The physics of skate skiing, Part i) free skate (no poles)
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0) Summary and implications

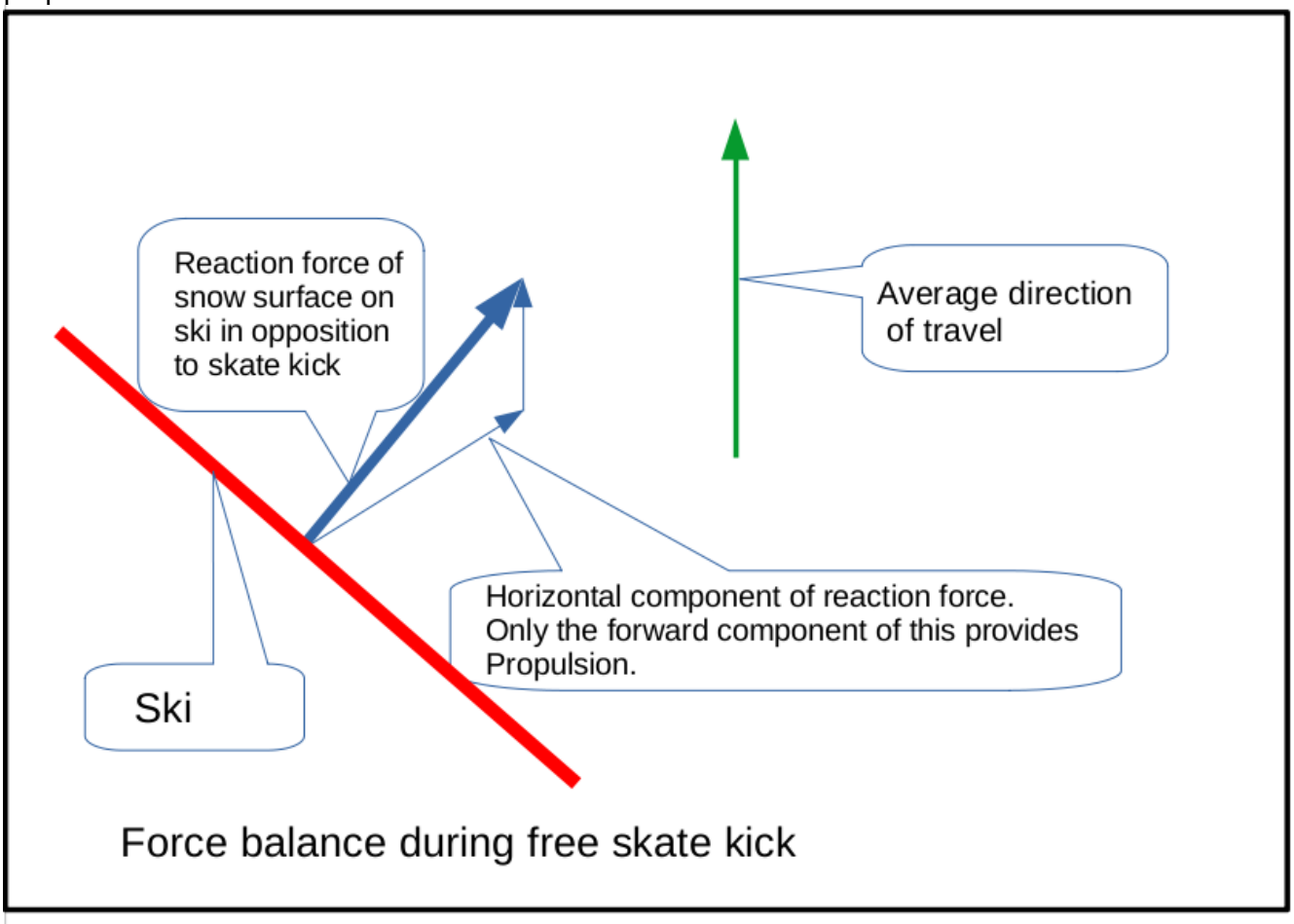
The force that propels a free-skating skier forward on the flat is the reaction force to the skate kick. This force is perpendicular to the ski, and approximately parallel to the lower leg. This basic understanding explains skate technique fundamentals:

a) knees more bent (shins more forward) will increase the forward propelling force on the skier as more of the reaction force will be directed horizontally instead of vertically. Thus the "down,across,up" box drill motion for one-skate.

b) the centre of mass of the skier (approximate inside of the belly button when standing straight) needs to be inline with the kick and reaction forces. Knees more bent then also requires hips and chest forward to get the centre of mass in the correct place.

c) as more propelling force is required (eg going steeper uphill), ski tips need to be wider apart to increase the forward component of the propelling reaction force on the skis.

d) a stronger kick, enabled by starting from a more bent knee, will generate a stronger forward propulsive force on the skier.



