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Analysis of Pre-Service Physics Teachers' Understanding of Vectors and Forces

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ABSTRACT

The aim of this study is to analyze the ability of students to understand vectors as well as force concepts. Survey study was implemented in this study to obtain detailed information of students' ability and involved 212 physics education students of Tanjungpura University who have completed Basic Physics course. They were asked to solve tests of vector and tests of force adapted from physics education research group. Test of vector (TUV) consists of 13 items and covers addition, subtraction, and component. Furthermore, test of force (TOF) that has nine items covers three different contexts - horizontal surface, inclined plane, and pulling the rope. The results show that (i) students answer correctly 56% of TUV and 46% of TOF, (ii) subtraction concept is the most difficult for students to solve vector test and inclined plane is the lowest percentage done correctly by students in force test, and (iii) the correlation between students' ability of vector and students' ability of force is 0,304 ($p = 0.01$) with moderate category. This indicates that one of factors that can affect student's performance in solving force concept is vector skills. Hence, before students starting learning force concept, teachers can administer vector test to elicit students' prior knowledge of vector.

Keywords: vector, force, and free body diagram

INTRODUCTION

Newton's law of motion deals with force, and is a core concept in basic mechanics, usually taught as part of physics from secondary school to university level (Savinainen, Makynen, Nieminen, & Viiri, 2013). Besides mechanics, force is also taught in the topics of electrostatics and magnetism, etc; therefore, force is an essential concept in physics (Özdemir, 2015). However, students generally struggle to grasp the concept of force (Maloney, 1990; Savinainen, Scott, & Viiri, 2005; Bozdoğan & Uzoğlu, 2015). For example, students often do not have a clear understanding of the meaning of force (Palmer, 1997). They are also unable to differentiate between force, inertia, energy, power and even velocity. In addition, many students perceive that force simply influences an object's motion (Minstrell, 1982). For example, gravity is not a force, but simply 'what makes it fall' (Knight, 2004).

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Physics education research has investigated and promoted ways to improve the understanding of students, from senior high school to college level, about force (Thornton & Sokoloff, 1998; Savinainen & Scott, 2002; Nieminen, Savinainen, & Viiri, 2010; Önder et al., 2013). Researchers have also made studies of drawing a diagram of force (Free Body Diagram (FBD)). Rosengrant, Etkina, and van Heuvelen (2009) explain that a Free Body Diagram (FBD) is a diagrammatic representation that depicts some object of interest and the forces exerted on it by other objects. They propose six steps for drawing an FBD, in an effort to help students solve force problems. Their study found that the majority of students who used FBDs felt them to be helpful when doing exams. Also, students who drew diagrams correctly were significantly more successful in answering questions than those who did not. However, their study still has limitations qualitatively: the students only solved one problem. Hence, another investigation is required on whether using FBDs can improve students' grades. Other factors, such as mathematical skill, may also play a part.

A study has also been made on using Interaction Diagrams (ID) – representing interaction between objects – to help students in identifying forces when constructing FBDs (Savinainen et al., 2013). They found that students using IDs outperformed those not using IDs in identifying forces and constructing FBDs. They claim that IDs can help students to perceive force as a property of an interaction rather than of an object. They also investigated the effect of teachers' instruction on using IDs in teaching Newton's law. However, the correct identification of interacting objects in an ID did not always result in correct force identification, especially in the light group (not using IDs), and students could correctly construct FBDs even when their ID skills were low. This shows that in understanding the concept of force, students do not only need to know about FBDs and IDs, but also to have a sufficient grasp of the concept of vectors to construct a force diagram.

