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Can Aikido Help With the Comprehension of Physics? A First Step Towards the Design of Intelligent Psychomotor Systems for STEAM Kinesthetic Learning Scenarios

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ABSTRACT Educational stakeholders are promoting the development of educational approaches that go beyond classroom and engage learners in acquiring science, technology, engineering and mathematical (STEM) concepts with the support of arts (known as STEAM). Taking into account the recent advances in wearable technology to sense human motion, psychomotor intelligent tutoring systems (where students' motion interactions are collected with sensors and used to provide personalized vibrotactile feedback to support the learning process) can be designed to teach STEM concepts in a kinesthetic way. In order to investigate the feasibility of this approach, in this paper we have carried out an empirical study with high school students to determine if watching specific techniques of the defense martial art Aikido (which makes use of different types of rectilinear and curvilinear motion) can be used to learn some concepts of physics. Nonetheless, other martial arts could be used for similar purposes, but further studies are needed. Analyzing the outcomes of the 30 participants that took part in the study, we conclude that the proposed approach seems to have benefits in the learning of STEM concepts, and thus, the usage of martial arts deserves to be further investigated in STEAM kinesthetic learning scenarios, which can also consider the students' affective state.

INDEX TERMS STEM, physics education, sensors, adaptive systems, intelligent systems, martial arts.

I. INTRODUCTION

The acronym *STEM* (Science, Technology, Engineering and Mathematics) was coined in the 90s by the National Science Foundation (USA). One of the objectives behind it is to foster students' interest in these subjects by presenting related concepts in an integrated way and with a practical perspective [1]. STEM learning seems to be no longer confined to the classroom, but can also occur in informal settings like museums or science centers [2]. In addition, during the first decade of the 21st century, Yakman proposed to add the term 'arts' to the STEM acronym, defining *STEAM* as "Science and Technology, interpreted through Engineering and the Arts, all based in elements of Mathematics".[1] In this context, Henriksen pointed out the need to explore how arts can be meaningfully integrated into the educational process in STEM areas [3].

In a previous work [4], we have proposed that this 'A' of 'arts' can also refer to 'martial arts' and discussed the available sensor technology (both inertial and optical) to build an intelligent framework called *Phy+Aik* for learning physics together with Aikido, which is considered a defense martial art. Aikido is a soft style martial art and thus, it relies on circular movements that contribute to reuse the force of the attacker against herself. For this reason, it can be then used to study both rectilinear (from attacking-like movements) and curvilinear (from defensive-like movements). With *Phy+Aik*,

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[1] https://www.iteea.org/16991.aspx

educators can produce innovative visual educational material for teaching physics that is obtained with optical tracking devices and then synchronized and tagged with inertial data collected by wearable sensors from the aforementioned linear and twisted displacements performed by Aikido practitioners.

The added value of using martial arts is that they are built on codified movements for combat and self-defense training. The perfection of the basic techniques is the prime objective of martial artists who should practice over and over for years to master a set of precise movements. Training requires sequential repetition of prearranged movements until their performance becomes nearly automatic [5].

This suggests that there are benefits of using martial arts to understand concepts of physics, but little has been reported in scientific literature. Besides our research, we could only find in the academic literature the studies performed by Mroczkowski with high school students learning physics and practicing Aikido [6], and the didactic projects reported by Gianino [7] and Gianino and Gianni [8] to teach some physics concepts based on Karate movements. Nonetheless, there are other informative publications that discuss the benefits of martial arts to acquire physics concepts and/or which show the physics behind the performance of techniques in martial arts. Most of these works are either contents for teaching physics in some special sessions or informal posts in blogs addressed to and written by martial artists themselves (more details are provided in Section II). Aside the aforementioned work by Mroczkowski, the benefits of martial arts to learn physics are not sustained by scientific studies.

In this context, this research attempts to set the bases for the design of an *intelligent psychomotor system* in a STEAM kinesthetic learning scenario. For this, a user study has been carried out, where Aikido practitioners performed different techniques. The goal of the study was to determine if students watching the execution of those techniques can enhance their understanding of diverse physics concepts. This is related to the process of restructuring prior knowledge (also referred to as 'conceptual change'), which is especially relevant when learning complex physics concepts.

The rest of the paper is structured as follows. First, we comment on related works regarding teaching physics concepts with martial arts in general and Aikido in particular. Next, we present some background to our research approach. Then, we describe the study carried out to evaluate the usefulness of watching the execution of Aikido movements to understand concepts of physics. We subsequently report the results and discuss our findings. Finally, we outline the derived conclusions, comment on limitations and introduce some future work.

II. THE PHYSICS BEHIND MARTIAL ARTS

Following a commonly used but also simplistic classification, martial arts can be differentiated as: 1) hard styles, such as Karate, which focuses on punches, kicks, blocks and other hard strikes that aim to crush and damage the body of the opponent, and 2) soft styles, such as Aikido, which uses joint locks, throws, sweeps, take-downs and joint manipulations aimed to gain a certain degree of collaboration from the opponent to avoid extreme pain or injury. This distinction is relevant from a physics point of view, because in practice it means that motions in hard style martial arts are mainly linear (although they also have some rotational movements), but motions in soft style martial arts, such as Aikido, are based on circular movements. This is achieved by a sudden change of the defender's force direction into the one consistent with the force of the attacker, usually stepping out of the line of the attack to change the direction of the attacker's motion from rectilinear to curvilinear [6]. Thus, soft style martial arts have more potential to expose the dynamics of the rotational motion. As discussed in [9], students have difficulties with these kinetic-related notions in the way they are usually covered in introductory physics courses.

