The Physics of sit-to-stand

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Sit-to-stand is one of the essential movements that Alexander technique teachers use to teach. We generally leave the mechanical details of the movement aside and focus on teaching inhibition and direction. But understanding the basic physics of sit-to-stand offers insights into fundamental aspects of the movement that can assist in understanding the student's postural habits. It may also inspire new ways of communicating with more technically minded students as well as doctors and physical therapists. Furthermore many teachers already use words and concepts from physics and engineering, such as gravity, momentum, stability, efficiency, mechanical advantage, stiffness, and mobility, in their description of Alexander technique.

This article introduces the physics of sit-to-stand with respect to teaching and learning Alexander technique. It also demonstrates how different executions of sit-to-stand can challenge students in physically different ways. Six "games" that you can play while reading are included to give you a feel for what is being discussed. We've tried to keep the level of technical detail manageable for most readers. If the text gets overwhelming at times, feel free to skip ahead to the next game and return later to the text.

Many of the principles of sit-to-stand can be applied directly to the reverse movement (stand-to-sit) though there are some key differences. To keep the article concise, we will focus on sit-to-stand in our explanations and note a few of the key differences with stand-to-sit.

Some general body physics

At the heart of all actions, according to Newtonian mechanics, are forces. A force is a push or a pull. As you move through the world, every change in your state of motion is associated with a collection of forces that cause the change. These forces can be divided into external forces which act on the body from outside and internal forces which act inside the body.

Two kinds of external forces affect you, gravity and contact forces. Gravity pulls every part of you down towards the ground. Most of us know this. Less well known is that the ground also pushes on you with a contact force. If you are sitting in a chair right now both the chair and floor are pushing up on your bum and your feet. Another contact force is friction which prevents your feet from sliding as you stand up. As the name implies, contact forces only work when the objects are in contact with each other. By contrast gravity is constantly pulling you down, even if you are jumping in the air.

You can visualize the effect of the external forces by imagining what would happen if they were not there. If gravity were not there, the slightest movement would send your body floating up off the ground. If the contact forces were not there you would fall down through the floor as if it had no substance, or in the case of friction you would not be able to avoid sliding any which way along the floor.

Internal forces are generated inside the body by bones, muscles, tendons, ligaments, and other tissue. Some of these forces consume energy, such as the force from muscles. Others consume no energy, such as the forces from bones, ligaments, and tendons. Without the internal forces from the body, it would collapse due to the external forces gravity and contact forces.

The balance of all of these forces, both internal and external, determines whether and how movement will happen. Balanced forces are associated with a state of either rest or constant motion. Imbalanced forces are associated with change in the state of motion. To discuss how this works we must first define momentum.

The momentum of an object describes both its motion and its resistance to change of motion. The more mass and/or speed an object has, the more momentum. A car passing a cyclist has more momentum both because it has more mass and because it is travelling faster. The car will therefore be much harder to slow down than the bike. Momentum also has direction. A car heading south and an identical car heading north at the same speed have opposite momenta. The human body is a bit more complicated than the car because it can fold, bend, and twist in so many ways. In motion, the different parts of the body can be moving in different directions with different speeds and masses. Thus every part of the body can have its own momentum. For example at the beginning of the tipping phase of sit to stand the head has a forward momentum while the feet have hardly any momentum.

Forces and momentum are intimately related. A change in momentum requires a net force. If a moving car tries to suddenly skid a stop, an external force - the frictional force from the ground rubbing on the tires - is needed to slow it down. The tendency for objects to resist changes in momentum is called inertia. In the example of the car trying to stop, if the road is very icy and slippery the car continues forward because the frictional force is gone and inertia maintains its motion. In sit to stand, a combination of forces, both internal and external, are needed to speed up, slow down, or change the direction of the various parts in motion, while inertia can be used to carry a movement forward.

The last terms to know about are torques and rotational motion. Much of the motion of the body involves rotation of objects around joints. In these cases, it can be easier to talk about torques rather than forces and rotational momentum/inertia rather than linear momentum/inertia. Precisely defining these terms goes beyond the scope of this article. But for our purposes it is enough to remember that torque and rotational momentum/inertia are to rotating objects what forces and momentum are to objects moving in a straight line.

