The indirect measurement of biomechanical forces in the moving human body

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Inexpensive experimental techniques now exist for indirectly measuring forces within the moving human body. These techniques involve nontrivial applications of basic physical principles, have practical uses, and are appropriate for undergraduate experimentation. A two-dimensional video motion analysis is used to find the accelerations of various parts of the body, and anatomical geometry is used to determine specific biomechanical forces and torques. The simple movement of a dancer landing from a vertical jump is analyzed through the use of a theoretical model of the leg to find the forces in the tendons attached to the knee. It is shown that these forces can be sufficiently large to lead to injury if jumps are performed repetitively.

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I. INTRODUCTION

Some new tools have recently become available that allow for additional insight into the internal forces in the living human body, gained without the invasive procedures that are most appropriately performed on cadavers.

People control their positions and movements by means of the tensions in muscles and tendons and by compressive and bending forces in bones and joints. What magnitudes of forces occur in the body during various activities? For instance, what is the tensile force in the calf muscles, the quadriceps muscles, and the various connecting tendons when a person jumps or lands from a jump?

The purpose of this paper is to describe techniques to determine the magnitudes of these types of forces indirectly and noninvasively using video analysis. These techniques can be used to analyze a variety of movements with varying complexity. As an example of the technique we consider a dancer landing from a vertical jump. Because we analyze jumps of only two dancers, our results may not generalize to all dancers. However, our main purpose is to develop the method that can be used as a model for undergraduate research.

II. BACKGROUND

There are many studies of body mechanics using cadavers for experimental study and mathematical and computer models for movement analysis.[1–4] Cadavers cannot create their own movement, and there is no way to ensure that computer simulations provide quantitative determinations of the forces in living, moving human bodies. Present technology has allowed movement analysis to be done on live human performances through video recordings. Biomechanics research employs digitized recordings to determine biomechanical forces (for example, resultant joint forces in the knee of a skier landing from a jump[5]). The computer calculates the center of mass of the body or parts of the body by dividing the body into known segments.[6] The equations of motion are then solved using the segment masses, the calculated accelerations, and the external forces and moments.[5]

The video analysis equipment used in sophisticated research facilities is expensive, and ranges to over $250,000.[7] The technique described here uses live human subjects and similar methodology to measure internal forces, using relatively simple and inexpensive equipment. The more expensive systems have built-in three-dimensional capabilities and can automatically compute the joint forces. These capabilities are more powerful than the method described here, but the process of creating a physical model of an anatomical system and applying the laws of physics to solve for the internal forces allows students to use their physical insight and problem-solving skills instead of letting a computer do most of the analytical work. This process is an ideal type of project for an undergraduate physics student and is an opportunity to develop physical insight into how the body works and how certain stresses may result in injury.

The method can be easily implemented in the undergraduate physics classroom or laboratory and involves a digital video recording of the moving body, the use of video analysis software for finding the centers of mass of the various body segments of interest as functions of the time, an analysis of the position data to find the acceleration of the centers of mass of the body segments of interest, and the determination of the forces acting on those body segments from their accelerations and from anatomical geometry.

The modest equipment needed includes a digital movie camera and a computer with video analysis software such as VIDEOPOINT, currently available from Vernier Software and Technology. Undergraduate physics students have utilized similar but more basic techniques for quantifying human body movement using tools such as VIDEOPOINT.[8]

A simple example of a problem for which this technique provides a valuable method of measurement and analysis is the determination of the compressive force at the top of the spine that supports the head when a person lands from a vertical jump. The video recording of such a landing may be analyzed to find the position of the center of mass of the head in each frame. The second time derivative of the vertical position gives the acceleration of the head. The total force acting on the head, which consists of the downward gravitational force and the upward force F of the top of the spine, equals the mass of the head times its acceleration, $F-mg=ma$. For a landing from a vertical jump, the upward vertical force at the neck must exceed the weight of the head by an amount sufficient to produce the upward acceleration that results in the necessary decrease in the downward velocity.

There are some inherent difficulties with this technique. It is difficult to determine accurately the lengths and masses of the various body segments and the lengths and moment arms for various muscles acting at the joints. Fortunately, prior measurements and modeling have determined averages for specific populations (for example, female college-aged gymnasts), which give us a reasonable estimate of body segment parameters.[9–12] Also small errors in the position measurements are magnified considerably when time derivatives are calculated, because time derivatives involve finding small differences between the positions of adjacent points. So techniques must be found for smoothing the data without losing significant information.

