An outside-the-box activity to demonstrate how humans and animals turn

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INTRODUCTION

Engaging in science outreach is important because it increases understanding of science and highlights the benefits it has to society (6, 17, 19). Demonstrating how physiology specifically relates to everyday life is a critical first step for generating kindergarten through 12th grade (K–12) student interest in science and physiology-related careers. However, developing age-appropriate activities that maintain student engagement and generate the level of excitement that we hope for can be challenging. At Michigan Technological University, we design and implement hands-on outreach activities that include an engineering twist. Accordingly, we developed a unique hands-on activity for high school students that requires them to roll up their sleeves and integrate biology and physics concepts to experience how humans and animals maneuver through their environments, i.e., turning to avoid obstacles. Specifically, groups of students used 2 × 4-in. lumber, wood screws, and a power drill to build a wooden apparatus that, when held square with the body, makes it more difficult to turn. Understanding the physics of turning and how it impacts locomotion is important, because turning accounts for up to 50% of the walking steps during the day (7) and is performed frequently during sports (3). Moreover, changing directions and turning rapidly is needed for survival (9), as animals elude predators, capture prey, and compete against one another for resources.

One factor that influences turning performance is rotational inertia (i.e., moment of inertia). Rotational inertia is an object’s resistance to a change in its position and state of motion. The rotational inertia (I) of an object depends on the mass (m) of the object and distance (r) of that mass relative to the object’s axis of rotation (I = mr²). Because the distance of a mass from the axis of rotation (referred to as the radius) is squared, it has a profound effect on the rotational inertia. The concept of rotational inertia is often introduced in high school science courses such as physics, but can be difficult for students to fully understand and connect to meaningful real-world examples. Our activity was inspired by the work of Carrier et al. (4, 10) on how body shape and size influence turning performance in humans and animals, including therapod dinosaurs.

We created our activity to use with a range of science outreach events, including Physiology Understanding Week (11), Physiology Friday (18), and National Biomechanics Day (2). This activity was particularly well-suited for Physiology Friday, which showcases the important and amazing world of human and animal bodies and is part of a larger Biology Week (15) that embraces enthusiasm for biology all over the world. Our objective was to implement an activity that would engage high school students and highlight the real-world importance of rotational inertia on human and animal performance. At the end of the activity, we envisioned that students would be able to: 1) describe their turning performance results and indicate whether they supported their hypothesis; 2) explain how radius influences rotational inertia and ultimately turning performance; and 3) connect rotational-inertia-related concepts to real-world examples in sports, rehabilitation, locomotion, and evolution.

MATERIALS AND METHODS

Overview. This activity was implemented with high school students taking science courses in biology, physics, and anatomy and physiology. Time needed for the activity was 45–60 min, which is within...
the typical range for most high school class periods. It is important to note that this activity does involve construction assembly and exercise and thus may require approval through an Institutional Review Board. For the activity, students were placed into groups of up to 10, and thus 2–3 groups were formed for a class of 20–30 students. The following equipment and supplies were required for each group:

1. Three separate 8-ft. pieces of 2 × 4-in. lumber
2. Eight wood screws
3. Power drill
4. Safety glasses
5. Backpack
6. Ten to twelve orange field marker cones
7. Clipboard
8. Stopwatch
9. Calculator
10. Data sheet

This activity was best performed in a large space, such as a gymnasium, wide hallway, parking lot, or sports field. Some important safety considerations include finding a suitable location with a surface that provides enough traction (i.e., avoid slippery floors) and ensuring that students have on appropriate footwear for exercising.

The activity was divided into four parts: 1) introduction, 2) construction of a wooden apparatus and slalom course setup, 3) turning experiment, and 4) interpretation of results and discussion.

