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The anatomy of falls[1]

Introduction

The study of falls from heights remains an important subfield of Hungarian forensic physics to this day[2]. This fact, among others, justified the creation of this niche study, inspired by the film "Anatomy of a Fall". This multiple award-winning work is a psychological thriller and courtroom drama in terms of genre. The fundamental question of the work could also be a question posed to a physicist expert in an official appointment, namely whether the man who fell to the ground was intentionally pushed out of the window, perhaps voluntarily ended his life, or simply slipped and fell out? Undoubtedly, expert work does not play the main role in the film. Therefore, the following lines aim to give the appointing authorities a glimpse "behind the scenes", to present the physical, theoretical background of falls from height and its applicability in criminalistic practice. With the help of this study, we can gain insight into the process of forming an opinion. We can follow how, in cases similar to the event in the film, evidence, information, and data help the physicist expert differentiate between homicide, accident, and suicide.

[1] This study is the English version of the presentation delivered at the conference 'The Science and Practice of Law Enforcement' held in Pécs 27.06.2024.

[2] Fülöp, P. (2019): Brutális fizika másképp - Fizikusok az igazság nyomában [Brutal physics in a different way - Physicists in search of the truth]. Magyar Rendészet 2019/19 (2-3) 67-87

I begin the topic with a very sad outlook. According to data from the Hungarian Central Statistical Office (KSH), the number of deaths due to intentional self-harm in Hungary in 2022 was 1,647.[3] According to data from a comprehensive report examining the period between 1970 and 2010, among completed suicides in Hungary, the leading method (in about 60% of cases) was self-hanging, followed by self-poisoning and jumping from height.[4] The statistical data for 2020 reflect similar proportions.[5] CCTV footage now plays a major role in clarifying the circumstances of deaths caused by injuries sustained from falling from height. In recent years, appointing authorities have requested the involvement of physicist experts somewhat less frequently due to suspicious cases, which may be due to the increase in the number of CCTV cameras and the improvement in the quality of recordings. However, these recordings later provide a good opportunity for experts to study falls from height from a scientific perspective as well.

Physical and theoretical foundations of falls from a height

The physical impact of a passenger car traveling at 50 km/h colliding with a concrete wall without braking is, based on the equation $h = \frac{v^2}{2 \cdot g}$, the same as if we dropped it from a height of 9.83 meters onto a concrete sidewalk, which is roughly equivalent to falling vertically from three stories. However, from the perspective of impact, speed itself doesn't play a role; what

[3] Hungarian Central Statistical Office 22.1.1.10. Halálozások a gyakoribb halálokok és nem szerint [Deaths by common causes of death and sex]. STADAT table October 31, 2022

[4]Zonda, T. – Paksi, B. – Veres, E. (2013): Az öngyilkosságok alakulása Magyarországon (1970-2010) [The development of suicides in Hungary (1970-2010)]. In: Műhelytanulmányok 2. Központi Statisztikai Hivatal Budapest, 23-25.
Source: https://www.ksh.hu/docs/hun/xftp/idoszaki/pdf/muhelytanulmanyok2.pdf

[5] Hungarian Central Statistical Office: A fenntartható fejlődés indikátorai, Emberi erőforrások, Egészség, Öngyilkosságok [Sustainable Development Indicators, Human Resources, Health, Suicides]
Source: https://www.ksh.hu/ffi/1-16.html

is significant is the sudden stop, or the change in velocity per unit time, which we call acceleration (or deceleration with a negative sign). Acceleration is directly proportional to the force that ultimately leads to injuries in our case.

If we want to examine the fall of a human body from a height, we need to follow the usual procedure in physics, which is to simplify reality as much as possible and apply various models. A fall from a height can be essentially divided into two processes: the fall itself and the subsequent impact. During the fall, the human body can be considered a rigid body. The parts of a rigid body do not change their relative distances under the influence of forces acting on them. The distance between any two mass points of a rigid body remains constant, and its motion is composed of translational and rotational components. Every rigid body, including the human body, has a distinguished point, which is the centre of mass or centre of gravity, located at about navel height. This is a point as if the entire mass of the body were concentrated into this single point, so its motion (momentum) can be described more simply, practically like a material point.[6]

An ideal fluid – according to the phenomenological approach – is practically incompressible (furthermore, its internal friction is negligibly small, it takes the shape of the container, it continuously fills the available volume, and it ignores the corpuscular structure of the matter),[7] and although 72% of the human body is water, it must be considered partially compressible. Thus, from a biomechanical perspective, the human body during impact does not behave like a body filled with an ideal fluid, but can be replaced by a balloon filled with a bubble-free, gel-like, jelly-like substance.[8]

In physical terms, a fall from height can be treated as a projectile motion, which, depending on the direction of the initial velocity, can be vertical, horizontal, or oblique projection. In our case, only oblique projection is

