The Unique Physics of the Segway PT Balanced at All Times

Brian G. R. Hughes

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Balanced at All Times

by Brian G.R. Hughes - May 30, 2009

The Segway PT is a self balancing personal transporter that is immediately recognized because of the standing position of the rider. This standing attribute is valuable to many physically disabled people who, for a variety of reasons[2], find the Segway a comfortable and safe way to travel both in private and on public roads and sidewalks.

Because the standing attribute is so obvious, many focus on standing as the principal benefit of the Segway. What is missed are the unique attributes of the Segway PT during acceleration and deceleration that make the Segway possible, and make the Segway usable by such a diverse population.

This paper examines the way in which the Segway controls acceleration and deceleration and contrasts this to more traditional vehicles. To do this we go back to childhood and consider the first rule of "Little Red Wagons" which is "Stay Seated at All Times!" This will take a little physics, which we are going to take step by step.

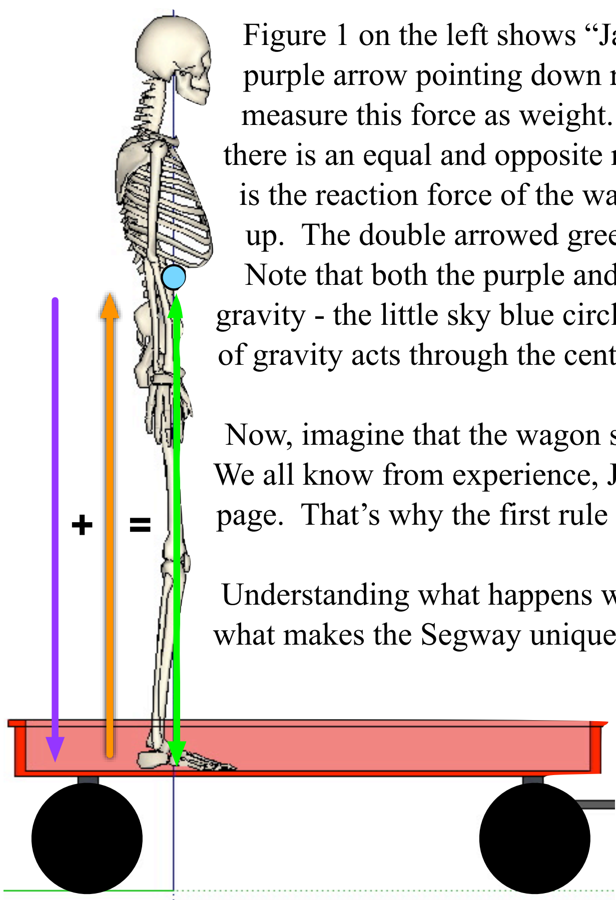

Figure 1: Standing on a "Little Red Wagon"

Figure 1 on the left shows "Jack" standing on a 4 wheeled little red wagon. The purple arrow pointing down represents the force that is a result of gravity. We measure this force as weight. You may remember from Newton, "For every action there is an equal and opposite reaction." In this case, the "equal and opposite reaction" is the reaction force of the wagon which is represented by the orange arrow pointing up. The double arrowed green line represents the balanced sum of these two forces. Note that both the purple and orange lines should be lined up on Jack's center of gravity - the little sky blue circle - but they are moved to the left for clarity. The force of gravity acts through the center of gravity.

Now, imagine that the wagon suddenly gets pulled towards the right. What happens? We all know from experience, Jack falls back and hits his head on the left edge of the page. That's why the first rule of wagon riding is "Stay Seated at All Times!"

Understanding what happens when Jack falls back is the first step to understanding what makes the Segway unique and valuable to the physically disabled.

Figure 2 on the next page illustrates in three diagrams the basic forces at work when standing on a wagon. By the bottom of page 2 you'll understand why Jack falls back. On pages 3 & 4 we'll explain how the Segway works, and on page 5 & 6 we'll explain the challenges of scooter based stand up vehicles.

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[1] Segway and Segway PT are trademarks of Segway Inc.