A number of researchers (Aviani, Erceg, & Mesic, 2015) have conducted research focusing on university students, by implementing two different approaches to drawing free body diagrams. They have analyzed the effect of these methods—superposition and decomposition—regarding students' understanding of Newton's laws, as well as regarding their ability to identify real forces. The decomposition method refers to the determination of a vector's components, followed by finding the resultant of the vector. By contrast, the superposition method refers to adding vectors, while placing the tail of a vector to the previous vector. It has been found by these researchers that many students lack the ability to distinguish amongst real forces, forces components and force resultant. Furthermore, it was found that students have an understanding that forces and their components act on a body independently and simultaneously. This means that students do not only understand force concepts, but also have developed mathematical skills, such as those involved in a vector. Flores, Kanim, and Kautz (2004) have argued that students should be aware that learning about Newton's law requires an understanding of vector concepts.

In physics, *vector* is defined as a quantity with both a magnitude and a direction (Arons, 1997). For example, velocity is a vector, as it describes both how fast an object moves and in what direction it moves. Most physical concepts involve vectors, such as acceleration, force, momentum, etc. (Serway & Vuille, 2012). Hence, vector is a very important skill for students to acquire, while studying physics (Knight, 1995). In Indonesia's physics curriculum, vector is usually taught from senior high school until university level.

However, students still struggle to understand physics material during their first year at university, even though all students begin learning physics in senior high school (Haratua & Sirait, 2016).

Studies about vectors have also been undertaken by educational researchers in physics. Nguyen and Meltzer (2003) have investigated students' understanding of vectors in introductory courses in physics. They found that more than 50% of students were not able to solve two-dimensional vector additions. Many students lacked understanding about vector direction and were confused about tip-to-tail and parallelogram addition rules. Flores et al. (2004) found that about half of the students attending introductory classes could not correctly determine the resultant of vector by the adding method. Subtracting two vectors was the most difficult task for students, when asked in the context of working on qualitative problems. Knight reached a similar conclusion (1995), arguing that only about 30% of students are able to provide an adequate definition of vector. Less than 50% of undergraduate students answered correctly regarding the vector addition problem, while presenting it in an arrow format.

Furthermore, Barniol, and Zavala (2014) also conducted research about vectors (vector test), by comparing the understanding of students who solved problems with no physical context, with those who solved problems with a mechanical context. The results showed that there was no significant difference between the number of items solved correctly by students with no physical context, compared to those with a mechanical context. However, they found significant differences in some items, and the ability of students who had learned calculus-based mechanics relied on the type of context. Rakkapao, Prasitpong, and Arayatthanitkul (2016) undertook a study focusing on the notion of vector, by employing a vector test designed by Barniol and Zavala. The results showed that most students were not able to differentiate between adding and subtracting two vectors. Once two vectors are presented in an opposite direction, students tend to directly add them, even if being asked to subtract them.

Having a good understanding of basic vector concepts is helpful for students to grasp the concepts of physics. For example, Shaffer and McDermott (2005) identified students' difficulties (undergraduate students, graduate students, and pre-service teachers) in understanding velocity and acceleration of pendulum bob as vectors, in one and two dimensions. Based on their research, they developed some instructions, by connecting vector skills and concepts from kinematics, helping students' learning in an introductory physics course. They were able to help students analyze motion in one dimension and transfer to two dimensions, by using vectors. Bollen, van Kampen, Baily, and De Cock (2016) investigated students' difficulties in an electrodynamic course, by using vector calculus. Students were not able to understand vector operators in solving Maxwell's formula. Based on their difficulties, these researchers helped students understand the concept of electromagnetism, by designing, implementing and evaluating instructions.

These findings indicate that having a good understanding of vectors is very important when it comes to learning physics. The purpose of this research includes: 1) analyzing students' understanding of vectors, as well as force concepts, comparing students at different levels; 2) establishing the relationship between students' understanding of vectors and their ability to grasp force concepts.

