EDUCA Revista Internacional para la calidad educativa
EDUCA International Journal for Educational Quality
ISSN 2792-7660
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Artículo Original / Original Article

The influence of force misconceptions on engineering students' performance in university introductory physics courses

La influencia de las ideas previas del concepto de fuerza en el rendimiento de los estudiantes en los cursos introductorios de física de la universidad

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Cronograma editorial: *Artículo recibido 29/11/2023 Aceptado: 18/12/2023 Publicado: 01/01/2024*

Para citar este artículo utilice la siguiente referencia:
Ramos Tejada, Mª. M.; Quesada Pérez, M.; Peláez, J. A.; Henares, J. (2024). The influence of force misconceptions on engineering students' performance in university introductory physics courses. *EDUCA International Journal*, 1 (4) 61-74, https://doi.org/10.55040/educa.v4i1.88

Contribución específica de los autores: Todos los autores han contribuido de forma equitativa.

Financiación: Este trabajo ha sido financiado por el proyecto PID10_201617 (Universidad de Jaén).

Consentimiento informado participantes del estudio: Se obtuvo consentimiento.

Conflicto de interés: Los autores no señalan ningún conflicto de interés.

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Abstract
Learning of physics becomes hard due, among other things, to the presence of misconceptions, i.e., ideas that students believe to be true but which are not scientifically correct. In this work, a reduced version of the Force Concept Inventory (FCI) was used to study the most common misconceptions about force among first-year industrial engineering students at the University of Jaen. The influence of these misconceptions on the students' performance on physics exams has been investigated. Misconceptions have a significant influence on academic failure (75 per cent of students that drop out had an inventory score, prior the teaching program, below 40 per cent). But not all misconceptions seem to have the same impact on academic results. We have analyzed in detail the eight misconceptions that are present in more than 30 % of the students and only one of them seems to be relevant to students' performance, whereas four of them do not appear to be influential.

Keywords: Misconception, physics, university education, academic achievement, Force Concept Inventory.

Resumen
El aprendizaje de la física puede resultar difícil debido, entre otras cosas, a la presencia de preconceptos, es decir, ideas que los estudiantes creen que son ciertas pero que no son científicamente correctas. En este trabajo hemos utilizado una versión reducida del Force Concept Inventory (FCI) para estudiar los preconceptos más comunes sobre el concepto de fuerza entre los estudiantes de primer curso de los grados de Ingeniería Industrial de la Universidad de Jaén. Se ha investigado la influencia de estos preconceptos en los resultados de los estudiantes en los exámenes de física. Se ha encontrado que los preconceptos tienen una influencia significativa en el fracaso académico (el 75% de los estudiantes que abandonaron la asignatura tenían una puntuación en el FCI, antes de comenzar el curso, inferior al 40%). Pero no todos los preconceptos parecen tener el mismo impacto en los resultados académicos. Se han analizado en detalle los ocho preconceptos que estaban presentes en más del 30 % de los estudiantes y sólo uno de ellos parece ser relevante para el rendimiento de los mismos, mientras que cuatro de ellos no parecen ser influyentes.

Palabras clave: Preconceptos, física, educación universitaria, rendimiento estudiantil, Force Concept Inventory.

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1. Introduction

Experienced teachers recognize that in spite of their best efforts, many students finish their physics studies without being able to interpret some simple physical phenomena (Mora and Herrera, 2009). At the end of the course, a large percentage of students in introductory physics courses have serious deficiencies in understanding the laws of physics. Although the students had learned to use one or more equations to find an answer to a particular problem, they do not fully understand the underlying physical concepts (Harrison and Serbanescu, 2017). In this learning process, students solve simple problems (substituting numerical values in the formulas), but are not prepared to solve basic qualitative problems (Clement, 1987). Their understanding consists of random facts and equations that have little conceptual meaning (Van Heuvelen, 1991).

One of the causes of this problem is that science students often have a vague system of ideas or beliefs, loosely based on their experience, which does not match what is known to be scientifically correct. These ideas, usually known as misconceptions, are deeply seated in the students' way of thinking and are very difficult to change. These common-sense misconceptions are often applied inconsistently depending on the context and most people who hold them are not aware of their ideas (Alwan, 2011). Therefore, most of the students systematically misunderstand basic science concepts so they cannot understand why they fail at problem solving, and they tend to memorize meaningless formulas and procedures (Hestenes, 1997).

Factors that could cause misconceptions are personal thoughts of students, language used, teachers, characteristics of teaching materials, reference books (Resbiantoro and Setiani, 2022)., movies and internet (Fadllan and Prawira, 2019) among others; Misconceptions act as a basis for new knowledge and, therefore, they play an important role when it is necessary to design teaching strategies or diagnose learning problems.