As anticipated in the introduction, Mroczkowski has carried out several studies on the knowledge of biomechanics in teaching Aikido martial art [6]. As reported in [10], this author compared pre- and post-test results from a control group, which learnt physics in the traditional way, and an experimental group, which received some Aikido instruction and used experiences and examples acquired in an additional physical training class. He found that Aikido practice and physics teaching helped each other in both ways: not only are Aikido techniques better executed if their dynamics are explained using the principles of physics, but their practice also accelerated the process of understanding the rules of classical mechanics. In his analysis [6], Mroczkowski refers the centrifugal force gained by the attacker (which increases as the attacker's velocity increases) and the relation of the force produced by the product of the moment of inertia and the angular acceleration (the closer to the axis of turn, the shorter the radius of the curvilinear motion and the larger the angular acceleration) due to the well-known principle of the conservation of the angular momentum. The position of the center of mass (known as *hara* in Japanese martial arts such as Aikido) is also presented as relevant.

In turn, Gianino reported a didactic project that video-recorded some Karate strikes to help high school students understand the difference between the theoretical model and the real system with the corresponding motion diagrams [7]. He used videos to reconstruct the trajectories in order to build the motion diagrams from which it was possible to deduce kinematic characteristics such as the duration of the technique, the average acceleration and the striking velocity. Gianino, in collaboration with Gianni, also performed another didactic experiment with high school children to measure the center of mass of the human body with data collected when performing some Karate techniques [8]. This second didactic experience aimed to develop in high school students ''critical attitudes by identifying and experimentally checking laws and principles of physics involved in the actions of the human body and to teach physics not simply as a school subject that 'has-to-be-learnt', but as a powerful research tool that allows to know and understand the laws that regulate nature" [8]. However, no evaluation of the learning achievements is reported in either of these two didactic experiences.

Besides these works (i.e., [6]–[8], [10]), we could not find any other scientific or didactic studies that relate the practice of martial arts in general and Aikido in particular, with the understanding of physics. The remaining literature we found simply assumes the benefits of using physics to understand the practice of martial arts. For instance, in Fightingarts.com, there is a post[2] on basic physics of forces, rotation and torques in Aikido. AikiSyience published initially some notes[3] and later a book [11] that explains seven physical principles to help understand why Aikido is so effective. These seven principles are 1) finding the lowest resistance way, 2) taking care of the distance with the opponent, 3) static and dynamic equilibrium depending on the center of gravity of the body, 4) the force, 5) the inertial force, 6) the amount of movement or impetus and 7) the momentum or torque in a circular movement. This book seems to have impacted on websites specialized in the Aikido practice, such as non-peer reviewed online periodicals[4,5] and blogs.[6,7,8]

In addition to the non-academic and non-peer reviewed contributions reported in the previous paragraph, there are a couple of videos from academics where some of these physical principles are explained with Aikido movements. The first one is a video[9] of a class taught at York's Department of Physics and Astronomy where physics concepts (namely forces, pressure, conservation of momentum, circular motion, torque) are explained with illustrations of their application to Aikido practice, including the use of the *bokken* (wooden sword) to show how the velocity of the tip depends of the distance from the center of the circular movement that is performed when moving it. The second video[10] also focuses on teaching physics and explains how the torque is used in the *kote gaeshi* defensive technique of Aikido (which consists in a turn ended with a wristlock) to avoid receiving a punch in the stomach (*chudan tsuki attack*) [12].

The circular movements of a soft style martial art, such as Aikido, are also used to teach a class on Classical Mechanics [13]. This author describes how the person receiving an attack (defender) tends to step around and behind the attacker and then pull the attacker closer to her to create a *single moving rigid body in circular motion*. In this aggregate, the defender is in the center of an *imaginary circle* and the attacker is outside the defined perimeter. This is a useful exercise from the physics teaching point of view because rotational mechanics tells us that the further a point is from the center, the faster is its linear acceleration. The author also discusses the conservation of the angular momentum of the attacker and defender when turning together, as well as the case where the combined linear momenta are transformed into their associated rotational/angular counterparts. In addition, he notes that the initial velocity of the attacker dictates the velocity of the rotation as to maintain the flow of the movement, so the defender minimizes her energy output.

Moreover, McGonagill also analyzes the punch attack and numerically computes the values of energy, forces, pressure and moment of inertia involved in the strike. As introduced before, the punch is one of the attacks from which an Aikido technique can be applied (recall that Aikido is a defensive martial art, so it only reacts when being attacked). But in other martial arts (the hard style ones, such as Karate) the punches are part of the main movement and are usually used in demonstrations to show their effectiveness by breaking boards [14], [15]. In fact, most of the works regarding physics in martial arts analyze forces, pressure, energies and other related variables in the punch or kick strikes, and this has been done for over 40 years [14]–[22]. Hachaj et al. have also shown that it is possible to use inertial sensors (accelerometer and gyroscope) to collect Karate strikes and compare different executions [5].

However, none of the studies listed above really investigated the utility of understanding the physics involved to better learn the corresponding concepts. In fact, the focus has been usually the other way around: how to successfully apply the laws of physics for maximum power in martial arts techniques [23]. Taking into account that there are hardly academic studies on this topic, a research opportunity exists to explore whether the performance of martial arts techniques can improve the understanding of physics concepts.