METHODOLOGY

a) Model of the research

The major purpose of a survey is to describe various aspects and characteristics of a concept, such as the abilities, opinions, attitudes, beliefs and / or knowledge of a specific population (Fraenkel & Wallen, 1993). In the case of this study, a survey was conducted with an aim to obtain detailed information about students' ability to understand vector and force concepts.

b) Population and Sample

Participants in the study consisted of 212 pre-service physics teachers—from the first, second and third year—who had taken a basic physics course at the Teacher Training and Education Faculty of Tanjungpura University (59 males and 153 females). Students graduating from this faculty then tend to teach physics at the middle and senior high school levels.

Table 1. *Description of the participants*

Students	Male (N)	Female (N)	Total
First Year	20	55	75
Second Year	24	62	86
Third Year	15	36	51

c) Data Collection Tool

To obtain data, we adapted an existing test—the Vector and Force Test—from the Physics Education Research group (Nguyen & Meltzer, 2003; Barniol & Zavala, 2014; Heckler & Scaife, 2015; Aviani et al., 2015). This test was translated from English into Bahasa Indonesian, by translators working at the science education department. We then chose items based on our needs for this research and designed a number of other items to complete the test. Afterwards, five faculty members of the physics department validated the items. They were asked to rate each item with a score from one to four, to measure how well the test items addressed physics content. The reliability of both tests was determined by using a statistical analysis (Ding, Chabay, Sherwood, & Beichner, 2006). Validation and reliability are needed to obtain a good test (Faize & Dahar, 2012). There are two tests with multiple-choice items used in this study: one is the test of vector (TUV) and the other is the test of force (TOF). Multiple-choice tests are powerful when it comes to examining students' understanding, because they are easy and economical to administer and grade and their scoring is objective (Singh & Rosengrant, 2003; Ding & Beichner, 2009). TUV consists of thirteen items, covering addition, subtraction and component; this was used to measure students' understanding of vectors. Meanwhile, TOF consists of nine items with different contexts—horizontal surface, inclined plane and pulling the rope—examining students' ability in free body diagrams. The two types of test were administered to students, in order to establish their understanding about vectors and force. Students were given one hour to solve both tests (twenty minutes for TUV and forty minutes for TOF).

Table 2. *Number of items of each test*

TUV			TOF		
Addition	Subtraction	Component	Horizontal surface	Inclined plane	Pulling the rope
4	3	6	4	3	2

d) Data Analysis

To establish students' understanding about vectors and forces and the correlation between them, we first tabulated students' answers for every item, with options for both tests. We then statistically analyzed (Moore, McCabe, & Craig, 2012) the students' answers, looking for example at the percentage of students answering the test correctly, divided into four categories (<25%, 25%-50%, 50%-75%, and >75%), as well as looking at the students' performance for each test, their performance for every concept and context, and the correlation between students' ability in solving vector and force. We used SPSS 24 (Statistical Package for Social Sciences Program, Version 24) to analyze the data.

FINDINGS

The details of the statistical analysis of both tests are presented in Table 3. The difficulty index of the vector test and the force test measuring the proportion of students who answered correctly was 0.55 and 0.46, respectively. These values are between 0.3 and 0.9, as an appropriate range of the difficulty index. For students, these values indicate that the vector test is easier than the force test. Furthermore, the average of the discriminatory index in both tests is above 0.3. This number is appropriate for the discriminatory index criteria. The self-consistency of the whole test was also determined by using the Kuder-Richardson analysis. It found that the reliability indexes of TUV and TOF are 0.75 and 0.70 respectively.

Table 3. *Summary of statistical analysis*

Test statistic	Desired values	TUV values	TOF values
Item difficulty index	≥ 0.3	Average: 0.55	Average: 0.46
Item discrimination index	≥ 0.3	Average: 0.37	Average: 0.36
Kuder-Richardson reliability index	≥ 0.7	0.75	0.70

For the purpose of analyzing the students' understanding of vectors and forces, we looked at answers from all 212 students who completely solved both tests, the TUV and the TOF. The results regarding students' understanding of vectors and forces are shown in Table 4. The percentage of students who solved more than 75% (ten to thirteen items) correctly on the vector test was 22%. The third-year students were more successful in solving more than 50% of the TUV, than first and second-year students were. The percentage of students in the third year who could solve correctly more than a half of the vector test was 61%, while the percentage in the first year was a little bit lower (60%). However, only 54% of second year students were able to answer more than 50% of the items (seven to thirteen items).