[2] Sawatzky B, Denison I, Tawashy A: **The Segway for People with Disabilities**: Meeting clients' mobility goals. American Journal of Physical Medicine & Rehabilitation 2009, Vol 88, No. 1

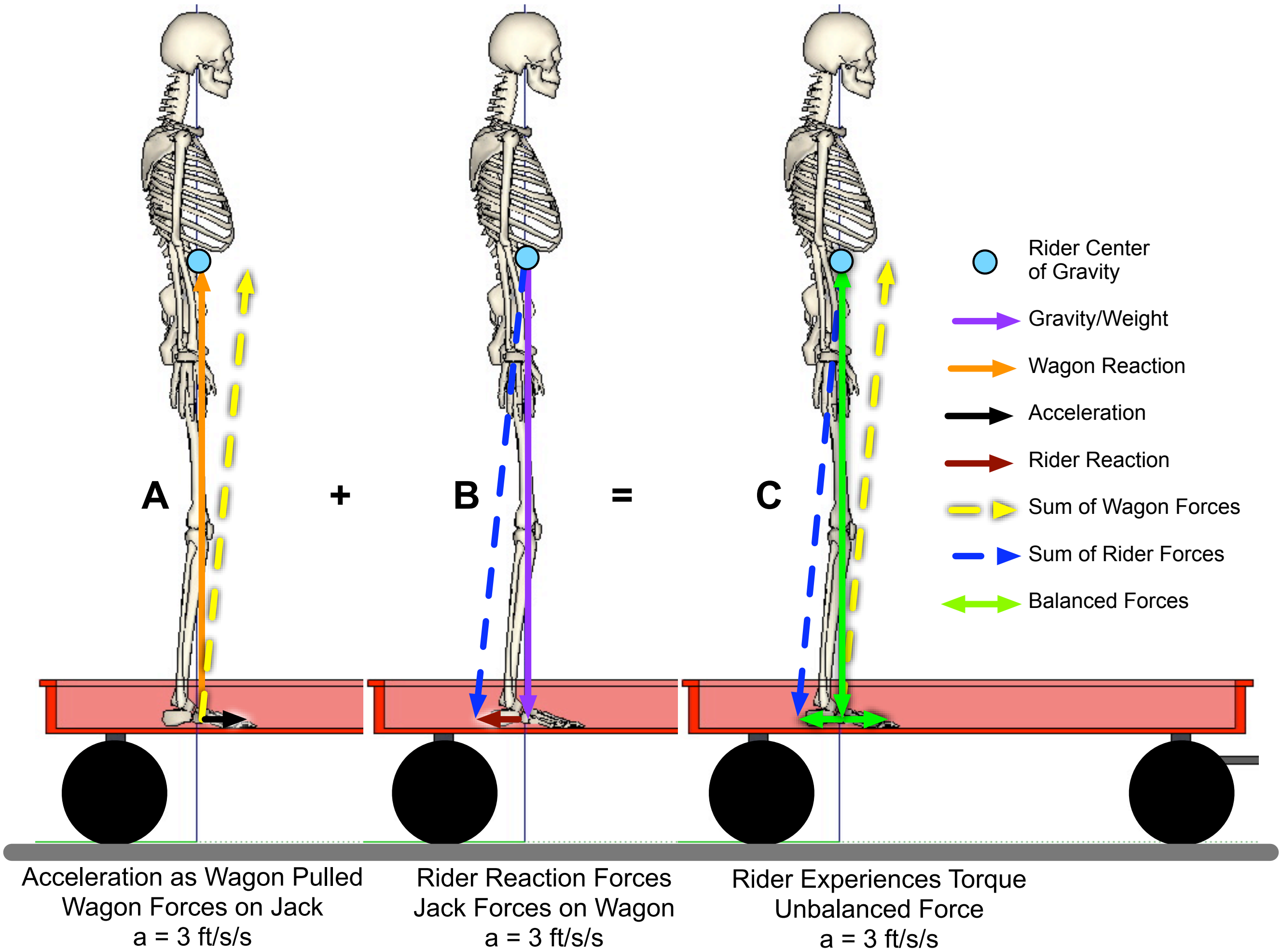

Figure 2: The Forces Acting on a Wagon Rider

Diagram A shows the forces from the wagon which act on the rider when the wagon is pulled to the right with enough force to accelerate the loaded wagon at 3 feet per second per second. (This means that for every second the loaded wagon feels this force it will go 3 feet per second faster.) The force of the acceleration is represented by the horizontal black line pointing to Jack's toes. The reaction force of the wagon to the weight of Jack is the vertical orange line. The dashed yellow angled line is the sum of these two.