Concept surveys provide a good method for gauging students' misconceptions, providing information that can be used to develop and evaluate teaching strategies (Wattanakasiwich et al., 2013). For instance, information about some of the compilations of physics concept surveys can be found in Ramos-Tejada et al. (2018) and Physport (2011).

Concept surveys results have shown that traditional instruction (lecture-demonstration) fails badly in meeting a minimal performance standard for mechanics (Covián Regales and Celemín Matachana, 2008; Hestenes, 1997). Misconceptions seem to be persistent regardless of the teacher, the methodology (Hestenes et al., 1992), the country and the students' knowledge (Mora and Herrera, 2009). Therefore, new approaches are needed to investigate and work on conceptual understanding on a qualitative level. Some alternative methodologies have been proposed to solve this problem (Physport, 2011). But it is difficult to specify strategies, and it is an open field for research and innovation (v.g., Aviani et al., 2015; Bain et al., 2014; Chong et al., 2019; Liang et al., 2012; Mercier et al., 2020; Olmstead, 2019; Vicovaro, 2023).

Force Concept Inventory (FCI) (Hestenes et al., 1992) is a widely used multiple choice test developed to investigate the students' most common misconceptions on their perception of force, a central concept of Newtonian mechanics (v.g., Dwyer, 2019; Eaton et al., 2019b; Scott and Schumayer, 2018; Syuhendri, 2021; Wells et al., 2019). Stoen et al. (2020) consider the idea that FCI performance may reflect another student attribute, including relational knowledge structures of physics concepts, expert like attitudes, and problem-solving skills. FCI has some limitations. For instance, dichotomous scoring neglects the possibility that there could exist different degrees of incorrectness within the distractors themselves. Stewart et al. (2021) apply Bock's nominal response model to evaluate student responses to FCI and investigate how correct and incorrect Newtonian thinking coexist in the same student. Eaton et al. (2019a) propose a partial credit model that assigns nonzero values to the distractors of any given question for the FCI. They claim that this model could account for student progression through prominent misconceptions as their worldviews become more Newtonian.

FCI has been widely used to evaluate the persistence of misconceptions in the area of mechanics in higher education (Covián Regales and Celemín Matachana, 2008; Mackay, 2019; Prada-Núñez et al., 2022; Tarjányiová et al., 2020). For instance, Covián Regales and Celemín Matachana (2008) used the FCI to detect the existence of misconceptions in engineering studies, measure the efficiency of the teaching-learning process in the first year of university, and explore the stability of misconceptions. In addition, Martín-Blas et al. (2010) analyzed the results of the Force Concept Inventory test of two different groups of first year engineering students. They found that, although there were significant performance variations between the two groups, both of them shared common incorrect answers that were consistently triggered by the same misconceptions.

This study is concerned with the misconceptions in the force concept and their impact on students' performance in university introductory physics courses. To do it, the FCI was used to research what are the main students' force misconceptions and their persistence. Moreover, its possible influence on academic failure has also been investigated.

2. Metodology

The subjects of this study consisted of four groups of Industrial Engineering from the University of Jaén following a first semester introductory physics course. The teaching topics were mechanics, oscillation and waves.

In this study, only some of the concepts of FCI were considered. A selection of thirteen questions of the Spanish translation of the FCI (Hestenes et al., 1992) was used. Table 1 shows the chosen questions of the FCI, and the studied Newtonian concepts. This test, hereinafter referred to as rFIC, was administered prior to, and on completion of, the teaching program. From our study, total (126 pre-test and 80 post-test) and partial results (73 results of the students who took both the pre- and post-test) are reported. In order to evaluate the successfulness of the mechanics course, the average rFCI score of the students who took both the pre- and post-test were compared using Hake's normalized gain (Hake, 1998; Savinainen and Scott, 2002):

$$\langle g \rangle = \frac{\langle S_{post} \rangle_p - \langle S_{pre} \rangle_p}{100\% - \langle S_{pre} \rangle_p} \quad (1)$$

being $\langle S_{pre} \rangle_p$ and $\langle S_{post} \rangle_p$ the average rFCI score of the students pre- and post-test, respectively.

