How did Jack Sparrow survive?

Thousands of years ago, men started telling stories to spend their nights. Stories became more and more sophisticated, with details and points of reflection.
Many genres were brought up but certainly stories about courage and epic battles mainly attracted attention from the audience listening to the storyteller (e.g. The Illiad or the Arthurian cycle).
Centuries later, cinema was born and impossible or almost impossible scenes were filmed and they became cult: for instance, Matrix's dodging projectile scene or the one that will be discussed in this little essay: Jack Sparrow falling from a cliff in "Pirates of the Caribbean: Dead Man's chest" (2006). The scene I'm referring to is the one where (captain) Jack Sparrow is on an island with a native tribe, who want to eat the pirate.
As soon as he discovers his faith, he starts to draw a plan to escape from the island. There is a huge issue: he is binded to a long pole behind his back and this will make the escape much harder (and maybe our calculation). To cut it short, he jumps off a cliff from one part to the other using the pole as a pole vaulter in some way, then he loses equilibrium and he falls into the clift, but the pole sticks against the walls, then it slips and he falls to the ground hitting many bridges and touching the ground next to where the pole would have stuck and he is safe. As previously said, this scene is obviously meant to be excessive but **we'll try to calculate how possible it is**, by making calculations and then comparing them to the scene. To keep this essay sharp and interesting, we will make some approximations, using average values when some data are not available(e.g. the type of wood of the pole) and in the process the results will follow the International System unit measure and notation for physical quantities but there will be the "translation" to the British Imperial System.
With this said, the scene has become a physics problem we can divide in 5 parts:

1. Jack runs towards the clift;
2. He jumps over the clift;
3. He falls in to the clift and the pole slows him down by tugging his ankle;
4. The pirate falls and hits many Tibetan bridges and he hits the ground
5. The pole doesn't hit him.

In this essay, we'll try to understand how possible it is to do all of this with no damage for the pirate.
Let's take a look at the information we surely know:

- Jack Sparrow's height is Johnny Depp's one (1.78 m), since he is the actor;
- Jack Sparrow's weight is 68 kg (Johnny Depp's weight).

From this, it is clear we'll not find perfect values but just likely results.
(The data used are at the end of the article)
We can estimate the length of the pole (L) by comparing the pole to Jack Sparrow when he is standing up on the edge of the clift before falling. With Tracker (a free software) I calculated the pole is 4.48 m long.
Using the same method the width of the pole is around 0.062 m.

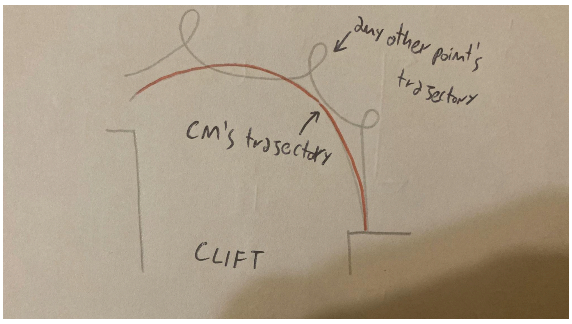
1st part

Jack runs for his life so we can assume he is sprinting. The average man can sprint at a speed of roughly 31.4 km/h=8.72 m/s so we can consider it to be the pirate's speed.

2nd part

Jack jumps over the clift and during the parabolic movement he also rotates mid air.

Since from the clip we can see Jack and the fruits at the end of the pole don't slip along the pole, so the system can be considered as a rigidbody. Any point will have 2 movements: parabolic and rotational. This makes calculation much harder since this is the kind of trajectory of any point:



There is a particular property during this movement: the center of rotation will just be under the parabolic movement, because it is by definition the united point of rotation, so the point that doesn't change after a geometric transformation.
We just need to calculate the center of mass (CM)'s position and then we can write the parabolic movement of that specific point.
We have 3 objects in the system: Jack, the pole and the fruits.
Specifically, to find the center of mass of a complex figure we can find the center of mass of the centers of mass of its parts.
Thus we need the center of mass and the mass of Jack, the pole and the fruits.
The pole looks like bamboo so we can calculate the mass of it considering it to have the density of bamboo and calculate its volume as a cylinder.