Diagram B shows the equal and opposite forces from the rider which act on the wagon. The reaction force of Jack to the acceleration from the wagon is the horizontal maroon line pointing to Jack's heels. The weight of Jack is the vertical purple line. The dashed blue angled line is the sum of these two, which shows that Jack is reacting down and back.

Diagram C shows what's really going on, which is the sum of diagrams A & B. The wagon is pushing up and forward (yellow) while Jack is pushing down and back (blue). These forces are not acting along the same vector, so they create a torque - a twisting force - which is why Jack tumbles backward. You may remember this from your childhood. As adults we feel the same forces in our cars. We are pressed into seat backs when we accelerate - without the seat back we'd tumble into the back.

What is it that makes the Segway PT unique? The Segway is smart. It uses an array of sensors that enable its onboard computers to determine what the rider is doing and to immediately respond to keep the Segway under the rider. The Segway computers run their control program a hundred times a second. How fast is that? At top speed on the Segway you'll move 2 inches in 1/100th of a second, during which time the Segway control software will balance the forces acting on you. This is shown below.

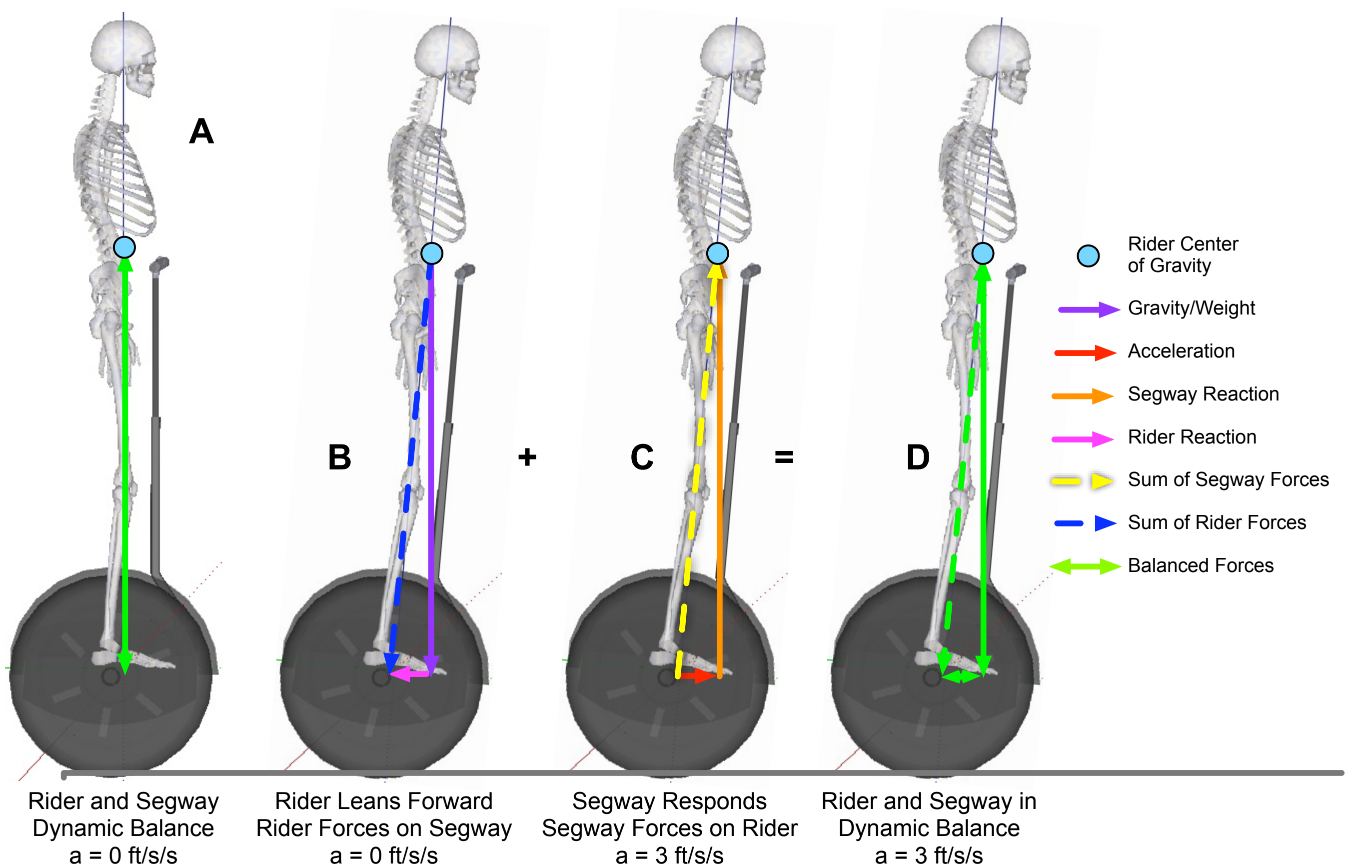

Figure 3: The Forces Acting on a Segway Rider

Diagram A, on the left shows "Jack" standing, with gravity and the Segway reaction force in balance. In diagram B Jack has leaned forward to start moving. The purple arrow is gravity/weight. The magenta arrow is the reaction force of Jack against the Segway. The dashed blue line is the vector sum of the two. If the Segway doesn't respond Jack will fall forward as the Segway is pushed backward.

Diagram C shows the response of the Segway as it senses the tilt of the Segway platform as Jack leans forward. The computers order the motors to power the wheels and accelerate the Segway. The force of acceleration is the red arrow, and the reaction force of the Segway to Jack is the orange arrow. The dashed yellow line is the vector sum of the two. Diagram D shows that the sum of the forces in diagrams B and C are in balance. The vector sums run through each other and the rider, so there are no unbalanced forces or torque.

The onboard computers adjust the power to the wheels to keep the forces balanced through the rider. This is what makes the Segway PT unique.