Table n. 1. FCI chosen questions and related Newtonian concepts

Kinematics	Newton's 1st Law	Newton's 2nd Law	Newton's 3rd Law	Types of forces
23, 24, 25	4, 6, 10, 26, 28	6, 24, 25	2, 11	16, 22, 23 29

It has been considered that the students have a misconception if they are chosen any of the items related to this misconception. In order to evaluate the influence of the misconceptions on student performance, correlations between them and the exam score (from 0 to10) were examined. The exam score was an average of two mid-term exams, consisting of a theoretical question (10 %), conceptual questions (15 %) and problems (75 % of the total score). The first exam covered the principles of particle mechanics, and the second one the systems of particles, rigid body mechanics, oscillation and waves. Students passed the exam if their score were 5 or higher. To study the persistence of the misconceptions, the efficacy of the instruction (*e*) was calculated by means of the following expression:

$$e = \frac{incidence_{pre} - incidence_{post}}{100\% - incidence_{pre}} \qquad (2)$$

where $incidence_{pre}$ and $incidence_{post}$ are the incidence percentages in the corresponding tests.

3. Results and discussion

3.1. Overall rFCI results

The global rFCI results are shown in Table 2. Although these results are not directly comparable with data from other studies, because a reduced FCI was used, the scores and Hake's normalized gain was similar to the ones given by Covián Regales and Celemín Matachana (2008) for other engineering High Schools in Spain.

Table n. 2. Student reduced FCI average score (%) total and partial, and Hake's normalized gain (partial averages)

$\langle S_{pre}\rangle_{tot}$	$\langle S_{pre}\rangle_p$	$\langle S_{post}\rangle_{tot}$	$\langle S_{post}\rangle_p$	$\langle g\rangle$
40.0	41.2	53.4	53.7	0.21

Force Concept Inventory is a multiple-choice "test", each question has five possible responses (a, b, c, d and e). The pre- and post-course test student answers for individual items are showed in Table 3. It is interesting to compare the answers 25a and 28a. These answers are associated with the misconception AF4 (see Table 4), however there are clear differences between them (25% and 4% respectively post-test). We can find the same differences, for instance, among 6d (15%), 24d (19%) and 29e (3%) related to the misconception CI3, and 4c (4%), 10d (0%), 16a (0%), 23c (5%) and 24c (15%) related to CI2, and 6d (15%), 24d (19%)

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and 29e (3%) related to I4. These differences highlight the context-dependency of students' misconceptions and explain why is so difficult to change these ideas.

Table n.3. The pre- and post-test rFCI answers (total averages) for individual items. Right responses in grey.

	Pre- test answers													Post-test answers												
	2	**4**	**6**	**10**	**11**	**16**	**22**	**23**	**24**	**25**	**26**	**28**	**29**	**2**	**4**	**6**	**10**	**11**	**16**	**22**	**23**	**24**	**25**	**26**	**28**	**29**
a	62	11	26	25	1	1	5	40	16	24	7	3	17	44	14	21	25	0	0	8	34	14	25	9	4	20
b	3	71	38	66	13	71	62	16	23	24	26	6	21	1	78	53	71	4	83	27	8	21	35	35	5	18
c	1	4	4	6	10	26	5	8	21	8	31	24	55	4	5	0	3	1	16	8	5	15	1	21	29	58
d	2	6	14	2	44	3	28	36	18	36	20	42	5	1	1	15	0	29	1	56	54	19	38	28	51	3
e	33	8	18	1	33	0	1	0	22	8	17	25	2	50	3	11	1	66	0	3	0	31	1	7	11	3

To obtain a more detailed idea about how misconceptions are present on students, Table 4 shows the percentage of them that marked as correct any of the options associated with each specific misconception. It was found that the most common misconceptions after teaching were RI, AR1, R2, I2, CI3, I1, AF6 and I5. This agrees in part with a previous work by Savinainen and Scott (2002), where AR1, CI3 and AF4 were found as the most common misconceptions.

As regards the persistence of the misconceptions, thirteen of them decrease, two of them remain the same, and five of them increase (Table 4). Concerning those that increase, if the distribution of the answers of the corresponding items is analyzed, it is possible to note that some of the wrong answers decrease but the right answers do not increase in the same proportion, that is, the students change a misconception for another one.