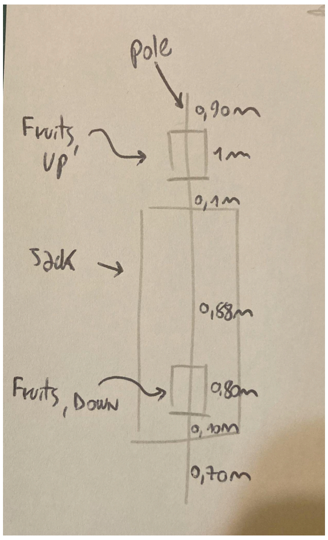
$M_{Pole} = \rho_{bamboo}\, x\, r^2\, x\, L \ = \ 750\, x\, \pi\, x\, 0.03^2\, x\, 4.48\, kg \sim \ 9.50\, kg$

From the scene in some frames the fruits are more or less visible, by watching every frame and comparing the fruits to the general tropic fruits I think there are: 1 pineapple, 2 durian, 1 annona cherimola, 1 jackfruit on each side of the pole.
With a little bit of geometry for the single n parts and using the formula for the position of the center of mass of the system:

$$R_{cm} = \frac{1}{M_{TOT}} \sum_{i=1}^{n} R_{cm,\,i} M_i$$

Object	Mass	Center of mass's position
Pirate	68 kg	$0.36\,\hat{i}\ +\ 1.59\,\hat{j}$
Pole	9.5 kg	$0.03\,\hat{i}\ +\ 2.24\,\hat{j}$
Fruits in the upper part	10 kg	$0.03\,\hat{i}\ +\ 3.08\,\hat{j}$
Fruits in the Lower part	10 kg	$0.03\,\hat{i}\ +\ 1.20\,\hat{j}$

Whole system	97.5 kg	$0.26\,\hat{i} + 1.78\,\hat{j}$



We can now apply the cinematic equations to the jump over the clift.
Using Tracker, it seems like Jack's initial velocity is inclined by 0.628 rad (50°) respect to the ground (x axis) thus, we can set:

- $y(t) = V_y t - \frac{1}{2}gt^2 + y_0$, where y(t) is the height reached at the time t, V_y is the vertical velocity at the jump instant, t is the time passed from the beginning of the jump, g is the gravitational acceleration and y_0 is the initial position (=y(0));
- $x(t) = V_x t + x_0$, where x(t) is the horizontal position reached at the time t, V_x is the horizontal velocity at the jump instant, t is the time passed from the beginning of the jump (exactly the one of the equation above) and x_0 is the initial position (=x(0)).

This time, we choose the Spatial Reference System whose center coincides with the CM position of the center of mass at the instant of the jump, in this way we lose the x_0 and y_0 terms.
In particular, $V_y = sin(\alpha)\,x\,V$ and $V_y = sin(\alpha)\,x\,V$, where V is Jack's velocity when jumping and α is the angle that V produces at the instant of the jump.
Now we have to be careful because V is not the speed with which Jack is running towards the clift, it is just the translational speed of the system.
As written above, in the scene, we can see the pirate during the jump has a vertical, horizontal and rotational movement.
We can approximately say the energy is conserved when Jack embeds the pole in the rocks because of the elasticity of bamboo.
Thus: $K_{run} = K_{rotational} + K_{translation} + U_{gravitational}$, therefore:
$\frac{1}{2}M_{tot}V_{run}^2 = \frac{1}{2}I\omega^2 + \frac{1}{2}M_{tot}V(t)^2_{translation} + M_{tot}gh(t)$
We need to find $V(0)_{translational}$. We need to find: I and ω. This last one is pretty simple, we can see that Jack completes the semi rotation and then he makes another rotation, for a total of 90°+50°+360° =500°= 8.72 rad in t seconds, and so, $\omega = \frac{angle}{time} = \frac{8.72\,rad}{t\,s}$.

I is the moment of inertia and since there is not a formula for this specific case, we have to consider the system as made of 4 parts: 2 hollow cylinders (the 2 groups of fruit), 1 pole and 1 parallelepiped (Jack Sparrow). The moment of inertia of the whole system will just be the sum of the moments of inertia of the 4 parts:
$I_{TOT} = I_{Fruits,\,DOWN} + I_{Jack} + I_{Pole} + I_{Fruits,UP}$. Since part of the pole is covered by the fruits we have to consider the groups of fruits as two hollow cylinders.
We can now calculate the single parts's moment of inertia using the formulas that consider the center of rotation not in the center of the figure but translated vertically by a distance s, in particular:
$I_{Hollow\ cylinder} = \frac{1}{2}M(R_{est}^2 + R_{int}^2) \Rightarrow I_{Fruits,\,DOWN} = I_{Fruits,\,UP} = \frac{1}{2}M_{Fruits,UP}(Width_{fruits,UP}^2 + Width_{Pole}^2)$
which is $I_{Fruits,\,UP} = \frac{MR^2}{4} + \frac{ML^2}{3} + Ms^2 + MLs$, which produces two moments of inertia since one is for the upper fruits and the other for the lower ones: $I_{Fruits,\,UP} = 33.33\ kg\ m^2$ and
$I_{Fruits,\,DOWN} = 16.00\ kg\ m^2$
$I_{pole} = \frac{1}{12}M_{pole}L^2 + Ms^2 = \frac{1}{12}x\ 9.50\ x\ 4.48^2\ kg\ m^2 + 9.50\ x 0.46^2 kgm^2 \sim 17.90\ kg\ m^2$

