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Students' Understanding in Kinematics: Assessments, Conceptual Difficulties and Teaching Strategies

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Abstract
This paper scrutinizes reported education studies in kinematics, which is a basic topic in the field of physics. Articles were searched on major databases about the related studies using keyword search. These were classified into the assessment tools, conceptual difficulties and teaching strategies in kinematics.
Keywords: Kinematics, Assessments, Conceptual Difficulties, Teaching Strategies, Physics Education

Introduction

Kinematics is the study of motion without considering the cause of the motion. Basic concept in kinematics is introduced as early as in pre-school level by recognizing the different between two states of motion, for example objects in fast and slow motion. The nuance of various states of motion starts with qualitative observation and progresses toward quantitative measurement of a motion in higher level of education.

In Malaysia, students should be able to calculate speed using formula and interpret space-time relation using graph in Year 6 (Kementerian Pelajaran Malaysia, 2014). It is worth noted that primary school level in Malaysia starts from Year 1 at 7 years old until Year 6 at 12 years old. Secondary school level is divided into lower level (Form 1 at 13 years old until Form 3) and upper level (Form 4 and Form 5 at 16 and 17 years old). In the upper level, students can choose between various streams of education according to their interest and previous academic performance such as vocational, art, Islamic and science streams. Subjects are set in packages according to the stream. In Form 2, students should be able to identify planet according to their travelling time, orbital distance and speed of rotation as well as orbiting speed (Kementerian Pelajaran Malaysia, 2016). As students are progressing toward Form 4, they should be able to relate between particles motion and temperature to understand kinetic theory of gasses (Kementerian Pelajaran Malaysia, 2010a). In

Form 5, they should be able to solve quantitative problem related to velocity and acceleration in scalar form (Kementerian Pelajaran Malaysia, 2010b). For those taking science streams, a specialized Physics subject is usually compulsory. More advanced analysis of linear motion is introduced with emphasizing on the connection between scalar and vector variables. Linear motion equations with uniform acceleration are required for Form 4 to solve practical problems in one dimension (Kementerian Pelajaran Malaysia, 2012).

In pre-university level, kinematics study involves two-dimensional analysis by the introduction of projectile motion, circular and rotational motion (Majlis Peperiksaan Malaysia, 2012). The continuous change of kinematics variable such as position and speed in time is learned using graphs. Graphing skills are usually taught in separate lesson through mathematics subject.

The progression in kinematics learning toward more complex analysis is carefully designed to accommodate students' level of understanding in other topics in science subjects as well as in mathematics subject. For example, good understanding in acceleration is important to get deeper in the topics of dynamics since force is related to the acceleration. Advanced topic in physics such as hydrodynamics, thermodynamics and electromagnetism require students to strongly master kinematics concepts to avoid learning difficulties (Suarez, Kahan, Zavala, & Marti, 2017). Thus, it is important for educators to understand students' prior knowledge regarding kinematics before they introduce the new learning objective. This paper scrutinizes reported studies on kinematics learning at secondary education level and above.

Methodology

A search of reported studies was started with the assessment tools listed under the subject of mechanics in PhysPort, which is an online platform containing teaching resources for physics educators community (American Association of Physics Teacher, 2018). Five of 15 research-based assessment are related to kinematics, while the others assess mainly about force concept, energy and momentum. References are provided for each assessment as a guide for our search in finding more related reported studies.

For further search, Mendeley reference manager was used on keywords kinematics, motion and physics education. For studies reported in Malaysia, MyJurnal database by Malaysian Citation Center was used on keywords *kinematik*, *gerakan* and *pendidikan fizik.* When keyword mechanics was used in both Mendeley and MyJurnal, most references are related to the study of force and energy concepts. Thus, we have to refine by reading each abstract of the results. Other than peer-reviewed papers such as conference papers, technical reports, theses and reviews were omitted. Finally, our search are listed in the reference and discussed in the following sections.

Findings

Studies were categorized according to three main themes; assessment tools, conceptual difficulties and teaching strategies. These are discussed in the next sections.

Assesment Tools

A valid and reliable instrument is required to probe students understanding in kinematics. Here, we describe assessment tools from reported studies. These tools can be used as a diagnostic tool, evaluation on instruction or a placement test depending on the instructor's intention. One may adapt any tool, or combine questions of the tools to create another new tool.

