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Cross-Disciplinary, Authentic Student Research Projects

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In the Dutch secondary education system, students must carry out at the end of their school career a rather large research or design project to demonstrate their ability to apply acquired knowledge and skills while pursuing a research question or design goal in some depth. They are encouraged to choose the topic themselves and they are to some extent free in setting up their work. Ideally, the students do not only see it as a compulsory subject but also enjoy the stimulating aspects of doing their own research or design. Challenging and authentic projects, which are representative for actual research and design work done by professionals, seem effective in this respect. The focus of this paper is on how the use of ICT for data acquisition, video-analysis, modelling, and data analysis can contribute to the realisation of such projects in mathematics and science education and on how it can give students opportunities to take the nature and level of their work close to the characteristics of work of experts in the field. We present two examples of students' inquiry work, in the context of bungee jumping and human gait, and we discuss the ICT usage, the authenticity and resemblance with an expert's approach.

Introduction

We concur with Hodson (2009) and other educational researchers (e.g., Roth, van Eijck, Reis & Hsu, 2008) that there are at least three major goals of mathematics, science and technology (MST) education: (1) learning MST, by which we mean the familiarity and understanding of ideas and concepts inherent in these fields; (2) learning about MST, which adopts a much broader view of MST, focusing on the philosophy, history and methodology of these fields; and (3) learning to do MST, by which we mean that the learner gains the ability to engage in and develop expertise in scientific inquiry and problem solving. The cited authors distinguish a fourth purpose of MST education, viz., engagement in sociopolitical action, but it hardly plays a role in our work. Our focus is on providing students with opportunities to experience how science is enacted, i.e., with authentic science, and in particular on providing students with ICT tools that allow them to act as 'real' scientists.

The intention to approach MST education as a study of scientific practice is more easily stated than implemented in a nationwide MST curriculum. The Dutch curriculum reforms of the last two decades in upper level secondary education, introducing new concepts like the 'study house' as a place for students to learn to learn and the so-called 'study profiles' consisting of fixed combinations of subjects, can be looked upon as necessary steps in this direction. Students must build up a portfolio consisting of small practical investigation tasks (4-10 hrs) and one rather large (80 hrs) cross-disciplinary research or design experiment in order to record the progress in their learning of doing science. The main instructional purposes of the small investigation tasks are to give students opportunities to (1) build up general competencies such as research skills, ICT skills, communication skills, and so on; (2) deepen or enlarge existing mathematical and scientific knowledge; and (3) become more proficient in applying knowledge and skills in practice. In the final project students must demonstrate their achieved level of knowledge, skills, and attitude in the form of a report and/or presentation of independent work on a topic of their own choice. For example, in a research project students must demonstrate their research abilities, ranging from choosing a manageable problem, formulating a good research question and structuring their work to drawing conclusions and presenting the results. Not withstanding that the final project is part of the examination programme and a sufficient mark is needed for obtaining a secondary school diploma, many curriculum developers and teachers see it as a chance to expose students to the real world of research and design, and as an opportunity to let students enjoy doing research and development on a subject they personally relate to. In this paper, we explicate our meanings of the adjectives 'cross-disciplinary' and 'authentic' in the context of secondary school students' inquiry work. We illustrate this with two examples, one about bungee jumping and the other about gait analysis. We briefly discuss the authentic nature of these projects and the role of technology. More detailed accounts of the projects can be found elsewhere (Heck & van Dongen, 2008; Heck, Ellermeijer & Kędzierska, 2010; Heck, Uylings & Kędzierska, 2010).

What do we mean by cross-disciplinary, authentic inquiry by students?

We deliberately refer in the title of this section to *our* meaning of cross-disciplinary, authentic student inquiry because there is no general consensus amongst researchers of mathematics and science education. They use terms like authentic science, authentic learning, authentic inquiry, authentic modelling, and so on, in various meanings (see, for example, Hodson, 2009; Roth et al., 2008; Woolnough, 2000).