Slow, smooth sit to stand

We start our discussion of sit-to-stand by considering very slow continuous movement. Picture a Tai Chi master moving very slowly. Not only is the movement slow but there are also no jerks or sudden shifts during the movement. In this case the momentum and changes in momentum are nearly zero. With little momentum, all forces must stay approximately balanced throughout the movement. This means that as the movement slowly flows forward, the mover can pause at any moment with no adjustments and stay in balance. This absence of momentum and subsequent balance of forces makes the physics easier. It also means that the direction of the motion does not affect the physics. I.e. very slow sit-to-stand and stand-to-sit are, from a physics perspective, identical. Physicists call this kind of extremely slow smooth movement “quasistatic”, which means practically not moving.

Game 1: Try moving quasistatically from sitting to standing and vise versa now. Be sure that you are really moving slowly with no jerks and that you are never "throwing" yourself or falling from one balance point to another. Check that you can stop at any moment with no adjustment. Try in particular to eliminate any jerks at the moment that your bum leaves the chair (in this article we will call this moment liftoff).

Quasistatic movement requires that your center of mass stay above your base of support at all times - i.e. that you stay continually in balance. Roughly speaking, the center of mass is the point about which mass is evenly distributed. In the sitting position it is located roughly around the belly button but it will shift its position as the body changes shape during the movement. Only when the center of mass is directly above its base of support can the object balance at rest. The base of support in sitting is the area defined by the sits bones and the two feet, while in standing it is the single rectangle defined by the outer edges of the two feet. To stay in balance throughout the slow movement, you must first move your center of mass forward, across the sitting base of support, until it is above your feet. Only then can you lift your bum off from the chair without falling. If you try to liftoff before the center of mass reaches the feet you will either need to suddenly lurch forward in preparation (to generate forward momentum) or else you will fall backward to the chair.

Getting the center of mass over the feet is achieved by tipping the trunk (Fig. 1). The closer the feet are to the chair the less the trunk needs to tip forward to get the center of mass above the feet. The trunk tilt at lift off is also reduced when the weight is in your heels rather than the center or balls of the feet. One advantage of sit-to-stand compared to stand-to-sit is that the distance between the bum and the feet can be chosen before the movement thus defining what kind challenges that the mover will face.

Game 2: Try quasistatic sit-to-stand now with different feet positions. Remember to move very slowly and smoothly throughout the movement. Notice that the further the feet are positioned from the chair the further you must tip forward and the more challenging it is to maintain quasistatic movement. Notice what changes when you initiate liftoff on the heels of the feet as opposed to the balls of the feet. Now try quasistatic stand to sit. Notice that the depth of the trunk tilt determines how far back the bum can land on the chair.

We can think of the slow movement as a force matching task. Gravity would collapse the spine forward and fold the body at the hips and knees (flexion) were there no internal muscle action. To prevent this collapse and control the movement, activation of extensor muscles is needed in the trunk, hip, and leg to match gravity. Note that in principle no *flexor* activation of the trunk, hip, or knee flexors is required for the movement to happen. Up through liftoff gravity drives the movement and the extensors control it. In technical terms, the hip and knee extensor muscle contractions are eccentric. After the pelvis leaves the chair, these extensors continue to work to unfold the body to the standing position. Thus both the tipping forward phase and the unfolding to standing phase require constant extensor activity.

Tipping the trunk to shift the center of mass above the feet shifts more weight to the feet, pushing the feet onto to the floor. This is balanced by the external contact force from the floor upwards. This contact force can be measured with a bathroom scale.

Game 3: You can feel and/or measure the contact force from the ground. Place a bathroom scale under your feet and watch the contact force, measured by the scale, increase as the feet are weighted (you need an analogue scale or a digital scale that continually updates). When the sit-to-stand is performed slowly and smoothly you (or a friend) can track the continuous increase until *you reach roughly your body weight at liftoff. If you don't have a scale, just turn your attention to the changing pressure on the bottom of the feet.*

Interestingly, you can also weight and unweight the feet without tipping the trunk. Generating a horizontal force with the feet against the floor, either forward or backwards, generates horizontal frictional forces from both the floor and the chair. These generate torques that either push down or lift up the feet. It is beyond the scope of this article to explain the physics of this in more detail, but you can easily feel this happening and/or measure it with a scale. Perhaps you can figure out exactly what is going on yourself.

Game 4: Sit in the chair with your feet on the ground or on a scale and try to slide your feet forward (knee extension) while keeping your feet stuck to the ground (don't actually move the feet). You will feel and/or measure more weight come onto the feet. Likewise if you pull your feet backwards you will lesson the weight of the feet on the ground.