[6]Budó, Á. (1997): Kísérleti fizika I. kötet [Experimental Physics Volume I], Nemzeti Tankönyvkiadó. Szeged 116-148
[7]Budó, Á. (1997): Ibid, 315.
[8]Strejc, P. – Šachl, J. – Vlčková, A – Dreßler, J. – Vajtr, D. (2010): Another Mechanism of Décollement. Soudní lékařství 55(4). 51-53

relevant, which has two independent components. This so-called compound motion can be decomposed into a horizontal linear motion with a given initial velocity, and a vertical free fall due to the force of gravity.[9] The horizontal component of the projection is responsible for the horizontal distance from the point of fall (e.g. wall plane), while the other component accelerates the body vertically with an acceleration of $g = 9.81$ m/s². As a result of these, the centre of mass of the human body follows a parabolic path in an ideal case – neglecting air resistance. If we were to consider air resistance, it would increase the time of a 30-meter (about ten-story) fall by only 0.5%, and cause a deviation of less than 1% (at most a few centimetres) in the horizontal distance from the wall plane.[10]

Before we proceed to present the examination method, we must mention one more important law through a practical example. The pieces of an obliquely thrown grenade or fired fireworks – after explosion in the air – behave as separate mass points, but they continue to move in such a way that their common centre of mass continues to move along the original path, along a parabola.[11] The explanation for this is the momentum theorem, which states that in a closed system, the path of the centre of mass cannot be changed by internal forces, only by external influences.[12]

Examination method for falls from a height

The first thing a physicist sees in a scene photo of a fall from height is the position of the body's centre of mass, or more precisely, its horizontal distance from the point vertically projected onto the ground from the presumed point of fall. Generally, based on geometric measurements conducted during the on-site inspection, this data is already available at the moment of appointment. In almost every case, an expert inspection takes

[9]Budó, Á. (1997): Ibid, 35-39
[10]Wu-ting Tsai, Chia-I Hu, Chia-Yun Chang (2020): Effect of Wind on Horizontal Displacement of Fatal Fall from a Height. Journal of Forensic Sciences, 65(1). 255-258
[11]Budó, Á. (1997): Ibid, 187
[12]Budó, Á. (1997): Ibid, 184

place to clarify the circumstances more accurately, where we personally verify or confirm previous measurement data about the site's characteristics, geometry, and the actual displacement of the centre of mass through measurements. Subsequently, knowing the height of the fall and the body height (indirectly, the height of the centre of mass from the sole plane), we can perform calculations for two simplified limiting cases. We theoretically determine how far the body's centre of mass would have moved from the point vertically projected onto the ground from the presumed point of fall in cases of falling over while standing or sitting.[13]

The difference between the calculated and actual displacement can provide answers to the arising questions. From a criminalistic perspective, the displacement during falling over can be considered free from external or internal forces, so any deviation from this theoretical value certainly requires explanation. We compare the theoretical values obtained through calculations with the values measured at the scene, then make theoretical considerations based on the available case files (such as forensic medical reports, witness interrogation and suspect interrogation protocols, etc.), studies and cases already published on the topic, and not least, expert experiences. From the totality of this data we arrive at an expert conclusion that ultimately gives us a partial reconstruction of the sequence of actions or events and the motion process that occurred.

During a fall from a height, numerous factors influencing the actual displacement must be considered. These include the initial body position, which may be determined by the window or available space, objects in the path of the fall, the nature of the impact site, and movement created by an internal or external force preceding the fall. Such movements can include a self-willed and determined run-up, jump, external intervention (pushing, thrusting, throwing, swinging), and in certain cases, the effect of wind.[14]

[13] Kosztya, S. – Tóth, P. (2016): Emberölés bizonyítása komplex fizikus és orvos szakértői módszerekkel [Proving Homicide with Complex Physicist and Medical Expert Methods]. Belügyi Szemle 64(7-8) 24-30

[14] Wu-ting Tsai, Chia-I Hu, Chia-Yun Chang (2020): Ibid, 255-258

The absence of displacement indicating these processes can lead to the conclusion of an unusual, unexpected event or accident.

The initial body position - alongside the fall height - affects the body position at impact, which is also related to the resulting injuries.[15] After consulting with a medical expert – given the appropriate data – professional determinations can be made regarding the possible body position of the deceased at the beginning of the fall. The nature and location of injuries help determine the body surface or part that impacted first, thus allowing selection of the most likely scenario among possible event processes (falling face forward or backward from a standing, sitting, or crouched position between these two extremes, turning over or hanging from a railing or windowsill).[16]

It is an eternal debate whether the human body bounces after impact or not. Let us clear this up and somewhat explore this question, as this interaction can fundamentally influence the extent of displacement! The elasticity of the collision can be characterized by a dimensionless ratio – characteristic of the material quality of the bodies – called the collision coefficient *k*. Without derivation, let us accept that the ratio of impulses before and after the collision gives the value of *k*, which is a number between 0 and 1. (The collision is perfectly inelastic when *k=0*, while it's perfectly elastic when *k=1*.)[17] Based on available experiences and theoretical con-

[15] Cywka, T. – Milaszkiewicz, A. – Teresiński, G. (2019): Differentiation between suicidal and accidental falls from height using the method proposed by Teh et al. Archives of Forensic Medicine and Criminology 69(3) 100-107.
Károly, L. – Simon, G. (2023): Magasból történő lezuhanás során elszenvedett sérülések. [Injuries sustained during falls from height]. Thesis. University of Pécs, Faculty of Medicine, Institute of Forensic Medicine.