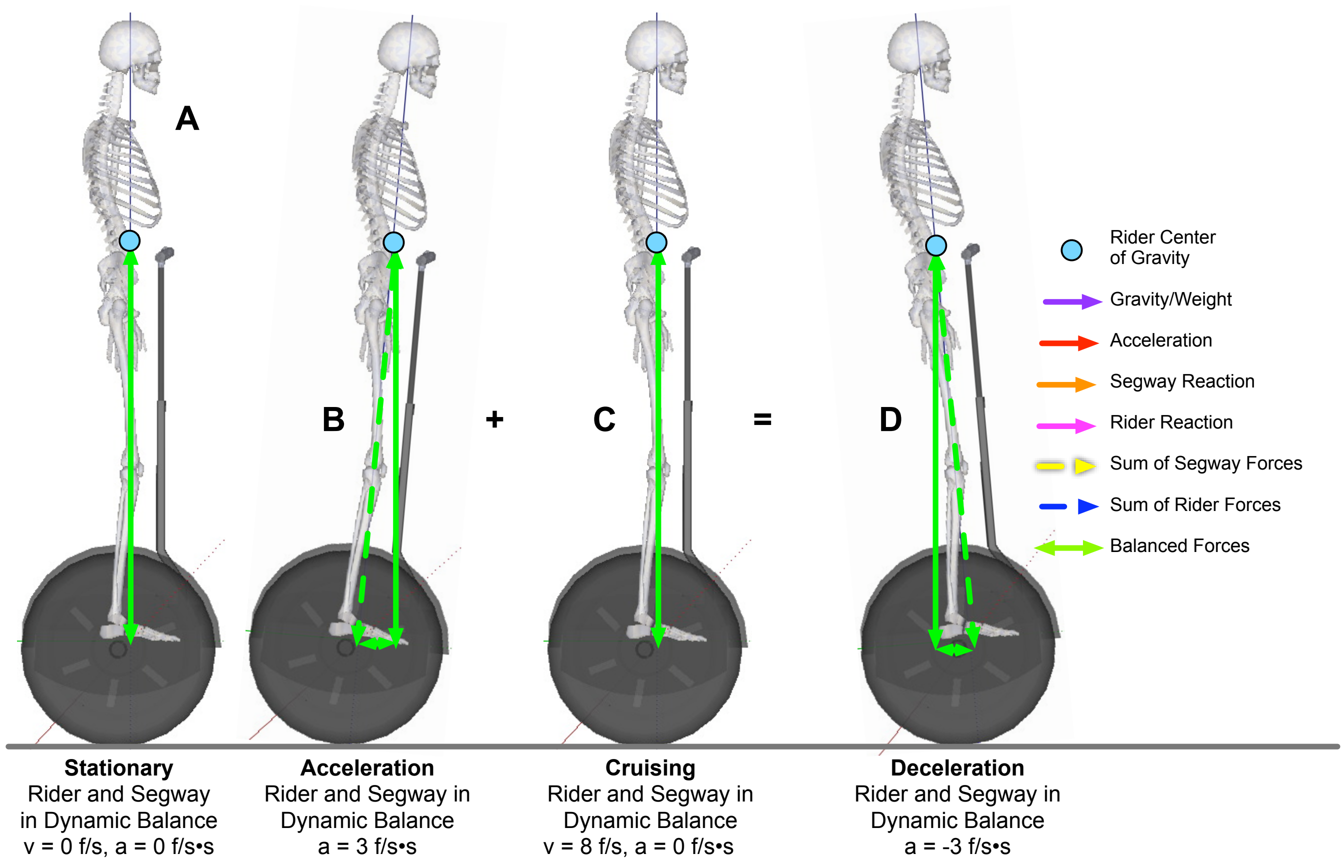

Figure 4: Segway Balances the Forces on the Rider in All Phases of Riding

Figure 4 shows how the Segway keeps the rider in balance during all phases of a ride: stationary, accelerating, cruising at 6 mph, and decelerating. This continuous balancing of forces is what makes riding the Segway possible. There are no unbalanced forces to topple the rider off the Segway, which is why many people with diseases or injuries which result in muscular weakness, such as Muscular Dystrophy or Multiple Sclerosis, can safely ride a Segway. They do not have to compensate for unbalanced forces with their own strength - the Segway does it for them.

The Segway is very different from what we are used to. At first glance it looks like magic, which is why it attracts so much attention. Given this, how can Segway tour operators train complete novices and get them safely up on a Segway and riding in public in 15 minutes?

The reason people are able to learn how to use a Segway so quickly is that the Segway borrows its control scheme from walking. You initiate walking by leaning forward, and as you begin to fall you swing a foot forward to catch yourself. Repeat this and you are walking.

On a Segway you initiate moving forward by leaning forward. The Segway senses your leaning and accelerates forward, balancing the forces, and you are underway. This is the process shown in Figure 4 above. The beauty of this is that the Segway is controlled by same set of reflexes and reactions that control basic human locomotion. Even if you can't walk due to physical limitations, you retain these reflexes and reactions.

Now, let's take a look at a motorized scooter designed to allow the rider to stand. Typically these are based on familiar controls: a throttle to control power and acceleration, and a brake to reduce speed. A typical throttle is a thumb controlled lever. The typical brake is a bicycle style hand lever. A generic "Stand Up Scooter", or SUS, is shown in Figure 5 below. The same analysis of forces will highlight the differences between the Segway and the SUS.