This kind of static weighting and unweighting of the feet without change of position is unnecessary in sit to stand. As you experienced in game 3, it is enough to bring the center of mass forward for the feet to be weighted. No extra pushing is needed. Furthermore, if the bum leaves the chair while this extra horizontal force is still active, the body will suddenly be either pushed backwards or forwards by the horizontal force from the floor.

While a student can weight the feet without tipping forward she will never be able to stand quasistatically without getting the center of mass above the feet. If she tries, she will just fall back into the chair. However if a teacher's hand is delivering a force to keep the student from falling backwards, she can indeed slowly rise up vertically. In this case the contact force from the ground can be more than the body weight at lift off depending on the feet position. At liftoff, the student's feet need to generate both a horizontal backward force to meet the force of the teacher's hand as well as a vertical force to meet the full weight of the body. The vector sum of these two forces adds up to more than the student's weight.

This hand assisted movement poses some interesting challenges for both the student and the teacher, beyond just the novelty of the trajectory. The student is challenged to continuously match not only gravity and the contact forces from the ground but also the force of the teacher's hand. The teacher is also challenged; providing a steady force match to the student is quite a subtle task. Both student and teacher need to smoothly ramp up the matching forces together, with no jerks or momentum generating strategies. At liftoff itself, the student needs to generate a force greater than their body weight. Finally, all of these challenges need to be achieved while minimizing cocontraction (stiffening of the joints) which would just add unnecessary resistance to the motion.

In general, when the teacher pushes the student forward with a hand it can change the physics quite dramatically, allowing the teacher more control of the use of momentum and the forces at liftoff.

Using momentum smoothly

Thus far we've been discussing the quasistatic limit. But we typically use a fair bit of momentum to rise up out of a chair.

From a balance perspective, the role of momentum can be compared to throwing a ball to a friend. The ball is first in static balance in your hand. The motion of your hand generates momentum in the ball. This momentum allows it to fly off its support and then land and decelerate back into balance in the hand of your friend.

Let's see how this image applies to smoothly using momentum to quickly rise from a chair (Fig. 2). You start by allowing gravity to generate momentum in the torso by keeping the hip extensor action low during the beginning of the tipping phase. The forward momentum of the trunk allows you to launch the trunk from the chair *before* the center of mass is above the feet. After liftoff, momentum carries the body forward while the rearward, off balance, position of the center of mass slows this motion so that the center of mass comes to a soft landing above the feet. This use of momentum speeds up the overall movement and limits the amount that the trunk needs to tip forward. You can generate plenty of momentum this way, using only gravity with no net activation of the flexors, to stand up in about 1.5 seconds [1].

Adding momentum to the movement also requires additional forces for overcoming inertia. As mentioned, changing the momentum of an object, be it at rest or moving, requires a force. In the ball throwing analogy both slowing down and speeding up the ball both require contact forces from the hands. Likewise, a rotating object will require torques to speed or slow down rotation. For example a long springy rod being waved back and forth bends and springs back. Inertia created by momentum bends the rod while the springiness of the rod resists bending.

Just like the ball and the rod, accelerating and decelerating the trunk in sit to stand requires forces. Acceleration during the tipping forward phase can be accomplished using gravity alone. In this case the trunk falls forward due to release of hip joint resistance. Deceleration is then required to extend into liftoff. This deceleration requires extensor activity in the back and hips to overcome both gravity and slow the flexion motion. Like the springy rod, tipping motion the trunk creates forwards inertia which tends to flex the spine as soon as the hip extensors slow the tipping motion. The back extensors prevent this flexion thus maintaining spinal length throughout liftoff.

Thus extensors need to smoothly both to adjust to gravitational forces and to overcome the inertia of the trunk. If the extensors under or over compensate the mover will either collapse or arch the back respectively. Using momentum is a tradeoff: the more vertical trunk reduces the gravitational torques but additional extensor torques are needed to slow the body’s forward momentum.

Game 5: Move from sit-to-stand first quasistatically, and then using momentum smoothly. Notice that for the same foot position, the trunk can tip less forward when using momentum. Notice however that considerable direction of the spine is needed to prevent the trunk from collapsing in both cases - in the quasistatic case to resist gravity and in the momentum case to additionally resist forward inertia.

Momentum offers an additional range of challenges for mobilizing and stabilizing the body against external forces in different positions. Depending on what the teacher wants to test, the student can be coached or guided through the movement along a variety of trajectories at different speeds.