III. DESCRIPTION

Our goal is to determine the force in the patellar tendons during a dancer's landing from a vertical jump. Those tendons and the quadriceps tendons are responsible for transmitting the force from the quadriceps muscles to the lower legs via the kneecaps, in order to cause the legs to straighten. This mechanism is employed as the descent is slowed upon landing from a vertical jump.

Obtaining the magnitudes of biomechanical forces by a physical analysis not only leads to a greater comprehension of how our bodies work. The magnitude of the tensile stress can be determined given the force in the patellar tendon from the results of this study and knowledge of the cross-sectional area of the tendon. This stress can be compared to the ultimate tensile strength of tendons, the amount of force per unit cross-sectional area a tendon can withstand before rupturing.[13] If a tendon is repetitively subjected to a substantial fraction of the ultimate tensile strength, overuse injury is possible.

Knee problems sustained in dance, most of which are due to overuse,[14] can jeopardize a dancer's health and career, and can be extremely costly to performing companies. For example, one study reported that a single season's injuries had cost the Boston Ballet \$250,000 in health care and related costs.[15] The patellar tendon is a commonly mentioned site for overuse problems such as patellar tendonitis.[16,17] Determining the magnitudes of internal body forces can provide useful information about a dancer's vulnerability to injury and ways of adjusting technique to help alleviate the vulnerability.

From the position of the centers of mass of various body parts we wish to indirectly determine the stress in the patellar tendon. To do so we need to do the following: (1) Find the vertical position of the center of mass of the whole body as a function of time using VIDEOPOINT. To test the accuracy of locating the center of mass, the acceleration of the center of gravity during free fall is compared to the theoretical value of g, the acceleration due to gravity. (2) To validate the use of the acceleration to find the forces acting on individual body parts, the force acting on the whole body determined by the acceleration of the dancer's center of mass during landing from a jump is compared to the force exerted on a force plate on which the dancer landed. (3) These two steps were repeated for a second dancer's jumps to increase confidence in the procedure. (4) A theoretical model of a leg was constructed so that the forces and torques acting in the upper and lower leg could be identified. These forces were related to anatomical characteristics of the human body and the equations of motion were established and solved for the forces in the tendons of interest. We then compare the results with the known magnitudes of tensile force that could cause rupture of the tendons.

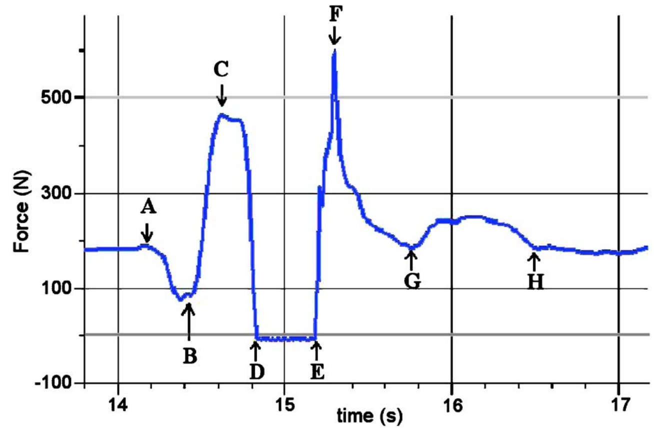


Fig. 1. The force N exerted by one foot on the force plate as a function of time (Ref. 18). The plot begins with a constant force equal to one-half of the dancer's body weight. The force begins to decrease (A) as she bends her knees, accelerating the body downward, and then starts to increase (B) as she slows her descent and straightens the legs, pushing on the ground to accelerate the body upward. The maximum force (C) she exerts during preparation for the jump quickly drops to zero (D) when she leaves the ground. From D to E the dancer is in the air; then the force quickly peaks at F (about 3.3 times half of her body weight) as the dancer's feet hit the floor. As she bends her knees, the force decreases until it plateaus (from G to H) as the body accelerates upward from plié (a bending of the knees to lower the upper body) to a standing position. Finally it settles back to one half of the body weight.