III. BACKGROUND

As a first step, we have attempted to model a characteristic movement in Aikido called *shikko* (knee walking) by using inertial sensors [24]. Specifically, the physical variables acceleration and angular velocity were registered relative to the *hara*'s coordinate system using a smartphone. Of course, Aikido, as well as other martial arts and sports, involves more complex movements and actions (e.g., stretching, presses, pull-ups, curls, displacements, the rigging present in joints, etc.). However, Aikido specifically fosters the intercession of the aforementioned *hara* point in all techniques, so it is definitely a good idea to concentrate the inertial monitoring effort around this anatomical part. Together with budget-related reasons, this fact accounts for why we have chosen this movement with this specific single sensor setup as a starting point.

In addition to showing the feasibility of modeling Aikido movements with these physical variables following the approach proposed elsewhere [25], it can also be explored if watching acceleration data corresponding to Aikido movements could be used to teach physics. In this sense,

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[2] http://fightingarts.com/reading/article.php?id=284

[3] https://issuu.com/aikisyence/docs/slides-fisica_aikido-congreso.es

[4] http://www.elbudoka.es/revista/budoka16.pdf (p. 90-93)

[5] http://www.elbudoka.es/revista/budoka13.pdf (p. 70-73)

[6] http://samuraissigloxxi.blogspot.com/2010/05/la-torca.html

[7] http://entrenandoaikido.com/butsurigaku-fisica/

[8] https://es-la.facebook.com/notes/aikido-para-compartir/butsurigaku-la-f%C3%ADsica-del-aikido-de-ver%C3%B3nica-lorena-labourie/243304785695460/

[9] https://www.youtube.com/watch?v=OoLjjMGKHgg

[10] https://www.efdeportes.com/efd165/fundamentacion-fisica-del-aikido.flv (it launches a pop-up window to download the .flv file)

Knight *et al.* have already discussed the uses of accelerometer data collected from wearables to help high school students understand that acceleration is a change in velocity per unit time and that only unbalanced forces can alter the acceleration of the moving object [26]. In this way, students are involved in the scientific inquiry, where they are encouraged to generate hypothesis and test them by collecting and interpreting empirical data.

In this spirit, we carried out some live demonstrations testing the possibilities of streaming in real-time human motion sensed in a non-intrusive way with current wearable technology. Here we comment on the real-time streaming of data performed during the activity 'Aikido and Artificial Intelligence'[11] organized on behalf of UNED, the Spanish National University for Distance Education, at the AULA 2019 event which took place in Madrid (Spain) during the 2019 Education Week.

FIGURE 1. **Photogram of the activity 'Aikido and Artificial Intelligence' carried out in the UNED stand at AULA 2019. Demonstrations of several Aikido techniques were performed to show in real-time the inertial time series data that can be used to model the motion performed with some physical variables (acceleration and angular velocity). Top left: a *ukemi* (roll). Top right: defensive technique *nikkio-ura*. Bottom left: defensive technique *irimi-nage*. Bottom right: *kote gaeshi* to defend from a *tanto* (wooden knife) attack. All techniques were performed with a smartphone attached to the waist at the *hara* while the corresponding measured inertial data (acceleration and angular velocity) were shown in real-time on a large LCD screen.**

FIGURE 2. **Photograms of the activity 'Aikido and Artificial Intelligence' carried out in the UNED stand at AULA 2019. Left: two aikido practitioners performing some techniques wearing each a smartphone attached to their waist in a funny pack while the corresponding motion information is presented live on the screen. These smartphones sent the data collected by their internal sensors via UDP. Right: the host (in this case, a laptop) that received the UDP-stream sent by the smartphones' sensors and then shared the whole bitmap screen of the device wirelessly to a large LCD screen.**

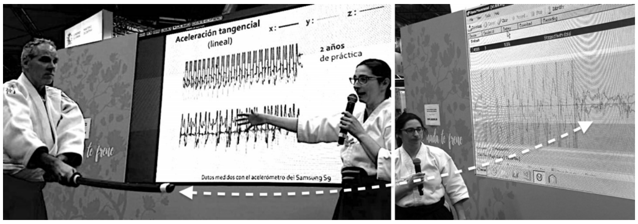

FIGURE 3. **Photograms of the activity 'Aikido and Artificial Intelligence' carried out in the UNED stand at AULA 2019. Left: *bokken* (wooden sword) with an AX3 accelerometer attached to the tip. The slide on the background shows data previously gathered with a smartphone which had been swung as if it was attached to *bokken* in order to track some *shomen* attacks and show the different output signals between an expert and a novice practitioner. Right: real time streams collected with the AX3 sensor and shown while the *bokken* was swung during the demonstration.**

Sensorized live demonstrations of Aikido techniques were performed at AULA to an audience of potential UNED students who were illustrated with a sample of the research that can be carried out in the Master degree in 'Research in Artificial Intelligence' at UNED regarding the modeling of complex psychomotor skills using artificial intelligence techniques. Several Aikido techniques (both empty-handed and with wooden arms) as shown in Figures 1, 2 and 3 were performed live by one of the co-authors of this paper and members of Aikime, the Aikido practitioners at the Kime *dojo* (Japanese for "martial art school") in Madrid, Spain. During the demonstration, sensors were placed on the human body (as shown in Figure 2-left, where a smartphone was located close to the aforementioned *hara* point of both attacker and defender) and on some wooden instruments used in Aikido techniques: i) the *tanto* (wooden knife) as shown in Figure 1 at the bottom right, and ii) the *bokken* (wooden sword) as shown in Figure 3 in the left-hand image. The inertial data collected by the sensors was transmitted wirelessly and in real-time through UDP-streams to be shown to the audience (see Figures 1, 2 and 3) in a large LCD screen. In this case, data captured by sensors was broadcasted to a laptop running a client application that was listening with the corresponding permissions. The data was received almost instantaneously (or at least, fast enough regarding the users' perception) and re-drawn at destination with the open source charting frameworks described by Bostock *et al.* [27]. Then, to visualize the data of the smartphones to the audience, the whole bitmap screen of the device was wirelessly displayed on the large screen also almost in real-time frame-rate thanks to today's fast networking standards [28] and equipment. Screen sharing capabilities are extremely dependent on the operative system underneath, and in this case, a proprietary protocol was used [29], but there exist other open solutions such as DLNA [30], Miracast [31] and DoubleTwist [32].

