EXAMPLE 7–6 **Bend your knees when landing.** (*a*) Calculate the impulse experienced when a 70-kg person lands on firm ground after jumping from a height of 3.0 m. (*b*) Estimate the average force exerted on the person's feet by the ground if the landing is stiff-legged, and again (*c*) with bent legs. With stiff legs, assume the body moves 1.0 cm during impact, and when the legs are bent, about 50 cm.

PHYSICS APPLIED
How not to break a leg

APPROACH We consider the short time interval that starts just before the person hits the ground and ends when he is brought to rest. During this time interval, the ground exerts a force on him and gives him an impulse which equals his change in momentum (Eq. 7–5). For part (*a*) we know his final speed (zero, when he comes to rest), but we need to calculate his "initial" speed just before impact with the ground. The latter is found using kinematics and his drop from a height of 3.0 m. Then Eq. 7–5 gives us $F\Delta t$. In parts (*b*) and (*c*) we calculate how long, Δt, it takes him to slow down as he hits the ground, using kinematics, and then obtain F because we know $F\Delta t$.

SOLUTION (*a*) First we need to determine the velocity of the person just before striking the ground, which we do by considering the earlier time period between the initial jump from a height of 3.0 m until just before he touches the ground. The person falls under gravity, so we can use the kinematic Eq. 2–11c, $v^2 = v_0^2 + 2a(y - y_0)$ with $a = -g$ and $v_0 = 0$, so

$$v^2 = 2g(y_0 - y)$$

or

$$v = \sqrt{2g(y_0 - y)} = \sqrt{2(9.8\,\text{m/s}^2)(3.0\,\text{m})} = 7.7\,\text{m/s}.$$

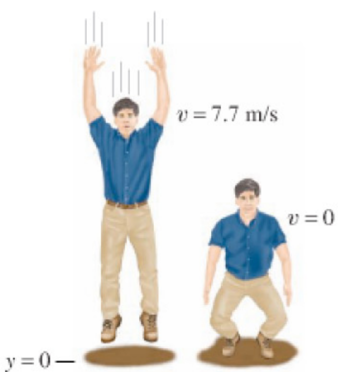

FIGURE 7–11 Example 7–6. Time interval Δt during which the impulse acts.

This $v = 7.7\,\text{m/s}$ is his speed just before hitting the ground, and so it is the initial speed for the short time interval of the impact with the ground, Δt. Now we can determine the impulse by examining this brief time interval as the person hits the ground and is brought to rest (Fig. 7–11). We don't know F and thus can't calculate the impulse $F\Delta t$ directly; but we can use Eq. 7–5: the impulse equals the change in momentum of the object

$$\bar{F}\,\Delta t = \Delta p = m\,\Delta v$$
$$= (70\,\text{kg})(0 - 7.7\,\text{m/s}) = -540\,\text{N}\cdot\text{s}.$$

The negative sign tells us that the force is opposed to the original (downward) momentum; that is, the force acts upward.

(*b*) In coming to rest, the person decelerates from 7.7 m/s to zero in a distance $d = 1.0\,\text{cm} = 1.0 \times 10^{-2}\,\text{m}$. If we assume the upward force exerted on him by the ground is constant, then the average speed during this brief period is

$$\bar{v} = \frac{(7.7\,\text{m/s} + 0\,\text{m/s})}{2} = 3.9\,\text{m/s}.$$

Thus the collision with the ground lasts for a time interval (recall the definition of speed, $\bar{v} = d/\Delta t$):

$$\Delta t = \frac{d}{\bar{v}} = \frac{(1.0 \times 10^{-2}\,\text{m})}{(3.9\,\text{m/s})} = 2.6 \times 10^{-3}\,\text{s}.$$

Since the magnitude of the impulse is $\bar{F}\,\Delta t = 540\,\text{N}\cdot\text{s}$, and $\Delta t = 2.6 \times 10^{-3}\,\text{s}$, the average net force $\bar{F}$ on the person has magnitude

$$\bar{F} = \frac{540\,\text{N}\cdot\text{s}}{2.6 \times 10^{-3}\,\text{s}} = 2.1 \times 10^5\,\text{N}.$$

PROBLEM SOLVING
Free-body diagrams are always useful!

We are almost there. $\bar{F}$ equals the vector sum of the average force upward on the legs exerted by the ground, F_{grd}, which we take as positive, plus the downward force of gravity, $-mg$ (see Fig. 7–12):

$$\bar{F} = F_{\text{grd}} - mg.$$

Since $mg = (70\,\text{kg})(9.8\,\text{m/s}^2) = 690\,\text{N}$, then

$$F_{\text{grd}} = \bar{F} + mg = (2.1 \times 10^5\,\text{N}) + (0.690 \times 10^3\,\text{N}) \approx 2.1 \times 10^5\,\text{N}.$$