IV. EXPERIMENTAL METHODS

NM and TSN collected data for two advanced female ballet dancers from the Central Pennsylvania Youth Ballet. The dancers performed a series of vertical jumps in ballet first position (rotating the legs such that the heels are together and the toes and knees point outward in the frontal plane), landing on a force plate (obtained from Vernier Software and Technology), which was interfaced to a computer with LOGGERPRO software. Simultaneously the dancers were video taped in the frontal and sagittal planes. (The sagittal plane is the plane of symmetry that divides the body into right and left sides.)

One jump per dancer was chosen for analysis based on the jump's smoothness, symmetry, and quality. The recording of the vertical force between dancer 1's feet and the floor as a function of time is shown in Fig. 1. (Dancer 2's graph displayed the same properties.) The various identifying points described in the caption explain the relation between the graph and the physical processes. The landing phase of the vertical jump starts at point E in the graph and shows a peak shortly after landing (point F), when the deceleration is most pronounced.

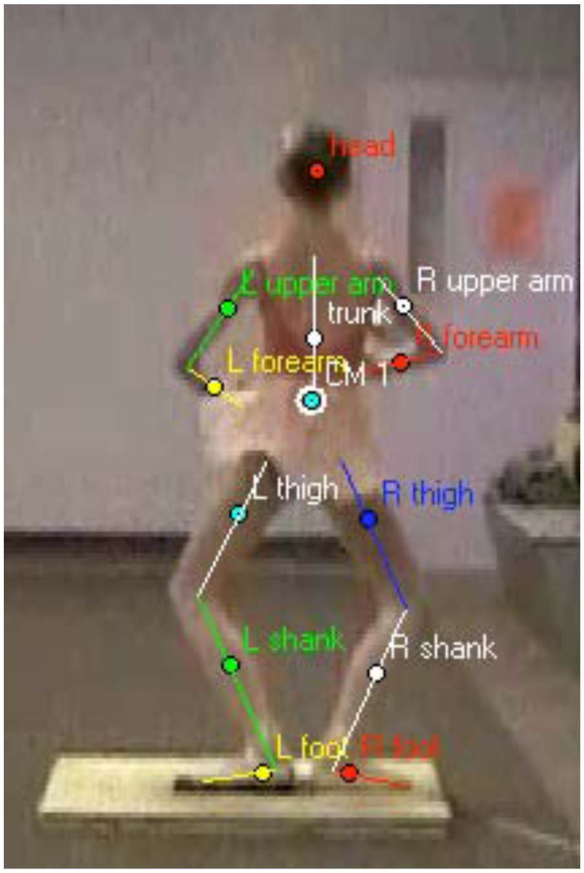


Fig. 2. Frontal plane view of the dancer landing a vertical jump with her feet in a turned out ballet first position. This view is one frame of the video that was analyzed to find the locations of all the body segments and the total body center of mass.

A. Free fall phase

The videos of the two dancers' jumps were uploaded from the original tape to a computer using VIDEOPOINT software and a video camera IEEE1394 interface. The videos were formatted to 60 frames/s from the original 30 by using QUICKTIME PRO.

The locations of the centers of mass of 12 body segments of each dancer were determined and recorded for each video frame during the flight and landing of the jump (see Fig. 2). The segments of the body and their relative masses expressed as a percentage of the total body mass are shown in Table I. Table II was used to determine the locations of each segment's center of mass along a reference line. The end points of the reference lines (neck base, waist, left and right shoulders, elbows, fingers, hips, ankles, and toes) were manually tracked as points in each frame along with the center of mass of the head (assumed to be at its geometric center). Designated points for each segment in Table I (for example, trunk and lower arm) were created from these reference points at the appropriate location along the reference line.

Table I. Masses (as percentage of total body mass) of body segments for female college-age gymnasts (Ref. 19).

Segment	Relative mass
Head	9.4
Trunk	50.8
L/R lower arm	2.1
L/R upper arm	2.7
L/R foot	1.2
L/R lower leg	5.5
L/R thigh	8.3

Table II. Locations of centers of mass of each segment expressed as a percentage of total distance between two end points of a reference line (Ref. 20).

Segment	c.m. Location
Trunk	65% from neck base to waist
Lower arm	50% from elbow to fingers
Upper arm	40% from shoulder to elbow
Foot	20% from ankle to toe
Lower leg	40% from knee to ankle
Thigh	40% from hip to knee

The first step in the analysis is to validate the accuracy of the center of mass location and the use of center of mass positions for finding accelerations. When the free-fall phase of the dancers was investigated, the acceleration of the whole body center of mass was found to be within 2% of g for both dancers.

