Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Newton's law learning assessment: an experience with high school students

To cite this article: R Prada Nuñez *et al* 2022 *J. Phys.: Conf. Ser.* **2153** 012020

Newton's law learning assessment: an experience with high school students

R Prada Nuñez[1], C A Hernández-Suarez[1], and A A Gamboa Suarez[1]
[1] Universidad Francisco de Paula Santander, San José de Cúcuta, Colombia

E-mail: cesaraugusto@ufps.edu.co

Abstract. The Force Concepts Inventory is a test to determine the level of conceptual knowledge of students about mechanical physics and to evaluate the effectiveness of different teaching strategies on the conceptual component of learning. The test is applied with the purpose of knowing the level of conceptualization of the students of a Physics subject course. The results of the pre-test made it possible to find out the level of conceptualization that the students possessed and provided information for the development of workshops based on real physical situations that required the elaboration of force diagrams. The results of the post-test allowed estimating Hake's learning and showed evidence about the conceptual evolution of the students and information to develop future teaching activities on Newton's laws.

1. Introduction

In mechanical physics, the concept of force is fundamental in academic programs in science and engineering, so students (who come from pre-university education), need to conceptualize it to apply Newton's laws in the resolution of different concrete problem situations. One of the curricular orientations for the teaching of natural sciences in secondary education (by the "Ministerio de Educación Nacional, Colombia"), is related to the theoretical and practical foundations of classical mechanics, from the movement of bodies and their interactions, the concept of force, work, and energy, supported by mathematical modelling, for the explanation of situations in nature [1,2].

Therefore, the students' learning, before focusing on algorithmic and algebraic procedures, must be oriented towards a conceptual domain that allows them to understand the laws and the explanation of physical phenomena, since, when approaching the solution of a problem, it is decontextualized from the conceptual arguments of physics. This adds to the inherent difficulty of concepts and their relationships to be understood; acceleration and force, equivalence between rest state and movement with constant speed, inertial and non-inertial systems, among others [3].

One of the difficulties that hinder the learning of mechanical physics is related to the erroneous preconceptions of the students [4], that are born from the daily experience that led to internalize incorrect relations between different physical magnitudes, for example, to use the term force in a variety of contexts, using vague and ambiguous associations [5], which are difficult to modify in structural terms.

The personal construct of students' previous ideas are representational schemes that do not model adequate scientific conceptions, thus becoming an obstacle that does not favor conceptual change despite teaching attempts [6]. Therefore, helping a conceptual change requires teaching activities that start from what the student knows, in a social teaching context [7,8], that favor the clear, stable, and organized reconstruction of knowledge with which they can face and solve diverse situations and, at the same time, acquire knowledge that demands a higher level of abstraction within the same field.

The intervention developed in this study that has as its axis of analysis the consistent representation of the interactions between systems through the so-called force diagrams (free body diagrams) [9], is based on the perspective of collaborative learning that is based on the psychological theory the sociocultural theory [7] and of cognitive development [10].

On the other hand, the force concept inventory (FCI) evaluates the degree of understanding of concepts in mechanical physics [11,12]. It is usually used as a pre-test/post-test (Hake's factor [13]) to determine the effectiveness of some teaching strategies used during students' conceptual learning. There are studies on the application of FCI in university students in the United States, Spain, and some Latin American countries but no studies are recorded in basic education students, which is where students are beginning to build their ideas of the physical concepts that will be used later in secondary and university education [3,14].

In accordance with the above, from the framework of the implementation of this strategy in the Physics subject in an educational institution of basic and secondary education, the hypothesis raised consists in whether the teaching of Newton's laws from the perspective of collaborative learning using force diagrams allowed a conceptual evolution of their learning. For this purpose, the FCI and Hake's factor were applied to know the students' conceptual level in relation to the concepts of mechanical physics.

2. Methodology

The research was done under the quantitative paradigm, with intentional sampling, because the target groups are formed through entry mechanisms outside of teachers' control. The design was quasi-experimental, in which the FCI was applied as a pre-test, to explore the preconceptions of Newtonian mechanics that students had, followed by a teaching intervention with the following activities: design, implementation and application of workshops based on real physical situations and where the elaboration of force diagrams is the central axis [7,10,11]. At the end of the intervention, the FCI was applied again as a post-test allowing to estimate the so-called Hake's learning gain [13].

2.1. Population and sample

The implementation of the proposal was developed in 40 of 10^{th} grade students divided into two groups belonging to an educational institution located in Norte de Santander, Colombia. The ages of the students are between 14 years old and 16 years old. It should be noted that this is the first introductory physics course in their academic training. All the young people who participated in the implementation of the experience were informed orally about the nature and purposes of the experience; their response was of unanimous acceptance of wanting to participate actively in the process. In addition, they were informed of the commitment made with the institutional directives to deliver a copy of the project and its results, which will be available for any type of consultation.

