Physics Education Research*, *12*(2), 020131. https://doi.org/10.1103/PhysRevPhysEducRes.12.020131

Cahyadi, V. (2004). The effect of interactive engagement teaching on student understanding of introductory physics at the Faculty of Engineering, University of Surabaya, Indonesia. *Higher Education Research & Development*, *23*(4), 455–464. https://doi.org/10.1080/0729436042000276468

Cashman, A., & O'Mahony, T. (2022). Student understanding of kinematics: A qualitative assessment. *European Journal of Engineering Education*, *47*(6), 886–909. https://doi.org/10.1080/03043797.2022.2073200

Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics*, *50*(1), 66–71. https://doi.org/10.1119/1.12989

Diyana, T. N., Sutopo, S., & Sunaryono, S. (2020). The effectiveness of web-based recitation program on improving students' conceptual understanding in fluid mechanics. *Jurnal Pendidikan IPA Indonesia*, *9*(2), 219–230. https://doi.org/10.15294/jpii.v9i2.24043

Docktor, J. L., & Mestre, J. P. (2014). Synthesis of discipline-based education research in physics. *Physical Review Special Topics-Physics Education Research*, *10*(2), 020119. https://doi.org/10.1103/PhysRevSTPER.10.020119

Fadllan, A. (2011). Model pembelajaran konflik kognitif untuk mengatasi miskonsepsi pada mahasiswa tadris fisika program kualifikasi S1 Guru Madrasah. *Phenomenon: Jurnal Pendidikan MIPA*, *2*(1), 139–159. https://doi.org/10.21580/phen.2011.1.2.441

Fazio, C., & Battaglia, O. R. (2019). Conceptual understanding of Newtonian mechanics through cluster analysis of FCI student answers. *International Journal of Science and Mathematics Education*, *17*, 1497–1517. https://doi.org/10.1007/s10763-018-09944-1

Gilbert, J. K., & Zylbersztajn, A. (1985). A conceptual framework for science education: The case study of force and movement. *The European Journal of Science Education*, *7*(2), 107–120. https://doi.org/10.1080/0140528850070201

Hadjiachilleos, S., Valanides, N., & Angeli, C. (2013). The impact of cognitive and affective aspects of cognitive conflict on learners' conceptual change about floating and sinking. *Research in Science & Technological Education*, *31*(2), 133–152. https://doi.org/10.1080/02635143.2013.811074

Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics*, *66*(1), 64–74. https://doi.org/10.1119/1.18809

Hammer, D. (1996). Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions. *The Journal of the Learning Sciences*, *5*(2), 97–127. https://doi.org/10.1207/s15327809jls0502_1

Han, J., Bao, L., Chen, L., Cai, T., Pi, Y., Zhou, S., ... & Koenig, K. (2015). Dividing the Force Concept Inventory into two equivalent half-length tests. *Physical Review Special Topics-Physics Education Research*, *11*(1), 010112. https://doi.org/10.1103/PhysRevSTPER.11.010112

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force Concept Inventory. *The Physics Teacher*, *30*(3), 141–158. https://doi.org/10.1119/1.2343497

Kattayat, S., & Josey, S. (2019, March). Improving students conceptual understanding of calculus based physics using problem based learning approach on an e-learning platform applied to engineering education. In *2019 Advances in Science and Engineering Technology International Conferences (ASET)* (pp. 1–6). IEEE. https://doi.org/10.1109/ICASET.2019.8714298

Limón, M. (2001). On the cognitive conflict as an instructional strategy for conceptual change: A critical appraisal. *Learning and Instruction*, *11*(4–5), 357–380. https://doi.org/10.1016/S0959-4752(00)00037-2

Linn, M. C. (2006). The knowledge integration perspective on learning and instruction. In R. K. Sawyer (Ed.), *The Cambridge handbook of: The learning sciences* (pp. 243–264). Cambridge, UK: Cambridge University Press.

Luangrath, P., Pettersson, S., & Benckert, S. (2011). On the use of two versions of the force concept inventory to test conceptual understanding of mechanics in Lao PDR. *Eurasia Journal of Mathematics, Science and Technology Education*, *7*(2), 103–114. https://doi.org/10.12973/ejmste/75184

Martin-Blas, T., Seidel, L., & Serrano-Fernández, A. (2010). Enhancing Force Concept Inventory diagnostics to identify dominant misconceptions in first-year engineering physics. *European Journal of Engineering Education*, *35*(6), 597–606. https://doi.org/10.1080/03043797.2010.497552

McDermott, L. C. (1984). Research on conceptual understanding in mechanics. *Physics Today*, *37*(7), 24–32. https://doi.org/10.1063/1.2916318

Morris, G. A., Harshman, N., Branum-Martin, L., Mazur, E., Mzoughi, T., & Baker, S. D. (2012). An item response curves analysis of the Force Concept Inventory. *American Journal of Physics*, *80*(9), 825–831. https://doi.org/10.1119/1.4731618

Munfaridah, N., Avraamidou, L., & Goedhart, M. (2021). The use of multiple representations in undergraduate physics education: what do we know and where do we go from here?. *Eurasia Journal of Mathematics, Science and Technology Education*, *17*(1), em1934. https://doi.org/10.29333/ejmste/9577

Pertiwi, C. A., & Setyarsih, W. (2015). Konsepsi siswa tentang pengaruh gaya pada gerak benda menggunakan instrumen Force Concept Inventory (FCI) termodifikasi. *Jurnal Inovasi Pendidikan Fisika (JIPF)*, *4*(2), 162–168.