An Apple iPhone 5 and an iPhone 8 (released in September 2012 and September 2017, respectively) were used to collect the inertial data. Both smartphones provide acceleration in g units (where a value of 0 g entails no acceleration, that is, a free fall in the case of the vertical

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[11] http://portal.uned.es/portal/page?_pageid=93,69876615&_dad=portal

axis) and gyroscopic data in units of angular velocity (rad/s). Sampling frequency can reach a nominal frequency of 60 Hz but can be modulated according to the demands of the operative system in order to preserve battery life.

In addition to the smartphones used in Figure 2, Figure 3-left shows an AX3 scientific-range 3-axis accelerometer (from Axivity, LTD., a spin-off from the Newcastle University) attached to the tip of the *bokken*, following a similar approach to the one used in [33]. This tiny sensor can measure accelerations up to 16 multiples of g and with a frequency up to 3200 Hz. This rate even allows the execution of dead-reckoning processes (i.e., derive 3D paths from accelerations). However, for demonstration or learning purposes, the typical 100 Hz rate is more than enough. Data can be also stored in a packed way (18 bits, instead of 24), which makes it appropriate for long-term experiments.

At the demonstration, it was also commented, for conceptual understanding, that it could have been feasible to use a regular smartphone to gather the inertial data during the *bokken* swings. However, this exercise can be practically difficult and above all, risky for the device (which could be accidentally damaged if unbeknownstly detached from the *bokken*). Even so, to illustrate this possibility, the background slide in Figure 3-left shows some prerecorded swing movements measured by a smartphone (Samsung Galaxy S9), where two different Aikido practitioners with different levels of seniority (two months and two years, respectively), simulated repetitions of a common *bokken* attack (known as *shomen*) by gently (and directly) swinging the aforementioned smartphone while it was held directly with their own hands (in the same way as a *bokken* would have been held).

With this theoretical and practical background in mind, we have designed an empirical study to investigate whether the performance of Aikido techniques can be useful for high school students to better understand some concepts of physics, which is reported next.

IV. USER STUDY

A user study was carried out to evaluate if watching the performance of Aikido techniques helps to better understand some concepts of physics in high school students. We have used the martial art Aikido because it intensively involves circular motions and thus, can be used to also learn rotational mechanics (usually more complex than linear mechanics).

A. SETTINGS

The study was carried out in the context of 'Feria Madrid 2019 for Science and Innovation'[12], which is addressed to high school students with physics in their curriculum and aimed to disseminate science in a participatory atmosphere. This event also took place in the context of the Education Week and was aligned with the STEMadrid Plan that promotes scientific and technological subjects among teenagers. UNED was invited to participate in that event and asked to one of the authors of this paper to prepare an activity regarding her research. She prepared the activity "Physics, Aikido and Artificial Intelligence" to be developed in that event during a four-hour slot. Members of the Aikime *dojo* performed the techniques.

FIGURE 4. Photograms of the activity 'Physics, Aikido and Artificial Intelligence' carried out in the UNED stand at Feria Madrid 2019. Left: a group of high school students are asked by the researcher to participate in the activity (photo from divulgaUNED[13]). Center: a participant watches the *kote gaeshi* technique (photo from madrimasd[14]). Right: the researcher debriefs the study to two participants; in this case, regarding the moment of inertia that was explained with the *shikko* movement (photo from divulgaUNED[15]).

The activity was designed to be used as the user study for this research. The proposed activity (see Figure 4) consisted of:

1) receiving students in the stand,
2) asking students to fill out individually a pre-test on some physics concepts (see Table 1),
3) executing some Aikido techniques that relate to some physics concepts,
4) asking the students to individually fill out a post-test, similar to the pre-test, and
5) debriefing the study and commenting on the responses with the participants, while explaining the physics concepts involved with the help of some visual material (see Figures 5 to 8) that was prepared from snapshots obtained from videos recorded at the Kime *dojo* with Aikido black-belt practitioners.

Figure 4 shows some moments during the activity. On the left, the researcher (one of the co-authors of the paper) is receiving a group of students. In the center, one of the participants watches some of the Aikido techniques performed (in this case, the *kote gaeshi* defensive technique). On the right, the researcher chats with the participant after he has filled out the post-test. The activity called the attention of many participants (see Section 4.3) and even a local TV channel (Telemadrid) covered the event. [16]

B. STUDY DESIGN

Considering the outcomes of the literature review process, four Aikido movements were selected to illustrate four

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[12] https://www.madrimasd.org/feriamadridcienciainnovacion

[13] https://twitter.com/divulgaUNED/status/1111370950375862273/photo/1

[14] https://twitter.com/madrimasd/status/1111245501834412033

[15] https://twitter.com/divulgaUNED/status/1111370950375862273/photo/3

[16] http://telemadrid.es/programas/telenoticias-1/Madrid-Luna-Feria-Ciencia-Ifema-2-2107609260–20190328030808.html (time interval: 00:29 - 00:42).

TABLE 1. Rationale behind the selection of the techniques executed in the user study.