We refer to an 'authentic student research project' as a student's investigation having the following characteristics:

- Students work on a self-chosen, challenging, ill-defined, open-ended problem that is rooted in a real life situation instead of a more abstract or ideal situation;
- Students do not follow some standard recipes, but they examine their problem from different perspectives, using a variety of resources and high-order skills.
- A broad range of competencies is required to make the project a success. Think of making good use of ICT for information gathering, data acquisition, data processing and analysis, problem-solving, and reporting;
- Students' work is open-ended in the sense that there exist multiple methods or approaches to obtain many possible or even competing results. The student researchers actually decide if the investigation is finished for whatever reason;
- It offers students the opportunity to be in contact with contemporary, cross-disciplinary research and to learn about the nature of mathematics and science;
- Students disclose their own understanding through a portfolio and/or a more or less polished product like a report, paper, or presentation.

A project is called 'cross-disciplinary' when more than one discipline contributes in an essential way to the process of coming to an understanding of the problem situation. The student research projects presented in this paper are mainly rooted in applied mathematics, biology and physics. The term 'cross-disciplinary' is used, and not a term like 'inter-disciplinary,' to emphasise that all disciplines are required to get satisfactory results: the whole is more than the sum of the parts. In both projects discussed in this paper, mathematical modelling meets scientific experimentation.

Understanding Physics of Bungee Jumping

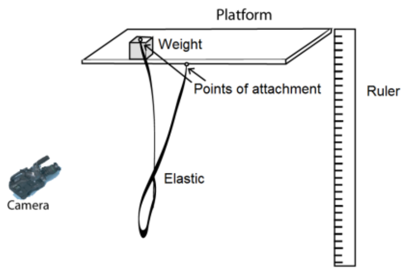
We discuss the first phase of bungee jumping, when the bungee jumper falls down, but the bungee rope is still slack. In instructional material this phase is often considered a free-fall, but when the mass of the bungee rope is taken into account, the bungee jumper reaches acceleration greater than g. This result is contrary to the usual experience with free falling objects. In 2003, two Dutch secondary school students read about this in the paper of Menz (1993) on the website www.bungee.com and were intrigued. They teamed up to investigate the physics of bungee jumping and, like 'real' scientists, they searched for more background information; at a later stage of their investigation they even contacted David Kagan, who is one of the authors of a paper on the subject (Kagan & Kott, 1996). The students formulated the following research question: "How large is the acceleration at a bungee jump and to what extent is this acceleration influenced by the relative mass of the rope and the jumper?" Using the analogy of the motion of a bullwhip, they hypothesized that the acceleration would be greater than g and that this effect would be more dramatic in case the rope is relatively heavier compared to the jumper.

In order to find quantitative support for their hypothesis the students designed an experiment in which they could collect position-time data through video measurements on a dropped scale model and on dropped wooden blocks of various weight attached to ropes of various stiffness. Figure 1a is a sketch of the experimental setting. The students realised that working with a scale model or wooden blocks is not the same as investigating real bungee jumping, but that it would provide them with enough information on what might happen in reality and probably lead to a good understanding. This indicates a research design in which procedures to address the problem are determined, relevant variables are identified and controlled, and measurements are planned.

Note that not the measured position is the variable of interest, but a derived quantity, viz., acceleration. In previous practical investigations based on video analysis with the Coach learning and authoring environment (Heck, Kędzierska & Ellermeijer, 2009), the students had learned that adequate numerical derivatives could be obtained from measured position data. Soon they realized that the mass ratio between rope and objects was too low to see an outstanding result and they repeated the experiment with objects of larger mass ratio. This is another aspect of authentic inquiry: researchers are responsible for detecting flaws in their experimental set-up and must decide how to adjust their original plans. In this case, the students also decided to concentrate on the moment when the object has fallen a distance equal to the rest length of the elastic (because they had observed that the acceleration is greatest at this point of the motion). The graph of the acceleration at the moment that the block has fallen a distance equal to the rest length of the elastic as a function of the mass ratio of elastic and block is shown in Figure 1b, together with the graph of the following theoretical result taken by the students from (Kagan & Kott, 1996):