**Introduction.** To initially engage the class, all students were instructed to walk around for 1 min and count the number of times they had to turn to avoid bumping into someone or something. Students found out rather quickly that they needed to turn quite frequently. We emphasized that walking in a straight line is well understood, and less is known about how humans and animals turn. Turning is critical for avoiding obstacles, changing directions, and survival. Next, students were asked to identify sports examples from the Olympics and X Games that rely heavily on turning of the entire body and/or manipulation of body segments, such as the arms and legs (e.g., diving, gymnastics, snowboarding). Accordingly, students were prompted to perform a spin like a figure skater. That is, students first began to spin around their central axis while positioning their arms far away from their body (increased radius and rotational inertia) and then positioning their arms close to their body (decreased radius and rotational inertia). As expected, students experienced faster rotation as they positioned their arms closer to their body resulting from the decreased radius and rotational inertia. We simply reinforced their observations that the radius seemed to influence the turning ability of the human body.

After these initial activities, we informed the class that they would conduct an experiment to investigate more about how radius impacts turning performance. We outlined that each group would: 1) build a wooden apparatus that, when connected to the body, would artificially increase the radius, 2) set up a slalom course, and 3) navigate through the slalom course with and without the wooden apparatus while being timed (Fig. 1). Students were divided into small groups, and each group was tasked with developing a hypothesis for what would happen (e.g., “We hypothesize that moving through the slalom course with the wooden apparatus will result in a slower slalom course time.”). Within each group, individual students were assigned the following roles so that all students were responsible for a task.

1. Master driller (1 student): a student who has experience using a power drill.
2. Construction workers (4 students): assist master driller with assembling apparatus.
3. Race course designer (1–2 students): design slalom course.
4. Backpacker (1 student): locates materials needed for the control condition, which includes a backpack filled with enough items (e.g., books) to equal ~15 lbs.
5. Timer (1 student): gives start commands and times slalom trials.
6. Data recorder (1–2 students): records data.

**Construction of wooden apparatus and slalom course setup.** Each group used the materials listed below. The lumber was purchased at a local home improvement store.

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**Fig. 1.** Overview of the activity including wooden apparatus construction, slalom course setup, turning experiment, and a representative class data set indicating a 20% decrease in slalom course performance.
1. Wooden apparatus: 3 separate 8-ft. pieces of 2 × 4-in. lumber; 8 wood screws.
2. Control apparatus: backpack filled with enough items (e.g., books) to equal ~15 lbs.
3. Slalom course: 10–12 orange field marker cones.
4. Data collection: clipboard, stopwatch, data sheet, calculator.
5. Other items: 1 pair of safety glasses, power drill.

Before implementing the activity with students, the instructor completed the following tasks:
1. Cut the 2 × 4-in. lumber into two 7-ft. pieces (sides) and two 20-in. crosspieces (ends).
2. Arrange the cut lumber into a rectangle.
3. Predrill two holes on each rectangle corner to make it easier for student assembly.

Each student group was tasked with completing the following steps:
1. Construction workers: position the cut lumber into a rectangle and hold each corner.
2. Master driller: insert wood screws into the predrilled holes to join each corner together.
3. Race course designer: space cones in a zig-zag manner ~5–8 ft. apart in a straight line.
4. Backpacker: locate a backpack to use and fill it with ~15 lbs. of materials (e.g., books).
5. Timer: time slalom trials.
6. Data recorder: records data (name, condition, slalom course time, difficulty rating).

**Turning experiment.** Students in each group performed two slalom course trials while being timed. Specifically, students navigated through the slalom course with (increased radius, experimental condition) and without the wooden apparatus (normal radius, mass-matched control condition). Students received a brief demonstration on how to navigate through the slalom course for both turning conditions. It was critical that students understood that they had to completely turn their hips and reorient their bodies after each slalom cone. Students also practiced navigating through the first few slalom cones to become familiar with each condition.

For the experiment, students within each group were numbered off by 1’s and 2’s, such that even numbers started with the increased radius condition, and odd numbers started with control condition. This alternating starting pattern enabled the experiment to progress in a timely manner.

For the increased radius condition, students stepped inside the wooden apparatus and held onto it so that it was square with the hips and in the most balanced position (Fig. 1). For the control condition, students were equipped with a backpack filled with ~15 lbs. to account for the mass of the wooden apparatus. Students wore the backpack such that the pack was positioned across the front of the body and the straps were secured across the back. Students were instructed to navigate through the course quickly but safely. Times were recorded at the end of the slalom trial (see Fig. 2 for sample data sheet).