Force balance during free skate kick

Details of the actual physics (FYI, this is University physics 101)

1) as long as the ski continues to move forward, snow/ski friction will only act to slow you down. So to simplify analysis, let's assume frictionless wax on the skis.

1a) force application in parallel with a sliding surface can only be done by friction. Therefore for "perfect" frictionless wax, there can be no propelling force (from the snow surface) parallel to a sliding ski surface.

2) Though the details of body motion are relevant to bio-mechanics and efficient use of our muscles, from the point of understanding how the skier's center of mass is accelerated forward (located roughly inside of the belly button when standing straight), we can ignore those details.

3) Newton's second law can be worded as the rate of change of momentum of an object (eg skier) is equal to the net EXTERNAL force acting on the object.

4) External forces have to act on us to propel us forward and continually overcome ski on snow friction and air drag as well as gravity if skiing uphill. The external forces are a) gravity, eg when skiing up- or down-hill, and the reaction forces of the ground/snow on our skis (and poles, but we are ignoring poles for now). Reaction forces (ie Newton's third law) are the equal and opposite forces applied to the skier balancing the ski force applied to the snow (eg skate kick) (and poles). For comparison, forward motion of a car is due to the reaction force from the pavement onto the tire balancing the backward force of the tire applied to the pavement. If we stand still, the reaction ("normal") force of the ground onto our feet balances our weight so that we don't fall into the ground.

5) In free skate with frictionless wax on the skis, the only reaction force is normal (perpendicular) to the ski surface (though depending on ski edging angle, there can also be a small perpendicular component to the ski edge). Any reaction (snow on ski) force parallel to the ski surface would require friction. In other words, during a skate kick, the reaction force is perpendicular to the ski, which resolves into a vertical component and a horizontal component perpendicular to the length of the ski. The horizontal reaction component accelerates the skier's center of mass in a direction perpendicular to the length of the ski. Again, there is no component parallel to the kicking ski.

5a) if you are having trouble understanding 5), consider a ski in a side-ways tilted frictionless track (again no poles). The skier on that ski can only kick away/perpendicular from the track, there is no

way to use a kick to move that ski parallel to the track.

6) The horizontal perpendicular force from a kick off an angled (horizontally and tilted) ski does have a forward component and it is this component that overcomes gravity (say when going up a hill), snow/ski friction, and air drag.

6a) a clarifying implication of the above is that side-ways kicking force on parallel skis pointed forward will not result in any forward propelling reaction force.

7) As the skate kick is complete, and the skier lands onto the other ski, the ensuing kick reverses the side-way motion and adds another forward reaction force component.

8) As such, the more a ski is angled sideways (tips wider apart), the more forward reaction force can be generated. On the other hand, the wider angle means that the skiers' feet will reach their maximum comfortable separation sooner and that reaction force will be for a short term thereby limiting the skier's change in momentum. This explains why when going up steep uphills, skiers need wider ski angles, while when conditions are fast on a flat, less forward reaction force is required and the high speed requires less angle to enable preservation of a reasonable skate tempo.

9) A more complete analysis accounting for the changing forces during a kick requires analysis of physical work done on the skier, where work is the integral of the product of the net force component parallel to displacement (distance travelled in some direction) and the displacement.

Part b), adding poles

In good skate technique, the poles are for forward propulsion. As such, the skier will want to maximize the forward reaction force of the ground on the pole (and thereby on the skier). This involves a trade-off between minimizing the pole angle to the ground (to maximize the rearward component of the pole force on the ground) and a wider pole angle (relative to ground) to enable better transmission of the force of the skier’s weight on the poles. This also requires poles and arms aligned in a purely forward direction.

Part c), bio-mechanical complications

The above is a pure physics analysis of the forces applied to a skate skier. On top of this, are the trade-offs involving optimizing bio-mechanics, tempo, and physical limitations of the body. Eg, the feet can only go so wide apart, skier fitness/strength/flexibility will put limits on how forward the shin angle can be,...