2.2. Instruments

The FCI is a test designed by Hestenes, Wells, and Swackhammer that measures the understanding of the basic concepts of Newtonian mechanics, the didactic efficiency of the teaching-learning process of the latter and allows to detect the preconceptions that it has he evaluated on this subject [11,12]. The FCI is composed of 30 questions. The advantage of the FCI is that it allows to determine the level of knowledge of mechanics, to evaluate the didactic efficiency of the teaching-learning process, the degree of comprehension, to detect and to classify the conceptual errors incurred by the students and their preconceptions and their evolution in time [15,16]. The FCI was used in its Spanish version [3] with questions with 5 answer options, grouped into the following categories [11]: cinematics; Newton's first law (inertia); Newton's second law (force and acceleration); Newton's third law (action and reaction); principle of overlap; types of force. This instrument was used because it measures (in a certain sense) the ability of Newtonian thought [17]. A high score on the FCI does not indicate a unified knowledge of the concept of force, however, a low score indicates a lack of knowledge of basic Newtonian concepts.

Free-body diagram, also called force diagram [5] of a body or a group of bodies (or a part of a body) which is called a system and is represented in isolation from its environment, where all the external forces acting on it are shown, allowing the modelling of a body and its interactions with its surroundings. The modelling process allows to solve problems by simplifying the situations to be studied, therefore, it will be incomplete and inaccurate, but it will explain and predict the behavior of an object or system; the model will be valid if the analytical results are experimentally verified.

Finally, the Hake's factor or relative gain of conceptual learning indicates the average real gain of standardized conceptual learning [13]. It is used to determine the level of conceptual learning achievements in the implementation of a didactic strategy, that is, with the results of an evaluation (pre-test and post-test) the impact on the assimilation of type knowledge is determined conceptual. In the case of this proposal, the g factor allows to establish the changes achieved in the different dimensions of the FCI when implementing a didactic strategy, since the low, medium, and high levels of achievement in the g factor are related to the level of conceptual mastery of the phases of the FCI. For the calculation of the Hake's factor (g) the Equation (1) is used [13].

Also, the value of g can take values between 0 and 1, where 0 represents no learning, while 1 corresponds to the maximum possible learning. Establishing with the relative learning gain it is possible to classify three levels of achievement, high ($g > 0.7$), medium ($0.3 < g \leq 0.7$), and low ($0 \leq g \leq 0.3$).

$$g = \frac{FCI_{post}(\%) - FCI_{pre}(\%)}{100 - FCI_{pre}(\%)}. \quad (1)$$

2.3. Data collection procedure

The collection procedure is described below, which plays an important role in the validity and quality of the data. To analyze the initial state (preconceptions and diagnosis) that the students of mechanical physics had, the modified FCI in their numbering was applied as a pre-test (only 20 items were taken: 1-4, 7, 13-18, 21-29). The selected questions were directed to reach the conceptual levels of the students proposed in their area plan related to the concepts of force and proper Newtons laws. To perform the analysis, it was divided into fundamental aspects defined by groups of topics (see Table 1).

The classes were of a theoretical-experimental type where inclined planes, wooden blocks, laboratory pulleys, dynamometer, chronometers, pita ropes and power table were used. These activities were carried out in 20 hours of class attendance. For the didactic interventions related to the subject of cinematics (5 exercises) it was analyzed if the students have clear concepts of position, speed, and acceleration; as well as if they recognize these physical magnitudes as vector magnitudes.

The topic of Newton's Laws (10 exercises), it was identified if the students understand the approach of the law of inertia (movement does not imply presence of external force. We also analyzed the ideas they have about the cause of movement and its implications in speed and acceleration. Finally, the understanding of the interaction between two bodies was investigated, since it is common to consider a dominance principle in which "the strongest exerts the greatest force"; the strongest is usually the object with the greatest dimension, the most activity and/or the greatest amount of mass. This conflict leads to erroneous interpretations of this law.

Table 1. Classification of FCI questions by topic.