Question	Answer 1	Answer 2	Answer 3	Physics background	Aikido movement
1. A car leaves Madrid towards Valencia (which are 350 km apart) with a velocity of 50 km/h and a motorbike leaves one hour later with a velocity of 100 km/h. What will happen?	Both will arrive at the same time	The motorbike will arrive earlier at Valencia	The car will arrive earlier at Valencia	Rectilinear movement: Space equals velocity times time [Correct answer: 2]	N/A (control question)
2. A basketball ball that weights 2 kg and a medicinal ball that weights 5 kg are 1 m away of a wall. What will happen if I push both balls towards the wall with the same acceleration?	I'll have to push both balls with the same force	I'll make more force to push the basketball ball	I'll make more force to push the medicinal ball	Linear dynamics: Force equals mass times acceleration [Correct answer: 3]	punch attack (*chudan tsuki*) Section 2 shows that punches are one of the most common movement when analyzing the physics in martial arts
3. A machine that launches balls lays on a slippery surface. What will happen if balls are launched towards the right?	The machine does not move	The machine moves towards the right	The machine moves towards the left	Linear dynamics: Conservation of linear momentum [Correct answer: 3]	N/A (control question)
4. A fly sits on the external side of a disc that measures 10 cm in radius and a wasp sits on the external side of another disc that measures 30 cm in radius. Both start turning with the same angular velocity. Which insect will be thrown away with more tangential velocity?	Both insects will be thrown away with the same tangential velocity	The fly will be thrown away with more tangential velocity	The wasp will be thrown away with more tangential velocity	Rotational dynamics: Tangential velocity equals angular velocity times radius [Correct answer: 3]	*shomen* attack with *bokken*, the so called *ichi no suburi* or *first suburi* This motion and its relation with physics is discussed in the University of York's class video
5. To tighten a nut, I can choose between two adjustable wrenches, a long one and a short one. Which is better?	With both, I need to apply the same force	I need to apply less force with the longest	I need to apply less force with the shortest	Rotational dynamics: Torque equals distance times force [Correct answer: 2]	*kote gaeshi* defensive technique in reaction to the *chudan tsuki* (punch) attack This motion and its relation with physics is discussed in the video by EF Deportes [12]
6. The ice skater Javier Martinez is making a pirouette turning on himself and decides to open his arms. What will happen?	He will continue turning with the same angular velocity	He will turn with higher angular velocity	He will turn with lower angular velocity	Rotational dynamics: Moment of inertia depends on mass form and the angular momentum must be conserved, which is equal to moment of inertia times the angular velocity [Correct answer: 3]	*suwari waza tai sabaki shikko ho* (180º or u-turn while knee walking). The moment of inertia and the conservation of the angular momentum are discussed in several works (e.g., [6], [13])

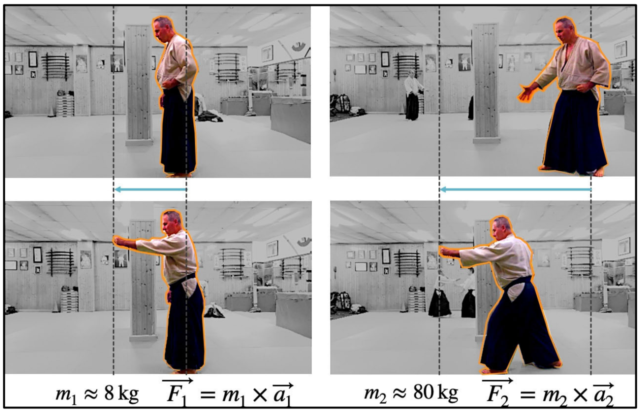

FIGURE 5. **Visual aids were used to support the explanations of the physics concepts that were demonstrated with live executions of Aikido techniques. This corresponds to force equals mass times acceleration, as demonstrated in the study with the *chudan tsuki attack*.**

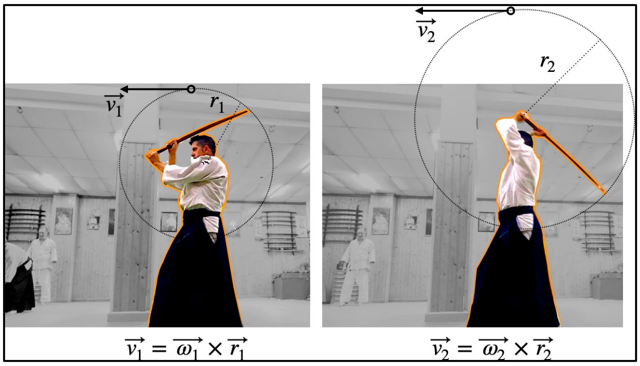

FIGURE 6. **Visual aids were used to support the explanations of the physics concepts that were demonstrated with live executions of Aikido techniques. This corresponds to tangential velocity equals angular velocity times the radius, as demonstrated in the study with the movement *ichi no suburi* or *first suburi* with a *bokken*.**

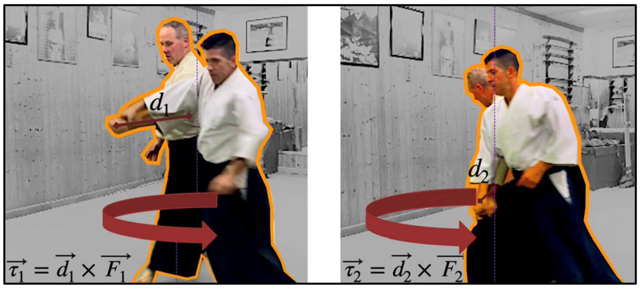

FIGURE 7. **Visual aids were used to support the explanations of the physics concepts that were demonstrated with live executions of Aikido techniques. This corresponds to torque equals force times distance, as demonstrated in the study with the *kote gaeshi* technique after the *chudan tsuki* attack.**