$I_{Jack} = \frac{M(Width^2+Height^2)}{12} + Ms^2 = \frac{68\ x\ (0.60^2+1.78^2)}{12} + 68x\ 0.19^2\ kgm^2 \sim 22.45\ kgm^2$
Summing them all, we get: $I_{TOT} = 89.68\ kg\ m^2$
$\frac{1}{2}x\ 97.5\ x\ 8.72^2 = \frac{1}{2}\ x\ 89.68\ x\left(\frac{8.72}{t}\right)^2 + \frac{1}{2}\ x\ 97.5\ x\ V(0)_{translational} + 0$. We need another equation to find t and $V(0)_{translational}$. We might use the equation of the vertical position since we can estimate the vertical gap Jack jumps.
The estimated jump (for the CM) is 2.89 m (=2.07 m + 1.90 m -1.08 m).
$-2.89 = V_y t - \frac{1}{2}9.81t^2$ (the - term is because jack lands lower than before) and setting the system of two equations in two incognitas we find:
$t = 1.46\ s$ and $V_{translational} = 6.57\ \frac{m}{s}$
from which, $V(0)_{translational} \sim 6.57\ \frac{m}{s}$. Using the equations written above, we find:

- $V_y = sin(\alpha)\ x\ V = sin(0.628)\ x\ 6.57\ \frac{m}{s} \sim 5.03\ \frac{m}{s}$;
- $V_x = cos(\alpha)\ x\ V = cos(0.628)\ x\ 6.57\ \frac{m}{s} \sim 4.22\ \frac{m}{s}$;
- $y(t) = V_y t - \frac{1}{2}gt^2 + y_0 = 5.03t - \frac{1}{2}gt^2$;
- $x(t) = V_x t + x_0 = 4.22\ t$.

The final position is 6.16 m away horizontally from the spot of the jump. From the scene, going frame to frame, I found a “good” one where it looks like the distance is 7.20 m so, our prediction is pretty close if we consider all the approximations done.
3rd part
The pirate loses equilibrium and he falls down into the clift. Fortunately for him, the pole sticks and the pirate is safe. But how didn’t the pole break?
We know the modulus of rupture (MOR) of bamboo is usually around
$91.725\ \frac{N}{mm^2} = 9.1725\ x\ 10^7\ \frac{N}{m^2}$. We know that when the pirate is still, on the pole the only

force is the gravitational one. Thus,
$\sigma = \frac{M_{Force}}{W_{Pole}} = \frac{M \, x \, g \, x \, L \, x \, 32}{4 \, x \, \pi \, x \, D^3} = \frac{97.5 \, x \, 9.81 \, x \, 4.48 \, x \, 32}{4 \, x \, \pi \, x \, 0.06^3} \frac{N}{m^2} \sim 5.0543 \, x \, 10^7 \frac{N}{m^2} < MOR$, so the bamboo pole doesn't break!
Before being still, the pirate slows down thanks to the friction the pole produces with the rock walls. However the pole slows down in a first moment and only when the rope becomes tensioned, the pirate's speed is reduced. Before this his speed can be approximated to $v(t) = gt$, not considering air friction and in this way the rope becomes tensioned only when he is at $v(6.91) = 9.81 \, x \, 6.91 \sim 67.79 \frac{m}{s} = 244 \frac{km}{h}$(a speed that would require an air friction study) and he slows down to v=0 in just 0.232 s (the two periods of time were found using Tracker). For a total deceleration of $a = \frac{\Delta_v}{\Delta_t} = \frac{67.79}{0.232} \frac{m}{s^2} \sim 292 \frac{m}{s^2}$, considering that Jack's mass is the one that is decelerating, the total force is
$F = ma = 68 \, x \, 292 \, N \sim 19856 \, N$ which is much greater than 4000 N, which is the minimum force to break a human femur, which is stronger than an ankle, so the force is much greater than the minimum required and we can quite confidently say that he would have broken his ankle.