Topic	Grouping of questions
Cinematics	1-3, 5-15
Newton's first law	5, 7, 9, 10, 12-16, and 20
Newton's second law	1-3, 5-8, 11-15, 17, and 18
Newton's third law	4, 8-10, and 19
Force classes	1-3, 5-7, 11, and 20

The analysis of the subject each exercise consists of construction of force diagrams; decomposition of forces into rectangular components, if necessary; presentation of the equations of Newton's laws, and solution of the equations to find the physical variable requested in each statement, considering the data from each exercise. For the topic types of force (20 exercises), we explored the conception that they have of the term concept force; if they recognize the force of contact (friction and normal), the forces present by the action of the strings and the forces at a distance as the force of gravity. In addition, for the construction of force diagrams, the student considered the following protocol:

- Description of the physical situation.
- Simplified representation of the physical situation.
- Matrix representation of the interactions between systems.
- Representation with closed dotted line of the physical system(s) of interest.
- Detailed list of the forces acting on the physical system(s) of interest and assign a notation.
- Representation of the forces (force diagram) acting on the system(s) of interest.
- Representation of forces by simplifying the model to a particle (if possible).
- Once the situation of the exercise to be solved has been described and its simplified representation has been carried out, it should be done:
  - ❖ Choose reference frame.
  - ❖ Select a coordinate system that is anchored to the reference frame.
- Make the decomposition of forces (rectangular components) and proceed to apply Newton's laws of motion in each direction.
- Solve the equations.
- Verify the results by performing some usual technique for this purpose.

Finally, the FCI was applied again, and the so-called learning gain was estimated using the Hake’s factor of each of the five aspects into which the study was divided.

3. Results and discussion

The presentation and analysis of the results was done considering the questions of the FCI (Table 2). The results are presented indicating the average percentage of success of the FCI questions in their pre-test and post-test applications and the calculation of the Hake’s factor to numerically visualize the level of learning achieved (see Table 2). According to Hake’s factor, the learning gain, for each of the subjects, is at the middle level, an index very similar to others.

Obtained in previous studies in the United States and Spain [18]. From the results of the table, it can also be highlighted that Newton’s third law had the highest mean level of gain (0.63), which can be attributed to the analysis of physical situations with the use of force diagrams in association with the matrix listing of interactions. The above is due to the understanding of physical concepts rather than the mechanization of mathematical formulas and the proper construction of force diagrams.

In addition, for Newton’s second law, it was the lowest level of profit (0.38). This is because some students failed to relate the acceleration to the resulting force; additionally, they presented deficiencies in the handling of the equations that in most of the cases were simultaneous. Here it is necessary to say that the time spent teaching this law was not enough. Some studies show that the concept with the greatest difficulty is Newton’s second law [3,14].

Table 2. Average percentage of success in the pre-test and post-test and gain of the Hake’s factor of the target group.

Topic	% Pre-test	% Post-test	Hake’s factor	Level
Newton’s first law	27.25	58.00	0.42	Medium
Newton’s second law	31.92	57.85	0.38	Medium
Newton’s third law	56.00	83.50	0.63	Medium
Force classes	32.15	58.71	0.39	Medium
Cinematics	39.45	68.21	0.47	Medium

Journal of Physics: Conference Series **2153** (2022) 012020 doi:10.1088/1742-6596/2153/1/012020

Finally, between the application of the pre-test and the post-test a progress in the students' understanding and correct application of Newton’s laws of motion is observed. The previous evidence shows that didactic intervention on the use of force diagrams (mental representations and their characterization), favored the significant learning of Newton’s laws in basic education students, in comparison with previous experiences developed in similar contexts [19].

The realization of the force diagrams of the different physical situations allowed the student to evidence the understanding of the phenomena studied. In this order of ideas, the following advances in the learning of the concept of force and Newton’s laws are highlighted.

- Construction of the interaction matrix, which contributed to differentiate the action-reaction pairs easily.
- Understanding sliding friction force.
- Correct interpretation of the friction coefficient.
- They adequately represent the external forces acting on the physical system.
- Improvements in mathematical procedures applied to the resolution of physical problems and interpretation of physical situations related to the environment.
- The feedback made it easier for the students to construct force diagrams.
- Resolution of more complex exercises.

Among the difficulties presented, the following stand out.

- The reference system or coordinates are not identified, and the physical variable requested is not found.
- Deficiencies in the handling of equations.
- Confusion of the concepts weight and mass, as well as in the nomenclature of forces.
- Difficulty in understanding physical situations such as underestimating friction, weightless pulleys and mass free ropes that can help simplify a problem.
- Incorrect decomposition of vectors into rectangular coordinates
- It is difficult in physical systems of three blocks to add masses and unite them into one.
- Difficulty to apply Newton’s laws according to their cases.
- Difficulties in formalizing force diagrams.
- Although the reference systems and coordinates, the matrix, and the equations derived from the force schemes are well posed, they have mathematical difficulties in solving the problem.

Some of these difficulties in students coincide with those found in previous studies on physical concepts [20,21]; and especially concepts linked to the conception of Newton’s laws [22-26]. Another of the limitations found was the decrease in the intensity of the weekly hours, due to the development of various academic activities at the institution.