Table 4. *Percentage of students who solved the test correctly*

Students	TUV				TOF			
	<25% (1-3)	25%-50% (4-6)	50%-75% (7-9)	>75% (10-13)	<25% (1-2)	25%-50% (3-4)	50%-75% (5-6)	>75% (7-9)
First Year	7	33	31	29	32	28	28	12
Second Year	10	35	38	16	20	23	29	28
Third Year	12	27	39	22	25	39	27	8
Average	10	32	36	22	26	30	28	16

There was a difference when it came to the force test. Sixteen percent of students successfully answered more than or equal to seven to nine items (> 75%) in the force test. Second-year students achieved a higher percentage and solved correctly more than 75% of the force test (seven to nine items), followed by students in the first and third year. However, when it came to five to six items (50-75%), there was no significant difference in the percentage of students; the difference was only found to be 1%.

The percentage of tests solved by students is presented in Figure 1. Students' ability to answer the TUV was 56%. The median was seven (out of thirteen), meaning that students who were on the median in the test had some difficulty answering six items correctly, whereas students' performance on the TOF was 46%, with most students being able to solve five to six items correctly.

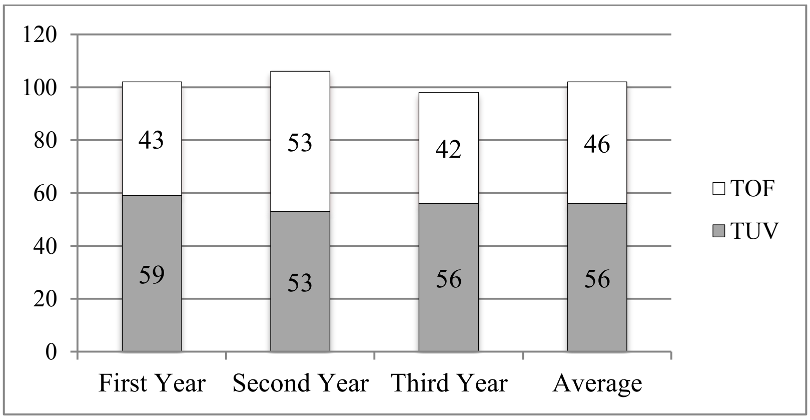

Figure 1. *Percentage of problems solved by students*

a. Vector

The test of Vector (TUV) consists of thirteen items and three concepts: addition, subtraction and component. Table 5 depicts the proportion of students correctly answering all items (bold font is the correct answer). Vector addition comprises of four items that are in one and two dimensions. Most students were able to solve the vector addition correctly in one dimension (items one and four); 96% of students were able to answer item one correctly, while 79% were able to answer item four. Two-dimension (2D) was the most difficult concept for students, as only 25% of them were able to solve both items (items seven and ten) correctly.