4th part

When Jack falls down and breaks many wooden tables (avg 9 for each bridge), he is losing kinetic energy so, if we knew the MOR of the wood we could know the velocity with which Jack hits the ground. Since I found no data to do so, I couldn't estimate, but this might become a little exercise for the reader.

5th part

In this part, we want to estimate the probability of not being hit by the pole when it hits the ground, but we don't exactly know where the pole passed because cameras were filming only Jack and not the pole (obviously). However it must have passed through the holes made by the pirate falling down. Thus, we can imagine it will fall in the central part of the imaginary circle that has a center in the pirate's ankle and radius the length of the rope (around 17.3 m). This induce the fact that throwing many poles from the top of the clift, they will fall and hit the ground following a Gaussian distribution, but to study this case we need a lot of poles falling from the clift in that condition of wind.
To simplify our study we can suppose the pole might have a horizontal velocity during the whole fall. Knowing the distance between the first bridge and the last one and from this to the ground we can find the maximum area covered by the fall of the pole, as in the image below, using a little bit of geometry.
After finding this area we can divide it by the area covered by Jack once he is lying on the ground. In this way we find the probability of being hit by the pole, and its complementary will be the probability of not being hit by the pole. There are many issues: how to find the distance, in this case we don't know whether the pole might hit the bridge and lose kinetic energy and we would need to study air friction during the rotation of the pole (that, as said before, is not visible in the scene).
Just to have an idea, we might consider the simplest model: the pole can fall in the whole circle that has the center in jack's ankle and the radius is the length of the rope.
So, $P_{HIT} = \frac{A_{Jack}}{A_{Pole}} = \frac{Width_{Jack} \, x \, Height_{Jack}}{\pi R^2} = \frac{0.60 \, m \, x \, 1.78 \, m}{3.14 \, x \, 17.3^2 \, m^2} = 1.13 \, x \, 10^{-3} = 0.113$ % and so
$P_{Not\ HIT} = (100 - 0.113)\% = 99.887$ %, but obviously has no actual meaning.

Conclusion:

To sum up, we found out that the scene is not physically impossible, but as said at the very beginning of this little and humble article, we watch movies to feel emotions, not to study the science behind…except if we are in STEM.

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Table with the data and where they were found:

Name of the data	**Value**	**Source:**
α, angle of the pole when leaving the ground	0.872 rad	Tracker
ρ_{bamboo}	750 $\frac{kg}{m^3}$	https://tuttobambu.blogspot.com/p/blog-page_3.html, by calculating the average of the values.
Average human sprint	8.72 m/s	https://marathonhandbook.com/average-human-sprint-speed/#:~:text=Average%20male%20sprinting%20speed%3A%2019.52,or%2031.4%20kilometers%20per%20hour.
Estimated height difference between the grounds	1.90 m	Tracker
Femur's strength	4000 N	https://www.foodnetwork.com/not-available.html#:~:text=Ounce%20for%20ounce%2C%20bone%20is,break%20the%20typical%20human%20femur, but the site is not completely visible in Italy
Jack's height	1.78 m	https://it.wikipedia.org/wiki/Johnny_Depp
Jack's thickness	0.24 m	Estimated
Jack's width	0.60 m	Estimated
Length of the pole	4.48 m	Tracker
Mass of the annona chemirola	1 kg	https://it.wikipedia.org/wiki/Annona_cherimola#:~:text=Il%20frutto%20si%20presenta%20con,pochi%20giorni%20dopo%20la%20raccolta.
Mass of the durian	1 kg	https://it.wikipedia.org/wiki/Durian#:~:text=Frutto,-Un%20

		venditore%20apre&text=Il%20frutto%20del%20durian%20cresce,viene%20definita%20ovoidale%20o%20tondeggiante.
Mass of the pineapple	1.5 kg	https://www.ilgiornaledelcibo.it/ananas/#:~:text=Quello%20che%20si%20chiama%20comunemente,kg%2C%20a%20seconda%20delle%20variet%C3%A0.
Mass of the jackfruit	6.5 kg	https://pharmeasy.in/blog/ayurveda-uses-benefits-side-effects-of-jackfruit/
MOR of bamboo	$9.1725\ x\ 10^{7}\ \frac{N}{m^{2}}$	https://www.guaduabamboo.com/blog/mechanical-properties-of-bamboo
Position of the “parts” of the rotational system		Tracker

Bibliography/Sitography:
apart from the sites cited:

- Tracker software: Brown, D, R. Hanson, and W. Christian. "Tracker Video Analysis and Modeling Tool." Version 6.1.5. https://physlets.org/tracker/ (accessed 31 March 2024);
- Elementi di Fisica by Mazzoldi, Nigro, Voci