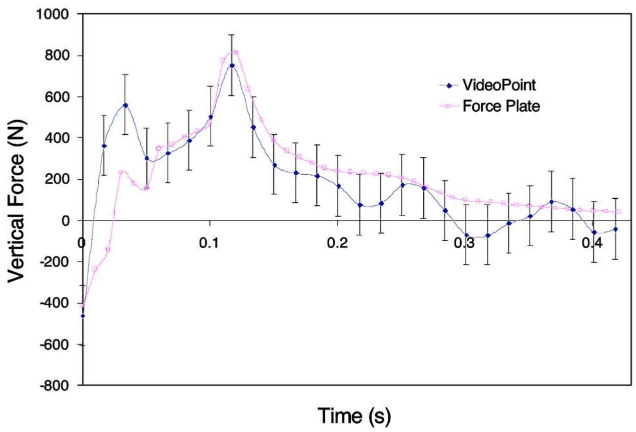
B. Comparison of direct and indirect measurements of force

We now focus on the landing phase of the jump when the body's downward velocity decelerates to zero. We test if the force acting on the body determined by means of the acceleration of the body's center of mass agrees with the force measured directly with the force plate. When the two force measurements were compared, the differences could be minimized by judicious smoothing. The vertical velocities of the center of mass were found by VIDEOPOINT, which uses several adjoining points when taking the derivative. The acceleration was found by similarly finding the slope of the velocity using several adjacent points to smooth the variations without losing much information.[21] Because the total force acting on the body is the sum of the gravitational force Mg and the force F from the floor, the constant Mg must be subtracted from the force plate reading to compare with the acceleration data (that is, $F_{\text{total}}=F-Mg=Ma$). Figure 3 shows the graphs for the two dancers' jumps.

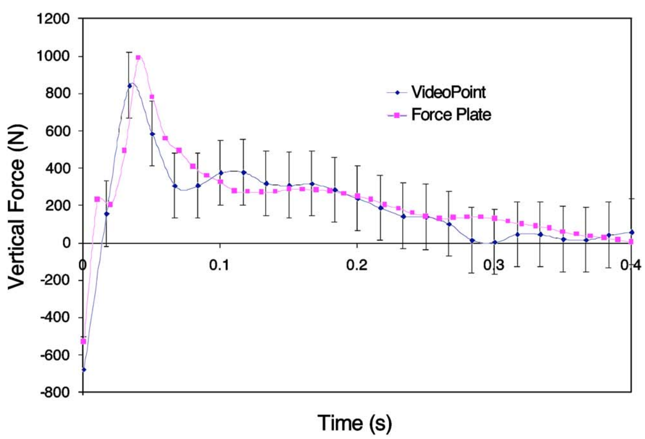
The similarity between the two graphs validates the use of the center of mass technique for finding biomechanical forces on parts of the body. The error bars are a statistical estimate of the uncertainties in the calculated accelerations of the center of mass.[22] The manufacturer's uncertainty in the force measured by the force plate (4.8 N) is smaller than the size of the data points.

C. Determination of the internal biomechanical forces

We now extend this technique to find the magnitude of forces in the body that cannot be measured with a force plate. We will determine the acceleration of the part of dancer 1's body above her hips to determine the forces acting on her knee joints. Then we will determine the torques in her knee



(a) Dancer 1



(b) Dancer 2

Fig. 3. (a) Total force acting on dancer 1 and (b) dancer 2 as a function of time during landing from a vertical jump as measured directly by a force plate and indirectly using VIDEOPOINT.