According to the results obtained from the didactic implementation, and according to the instruments used, it is evident that the students have obtained gains with respect to conceptual learning, in the different components of the FCI [27]. Hake’s factor does not seek to evaluate the student himself, but the teaching-learning process and the teacher’s didactic strategies. In relation to the above, it is possible to establish that the use of force diagrams as a fundamental part in the teaching-learning of Newton’s laws, allowed students to advance towards a high conceptual level, by improving their reasoning skills, developing an understanding of concepts, and solving more complex problems [28]. This, together with a better attitude of the students towards the study of physics.

4. Conclusion

After the analysis of the pre-test/post-test of the force concept inventory, it is shown that the didactic intervention that used the force diagrams as a fundamental element in the teaching-learning of Newton's laws allowed the systematic use of the interaction matrices of the forces of the physical systems, the experimentation of Newton's laws and their application to problematic situations achieving a significant learning in the students who were the objects of study. However, there is still much work to be done in this area since, although there are numerous proposals for didactic experiences of this type, their effectiveness must be evaluated with larger samples of students and those of different educational levels.

References

[1] Ministerio de Educación Nacional 1998 *Lineamientos Curriculares de Ciencias Naturales y Educación Ambiental* (Bogotá: Ministerio de Educación Nacional)
[2] Ministerio de Educación Nacional 2004 *Formar en Ciencias: ¡el Desafío!* (Bogotá: Ministerio de Educación Nacional)
[3] Budini N, Marino L, Giuliano M, Carreri R, Cámara C, Giorgi S 2019 *Revista de Enseñanza de la Física* **31** 107
[4] Machado C, Vieira P, Nascimento M A 2017 Combining two computational tools for teaching and learning physics *International Conferences New Perspectives in Science Education* (Florence: Pixel International)
[5] Tomara M, Tselfes V, Gouscos D 2017 *Themes in Science & Technology Education* **10(1)** 1
[6] Bello S 2004 *Educación Química* **15(3)** 210
[7] Vygotsky L 2009 *El Desarrollo de los Procesos Psicológicos Superiores* (Barcelona: Crítica)
[8] Ausubel D, Novak J D, Hanesian H 1983 *Psicología Educativa: Un Punto de Vista Cognoscitivo* (México: Trillas)
[9] Ocariz J 2000 Diagramas de cuerpo libre ¿Puede dibujarlos cualquiera? *Boletín del Departamento de Mecánica* (México: Univesidad Nacional Autónoma de México)
[10] Piaget J 1981 *Psicología y Pedagogía* (Barcelona: Ariel)
[11] Hestenes D, Wells M, Swackhamer G 1992 *The Physics Teacher* **30(3)** 141
[12] Hestenes D, Halloun I 1995 *The Physics Teacher* **33** 502
[13] Hake R 1998 *American Journal of Physics* **66(1)** 64
[14] Artamónova I, Mosquera J C, Mosquera J D 2017 *Revista Educación en Ingeniería* **12(23)** 56
[15] Huffman D, Heller P 1995 *The Physics Teacher* **33** 138
[16] Henderson C 2002 *The Physics Teacher* **40(9)** 542
[17] Morris G, Harshman N, Branum-Martín L, Mazur E, Mzoughi T 2012 *American Journal of Physics* **80(9)** 825
[18] Covián E, Celemín M 2008 *Enseñanza de las Ciencias* **26(1)** 23
[19] Prada Nuñez R, Hernández C A, Gamboa A A 2021 *Journal of Physics: Conference Series* **1981(1)** 012008:1
[20] Prada Nuñez R, Hernández C A, Gamboa A A 2021 *Journal of Physics: Conference Series* **1981(1)** 012007:1
[21] Elizondo M 2013 *Presencia Universitaria* **3(5)** 70
[22] Hestenes D, Wells M 1992 *The Physics Teacher* **30(3)** 159
[23] Hart G, Cottle P 1993 *The Physics Teacher* **31(8)** 470
[24] Roeder J 1998 *The Physics Teacher* **36(6)** 379
[25] Mora C, Herrera D 2013 *Latin-American Journal of Physics Education* **3(1)** 72
[26] Moreno J, Martínez Velásquez N 2017 *Amazônia: Revista de Educação em Ciências e Matemática* **13(26)** 82
[27] Hernández C A, Prada R, Gamboa A A 2021 *Journal of Physics: Conference Series* **2073(1)** 012003:1
[28] Leonard W J, Gerace W J, Dufresne R J 2002 *Enseñanza de las Ciencias* **20(3)** 387