Force Concept Inventory (FCI) is one of available prominent tools to probe students understanding in mechanics at pre-college level (Hestenes, Wells, & Swackhamer, 1992). FCI contains 29 questions of five answer choices. These questions are categorized in six conceptual dimensions; Kinematics, Newton's First Law, Newton's Second Law, Newton's Third Law, Superposition Principle and Kinds of Force. Four questions of the FCI are in the kinematics dimension; Item 20, 21, 23, 24 and 25. To date, the FCI has been translated into 29 languages including Malay, Japanese and Croatian (American Association of Physics Teacher, 2018). Representational Variant of the Force Concept Inventory (R-FCI) was a variant of the FCI which evaluates students' skills in multiple representations. Other variation of FCI, called FCIspm is also available for Malaysian high school population (Ahmad Tarmimi Ismail & Ayop, 2016). The FCIspm reduced to 22 items while remaining the original 5 kinematics-related questions with adaption to align with Malaysian Physics From 4 syllabus (Kementerian Pelajaran Malaysia, 2012).

Mechanics Baseline Test (MBT) was developed following the FCI (Hestenes & Wells, 1992). While the FCI focuses on the student preconception before receiving formal instruction, the MBT complements the FCI by assessing student concepts which could not be justified without formal instruction in mechanics. MBT covers three main concepts; kinematics, general principles such as Newton's Laws and specific forces (i.e. friction). Only six out of 26 questions with five answer choices are related to mere kinematics.

Test of Understanding Graphs in Kinematics (TUG-K) was developed to evaluate student's ability to interpret graphs in kinematics for high school and pre-university level (Beichner, 1994). The revised version of the TUG-K identified as TUGK 4.0 is recently available with modification of distractors and items substitution (Zavala, Tejeda, Barniol, & Beichner, 2017). TUG-K 4.0 consists of 26 questions of five answer choices which were categorized into seven objectives of assessment. The TUG-K may not suitable if one want to access kinematics without graphing knowledge.

Force and Motion Conceptual Evaluation (FMCE) is another tool for assessing kinematics concept (Ramlo, 2008). However, only questions 22 to 26 and 40 to 43 from 45 questions are suitable. Others are related to force and energy. One of the distinct differences between the FMCE and the previous tools is that several questions are based on a scenario with a set of answers. For example, question 40 to 43 refer to a car moving on a horizontal line. Four questions are asked about the situation and nine velocity versus time graphs are provided for answer options.

Rotational Kinematics Inventory (RKI) is different that the above mentioned tools in a way that it is specially designed to assess rotational kinematics which requires understanding of motion in two dimensions (Mashood & Singh, 2015). RKI consists of 39 questions of four answer choices.

Student Conceptual Difficulties

The critical conceptual difficulty is the inability to distinguish between velocity and acceleration (Hestenes et al., 1992). Students may unable to differentiate between position, velocity and acceleration for a given sequence of dots representing the object location in equally time interval. When velocity and acceleration is undifferentiated, this lead to the confusion in understanding the effect of force in the next level of mechanics learning. For example, using First Newton's law of motion, an object can be stationary or moving at constant velocity when the net force acting on it is zero. Thus, zero acceleration implies either zero velocity or constant velocity.

Two types of introductory physics are generally offered at university level; algebra-based and calculus based introductory physics. Usually the first course is offered to non-science undergraduates taking physics as minor. Bollen group found that students enrolled in the first course face difficulties in determining instantaneous speed from kinematics graphs (Bollen, De Cock, Zuza, Guisasola, & Van Kampen, 2016). This claimed that the students in the later course has less difficulties to transfer their mathematical knowledge regarding slope and gradient to the instantaneous quantity. However, even though mathematical knowledge is essential to understand the underlying physics of a graph, it does not guarantee the concept mastery (Planinic, Milin-Sipus, Katic, Susac, & Ivanjek, 2012)

When vector nature of kinematics quantities such as displacement, velocity and acceleration are introduced, students may hold a belief that they must always be in the same direction (Rosenblatt & Heckler, 2011). This is not the case if an object moves in a straight line with decreasing speed, the displacement and velocity vector are opposite its acceleration is to left. More complicated situations involving set of vectors when considering kinematics in two and three dimensional. For example centripetal acceleration direction is tangent to the instantaneous velocity in circular motion.