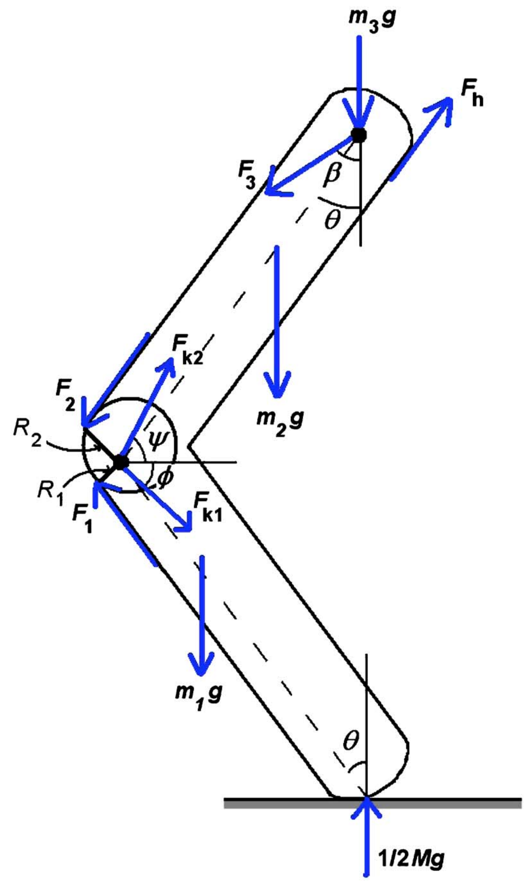


Fig. 4. Force diagram of the leg (frontal plane) as a dancer lands from a vertical jump with perfect turnout. The arrows representing the forces are not necessarily to scale.

joints and therefore the forces in the tendons connecting the quadriceps muscle in the thigh with the lower leg via the kneecap or patella. These forces are of interest because a sufficiently large repetitive tensile force in the tendons can be potentially damaging to the dancer's knee joints. Those forces are at a maximum when a dancer lands from a jump, after the heels arrive at the floor.

How does the body use its muscles to cushion the landing from a vertical jump? There are three mechanisms: (a) Before the heels touch the floor, the calf muscles help slow the descent by trying to keep the feet extended; the Achilles tendon plays an important role in this action. (b) After the heels touch down, the quadriceps muscles contract as the legs bend to prevent rapid bending of the knees, thereby distributing the deceleration over a duration that prevents large destructive forces. (c) As the legs bend, there is a torque acting on the femur generated by the hip extensor muscles, largely the gluteus maximus, to rotate it downward around the hip joint. This torque compresses the tibia longitudinally, contributing to the vertical force against the floor that helps slow the descent.

The following analysis involves a careful examination of the force diagram and equations of motion for the lower and upper leg segments and the patella. The force diagram is shown in Fig. 4. We assume a simplified model of the legs in which the entire process takes place in the frontal plane. This assumption is valid for a dancer with perfect turnout (legs bending in the frontal plane). The fact that the legs bend a bit forward out of the frontal plane is accounted for by a geometrical argument that we discuss later. The legs are assumed to be rigid bars with a known length. These bars are free to rotate about a frictionless pivot axle at the knee on which there is a frictionless pulley representing the patella, to which are attached the quadriceps tendon and the patellar tendon. The hip end of the upper leg is also free to rotate around a frictionless axle at the hip joint, while one end of the lower leg rests on the ground. For this purpose we will ignore the feet, because their mass is small, and their motion is small compared to the movement of the two leg segments.

In this idealized model all possible forces, many of which could be distributed in various ways around the body segment being investigated, can be combined into just a few generalized forces. For instance, at the hip joint, we identify the total vertical force that supports and later also decelerates the upper body, the sum of the forces that effectively act on the femur at the axle on which the femur rotates, and the sum of the forces that contribute to a torque on the femur, acting at that axle in the frontal plane. Forces that result in a torque around the longitudinal axis of the femur do not affect this analysis. Thus all relevant forces have been included in the generalized forces.

MRI scans of the dancer's knee showed that the line of action of the quadriceps tendon force is significantly farther from the pivot axis of the knee than that of the patellar tendon force. (See Sec. V A for some numerical results.) Therefore, the respective moment arms for the torques are different. One implication of this difference is that because the net torque on the patella is assumed to be zero, the force in the patellar tendon is significantly greater than that in the quadriceps tendon. According to the MRI information, the quadriceps tendon has a cross-sectional area more than twice that of the patellar tendon, so the stress in the patellar tendon will be comparatively even larger. This fact helps explain the observation of the orthopedic surgeon in our group (Mira) that tendonitis and other tendon afflictions in the knee are more prevalent in the patellar tendon than the quadriceps tendon.