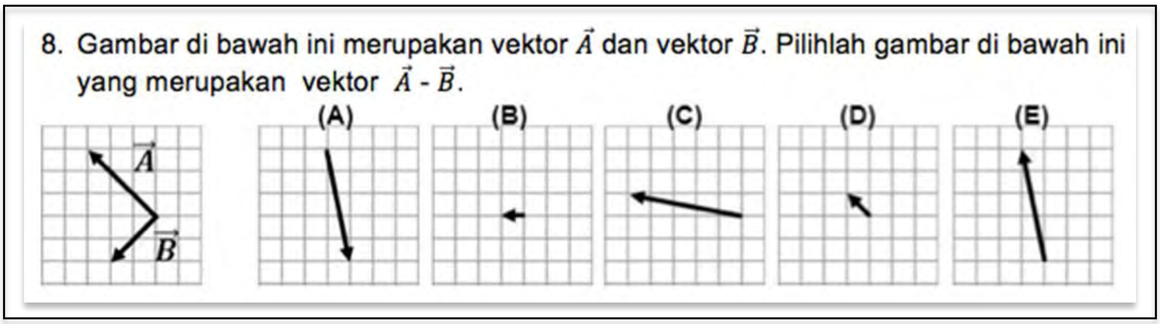

Figure 2. *Question number 8 of the vector test (Indonesian version)*

Vector subtraction consists of three items (two, five and eight), with two items in one dimension and one item in two dimensions. Sixty four percent of students correctly answered vector subtraction with the same direction (parallel), while only 43% of students were able to correctly solve these when given a different direction (anti-parallel). Moreover, vector subtraction with two dimensions was found to be the most difficult for students; only 21% of students correctly answered this item. Figure 2 shows the vector subtraction problem (item eight) in two-dimensional form.

Students' performance seems to be better in the vector component, than it is in the addition and subtraction vector. Students answered more than 50% of each item group correctly. Furthermore, 62% of students were able to determine the direction and magnitude of vector components. Most students (73% of them) seemed to be able to successfully identify the x and y components of a vector.

Table 5. The description of items and the percentage of students' answers on TUV

Concept	Item	A	B	C	D	E
Addition	1	3	0	1	**96**	0
	4	**79**	5	5	10	0
	7	10	14	2	49	**25**
	10	10	20	6	39	**25**
Subtraction	2	4	5	26	**64**	1
	5	3	45	6	**43**	3
	8	33	11	11	24	**21**
Component	3	6	8	**73**	8	4
	6	15	7	8	**69**	2
	9	30	**51**	5	2	11
	11	8	8	**66**	12	6
	12	13	12	6	**67**	1
	13	3	8	**48**	36	5

Figure 3 shows a histogram of students' achievement (students with different levels) in terms of solving tests of vector with three concepts—addition, subtraction and component. Students appeared to have some difficulty in solving additions and subtractions. It can be seen in the histogram that students were only able to correctly solve 42% of subtraction problems (the average score was 1.26 out of three possible points). Meanwhile, the addition concept was a little higher than subtraction; nevertheless, it was found to be lower than the component concept. This trend shows that first year students achieved higher scores for every concept than students in the second and third year did.