While momentum can be used to traject the center of mass through positions of static instability, similar strategies are not so smooth when sitting down. If the student throws himself off balance as he heading to the chair he has no choice but to land with a thump on the chair. We will leave the physics of this for the reader to think about further.

Using extra momentum

Often a student will generate a burst of momentum even when they are explicitly instructed to move smoothly. Having a student perform sit-to-stand very slowly can make this evident. Despite the instruction to stand slowly the student lurches at the moment just before liftoff. One plausible explanation for this is that the student relies on the burst of momentum to overcome stiffening in the hip joints, effectively throwing himself through the point of stiffness [1]. In stand-to-sit a similar pattern causes the student to fall back into the chair rather than landing smoothly. The alternative, in this model, would be to free the hip joints to allow the movement to happen without the extra burst. This is quite a challenge for most students, especially in the extreme feet forward position.

Another excess use of momentum in sit-to-stand is the activation of hip and knee flexors during the tilt phase in order to accelerate the trunk forward. This strategy is not necessary even for a brisk paced movement. Gravity accelerates the trunk with plenty of speed to stand up quickly without activating flexors [1].

Ever have a student that pulls the chair with them at liftoff so that the chair tips forward? The student is likely pulling the pelvis forward (and helping to flex the hip) using knee flexion. This can be thought of as either a momentum trick - to throw the trunk quickly above the feet after liftoff - or a sliding trick - the student chooses to slide the top of the chair with them to get the center of mass over the feet rather than just bending at the hips. Or it could be a remnant of the artificial pushing or pulling of the legs that we discussed earlier. Either way it is a strangely counterproductive action since knee flexion also unweights the feet.

Sometimes a teacher will take a student's trunk backwards from vertical before taking them forwards into the motion. This can be pedagogically very useful for emphasizing a number of aspects of good use (for example testing the integrity of the trunk and freedom of hips in a backward tilt position). It also challenges the trunk flexors, rather than extensors, to counteract the collapsing force of gravity on the spine. But the teacher should realize that they may be generating extra momentum at the vertical position that would otherwise not be there. It allows the student to rise up with a more vertical trunk than would be possible without the extra momentum generating preparation.

Most teachers intuitively use a variety of pathways to take the student from sit-to-stand - slow, fast, deep, shallow, with and without backward tilts, with and without support from the teacher's hands. This variety allows the teacher to place a wide range of demands on the student's system and thus explore the student's use and weaknesses therein from a number of perspectives.

Discussion

Sit to stand tests students' response to gravity, momentum, and contact forces. Do they collapse? Do they stiffen? Do they use momentum efficiently? What mechanical strategies are they employing? The answers to these questions give both the student and teacher insight into fundamental psychophysical patterns. In this article we have aimed to clarify the mechanical side of these questions.

Other factors in sit-to-stand beyond the scope of this article include the use of the arms or trunk flexion/extension to generate momentum and transfer forces and the role of the ankle flexors and extensors to name a few. Nor have we discussed any underlying neuromuscular mechanisms or pedagogical methods which are at the heart of Alexander technique and certainly more mysterious from a scientific perspective.

The basic physics can be very useful when working with students. For example understanding the quasistatic challenge can make postural problems and moments of extra lurching more evident for both the student and the teacher especially when combined with playing with the position of the feet. Understanding the variety of challenges that can be introduced by changing the speed of movement, position of feet, liftoff moment, and varying the pressure from the teacher's hand can also bring diversity to a lesson. Finally the language of physics can be useful for communicating with certain kinds of students and teachers.

The physics also gives insight into the complexity of the matching task. Perfectly matching the various forces at the feet, chair, and teacher's hands requires requires continuous smooth adjustment of the whole body's response. Given this complexity, it is unlikely that the student can complete the task by simply choreographing the movement - i.e. by consciously deciding what and when to push or pull. Any imperfectly matched forces will result in small jerks in movement or the level of resistance which the teacher or student will be able to either see or feel. It is therefore likely that the response being trained occurs at all levels of the student's system, from reflexive to higher level fine processes. Speculating further about the nature of this learning process is beyond the scope of this article.

Finally, understanding the physics clarifies how different positions and executions challenge the body in different ways. In the past there have been debates amongst teachers from different streams about the "best" pathways and feet positions in sit-to-stand. Grasping the physics can guide discussion more towards *how* one meets the various challenges, rather than the specific parameters of the challenge itself.