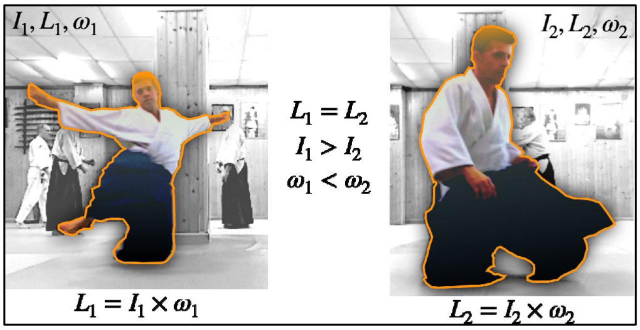

FIGURE 8. **Visual aids were used to support the explanations of the physics concepts that were demonstrated with live executions of Aikido techniques. This corresponds to angular momentum equals moment of inertia times angular velocity, as demonstrated in the study with the movement *suwari waza tai Sabaki shikko ho*.**

corresponding physics concepts in the user study. Table 1 justifies the rationale behind the above selection of the techniques. The formulas were included in the visual aids (see Figures 5 to 8) to facilitate the comprehension of the concepts in the debriefing. The concepts prepared were:

1) force equals mass times acceleration, which is shown with a *chudan tsuki* punch (Figure 5),
2) tangential velocity equals angular velocity times the radius, which is shown with the *shomen* attack with the *bokken*, i,e., *ichi no suburi*or *first suburi* (Figure 6),
3) torque equals force times the perpendicular distance of the line of action of force from the axis of rotation, which is shown with the *kote gaeshi* technique after the *chudan tsuki* attack (Figure 7), and
4) angular momentum equals moment of inertia times angular velocity and is conserved when no external forces are applied, which is shown while turning 180° (u-turn) when knee walking, i.e., *suwari waza tai Sabaki shikko ho*, or *irimi tenkan shikko* (Figure 8).

As already explained, in order to analyze if watching these techniques had an impact on the understanding of the physics concepts behind, a pre- and post-test were defined. They were to be filled out in no more than 2 minutes and their purpose was to evaluate the understanding of the worked physics concepts. With this constraint in mind, 6 questions were prepared and appeared both in the pre- and post-test. Four of them corresponded to the ideas being analyzed in the user study, and the other two had no relation with the user study. These later two were included as control questions, to identify if asking the same question twice influenced the correctness of the answer. We would expect to have improvements in the post-test answers only on those questions that correspond to concepts explained with the Aikido techniques. In addition, the structure of the questions was similar. They were asked to compare some physical effects on two objects and there were 3 possible answers for each question: answer 1 stated that all effects were equal, answer 2 highlighted one of the possible effects and answer 3 provided the other possible effect.

The questionnaire was presented in a single sheet, with the pre-test in one page and the post-test in the back of it. The background of each page was shadowed with different colors, so that it was easy to recognize which side was visible. In this way, the researcher could check that participants did not turn the page until they were asked to fill out the post-test. She also controlled that responses were not changed in the pre-test while participants were

TABLE 2. Statistical analysis with the Student's t-test of the pre- and post-test for the 6 questions. (SD: standard deviation; SEM: standard error of the mean; SED: standard error of the difference between two means).

	Q1 Linear velocity (control)		Q2 Force (punch)		Q3 Linear momentum (control)		Q4 Tangential velocity (wooden sword)		Q5 Torque (defense from punch)		Q6 Angular momentum (knee walking)	
	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post
#correct	23	25	22	23	24	27	17	18	16	16	17	27
mean	0.77	0.83	0.73	0.77	0.80	0.90	0.5	0.60	0.53	0.53	0.57	0.90
SD	0.43	0.38	0.45	0.43	0.41	0.31	0.5	0.5	0.51	0.51	0.50	0.31
SEM	0.08	0.07	0.08	0.08	0.07	0.06	0.09	0.09	0.09	0.09	0.09	0.06
t	1,4392		0.4412		1,3605		0.2969		0.0000		3,0104	
SED	0.046		0.076		0.074		0.112		0.107		0.111	
p	0.1608		0.6624		0.1841		0.7687		1,0000		0.0054 (*)	

watching the Aikido techniques. In addition, the pre-test asked some demographic information, namely: age, gender, course level, if they had repeated the school year, the grade on the last physics exam and if they liked physics in general.

C. PARTICIPANTS

30 high school students (63% boys ad 37% girls) between 14 and 18 years old (mean 16.4; sd 0.73) took part in the study. Most of the participants (80%) said they liked physics, which was expected because they went voluntarily to the UNED stand where the activity was taking place. Only one student had repeated the course and the average grades were 6.69 out of 10 (sd = 2.23).

D. RESULTS

Results from the pre- and post-test are compiled in Table 2. For each question, we have computed the number of correct answers received, both in the pre- and post-test. Assuming normality, the Student's t-test for paired results was applied.

The first three questions seem to be a little easier than the rest, since over 70% of the participants answered them correctly in the pre-test (Q1: 23, Q2: 22; Q3: 24). A slight improvement was done on the post-test (Q1: 25, Q2: 23; Q3: 27). Two of these questions were the control questions. Questions 4 and 5 caused more difficulties to the participants, and just over half of the participants answered them correctly, both in the pre and the post-test (Q4: 17 in pre-test, 18 in post-test; Q5: 16 both in pre- and post-test).