Students also rated the difficulty they experienced navigating the course using a 1–10 numeric/emoji scale (Fig. 3). After data were collected, groups were instructed to compile their data, graph their results, and prepare a summary of their main finding/conclusion from the experiment. Students were sometimes guided through this process, whereas other times this process remained more open ended. The class was then brought back together at which time each group briefly presented its findings. A general class discussion then followed.

**Interpretation of results and discussion.** Students discovered that, with an increased radius, it was much more difficult to change directions and navigate through the slalom course. Indeed, performance times for the increased radius condition were often considerably slower compared with the control condition. For example,
representative data presented in Fig. 1 indicate a 20% reduction in slalom course performance (control: 10.4 s vs. increased radius: 13.0 s). Thus, with a larger radius and increased rotational inertia, turning became more difficult and slower. An important part of the experimental design was the manipulation of the radius while maintaining similar mass by adding ~15 lbs. in the backpack for the control condition. As illustrated in Fig. 4, results from this activity were connected to several real-world examples. The notion of reducing the radius term was applied to sport movements, such as choking up on a baseball bat to swing it easier, and sport equipment, including developing shorter downhill skis to turn and carve better. Students often identified additional examples, such as the length of a golf clubs and hockey sticks. Furthermore, the idea of reducing the mass term was presented through an example of how cross-country ski manufacturers sometimes place a hole specifically in the tip of ski as a method to reduce the rotational inertia and allow the ski to swing more easily underneath the skier’s body. This same concept applies to how running mammals, such as horses (8), have more muscle mass located proximally to, with less muscle located distally from, the foot. Additionally, students were asked how rotational inertia would apply to a fractured leg bone that was casted. In this example, reduced muscle mass associated with immobilization theoretically could be beneficial, as it would reduce rotational inertia and make it slightly easier to move the injured limb (12). Finally, the idea of reducing both the radius and mass was highlighted through an example relating to the evolution of theropod dinosaurs. Briefly, Carrier and colleagues (4) proposed that, over time, a reduced dinosaur tail length and lighter skull, along with changes in posture, such as an arched back/tail and forelimbs held closer to the body, may have reduced rotational inertia, resulting in improved turning ability.

Calculation of rotational inertia. A more advanced version of the experiment that we recently developed requires students to determine the extent to which the wooden apparatus (~2 m long, ~0.5 m wide) changes rotational inertia. To do this, the wooden apparatus is theoretically divided into two equal regions (1 m long, 0.5 m wide), with one located in front of the body and the other behind the body. Each region is further divided into three equal segments (0.33 m long, 0.5 m wide) and one crosspiece. We assume that the mass of each segment is concentrated at a point in the center of that segment. Accordingly, the distance from the center of each segment to the body is 0.165, 0.495, and 0.825 m, for segments 1, 2, and 3, respectively. We estimate that 0.33 m of 2 × 4-in. pine lumber has a mass of 0.5 kg. Using the equation \( I = mr^2 \), rotational inertia for segments 1, 2, and 3 is calculated as 0.027, 0.24, and 0.68 kg/m², respectively. The distance from the crosspiece to the body is 1 m and has a mass of 0.8 kg. Thus rotational inertia of the crosspiece is 0.8 kg/m². Summing the rotational inertia values for segments 1, 2, and 3 and the crosspiece gives a regional value of 1.75 kg/m². Multiplying this value by 2 to account for both regions gives a total rotational inertia of 3.51 kg/m².

In contrast, a student maneuvering through the slalom course with the control mass has a rotational inertia of ~1 kg/m². A question for students is why a threefold increase in rotational inertia produced only a 20% reduction in performance. The answer is complex, but time spent turning represents only part of the time needed to complete the slalom course. Additionally, slowing down turning by increasing rotational inertia causes the muscles associated with turning to shorten more slowly and produce greater forces, which partially compensates for the effect of the added inertia (10). The calculation of rotational inertia emphasizes the importance of \( r^2 \) and introduces the concept of integration.