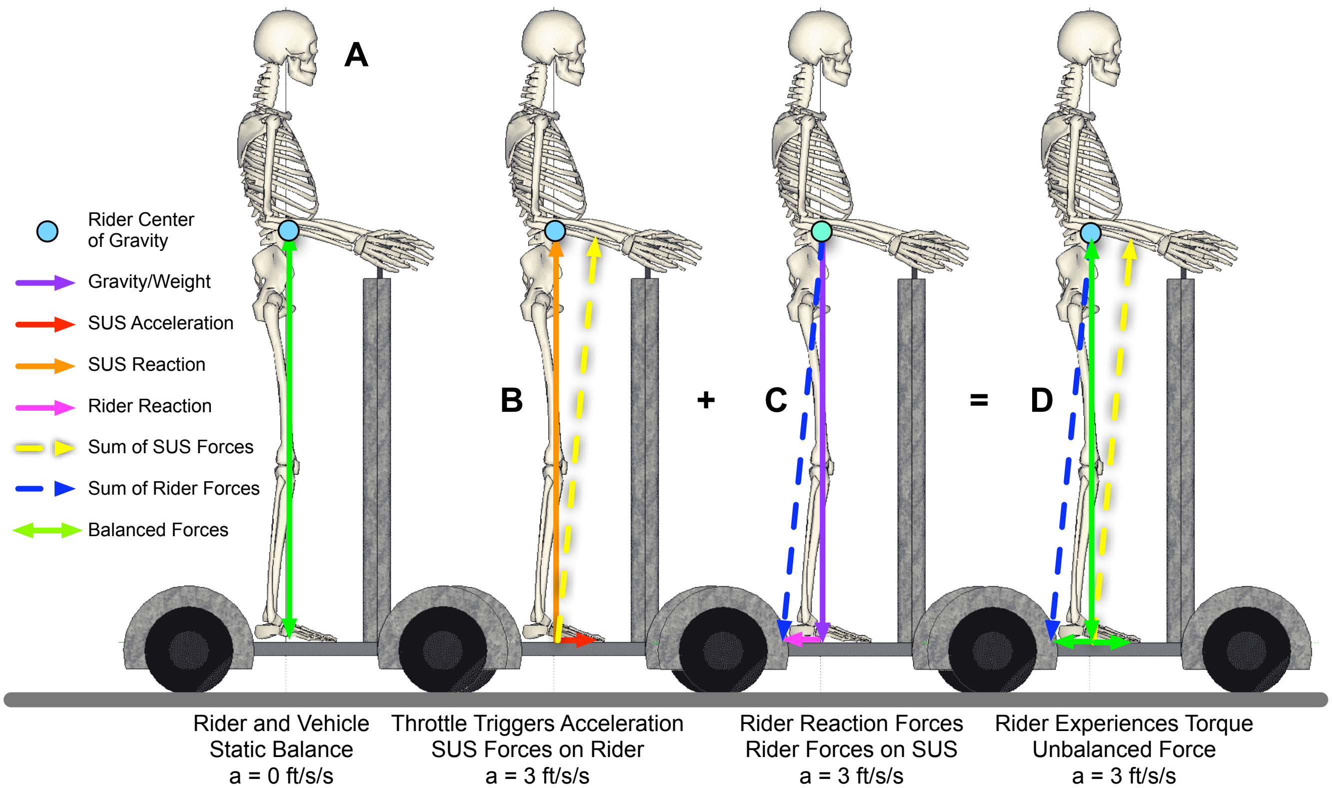

Figure 5: Stand Up Scooter - Forces on the Rider

Diagram A, on the left shows "Jack" standing, with gravity and the SUS reaction force in balance. In diagram B Jack has triggered the throttle and the SUS accelerates. The force of acceleration is the red arrow, and the reaction force of the SUS to Jack is the orange arrow. The dashed yellow angled line is the vector sum of the two.

Diagram C shows the response of Jack as his body reacts to the acceleration of the SUS. The purple arrow is gravity/weight. The magenta arrow is the reaction force of Jack to the SUS's acceleration. The dashed blue angled line is the vector sum of the two.

Diagram D shows the sum of forces in diagrams B and C. They do not balance each other. If Jack doesn't hold on to resist the torque he'll fall back, just like he did on the wagon.

In contrast, the Segway reacted to Jack's leaning forward by accelerating to keep under Jack and balance the imbalance caused by his leaning. The Segway reacts to Jack to keep the forces in balance. Jack doesn't need to hold on to the Segway while accelerating to counter out of balance forces.

On the SUS in contrast, Jack thumbs the throttle, and then has to react as the SUS accelerates. Just like driving a car, Jack needs to practice to learn how to apply the throttle. The SUS doesn't react to Jack, Jack reacts to the SUS. Jack must hold on to the SUS while accelerating to balance the forces.

On the Segway Jack stops by shifting his weight back, the Segway decelerates to keep under Jack. The further Jack shifts back, the harder the Segway decelerates. The Segway reacts to Jack.

On the SUS Jack stops by squeezing the brake lever, the SUS begins braking and Jack has to react to stay on the machine. He has to squeeze the brake lever to control the stop **and** he has to use his arm strength to prevent himself from being thrown forward during the stop. He has to coordinate both actions to safely stop. As with the car, Jack has to practice with the brake lever to learn how hard to squeeze in order to stop smoothly in the distance available. The SUS doesn't react to Jack, Jack reacts to the SUS.

Figure 6 shows how the rider on the Stand Up Scooter is out of balance during acceleration and deceleration. The rider has to provide a restoring force, i.e. hold on, or they may fall off in these phases.