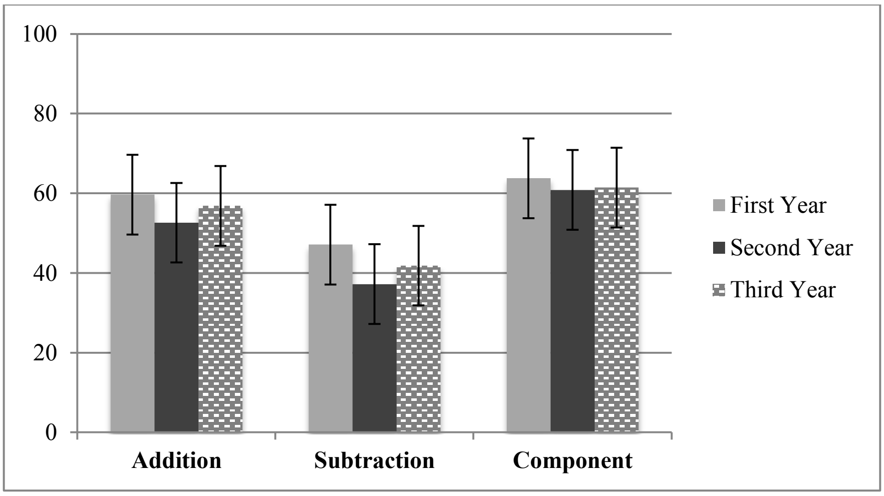

Figure 3. *Students' performance solving TUV*

b. Force

Table 6 presents the distribution of students' answers for every question item in the context of the force. The answers are interpreted by percentages, in which the bold font represents the correct answers. It can be clearly seen that the choice of every question item varies considerably across the context of force and students made mistakes in every context. Most students (83%) successfully answered item one: a block rests on a horizontal surface; students were asked to choose to correct free-body diagrams. However, in item two (a force acting on an object, while the object remains at rest), students had difficulties answering the problem. Students did not notice the force component. Furthermore, some students seemed to lack the ability to identify a free-body diagram, while an object moves with constant speed and constant acceleration (items three and four).

On the inclined-plane context, more than 50% of students were not able to provide correct answers to the problems. Students only understood the real forces on an object without thinking about vector components (why the object does not move on an inclined plane). In addition, when an object moves with constant speed and continuous acceleration, they were not able to correctly distinguish free-body diagrams for every situation.

Table 6. The description of items and the percentage of students' answers on TOF

Context	Item	A	B	C	D	E
Horizontal Surface	1	12	2	**83**	2	1
	2	**22**	9	33	34	2
	3	11	6	27	15	**40**
	4	**52**	16	10	13	9
Inclined Plane	5	4	40	18	7	**31**
	6	16	**42**	23	10	8
	7	**55**	15	10	7	13
Pulling the rope	8	**50**	36	1	7	5
	9	14	3	24	8	**52**

The percentage of students correctly answering the problems regarding pulling the rope context was more than 50%. They did not completely identify all the forces exerted on an object, such as the normal force and the gravitational force. Consequently, students were not able to successfully choose the right force body diagram on the object.

The ability of students from three different years to solve force tests is displayed in Figure 5. Based on the histogram, the lowest percentage of students' performance (41%) solving TOF was in inclined context. The average score was 1.23 out of three possible points. Students faced difficulties understanding free-body diagrams on an object, when moving with constant velocity and acceleration. Moreover, when students analyzed the rope problems, they did not include gravitational force and normal force.

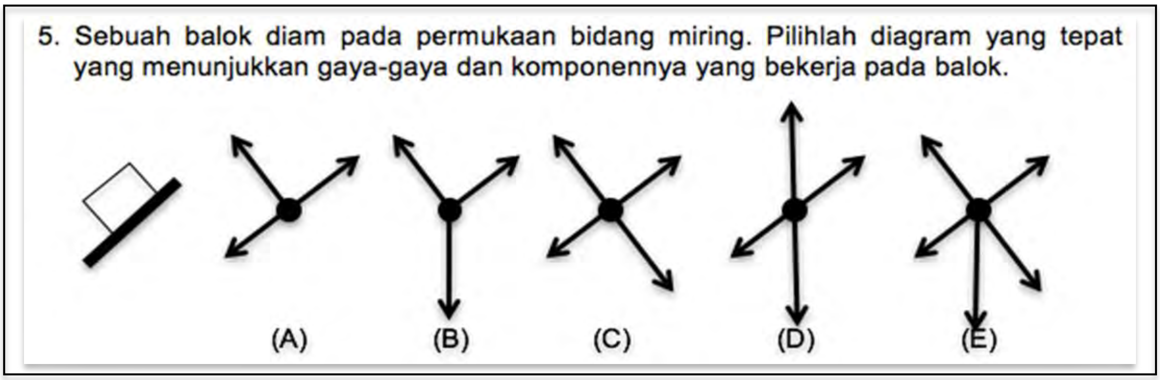

Figure 4. *Question number 5 of force test (Indonesian version)*

Relationship between Vector and Force

Based on the conducted correlation analysis, overall, the correlation between students' skills of vector and students' skills of force was found to be 0.304 (SD of vector was 22.3, while SD of force was 26.3, and p = 0.01). This value is moderate category. This means that there is a positive correlation, implying that students who have high skills in vector will achieve good performance in force. Furthermore, the correlation of students' performance on the vector component and force test was also established. The correlation is 0.325 (SD of vector is 28.3, SD of force is 26.3, and p = 0.01); therefore, it can be concluded that in order for students to successfully grasp force concepts, they first have to master vector concepts.