Game 6: Take a moment to think about the different sit to stand pathways you have your students execute during your lessons. Do you highlight certain challenges more than others? Are there any pathways that you might explore to challenge your students in new ways? How might you incorporate some of the language of physics to appeal to your more technically minded students?

[1] T. W. Cacciatore, O. S. Mian, A. Peters, B. L. Day, "Neuromechanical interference of posture on movement: evidence from Alexander Technique teachers rising from a chair", *Journal of Neurophysiology* **112 (3)**, 719-729 2014.

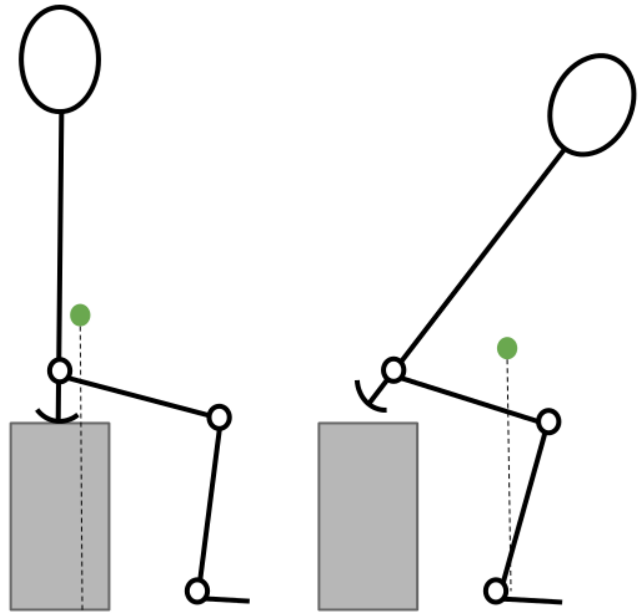

Fig. 1. Cartoon of sit to stand with the center of mass (green dot) for two positions, before the movement starts (left) and just after liftoff (right). In quasistatic movement the center of mass must move to above the feet before you can stand.

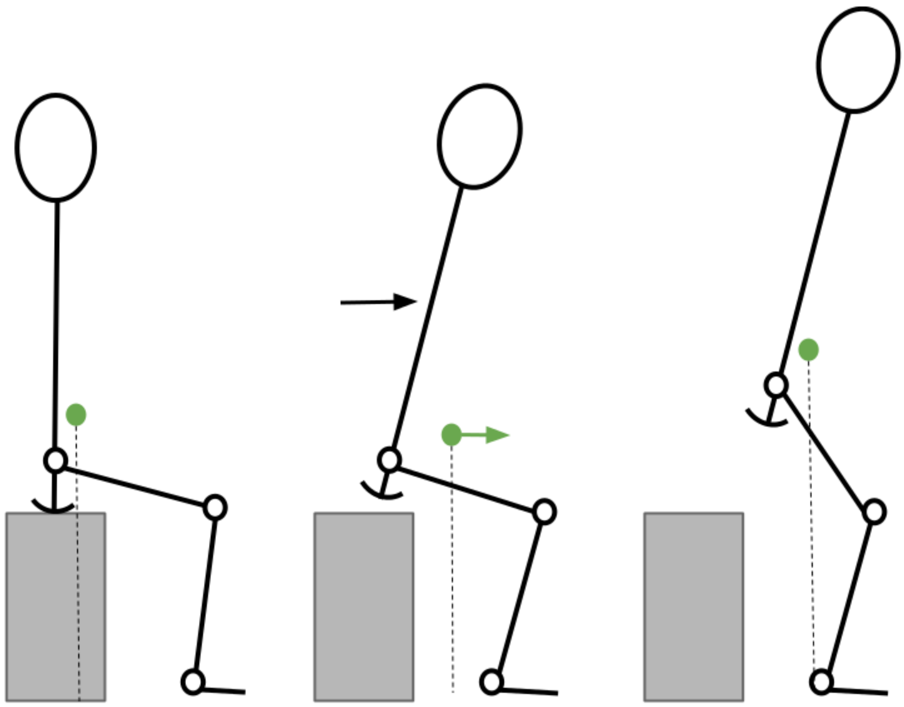

Fig. 2. Momentum generated during the tilt phase, between the left and middle position, allows liftoff to happen before the center of mass is above the feet (middle figure). The center of mass “lands” above the feet as the movement slows down (right). A contact force from the teacher’s hand on the back can have a similar effect.