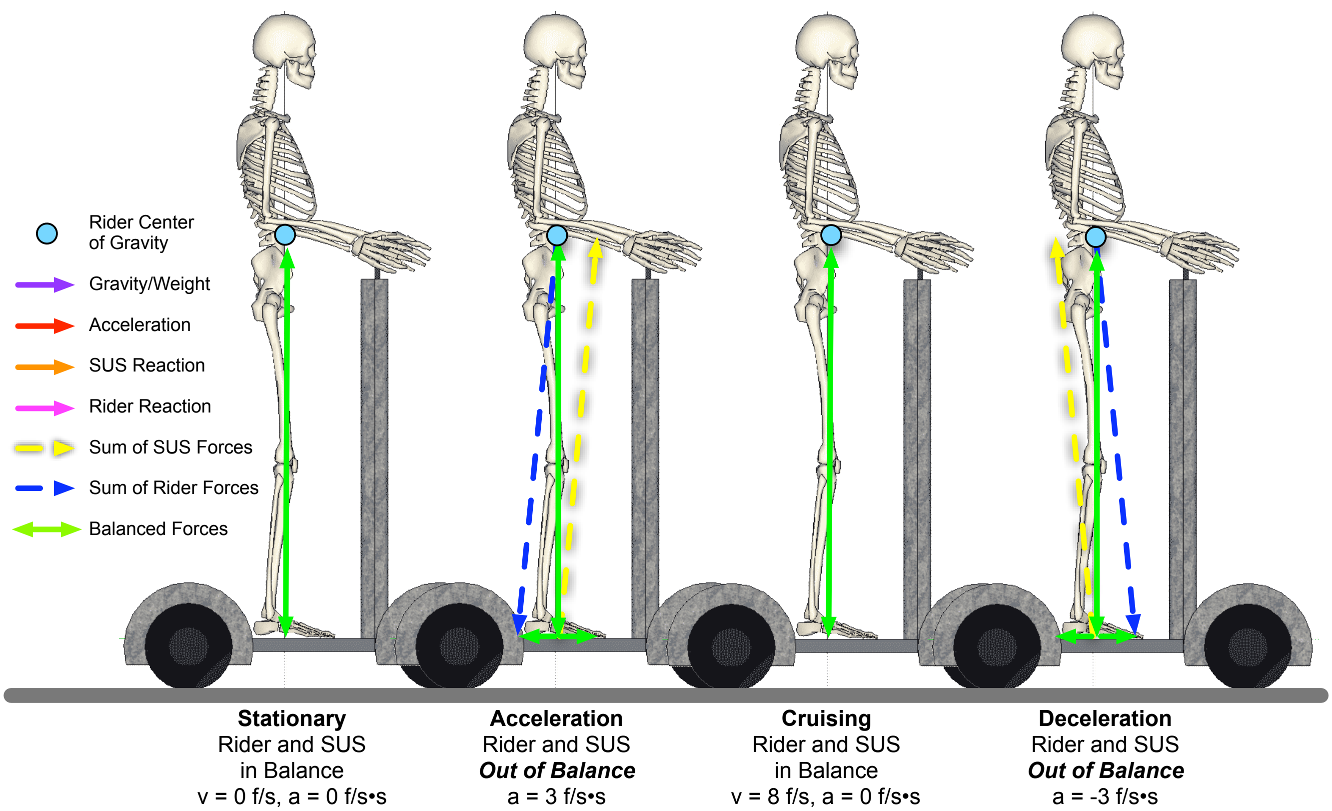

Figure 6: Stand Up Scooter - Out of Balance When Accelerating or Decelerating

Now let's compare a quick stop at typical walking speeds. Jack is on the Segway moving smoothly with pedestrian traffic at about 3 mph and someone steps in right front of him. Jack instinctively reacts by flinching back - the Segway reacts to Jack shifting his weight back by immediately decelerating the Segway. If Jack bumps into the person, the handle bar of the Segway will hit them at about 4 feet off the ground, close to their center of gravity, and that tilts the Segway back, increasing the deceleration of the Segway.

So far in this scenario Jack hasn't actively intervened yet - all the deceleration is a result of his reflexive action, and the geometry of the collision. His active role is to recognize what his flinching backwards means, and to keep shifting his weight back until he has stopped. He doesn't have to find and grab a brake lever, he just has to keep doing what he instinctively does.