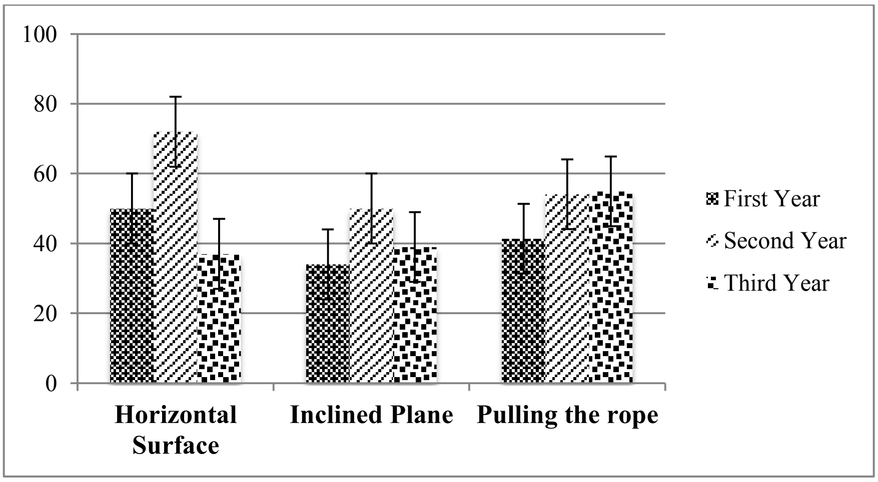

Figure 5. *Students' performance solving TOF*

DISCUSSION

In this study, we have presented three findings regarding pre-service physics teachers' understanding of vectors and forces. Most students were able to correctly answer vector additions with the same direction (parallel) and also with opposite direction (anti-parallel) in one dimension. However, students seemed to lack the ability to determine the resultant of two vectors, when presented in two dimensions. This finding is similar to findings by Barniol and Zavala (2014) and Nguyen and Meltzer (2003). Students tended to draw a line from the head of one vector to the head of the other vector. Students did not seem to notice the basic rule (head-to-tail method and Pythagorean theorem), in terms of how to sum vectors with two dimensions.

Furthermore, the subtraction concept is the most difficult one for students to grasp; more than half of the students were not able to solve subtraction problems. For example, students tended to subtract opposing arrows (one dimensional) incorrectly. Based on the students' answers, they were able to reach similar conclusions when it comes to vector addition. The most difficult aspect for students is to subtract two vectors in two dimensions. The students did not seem to be aware of the minus sign of the vector. Consequently, they tended to subtract two vectors, by using the addition method. This means that students do not have adequate abilities to sum and subtract vectors, while presented in two dimensions (Van Deventer & Wittman, 2007). Heckler and Scaife (2015) found that students found it easier to solve vector problems, when they were presented in *i j k* format, rather than when presented in arrow format. This suggests that students should be presented with various formats, when learning about the vector concept. Students do not only need to be taught how to successfully use mathematical tools, such as vector, while solving physics problems; they also need to learn how to interpret these tools and give meaning to them (Redish & Kuo, 2015).

The vector component was found to be more successfully attempted by students. The vector component measures students' understanding in terms of how to determine x and y component vectors. Students simply draw a line from the head of the vector to the x and y-axis. However, when students were asked to determine the magnitude of the vector component in mathematical representations, they had difficulties in distinguishing *Sin* from *Cos* (trigonometry). This indicates that students were not able to completely understand the meaning of the vector component. As Redish and Kuo (2015) have stated, teachers should equip students with an ability to interpret mathematical equations, not just to use and memorize them. Overall, first-year students were able to achieve the highest score for every vector concept. This means that they were most successful in solving TUV. This was the result of students' having just learned the vector topic in the first semester.