Table n. 4. The pre- and post-test percentage of incidence of individual misconceptions and efficiency of instruction

	Misconception (test options)	Pre (Partial)	Post (Partial)	e
AF7.	active force wears out (25c,e)	15.9 (11.0)	2.5 (1.4)	0.88
Ob.	obstacles exert no force (2c)	0.9 (1.4)	3.8 (4.1)	-2.00
CF.	centrifugal force (4c,d,e; 10c,d,e)	23.9 (20.5)	10.0 (9.6)	0.53
AF1.	only active agents exert forces (11b; 22a)	15.9 (16.4)	11.3 (12.3)	0.25
R3.	resistance opposes force/impetus (28e)	23.9 (24.7)	11.3 (12.3)	0.50
I4.	gradual/delayed impetus build-up (6d; 24d; 29e)	14.2 (16.4)	12.5 (12.3)	0.25
AF2.	motion implies active force (29 a)	16.8 (20.5)	20.0 (21.9)	-0.07
CI2.	f. compromise determines motion (4c; 10d; 16a; 23c; 24c)	27.4 (23.3)	22.5 (23.3)	0.00

AF4.	velocity proportional to applied force (25a; 28a)	24.8 (26.0)	27.5 (27.4)	-0.05
AR2.	most active agent produces greatest force (11d)	43.4 (39.7)	28.8 (27.4)	0.31
I3.	impetus dissipation (16c,d; 23e; 29 b)	43.4 (41.1)	28.8 (28.8)	0.30
I5.	circular impetus (4a,d; 10a)	34.5 (32.9)	35.0 (32.9)	0.00
AF6.	force causes acceleration to terminal velocity (25d)	35.4 (35.6)	37.5 (38.4)	-0.08
I1.	impetus supplied by "hit" (22b,c,e; 29d)	69.0 (69.9)	38.8 (39.7)	0.43
CI3.	last force to act determines motion (6a; 24b; 26c)	49.6 (53.4)	41.3 (42.5)	0.21
I2.	loss/recovery of original impetus (4d; 6c,e; 24a; 26a,d,e)	57.5 (56.2)	51.3 (47.9)	0.15
R2.	motion when force overcomes resistance (28b,d)	45.1 (43.8)	55.0 (52.1)	-0.19
AR1.	greater mass implies greater force (2a,d; 11d)	77.0 (76.7)	55.0 (54.8)	0.29
Rl.	mass makes things stop (23a,b; 29a,b)	68.1 (68.5)	55.0 (56.2)	0.18

3.2. Misconceptions influence on students' performance

Students' performance in the first-year physics course depends on several factors, such as their mathematical level, abstraction capacity, motivation, personality, etc. Our results show that misconceptions are one of the factors with a significant influence on physics academic success.

Table n. 5. Contingence table presenting data related to rFCI score and academic performance

Test score	Drop out	Fail	Pass	Pearson's Chi-squared test
$S_{pre} < \langle S_{pre} \rangle_{tot}$	9	49	15	p-value = 0.0072
$S_{pre} > \langle S_{pre} \rangle_{tot}$	2	18	19	
$S_{post} < \langle S_{post} \rangle_{tot}$	-	27	7	p-value = 0.0063
$S_{post} > \langle S_{post} \rangle_{tot}$	-	20	21	

Finally, the Pearson's Chi-square test was applied to search for an association between the rFC score of pre- and post-tests (higher or lower than the mean) and levels of academic performance (drops out, fail or pass their exams). Since the p-values, 0.0072 and 0.0063 on pre- and post-test, respectively, are less than alpha value of 0.05 (Table 5), we can reject the null hypothesis that they are independent. Only 7 of the 34 students with S_{post} score lower than the mean pass their exams. It is not surprising, since misconceptions are barriers to understand mechanics concepts, and therefore, students fail at problem solving. Our results show that pre-

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test scores are also important; Figure 1 shows pre-test scores for the different groups of academic performance. 75 per cent of the students that drop out have an average pre-test score lower than 40. These results indicate that misconceptions are a factor that should not be overlooked for preventing school failure.

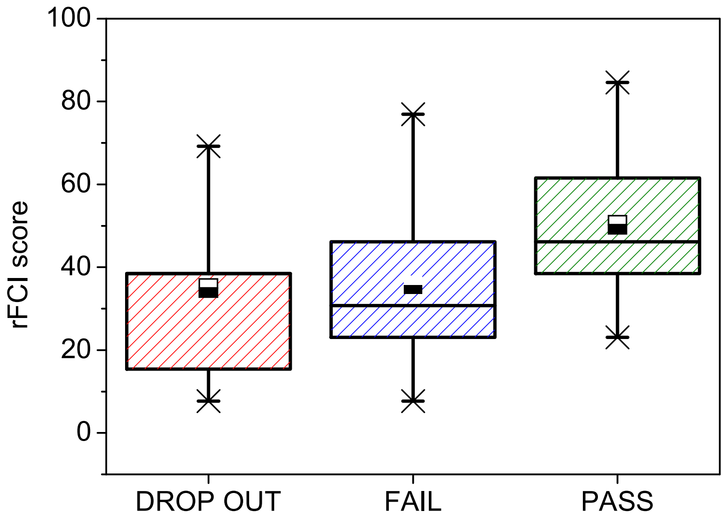

Figure n. 1. Pre-test rFCI score and the achievement levels of the students

Table n. 6. Contingence table presenting data related to test score and academic performance

