Being Careful with PASCO's Kinetic Friction Experiment: Uncovering Pre-sliding Displacement?

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The widely used PASCO laboratory equipment is an excellent way to introduce students to many topics in physics. In one case, PASCO's equipment may be too good! Various experiments exist for calculating the kinetic coefficient of friction by measuring the acceleration of a sliding object under some constant force. With ever more accurate equipment, such as electronic motion sensors, students are capable of measuring motion over quite small time intervals. In measuring motion including friction, PASCO equipment can record more complicated aspects of friction associated with the transition between static friction and kinetic friction. This serves as an excellent exercise to introduce some fine details of friction not typically discussed in an introductory physics course. In fact, if one does not consider these fine details (or at least does not omit them) the "canned" PASCO friction lab will yield wildly spurious results. The erroneous results obtained are due to a nonconstant "recoil" acceleration during the first ~0.2 seconds of motion. The problem does not show up in the PASCO instructor's manual because the manual restricts the experiment to a small range of low applied forces for which the effect is minor. The recoil was actually observed previously[1] but was written off as equipment noise. If one ignores this "noise," a relatively constant coefficient of kinetic friction can be found in this lab experiment, as we will show. We describe here the original experiment, a second experiment to rule out that this is an experiment-specific phenomenon, and how the experiments can be used for two or three different topics. Finally, we tabulate results and discuss what may be causing this "recoil."

Experiments

The basic setups of two experiments are illustrated in Fig. 1. On the left, a wooden block is attached by string over a pulley to a hanging mass, which applies a constant force supplied by gravity. On the right is a similar experiment that instead employs an inclined plane, with gravity on the block itself being the constant applied force. Once the block system is released in both cases, the velocity can be measured by the PASCO motion sensor and is plotted as a function of time on a computer by PASCO software (either Science Workshop or Data Studio). From this data, students obtain the block's acceleration along the flat or inclined plane and thus can, after

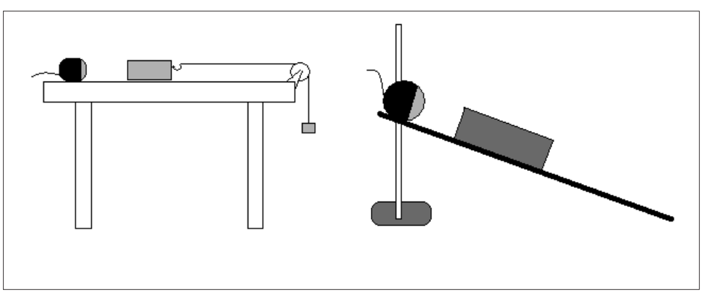

Fig. 1. Left: Wooden block on a horizontal track is accelerated by a hanging mass. Motion is recorded by a motion sensor. Right: Wooden block slides down an inclined plane. Motion is recorded by a motion sensor.

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a bit of physics, calculate the coefficient of kinetic friction. In the hanging mass experiment, one can sum the forces on the sliding block and the hanging mass in the usual way, obtaining the coefficient of kinetic friction,

$$\mu_k = \frac{m}{M} - \left(1 + \frac{m}{M}\right)\frac{a}{g}, \tag{1}$$

where m is the mass of the hanging mass, M is the mass of the block, and a is the acceleration along the track. Interestingly, one can obtain the same result from energy considerations, using

$$W_{nc} = \Delta K + \Delta U \tag{2}$$

and

$$v^2{}_f = 2ad, \tag{3}$$

where

$$W_{nc} = \mu_k Mgd \tag{4}$$

is the work done by friction and d is the distance m has fallen (or the distance M slides). The PASCO pulley is low mass enough that the rotational kinetic energy can be ignored; however, using a more massive pulley would add a third topic to study from one experiment.

In the inclined plane experiment, coefficient of kinetic friction can also be found either by summing forces along the inclined plane, or again using energy considerations. In either case one obtains

$$\mu_k = \tan\theta - \frac{a}{g\cos\theta}, \tag{5}$$

where θ is the angle of inclination of the plane. To obtain this result using energy considerations, Eq. (3) is again used.

Results

We have performed two independent experiments to confirm that the recoil effect does not depend on a specific situation. We show sample plots of each, displayed exactly how they appear as produced by

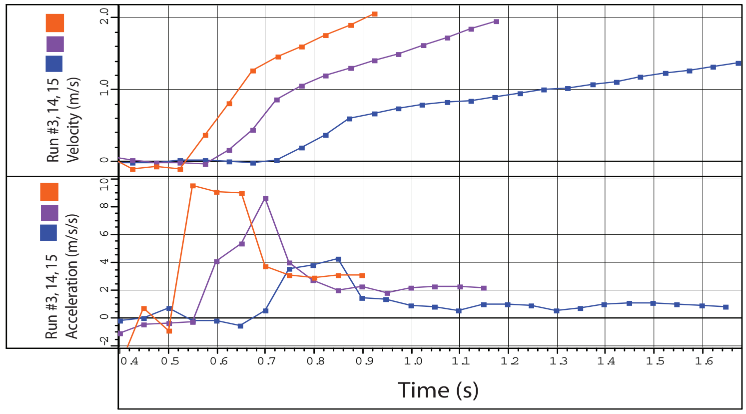

Fig. 2. Sample output for three angles for a block sliding down an inclined plane. Plotted are the block's velocity (top) and acceleration (bottom) vs time.