We make the following assumptions about this system model: (1) The horizontal friction force at the floor is zero. (The dancer lands as if the floor were slippery.) (2) The lower leg and upper leg have the same length, make the same angle with the vertical at all times, and each has a center of gravity located 40% of the way from the upper end to the lower end (see Table II). (3) The patella has insignificant mass, so the total force and torque acting on it in this idealized model must be zero, even if the patella accelerates. We will also assume that a force from the hamstring muscle acting to make the leg bend is negligible, because such a force would create a torque in the opposite direction to that of the quadriceps and patellar tendons, thereby being counterproductive to the aim of cushioning the descent. (4) The quadriceps and patellar tendon forces act along lines parallel to the bars that represent the upper and lower legs. (5) The mass of the foot and its role in slowing the descent of the body upon landing are ignored; we look only at the use of the quadriceps muscle acting on the tibia via the patella to exert leg-straightening forces and the rotation of the femur downward against the tibia. (6) We will also assume that the body is stationary; later we will adjust the model to incorporate the accelerations of the various body parts.

From the force diagram and these assumptions we can obtain the vertical and horizontal force equations and the torque equation for the lower leg, the upper leg, and the patella. The equations of motion are as follows. Equation (1) represents the vertical y force, the horizontal x force, and the torque τ about the knee pivot for the lower leg. Equation (2) represents the same for the upper leg, and Eq. (3) applies to the patella.

Lower leg:

$$\tfrac{1}{2}Mg - m_1 g + F_1 \cos\theta - F_{k1}\sin\phi = 0 \quad \text{(vertical)}, \tag{1a}$$

$$F_1 \sin\theta - F_{k1}\cos\phi = 0 \quad \text{(horizontal)}, \tag{1b}$$

$$\tfrac{1}{2}MgL\sin\theta - m_1 g\alpha L\sin\theta - F_1 R_1 = 0 \text{ (torque)}, \tag{1c}$$

where M is the total body mass, m_1 is the mass of the lower leg, L is the length of the upper leg from hip pivot to knee pivot, which also equals the length of the lower leg from the knee pivot to the point of contact of the lower leg with the floor. We also have that F_1 is the patellar tension force, F_{k1} is the force acting from the knee axle on the lower leg, θ is the angle of the lower leg with the vertical (which is equal to the angle of the upper leg with the vertical), α is the ratio of the distance between the pivot at the upper end of the leg segment and the leg segment's center of mass to the total length of the leg segment, assumed to be the same for the upper leg and lower leg, and ϕ is the angle between F_{k1} and the horizontal.

Upper leg:

$$\tfrac{1}{2}m_3 g + m_2 g + F_2\cos\theta - F_{k2}\sin\psi - F_h\cos\theta + F_3\cos\beta = 0, \tag{2a}$$

$$F_2\sin\theta - F_{k2}\cos\psi - F_h\sin\theta + F_3\sin\beta = 0, \tag{2b}$$

$$F_2R_2 + F_hR_h + F_3L\sin(\beta-\theta) - \tfrac{1}{2}m_3gL\sin\theta - m_2 g(1-\alpha)L\sin\theta = 0, \tag{2c}$$

where m_2 is the mass of the upper leg, m_3 is the mass of the body above the hips, R_2 equals the moment arm of the line of action of the quadriceps tendon force on patella to the pivot axis in the knee, F_2 is the quadriceps tendon tension force, and F_{k2} is the force acting from the knee axle on the upper leg.

Patella:

$$F_1\cos\theta - F_2\cos\theta - F_{k1}\sin\phi + F_{k2}\sin\psi = 0, \tag{3a}$$

$$F_1\sin\theta + F_2\sin\theta - F_{k1}\cos\phi - F_{k2}\cos\psi = 0, \tag{3b}$$

$$F_1R_1 - F_2R_2 = 0. \tag{3c}$$

Note from Eq. (3c) that because $R_1 < R_2$, F_1 will be greater than F_2, and thus F_1 is the interesting quantity to be investigated.