It is also interesting that the knowledge of getting velocity information from the slope of displacement versus time does not necessarily transfer to getting acceleration information from the slope of velocity versus time (Zavala et al., 2017). Thus, simple analogy of slope in both cases must be clearly distinguished by instructors during lesson. Students face difficulties on describing motion of an object based on the shape of line graph indicates the lack of understanding in differences between important graphs of position, velocity and acceleration versus time (Ahmad Tarmimi Ismail & Ayop, 2016).

The incorrect interpretation of graphical representation in kinematics is possible rooted from the problem in mathematical understanding about graph. Students assume graphs as iconic interpretation of a motion (Leinhardt, Zaslavsky, & Stein, 1990). For example, a positive linear line graph of position versus time is taught as the representation of an object going up an inclined plan.

Finally, it is important to provide good quality learning resources. For example, instructors may tend to provide real data in from of a graph of a moving object to teach graphical representation of kinematics quantities. Learning difficulties may occur in interpreting those graphs since they differ from the theoretical and ideal graphs (Testa, Monroy, & Sassi, 2002). Students are not ready to be introduced with too much uncertainties in real data without proper instructor guidance.

Teaching Strategies

Teaching strategies described in this section do not only specifically useful for teaching kinematics but can be extended to other topics and subjects as well. The reported strategies are mainly developed by physics educator.

Peer Instruction (PI) is one of the strategies to engage peer interaction between students (Crouch & Mazur, 2001). During a lesson, some conceptual questions are imposed to gauge current students' understanding. At first, students response to the question then argue with their next peer within short period of time to explain or defense their answer. Finally, they response again to the same question as the result of their discussion with peer. The change in students response might be observed and recorded by instructor using flash card or electronic response system. If the correct answer percentage is lower than expected in the post-discussion response, revision may be required to strengthen the concept before advancing to the next lesson.

As the computer technology become accessible in schools, Microcomputer Based Laboratory (MBL) can be adapted in classroom and laboratory exercise to support kinematics learning (Russell, Lucas, & McRobbie, 2003). The MBL uses automated sensors such as motion sensor and force sensors in combination with data logger to record and display experimental result. Quantitative relations between measured variables are easily and quickly obtained using the MBL. Simple physics experiments are also implementable anywhere and anytime by using smartphone with video recording capabilities and dedicated mobile apps (Ayop, 2017). Fun physics teaching is also possible using simple educational games (Rodrigues & Simeão Carvalho, 2013). Modelling software such as *Modellus* and open source simulation such as *Phylets* are readily available to help students visualize kinematics concepts (Araujo, Veit, & Moreira, 2008; Christian & Belloni, 2000). In another work, the use hypertext media has been shown to improve kinematics learning as well logical ability (Manurung & Mohardi Satria, 2016).

Just-in-Time Teaching (JiTT) is another interactive engagement which take advantage of a web technology (Novak, 2011). The instruction starts before the formal lesson. Students were expose to assignment called warm-ups . The assignments are well-designed to trigger students interest and allow early feedback for instructor to plan their lesson.

Time constraint is one of the most difficulties for educators to deliver lesson with hands-on activities. In such condition, Interactive Lecture Demonstrations (ILD) provides alternative to expose kinematics concept through demonstration of experiments or physical phenomena (Sokoloff, 2016). Predict-Observe-Explain formatted worksheet is provided to students to challenge their preconception.

Despite all available teaching strategies, it is important for an instructor to learn how students learns the lesson to optimize the instruction effectiveness (Hestenes et al., 1992). Thus, we strongly suggest that each provided strategy is unique to every group of students and an instructor should properly prepare and effectively deliver the instruction.

Conclusions

Kinematics is a basic concept needed to grasp in order to construct more advanced concepts in various branch of science. The TUK-G is the only assessment tool which cover mere kinematics. An adapted new tool can be developed by combining or revising questions from several tools to suit an instruction. Correct assessment tool provide instructor with informed decision to plan an effective instruction. Several research based instruction in physics were described to provide readers with teaching strategy ideas.

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