Poutot, G., & Blandin, B. (2015). Exploration of students' misconceptions in mechanics using the FCI. *American Journal of Educational Research*, *3*(2), 116–120. https://doi.org/10.12691/education-3-2-2

Rebello, N. S., & Zollman, D. A. (2004). The effect of distracters on student performance on the force concept inventory. *American Journal of Physics*, *72*(1), 116–125. https://doi.org/10.1119/1.1629091

Sadanand, N., & Kess, J. (1990). Concepts in force and motion. *Physics Teacher*, *28*(8), 530–533. https://doi.org/10.1119/1.2343138

Savinainen, A., & Scott, P. (2002). The Force Concept Inventory: A tool for monitoring student learning. *Physics Education*, *37*(1), 45. https://doi.org/10.1088/0031-9120/37/1/306

Scott, T. F., & Schumayer, D. (2017). Conceptual coherence of non-Newtonian worldviews in Force Concept Inventory data. *Physical Review Physics Education Research*, *13*(1), 010126. https://doi.org/10.1103/PhysRevPhysEducRes.13.010126

Scott, T. F., & Schumayer, D. (2018). Central distractors in force concept inventory data. *Physical Review Physics Education Research*, *14*(1), 010106. https://doi.org/10.1103/PhysRevPhysEducRes.14.010106

Scott, T. F., & Schumayer, D. (2021, February). Network analysis of misconceptions in FCI data. In *AIP Conference Proceedings* (Vol. 2319, No. 1, p. 110001). AIP Publishing. https://doi.org/10.1063/5.0037733

Stoen, S. M., McDaniel, M. A., Frey, R. F., Hynes, K. M., & Cahill, M. J. (2020). Force Concept Inventory: More than just conceptual understanding. *Physical Review Physics Education Research*, *16*(1), 010105. https://doi.org/10.1103/PhysRevPhysEducRes.16.010105

Suprapto, N., Syahrul, D. A., Agustihana, S., Pertiwi, C. A., & Ku, C. H. (2016). College students'conceptions of Newtonian mechanics: A case of Surabaya State University Indonesia. *Chemistry: Bulgarian Journal of Science Education*, *25*(5), 718–731.

Sutopo, S. (2021). Memfasilitasi siswa memahami fisika secara bermakna dan koheren: Tantangan dan alternatifnya. In N. F. Choiron et al. (Eds.), *Kumpulan pidato pengukuhan guru besar Universitas Negeri Malang (UM)* (pp. 201–216). Malang, Indonesia: Penerbit Universitas Negeri Malang.

Sutopo, S., Hidayah, N., Wisodo, H., & Haryoto, D. (2020, April). Improving students' understanding of kinematics concepts through multi-representational learning. In *AIP Conference Proceedings* (Vol. 2215, No. 1). AIP Publishing. https://doi.org/10.1063/5.0004063

Sutopo, S., Jayanti, I. B. R., & Wartono, W. (2017). Efektivitas program resitasi berbasis komputer untuk meningkatkan penguasaan konsep mahasiswa tentang gaya dan gerak. *Jurnal Inovasi dan Pembelajaran Fisika*, *4*(1), 27–35. https://doi.org/10.36706/jipf.v4i1.4260

Tawil, M., & Said, M. A. (2022). Understanding the Newton's motion concept through qualitative and quantitative teaching. *JPPPF (Jurnal Penelitian dan Pengembangan Pendidikan Fisika*, *8*(1), 135–154. https://doi.org/10.21009/1.08113

Trumper, R., & Gorsky, P. (1996). A cross-college age study about physics students' conceptions of force in pre-service training for high school teachers. *Physics Education*, *31*(4), 227–236. https://doi.org/10.1088/0031-9120/31/4/021

Viiri, J. (1996). Teaching the force concept: a constructivist teaching experiment in engineering education. *European Journal of Engineering Education*, *21*(1), 55–63. https://doi.org/10.1080/03043799608923388

Wells, J., Henderson, R., Stewart, J., Stewart, G., Yang, J., & Traxler, A. (2019). Exploring the structure of misconceptions in the Force Concept Inventory with modified module analysis. *Physical Review Physics Education Research*, *15*(2), 020122. https://doi.org/10.1103/PhysRevPhysEducRes.15.020122

Yasuda, J. I., Hull, M. M., & Mae, N. (2023). Visualizing depth of student conceptual understanding using subquestions and alluvial diagrams. *Physical Review Physics Education Research*, *19*(2), 020121. https://doi.org/10.1103/physrevphyseducres.19.020121

Yasuda, J. I., Mae, N., Hull, M. M., & Taniguchi, M. A. (2018). Analyzing false positives of four questions in the Force Concept Inventory. *Physical Review Physics Education Research*, *14*(1), 010112. https://doi.org/10.1103/PhysRevPhysEducRes.14.010112