The only unknown in Eq. (1c) is the patellar tendon force F_1, so that it can be easily obtained. The result is expressed as a ratio of the force to body weight to make it generalizable to different sized bodies:

$$\frac{F_1}{Mg} = \frac{L}{R_1}\sin\theta\left[\frac{1}{2} - \alpha\frac{m_1}{M}\right]. \tag{4}$$

What is the effect of the deceleration of the body while it comes to rest after landing? The center of mass of all body segments is now undergoing upward acceleration, decreasing its downward velocity if the total positive force is greater than Mg. The various forces acting on the body segments must be modified. To do so, we assume that the forces that determine all the other forces are those representing the gravitational force acting at the center of mass of the body segments. How do these forces differ when the body is undergoing a vertical acceleration upward? We know that the total upward force that must be exerted at the feet to support the entire mass of the body and cause a deceleration of the entire body of magnitude a must be

$$F_{\text{total}} = M(g+a). \tag{5}$$

The effective total vertical force acting on the lower leg is a little trickier. Note that the vertical acceleration of the knee is just one-half of the vertical acceleration of the hip and all of the body above the hip, which we will call a_3. But the gravitational force acts on the lower leg at a distance αL from the knee. The acceleration of the center of mass of the lower leg is $(1-\alpha)$ times the acceleration of the knee. Hence we perform the following replacement for the gravitational force acting on the lower leg:

$$m_1 g \rightarrow m_1[g + a_3(1-\alpha)/2]. \tag{6}$$

To find the effective acceleration of the upper leg, note that the acceleration of the center of mass of the upper leg is the same as if the lower leg were a parallel extension of the upper leg, so the acceleration is $(2-\alpha)$ times the acceleration of the knee. Hence, we have

$$m_2 g \rightarrow m_2[g + a_3(2-\alpha)/2]. \tag{7}$$

We have assumed the nonzero acceleration of the upper body (everything above the hips), so the adjustment in Eqs. (2a) and (2c) is

$$m_3 g \rightarrow m_3(g + a_3). \tag{8}$$

With these changes, the resulting equation for the patellar tendon force as a proportion of total body weight, taking into account the upward acceleration, becomes

$$\frac{F_1}{Mg} = \frac{L}{R_1}\sin\theta\left\{\frac{1}{2}\left(1+\frac{a}{g}\right) - \left[1+\frac{a_3}{2g}(1-\alpha)\right]\frac{\alpha m_1}{M}\right\}. \tag{9}$$

For typical values of α and m_1/M, the term in brackets $[\ldots]$ is of the order of 2% of the first term. If these terms are ignored, Eq. (9) reduces to

$$\frac{F_1}{Mg} = \frac{L}{R_1}\sin\theta\left[\frac{1}{2}\left(1+\frac{a}{g}\right)\right]. \tag{10}$$

Note that Eq. (10) could be obtained by multiplying the right-hand side of Eq. (4) for the static case by $(1+a/g)$ for the dynamic landing situation.

The other equations of motion can be solved for the other unknowns for the static or accelerating cases, providing rich information about other stresses in the body.

V. RESULTS

A. Patellar tendon forces in dancer 1

From Eq. (10), F_1 depends on the measurable parameters L and R_1 and the variables θ and α. The leg length L was measured directly for dancer 1. The value of $L = 0.45$ m used in the calculations was the average of measurements from the knee pivot to the hip pivot, to the ball of the foot, and to the heel.

An analysis of the MRI scans of her knee allowed us to determine the location of its pivot axis, from which we could determine the moment arm of the forces, the perpendicular distance from the pivot axis to the line of action of the force. The moment arm for the patellar tendon force was determined to be $R_1 = 4.2$ cm; the moment arm for the quadriceps tendon was $R_2 = 5.4$ cm.

By tracking the vertical position of the dancer's total center of mass in each frame of the video, the dancer's vertical acceleration a was determined using the smoothing methods described in Sec. IV B. Finding the angle θ that the upper leg makes with the vertical requires careful analysis. Because dancer 1 did not land with perfect turnout, this angle could not be measured directly using VIDEOPOINT. The angle that the leg seems to make with the vertical as viewed on the video, θ', is a projection onto the frontal plane of the true angle θ (see Fig. 5).