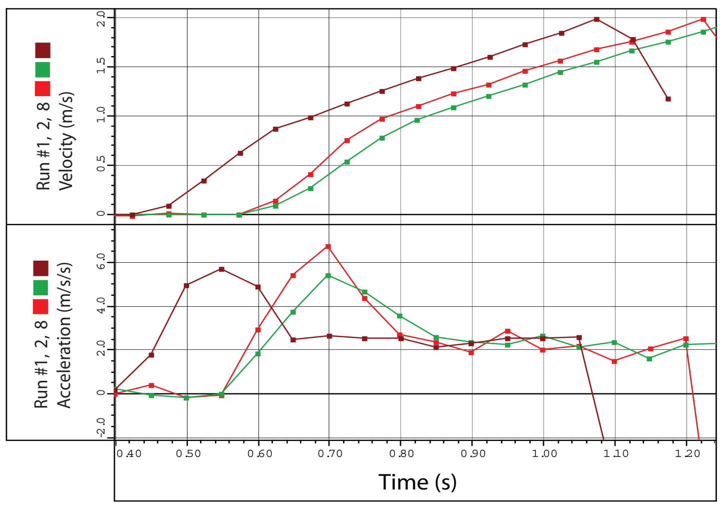

Fig. 3. Sample output for three trials using a 100-g hanging mass. Plotted are the block's velocity (top) and acceleration (bottom) vs time.

PASCO software. In Fig. 2 velocity and acceleration versus time are plotted for a block sliding down an inclined plane. The effect of recoil acceleration is noticeable in both plots but is most conspicuous in the plot of acceleration, which is not specified in the PASCO lab manual. A similar plot and effect are shown in Fig. 3 for a hanging mass experiment with a hanging mass of 100 g. Almost invariably, we have found that the first 0.20–0.25 seconds of sliding exhibit a significant and sudden increase in acceleration immediately after breaking free from static friction. As the angle of inclination is decreased, the magnitude of the recoiling acceleration also decreases. The same was true for decreasing the hanging mass in the hang-

Table I. Coefficient of kinetic friction and acceleration for three hanging masses. Values are given for both considering the break free recoil and not. In all cases, the sliding block has a mass of 0.122 kg.

Hanging mass (g)	*a* (m/s²)	μ_k	*a* (m/s²) uncorrected	μ_k uncorrected
100	1.03	0.33	1.22	0.31
150	2.24	0.35	2.96	0.26
200	3.18	0.34	4.51	0.17

Table II. Coefficient of kinetic friction and acceleration for three hanging masses. Values are given for both including the break free recoil and not.

θ^o	*a* (m/s²)	μ_k	*a* (m/s²) uncorrected	μ_k uncorrected
23.9	2.47	0.35	2.94	0.27
31.7	3.92	0.34	4.67	0.16
36.7	4.80	0.34	5.79	0.08

ing mass experiment. This explains why in past labs we found this effect to make a difference only when the acceleration is high (either by using a large angle or hanging mass). Predictably, students in the introductory lab almost always choose to push the limit of large accelerations. Initially, they found a nonconstant coefficient of kinetic friction, even over a rather modest range of hanging masses or angles of inclination. Assuming that physics books were not being rewritten in our lab, we began to investigate further, uncovering the stick-slip transition.

In Table I the acceleration is shown and coefficient of kinetic friction is calculated in two ways: by using only the data during the time when the acceleration curve is more or less constant (or flat) and by using the slope of the velocity-versus-time plot, as prescribed by the original PASCO Lab write-up (called "uncorrected" in Tables I and II). In both cases, it is quite clear that excluding the break-free data does result in a more or less constant coefficient, thus comforting undergraduates who hold Haliday and Resnick in high esteem. To the contrary, not omitting this recoil data yields a highly variable result. Surprisingly, the author was unable to find mention of friction recoil in existing literature, a fact that is unsettling considering how common the friction experiment is at all levels of physics education. The issue of recoil can either be discussed in the lab experiment or it can be sidestepped completely by restricting the experiment to small applied forces. A 50-g hanging mass, for example, produces a fairly linear velocity plot for the standard PASCO friction block.

Discussion – What's Happening?

On first inspection, the recoil acceleration appears to be just that—the breaking loose from the larger static friction force, perhaps something analogous to a rope snapping during a stagnant tug-o-war. Nonetheless, further explanation or at least speculation seems warranted. So far as the author can tell from existing literature, this effect appears to be related to a phenomenon known as pre-sliding displacement, discussed in numerous sources.[2-8] According to one of these referenced works,[2] "When a frictional contact is in static friction (or stiction), there may nonetheless be relative motion." This is the case for an applied force that is below the breakaway force that produces elastic deformation and movement. Multiple models of friction have been suggested to explain this behavior such as the Dahl Model, the Karnopp Model, the LaGre Model, and the Elasto-plastic Model, all discussed in the before-mentioned references. Typically, these papers present calculation of a model friction force as a function of relative velocity between the two surfaces and introduce microscopic "bristles," which can exhibit spring-like effects such as damping, each bristle having an average stiffness constant. Though much of this work is beyond the scope of an introductory physics course, it is interesting that it cannot be avoided. Also of note, if the friction *model* includes an elastic damping term (as does the LaGre and the Elasto-plastic models), the elastic damping can reverse the direction of the static friction force.[5] Although the effect, known as the "Stribeck slingshot effect," is described in at least one work as a modeling artifact, it does appear to be a good description of what's being observed in our simple experiments. There is clearly sudden recoil acceleration when the block first breaks free from sticking.

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