Finally, a significant improvement on the post-test (from 17 correct questions to 27) was found in Question 6. The two-tailed p value equals 0.0054, which by conventional criteria is considered to be very statistically significant. The mean of pre-test minus post-test equals −0.33. The 95% confidence interval of this difference is from −0.56 to −0.11.

E. DISCUSSION

No improvement was found on the control questions (Q1 and Q3). However, since most of the participants answered them correctly in the pre-test, it might be questionable if they were useful. In any case, as shown in Table 2 the improvements achieved were very small (from 23 to 25 in Q1 and from 24 to 27 in Q3), and still there were participants who answered Question 1 and 3 wrongly in the post-test.

Regarding the experimental questions (Q2, Q4, Q5 and Q6), there was only statistical improvement in Question 6, which showed how the moment of inertia depended on the distribution of the mass of the body (i.e., the form) as well as the relationship of this change with the velocity of the rotation (angular velocity). This was demonstrated with the turns performed by the Aikido practitioners while walking on their knees (*shikko* movement). If they turned with their arms extended (higher moment of inertia), the velocity of the turn was reduced. This was clearly perceived in the demonstration, which supports the improvement obtained in the post-test. In fact, only 3 participants (10%) were not able to answer this question correctly after the live performance.

Question 2 was an easy one, as force equals mass times acceleration is one of the basic concepts in dynamics. This was demonstrated with the punch attack, as shown in Figure 5. In the first case (Figure 5-left), the Aikido practitioner only extends the arm, but the rest of the body is not involved in the movement. Thus, only the mass of the arm is involved. However, in the second case (Figure 5-right), the Aikido practitioner involves the whole body with the help of a hip movement, thus increasing the mass used to apply the force. Although 73% of the participants answered it correctly in the pre-test, there was only one additional correct response in the post-test. Our interpretation here is that it is hard to watch the differences in force applied with both executions of the attack. Here it might be more useful to ask the participant to perform both movements by herself, following a more kinesthetic approach that is foreseen in our research. Thus, we will plan another study in which participants are asked to perform the movements by themselves.

Question 4 related to the link between angular and tangential velocity in a circular movement. The proposal was to demonstrate it with the *shomen* attack with the *bokken*, showing how the change of the radio modifies the tangential velocity. However, the length of the *bokken* was fixed, and the change in the radius was only possible by shrinking the arms. However, that modification is anatomically quite difficult in practice, and thus, it was difficult to really change the radius, so participants could not perceive the change in the velocity of the end of the *bokken*. In a future study, we could compare the *bokken* with the *tanto*, which is much shorter than the *bokken*.

Finally, Question 5 was aimed at showing the torque when performing the *kote gaeshi* technique. If the defender performs the movement with the arm extended, then the torque is larger, and the attacker can be thrown away easier that if the defender makes the movement with her arm close to the body. During the Aikido demonstration, the study participants seemed to see clearly the difference and understood well the concept of 'torque'. However, the results of the post-test do not agree with that impression. One reason for this could be the phrasing of the answer. The use of first person (i.e., "I need") changes the perception of the question by forcing the participants to consider themselves and their individual physical abilities as part of the test, thus drawing their attention away from what is really being tested: their understanding of physics. In addition, another problem could also have been the way the responses 2 and 3 were written for this question, focusing on applying "less force". In the debriefing part of the study, several participants commented that they misunderstood the options, and had not really marked the one they thought it was correct. It seemed that they had read "more" instead of "less". Considering both issues, we think it should have been better to write the answers as "More force is needed for…". Anyway, before getting to a conclusion, we should change the writing of the responses and carry out another study to evaluate the torque concept with the *kote gaeshi* technique.

Finally, even though it can be argued the validity of Questions 1 and 3 (due to their easiness) to control the potential improvement in the post-test simply because they are answered for the second time, Questions 4 and 5 show that they did not get that improvement. So, we consider that asking the same questions both in the pre- and post-test is appropriate and did not cause a bias in the study results.

V. TOWARDS INTELLIGENT PSYCHOMOTOR SYSTEMS

The study performed and reported in this paper can provide some insights into the development of psychomotor intelligent tutoring systems, where students' motion interactions are collected with sensors and used to provide personalized vibrotactile feedback (a type of tactile feedback which applies vibrations to skin receptors) aimed to support the learning process. A review of the literature has shown the lack of intelligent tutoring systems to support the learning of motor skills [25]. However, at the same time, it seems feasible to model the human motion of these motor skills with artificial intelligence techniques and the data collected with inertial sensors [34]. In addition, it seems also possible to provide vibrotactile feedback to guide educational oriented physical interactions [35]. This feedback can be applied not only to learn complex motor skills (such as the specific movements of each martial arts technique), but also in embodied learning scenarios [36] where learning takes place in a kinesthetic manner when students carry out physical activities that reflect on the cognitive processes (such as those commented in this paper regarding the physics concepts). In fact, haptic (or tactile) feedback (which uses the touch to communicate with users) has been proven relevant for learning activities that involve concrete observation and can support early science inquiry [37].

The contents of these psychomotor intelligent tutoring systems can be generated with the *Phy+Aik* framework as described in [4], so that students are provided with curated educational material that combines synchronized visual information (high-quality videos and live exhibitions) and tagged data streams collected by inertial sensors. These learning materials are then produced (or are carried out live) with the involvement of teachers of physics and even real Aikido instructors in scenarios or in prerecorded demonstrations. In addition to passively watching this type of content, students can also try to reproduce the corresponding movements and techniques through imitation and a guided process, so that they can even 'feel' on their own bodies the physics concepts involved. As a result, the learning experience can be performed in a kinesthetic way. Simultaneously, students can read (and with help, even interpret) the inertial signals captured by the worn sensors. The sensing technology of *Phy+Aik* can also even serve to monitor these imitated movements as they are executed by the students themselves. This psychomotor approach can contribute to guide the student through the identification of forces, movements and related complex magnitudes such as angular momentum, moment of inertia, and so on. This perception can be even extended to martial arts other than Aikido as well as real world (i.e., non-martial arts) scenarios. For example, dancing or ice skating.