From Fig. 5(a), θ can be found through the following trigonometric calculation, where y is the vertical component of the distance from the hip pivot to the knee pivot:

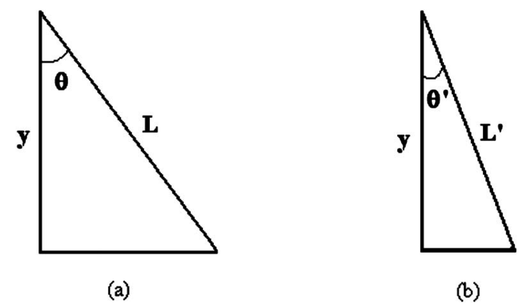


Fig. 5. (a) The actual angle the dancer's leg makes with the vertical as viewed in the plane, where L is the true length of the leg. (b) The projection of the triangle in (a) onto the frontal plane because the dancer's legs were rotated inward (away from the viewer in Fig. 2) as she landed from the jump. The quantities θ', L', L, and y can be measured using VIDEOPOINT.

$$\theta = \cos^{-1}(y/L). \tag{11}$$

The value of y varied with each frame as the amount of bend in the knees changed. Because y is the same in both Figs. 5(a) and 5(b), y could be tracked in each frame of the video to find θ as a function of time using Eq. (11).

By knowing L and R_1 along with θ and a (determined by a VIDEOPOINT analysis) for each video frame, it is possible to calculate the tension in the patellar tendon as a fraction of body weight throughout the dancer's descent using Eq. (10). The maximum force in the patellar tendon was 11.1 times dancer 1's body weight, when $a = 18.6$ m/s^2 and $\theta = 43°$.

B. Ultimate tensile strength and vulnerability to injury

Is this magnitude of stress tolerable? Based on studies of cadavers it has been reported that a tendon will undergo a traumatic rupture at a force per cross-sectional area of about 10^8 N/m^2.[13] The minimum cross-sectional area of dancer 1's patellar tendon was measured with an MRI scan to be 1.05 cm^2. For this cross-sectional area, and a body weight of 380 N (86 lb), the stress of 11 times body weight on this tendon is about 4×10^7 N/m^2, which is about half of the rupture magnitude. This stress level, if repeated often, could lead to problems in some people. Patellar tendonitis, commonly referred to as "jumper's knee," is one such affliction due to overuse. Dancers who repeatedly practice jumps and use their quadriceps muscles instead of hip external rotators and adductors when bending the knees can develop patellar tendonitis.[17]

VI. CONCLUSIONS

We have reported the process of determining the magnitude of the internal forces in a dancer's legs during landing from a vertical jump. We found that the centers of mass of the various body segments can be accurately determined by a video analysis of the motion, and the accelerations of the centers of mass accurately represent the total forces acting on these body segments.

Interesting information can be obtained about the stresses in the human body from those center of mass determinations. In particular, by analyzing the total forces acting on the leg segments and measuring the moment arms of the forces acting around the pivot axes of the body segments, the tensile force in the tendon can be determined. This force can be greater than ten times body weight, a magnitude that, if experienced repetitively, could produce damage to the knee area.

Because this study involves inexpensive equipment that is simple to use and a careful analysis of the physical processes involved in body movement, this type of study is ideal for an undergraduate research project. The physics is not beyond the level of an introductory course. However, the complexity of the problem and level of insight and analysis required can become quite challenging. Many subtleties can increase the level of sophistication. Making judicious assumptions (for example, ignoring the motion of the foot) can make the problem more manageable. The possibilities for undergraduate research are significantly enhanced by the techniques described here, which allow also for increased insight about the internal workings of the human body.

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[18]Only one foot was capable of fitting on the force plate; symmetry argues for doubling these values for the total force on the whole body.

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[20]These are estimates for the dancer used in this study based on and modified from data presented in Ref. 6.

[21]Acceleration was found using four adjacent velocity points (t_1,v_1), (t_2,v_2), (t_3,v_3), (t_4,v_4) and $a=((v_4+v_3)/2-(v_2+v_1)/2)/2\Delta t$, where Δt is the time between adjacent points. Note that this acceleration occurs at the time $t=(t_3+t_2)/2$. This calculation was repeated for points (t_2,v_2), (t_3,v_3), (t_4,v_4), (t_5,v_5), and so on.

[22]Although the center of mass may not be calculated at its exact location, we are confident that it is located consistently because of the mere 2% difference in the calculated free fall accelerations from the theoretical value of g. With this argument for consistency, a ± 0.2 cm uncertainty was assigned to the difference between adjacent center of mass vertical positions [that is, $\delta(\Delta y)=0.2$ cm]. Standard propagation of uncertainty in sums and differences was done to determine the calculated error in the vertical velocity and acceleration. The uncertainty in the acceleration was multiplied by the dancer's mass, $\delta F=M\,\delta a$, to calculate the uncertainty in vertical force (because $\delta M/M \ll \delta a/a$).