	I1		I2		I5		R1		R2		AR1		CI3		AF6	
	Y	**N**	**Y**	**N**	**Y**	**N**	**Y**	**N**	**Y**	**N**	**Y**	**N**	**Y**	**N**	**Y**	**N**
Fail	22	26	27	20	20	27	29	18	25	22	31	16	24	23	20	27
Pass	5	23	11	17	7	21	11	**17**	16	12	12	16	8	20	8	20
p-value	0.014		0.13		0.13		0.060		0.74		0.050		0.057		0.23	

It has been found that there are eight misconceptions present in more than 30 % of the students (post-test) (see Table 4). We have investigated if one of these misconceptions could itself be relevant to students' performance. Table 6 shows the observed frequencies across two variables, the misconception presence and the academic achievement of students (pass or fail). It is clear that there is a significant dependence between I1 and the student performance (*p*-value equal to 0.014 is less than the significance level, 0.05). There are three misconceptions,

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R1, AR1 and CI3, with *p*-values slightly above the significance level, and the remaining ones do not seem to have influence on the exams results. Figure 2 give a more detailed picture of the distribution of exam scores categorized depending on the presence or not of the I1, R1, AR1 and CI3 misconceptions. The exam score distribution is different, and the scores are lower when the misconceptions are present. Thus, the following question arises, what misconceptions are more relevant?

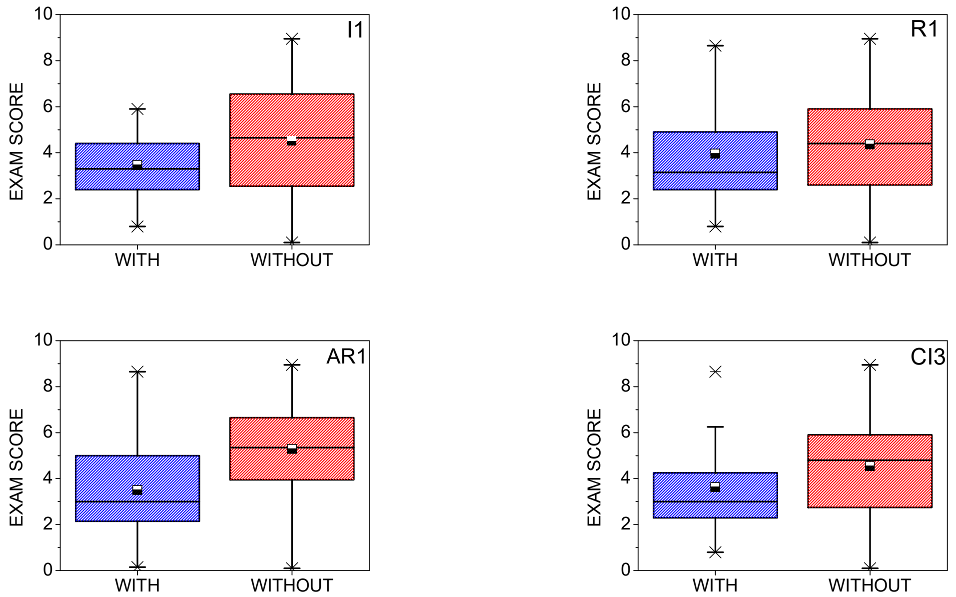

Figure n. 2. Presence of some misconception and the achievement levels of the students

4. Conclusions

The presence of force misconceptions on students in the first-year engineering physics course has been studied. Our results show that misconceptions are persistent and context-dependent, and that when a misconception disappears during the instruction it could be replaced by another one, so the problem remains. As regards the influence of misconceptions on the students' performance on physics tests, it has been found that misconceptions have a significant influence on students' performance in the first-year engineering physics. Students with lower rFCI score (before and after instruction) used to have worse academic results, indeed, 75 per cent of students that drop out had an inventory score, prior the teaching program, below 40 per cent. This fact should be considered during instruction. In addition, the isolated influence of the eight most common misconceptions found on academic results was analyzed, and results show that I1 affect itself to the global exam score, and maybe CI3, R1 and AR1 could be also relevant to students' performance.

While FCI can offer a general idea of mechanical misconceptions on students, it has some limitations. It may be necessary to introduce a complementary analysis or diagnostic tools to get a deeper insight into the problem. This mixed method approach could hopefully provide us with a richer understanding of the mechanical misconceptions and its influence on students' performance.

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