$$a = g(1 + \mu(4 + \mu)/8),$$

where μ is the mass ratio of the elastic and the wooden block. The students noted that these graphs were alike, with the theoretical values just a bit higher. They attributed the difference mainly to the development of heat during the motion. Again, this indicates a behaviour of the students that resembles the attitude of researchers: comparing their own results with work of others and trying to explain differences by scientific reasoning.



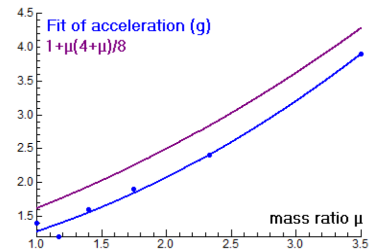


Figure 1: (a) Sketch of the experimental setting. (b) experimental and computed values.

The students published about their work in the journal of the Dutch Physics Society (Dubbelaar & Brantjes, 2003). It triggered quite a number of reactions in the journal and for almost a year on Internet. It seemed that part of the Dutch physics community, at all levels of education, was suddenly playing with chains, elastics, etc. There were complaints about the quality of physics teaching in the Netherlands, arguing that obviously(!) $a \leq g$ and that the students' work proved that the level of physics education in the Netherlands had decreased in the last decades. The editorial commentary was subtle, but to the point: "The students who wrote the paper may consider it a compliment that scepticism overcame professional physicists and physics teachers. That's how (or maybe it is just the point that) experienced intuition can be wrong." Physics intuition is easily fooled, as everyone is taught the Galilean paradigm of the motion of constant masses, according to which every acceleration must be produced by a force. A launched rocket and a falling chain or slinky are counterexamples to this line of thought. In these examples one does not deal with a rigid body, but instead with an object of changing mass. Therefore, the traditional form of Newton's 2nd law, $F = m \cdot a$, does not apply. The interested reader is referred to (Heck, Uylings & Kędzierska, 2010) for a detailed mathematical model that can be used in a quantitative approach with a modelling and simulation tool.

Gait Analysis

In this project, a high school student collected and analysed gait data in much the same way movement scientists do, namely, via recording and measurement of motions with a video tool and via electromyography, i.e., measurement of muscle activity. The authenticity of the student project was rooted in: (1) the use of inexpensive tools (a web cam, a simple EMG/ECG set and Coach software), which are on the one hand fit for educational practice and on the other hand in essence close to the techniques used by biomechanists; and (2) the student's use of the theoretical framework, nomenclature, and research methods of practitioners. That is to say, the student conducted many aspects of motion analysis herself: she formulated research questions about a self-selected gait pattern, searched and studied background information (amongst which articles and fragments of gait analysis books), designed and carried out experiments, processed, analysed and interpreted collected data, and finally wrote a paper (Heck & van Dongen, 2008).

The main research question in this project was: “What is the course of human gait?” It was specialized as follows:

1. “Which phases are distinguished in the gait cycle?”
2. “What muscle activity happens during gait?”
3. “How do bones and joints make gait possible?”

The first and third sub-questions were addressed by video measurement with a web cam of the planar motion of the leg around the hip and knee joint during normal walk on a motorised treadmill in a sports centre. The recorded data were analysed in a hip angle versus knee angle diagram and the periodic leg motion was modelled as a force-driven harmonic oscillator. The angular motion curve of the knee joint is described in this model by a sum of two sine functions, in which one frequency is nearly twice as large as the other one. These frequencies can be found by sinusoidal regression. Muscle activity is typically studied using dynamic electromyography (EMG). In case of measurement of activity of superficial muscles, surface electrodes are placed on the skin surface to detect the electric activity responsible for contraction of muscles (Perry & Burnfield, 2010). EMG recording is rather difficult because correct placement of electrodes is critical. Processing and interpreting an EMG for a muscle is also not easy. It is extremely useful in the experiment that Coach allows simultaneous measurement with sensors and video capture. The video clip and the measured data are synchronized: this means that pointing with the mouse at a point on the graph or at a table entry automatically shows the corresponding video frame and that selecting a particular frame highlights the corresponding points in diagrams, when scanning mode is on. Then, scrubbing reveals that extrema in the clearly periodic EMG signals are consistently linked to certain gait events.