In this way, a psychomotor intelligent tutoring system can contribute to the realm of research around physics education, especially regarding the so-called conceptual change. This term was coined after the fact that students can experience conceptual difficulties with the most basic ideas in science education in general and physics in particular [38]. The understanding of complex concepts in physics has been known for a long time as one of the key areas where educational efforts are needed to really achieve the aforementioned conceptual change. For instance, the Force Concept Inventory (developed by Hestenes, Wells and Swackhamer [39]) is a well-respected test that measures the knowledge of physics concepts among students in the first semester (university/college level), specifically to assess the students' understanding of the Newtonian concept of force. Hestenes discovered that while nearly 80% of the students could understand Newton's third law at the beginning of the course, less than 15% fully understood it at the end (in an apparent unlearning process) [40]. These results have been replicated in many other studies by different institutions and areas [41]. Thus, the Force Concept Inventory highlights the importance of student engagement with the materials to be mastered. And a kinesthetic system that supports the embodied learning of physics concepts by performing marital arts movements seems to be an interesting approach to explore.

In addition, it must be noted that the practice of martial arts in children has benefits beyond health and wellness, as it is supposed to positively influence children's success at school [42]. Moreover, regarding Aikido, in a previous work it was already discussed its benefits for training both the body and the mind [43], and these initial findings have been corroborated with a recent systematic review [44], which after the analysis of 20 works, concludes that there seems to exist positive effects on both physiological and psychological measures, including flexibility, scoliosis, balance stability, mindfulness, anger control and ego-orientation.

VI. CONCLUSION, LIMITATIONS AND FUTURE WORK

In this paper we have found some evidence that watching Aikido movements can serve to understand some concepts of physics such as the moment of inertia. However, as discussed in the paper and to truly support a STEAM based kinesthetic learning scenario, it should be explored the benefits of asking the students to perform the movements by themselves, and thus, feel the difference in the motion execution.

There are some methodological limitations to this study. One of them is that students voluntarily came to UNED stand to carry out the activity "Physics, Aikido and Artificial Intelligence", so they clearly demonstrated a tangible (and slightly biased) interest in science and physics (which was confirmed by their answers to the questionnaire). In order to promote statistical objectivity, we consider that future studies should be carried out in a conventional physics classroom with all the students enrolled in the course, so that we have also students with low interests in science and physics. This scenario can also facilitate that students are asked to fill out, as part of the class assignments, the aforementioned Force Concept Inventory [39] which consists of 25 questions to identify misconceptions on forces and Newtonian physics. This can provide additional information to be considered in the analysis. In addition, we could also explore how concepts about energy changes are also reflected in the practice of martial arts movements, as discussed elsewhere [13].

Another limitation of the study is that it has focused on the Aikido, but as introduced in Section II, there are differences among martial arts regarding the type of movements performed. The studied Aikido techniques can indeed be explained through physics and can in turn be used to teach physics. Different martial arts, including those that stem from the same historical and pedagogical branches as Aikido (e.g., Jujutsu and Hapkido) use different physics to execute techniques. Therefore, one needs to be an expert in both Aikido and physics to teach physics through Aikido. Aikido has been used as an exemplary martial art rather than assuming all martial arts can be used in the same manner as presented in the paper. Experts in other martial arts should likewise be experts in physics if they wish to teach their martial art from that cognitive perspective. Note that all martial artists may not be able to teach the whole of physics via their martial arts. In any case, further studies are needed to confirm that other martial arts could be used for similar purposes. These studies should quantitatively describe the results using mathematical analysis and statistics, and this could be used to determine the weight of individual parameters. Comparisons among those future studies with the one reported here should also be performed.

To summarize, the study performed and reported in this paper can provide some insights into the development of psychomotor intelligent tutoring systems, where students' motion interactions are collected with sensors and used to provide personalized vibrotactile feedback which can be applied in embodied learning scenarios where learning takes place by the students carrying out physical activities in a kinesthetic manner. In this way, personalized STEM contents based on that motion information when performing selected martial arts techniques can be provided. These stimulating educational material can be generated with the *Phy+Aik* framework [4] by Aikido masters and/or physics teachers and are grounded on the practice (or the viewing) of Aikido techniques enhanced with tagged inertial information and accompanied by proper live or prerecorded movements.

The implication of college-level STEAM students could be further fostered by, for instance, designing new activities in which they can numerically analyze signals (very doable with guided statements and with today's apps and services) and extract the differences between well-performed and unskilled motion.

Moreover, it may be beneficial to explore the affective issues that may arise during the kinesthetic learning approach, as it is currently being researched in the INT^{2}AFF project.[17] In fact, in our view, and following Bloom *et al.* [45], we consider that the next generation of tutoring systems should jointly deal with the cognitive, affective and psychomotor dimensions, thus providing personalized cognitive, affective

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[17] INT^{2}AFF project: INTelligent INTra-subject development approach to improve actions in AFFect-aware adaptive educational systems. Project website at: https://adenu.ia.uned.es/web/en/int2aff.

and psychomotor recommendations modeled in base of the students' interactions. For this, artificial intelligence methods should be applied, as they have been proven useful to model cognitive [46], affective [47] and psychomotor [34] aspects.

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