The average ability of students when it came to understanding force concepts was found to be in the middle category; it was shown that students were able to correctly solve problems in almost half the tests. Students had problems in understanding the free-body diagram of an object on the surface, in terms of whether it was a flat or an inclined surface. They then were not able to fully identify the concepts of gravitational force, normal force, frictional force, and component of the force. Aviani *et al*. (2015) found that students cannot always successfully distinguish between real forces and their components. This finding indicates that students should be helped to fully comprehend the definition of force, that is, the interaction between two objects. Students can use the interaction diagram in helping to draw a free body diagram (Savinainen et al., 2013).

Furthermore, students were not always able to identify a free body diagram of an object, while moving with constant speed and constant acceleration in a flat surface and an inclined plane. Most pre-service teachers were able to successfully determine the direction of velocity but were not able to establish the direction of acceleration of a pendulum bob, in terms of vectors (Shaffer & McDermott, 2005). Students should be helped to understand that the characteristics of an object can change its velocity (Redish, 2014). In this context, students must have enough skills in vector subtraction and addition, and they must also be able to distinguish between Newton's First and Second law. It seems that students are only aware of the equation of Newton's law: $\sum \vec{F} = 0$ and $\vec{a} = \sum \vec{F}/m$ (Tipler, 1991), without being aware how to determine the net force carefully, by using addition and subtraction methods. However, students can easily view force diagrams of an object placed on a horizontal surface, without external force exerted on it. Furthermore, on the inclined-plane, many students just chose the real force on the object, without noticing the component of each force. As a result, they had difficulties in determining a free-body diagram of an object, while at rest, moving with constant speed, and moving with constant acceleration. Rosengrant *et al.* (2009) argued that students who are able to draw the diagram correctly, will be able to reach the correct answer of the force problems.

In terms of the context of pulling the rope, students tended to solve the items correctly; a few students did not include external force—gravitational and normal force—in the system. Kuo, Hallinen, and Conlin (2015) have stated that a teacher should be careful prompting a force diagram, while solving problems in physics. Interestingly, the second-year students more successfully answered force tests than the first and third year students. This outcome might be affected by the fact that students in the second year had just learned about mechanics in a course covering equilibrium, rotational motion and fluids, all of which address the concept of force.

The correlation between the students' ability to solve TUV and their ability to solve TOF is in the moderate category. This means that there was found to be a positive relationship between vector skills and force skills. Students who scored highly in TUV also had high scores in TOF. Furthermore, students with a good understanding of addition and subtraction vector also seemed to have a good understanding of the concept of force, especially when it came to identifying free body diagrams.

Finally, in order to learn force concepts, this study suggests that students should not only have enough skills in drawing free-body diagrams; they should also be able to master vector concepts. Integration and making the link of multiple representations can help students learn the concept (Ainsworth, 2006; Li & Arshad, 2014). A physics teacher should focus on noticing how students perceive the use of vector in understanding the force concept and should on that basis design appropriate instructions for students who lack the ability to grasp vectors, as well as forces.

CONCLUSION

The analysis provided by the study shows that students who have learned the concept of vector remain challenged, especially when attempting subtraction vectors. Adding and subtracting two-dimensional vectors is very demanding for students. Meanwhile, when it comes to force problems, the ability to identify forces and the vector component, as well as the vector resultant, is one of the most crucial problems, especially in the inclined plane. As a result, students were not able to successfully identify an object while at rest, at constant speed and during acceleration. Based on the correlation between the vector and force tests, the results indicate that besides understanding the force concept, a factor that can affect students' performance in solving force problems is the ability to understand vectors (Flores *et al*., 2004; Knight, 2004). This study suggests that students should devise vector concepts (addition, subtraction, component, and resultant) before learning about the concept of force.

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