This research project offered the student the opportunity to personally experience the challenges faced in gait analysis. Although she found it difficult to process and interpret the recorded EMG data, she managed to read off from the EMG signal when muscle activity was on and off in various gait patterns. She also managed (Figure 2) to interpret the processed signal in terms of phases and events in the gait cycle, simply by reasoning about what muscle groups are involved in producing a particular body part movement.

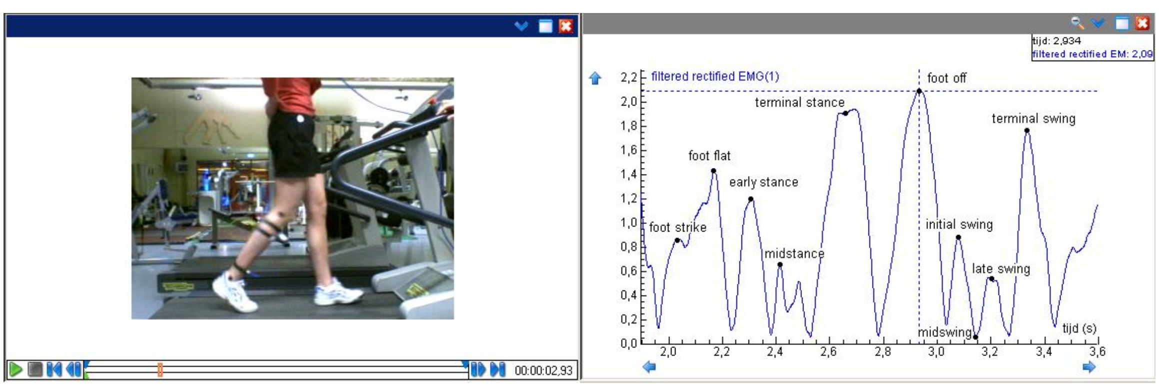


Figure 2: Processed EMG signal of the gastrocnemius for normal walking at low speed.

Conclusion

The educational issue in the students' investigative work that was described in this paper is the ICT-supported interaction between experimental work and mathematical model ling, in which the interpretation of results is based on methods from mathematics and science. The role of ICT in investigative work is to allow students to collect real-time data of good quality, to construct and use computer models of dynamic systems in much the same way as professionals do, and to compare results from experiments, models, and theory. Furthermore, students can develop and practise through the activities their research abilities, and be in con-tact with experts in the field of study. The fact that they must apply their knowledge of mathematics and science in a meaningful way in a concrete context leads at the same time to deepening and consolidation of this knowledge. Through this kind of practical investigation students practise the following important research abilities:

- formulate good research questions that guide the work;
- design and implement an experiment for collection of relevant data;
- apply mathematical knowledge and techniques, and science concepts in new situations;
- construct, test, evaluate, and improve computer models, and have insight in their role in science;
- interpret and theoretically underpin results;
- collaborate with others in an investigation task and reflect on the work.

ICT plays an important role in enabling students to carry out investigations at a high level of quality. It also brings the real world into mathematics and science education in an attractive way. We consider the student-driven experimental design, the modelling process, the underlying thinking processes, and the discussions with peers during the research as more important in the students' work than the obtained results. All the same, it is joyful when experiment, model, and theory are in agreement, as was the case in the project of understanding the physics of bungee jumping and in the human gait study.

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