What happens on the Stand Up Scooter? Jack is moving smoothly with pedestrian traffic at about 3 mph and someone steps right in front of him. Jack instinctively reacts by flinching back, nothing happens and he reaches for the brake lever. If he can squeeze the brake lever hard enough and fast enough he'll stop the scooter before he hits the person. If the scooter hits them, it will be well below their center of gravity, about knee height, and if Jack stays cool and squeezes the brake lever hard enough he'll stop the scooter before he knocks the person over, while managing to stay on his own feet.

Jack has to consciously and actively brake the SUS. His reflexes and the geometry of the collision do nothing to slow the SUS down before his conscious action to initiate braking.

Summary

The Segway is a uniquely sophisticated machine that uses onboard computers working with multiple sensors and redundant physical systems to sense the motions of the rider, and to react to those motions.

The "Stand Up Scooter" requires the rider to learn how the machine will respond to the throttle and brake, while physically holding on to the machine to counter the unbalanced forces of acceleration and deceleration.

I. Action - Reaction

A. The Segway reacts to motion of the rider. Forces are balanced by the Segway at all times.

B. The rider reacts to the motion of a Stand Up Scooter. Forces are unbalanced during acceleration and deceleration. The rider must compensate for these unbalanced forces to ride the machine.

II. Walking Reflex vs. Machine Specific Training

A. The acceleration and deceleration of a Segway is controlled by shifts in the center of gravity of the rider. These are the same motions that are used to initiate and to stop walking.

B. The acceleration and deceleration of a Stand Up Scooter is controlled by throttle and brake levers. The rider must learn to control the machine, and must have the physical capability to use these controls as required.

III. Quick Stops

A. On a Segway

1. The instinctive reflex of the rider to move away from an imminent collision is the action that initiates deceleration on a Segway.

2. If a collision happens on a Segway, the likely point of contact is the rider's hands on the steering handle, close to the center of gravity of the person being collided with. The collision immediately pushes the Segway steering handle back, tilting the Segway back, further increasing the amount of deceleration of the Segway.

3. Both the instincts of the rider and the geometry of the collision work to decelerate the Segway before the conscious intervention of the rider.

B. On a Stand Up Scooter

1. The instinctive reflex of the rider to move away from an imminent collision has no effect on a Stand Up Scooter. The rider must locate the brake lever and squeeze it to initiate braking.

2. If a collision happens on a Stand Up Scooter, the likely point of contact is well below center of gravity of the person being collided with. The rider must consciously and actively initiate braking by squeezing the brake lever to stop the Stand Up Scooter.

3. Neither the instincts of the rider, nor the geometry of the collision, do anything to slow the Stand Up Scooter before the conscious intervention of the rider.

Brian Hughes

Brian Hughes is co-founder and manager of SegSaddle LLC, which is developing aftermarket-seating systems to make the Segway PT™ of more use to more people. He is also the Chairman and Product Engineer of HBN Shoe, whose Insolia products make shoes more comfortable.

Prior to his current work, Mr. Hughes was CEO of the American Rocket Company (AMROC). AMROC was the world leader in the development of safe, clean, low cost hybrid rocket propulsion. AMROC technology was acquired by Space Dev and was used to develop the motor used for Space Ship One.

Mr. Hughes co-founded PTAT System Inc. in 1984, which built a privately funded transatlantic fiber optic telecommunications cable system, PTAT-1, which links New York, London, Bermuda and Dublin, and was sold to Sprint in August 1989, thus ending AT&T's international telecom monopoly. Prior to PTAT Mr. Hughes insured spacecraft, first as a broker and then an underwriter. Mr. Hughes received a MBA degree from the Harvard Business School. At Harvard he focused on the management of technological innovation.

Mr. Hughes received a Bachelor of Science degree in Mechanical Engineering from the Massachusetts Institute of Technology. He served three five-year terms as a member of the MIT Corporation; its board of trustees, and was elected a Life Member of the Corporation in June 2005. He serves on the Visiting Committees for the Department of Aeronautics and Astronautics (Chairman 1996-1998, and 2003-2006), the Departments of Nuclear Engineering (Chairman 2003-) and Mechanical Engineering. He was President of the MIT Alumni Association for 1999-2000.