Impact. To date, we have presented this activity as part of local, regional, national, and international science outreach events. Specifically, we have implemented it with high school students ranging from freshman to seniors in biology, physics, and anatomy and physiology courses (200 students). The activity was generally well received by high school students and teachers and provided a source of scientific inquiry and entertainment. Several undergraduate and graduate students in the Department of Kinesiology and Integrative Physiology assisted with delivering these activities as

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**Fig. 4.** Results from the activity were applied to sports, rehabilitation, animal locomotion, and dinosaur evolution.
part of course-based, service-learning assignments. Involvement of these undergraduate and graduate students is notable because evidence (1, 5, 6, 13) suggests that outreach participation from college students increases their understanding of science and physiology. We have also presented this activity as a brief demonstration in an introductory level undergraduate kinesiology course (38 students) and as a more advanced experiment in an upper-level undergraduate biomechanics course (18 students). Thus the activity was implemented with over 250 students, ranging from high school freshman to senior undergraduate students.

DISCUSSION

This activity engaged students and presented the concepts of locomotion, turning, and rotational inertia in a fun way. Moreover, it exposed students to the scientific process, promoted collaboration, and offered a hands-on, inquiry-based experience. The activity was a bit “outside the box,” as it involved a combination of drilling, building, turning, graphing, and application of results to some unconventional examples. This unique educational experience will likely have more of an impact on students, thus increasing the chance that it will be remembered. With its hands-on nature and broad-based integration of biology, physics, math, and engineering, the activity aligns with next-generation science standards (14) that focus on three-dimensional learning and engaging students in carrying out science like scientists and engineers would across multidisciplinary lines. Specifically, the activity engages students with the scientific method and prompts them to ask questions, carry out an experiment, analyze data, and formulate conclusions (dimension 1). It also emphasizes cross-cutting concepts, such as structure-function relationships (e.g., how limits on body size and shape impact movement) (dimension 2). Finally, this activity highlights disciplinary core ideas in life sciences and the application of science (dimension 3).

A strength of the activity was that it yielded large differences in performance times between the two turning conditions. Therefore, students could still make general conclusions even when things did not go perfectly. In addition, data collected by students generally agreed well with Carrier’s results (4) demonstrating a large reduction in turning performance velocities with increased rotational inertia. This is noteworthy because it demonstrates the importance of replication of scientific experiments and comparing results to peer-reviewed literature. Finally, there is potential for the activity to be adapted and implemented in other courses that incorporate first principles of physics to understand human and/or animal movement, and the results can be applied to a wide range of applications.

We found it best to allow 45–60 min to carry out the activity. Alternatively, the activity can be shortened by peasingsemble the wooden apparatus for the students or implementing it more as a demonstration involving only a few students. We acknowledge that it does require some initial work to gather and prepare the materials (i.e., cut the $2 \times 4$-in. lumber), but these items can be reused several times.

Summary. We presented a unique hands-on activity for K–12 and undergraduate students to experience how humans and animals maneuver through their environments. Groups of students used $2 \times 4$-in. lumber, wood screws, and a power drill to build a wooden apparatus that, when connected to the body, artificially increased their rotational inertia (radius term). Students found out quickly that increasing the radius compromised turning performance. Results were connected to a variety of applications in sports, rehabilitation, locomotion, and dinosaur evolution. Students and teachers appreciated the activity and found it entertaining.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

T.K.B., K.R.C., and S.J.E. performed experiments; T.K.B., K.R.C., D.R.C. and S.J.E. analyzed data; T.K.B., K.R.C., D.R.C., and S.J.E. interpreted results of experiments; T.K.B. and S.J.E. prepared figures; T.K.B. and S.J.E. drafted manuscript; T.K.B., K.R.C., D.R.C., and S.J.E. edited and revised manuscript; T.K.B., K.R.C., D.R.C., and S.J.E. approved final version of manuscript; D.R.C. and S.J.E. conceived and designed research.

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