[16] Han, I. (2020): Characteristic analysis and fuzzy simulation of falls-from-height mechanics, and case studies, Forensic Science International, 311
Han, I.– Park, Ch. (2022): Characteristic analysis and reconstruction method of falls from windows, Forensic Science International, 330
Muggenthaler, H. – Hubig, M. – Meierhofer, A. – Mall, G. (2021): Slip and tilt: modeling falls over railings. International Journal of Legal Medicine 135. 245–251

[17] Budó, Á. (1997): Ibid, 203

siderations, generally for a human body impacting a hard, infinitely massive, stationary surface, the value of the *k* coefficient, based on the quotient obtained from the equations (or as a first approximation, the velocity-independent expression), is about 0.1.[18] In practice, therefore, an important consequence of the compressibility of the human body is that a body falling from the 7th floor of an apartment building (about 21 meters high) onto the sidewalk can bounce back up to about 21 centimetres high. When considering displacement, it must be taken into account that in many cases the collision is not central but oblique, and the body also rotates. One possible explanation for the greater than expected displacement is that in these cases, the impact velocity has both a normal component perpendicular to the surface and a tangential component parallel to the impact surface.[19] If at the moment of collision, the impact velocity also has a tangential component, depending on the roughness of the surface, due to the friction between the two surfaces, the body may continue to slide after falling (e.g. onto a tiled surface). A similar result occurs if the body falls onto an inclined, sloping surface.

Case study

How can this theoretical knowledge be applied in criminalistic practice? A young woman in her early twenties falls from the 10th floor of a panel building and loses her life immediately. Witnesses from the street and other parts of the building - perhaps somewhat contradictorily - see her being pushed out of the window or hanging from the window. The immediate neighbour heard loud arguing, shouting, and thuds suggesting a fight at the time of the incident. At the time of the fall, the girl's ex-boyfriend and one of the man's relatives were in the apartment with her, but the ex-boyfriend hastily left the scene before help arrived. He only returned later at his mother's call and explained what had happened. According to his recollection,

[18]Wach, W. – Unarski, J. (2014): Fall from height in a stairwell – mechanics and simulation analysis. Forensic Science International 244, 136–151
[19]Budó, Á. (1997): Ibid, 202

the girl was already sitting outside the window with her back to him and feet first when, at his relative's call, he ran to the bedroom. Then, with the command *"Don't do it! Stop it!"* he slowly approached the window, jumping from the end of the bed – kicking his shin into the bed – and grabbed the woman's right hand, which was propped up on the window frame. Meanwhile, the girl half-turned and fell out of the window while sitting. At this point, the man braced his own body at the sill at the armpit line, fearing he might fall out himself, and held the victim by her right wrist with one arm while the young woman flailed and asked to be let go. To stabilize his grip and pull the body back, the suspect changed his grip several times, grabbing the woman's left hand as well, then her ponytail, and her clothing. Despite all this, the rescue attempt was ultimately unsuccessful, the victim slipped from his grasp and fell to her death.

According to calculations, from a height of 28.9 meters, in 2.2 seconds, falling from a sitting position, the body's centre of mass would move 1.5 meters away from the wall plane, while from a standing position, it would move 4.3 meters. Based on on-site measurements, the actual displacement was 2.95 meters, which, assuming a sitting position, can be explained by a horizontal movement with an initial velocity of 0.6 m/s (2.16 km/h). Jumps typically can accelerate the human body to about 2-3 m/s (7.2-10.8 km/h), while a push can accelerate it to about 0.02-1.5 m/s (0.072-5.4 km/h).[20] Compared to these velocity values, 0.6 m/s suggests a push rather than a jump as the cause of the displacement.

During the examination of the crime scene photos, a very peculiar thing could be noticed when determining the impact point of the centre of mass. The body was found at a location different from the expected impact point according to the momentum theorem, not in line with the incriminated window, but to the right of it when viewed from the front, at a distance of about 2-2.5 meters. The cause of this significant lateral displacement is an external force that resulted in a movement parallel to the building's wall plane with an initial velocity of 0.8 m/s. The resultant of these two movements

[20]Cross, R. (2008): Falls from a height. American Journal of Physics 76(9) 833-837

suggests that the woman might have fallen out of the window at an angle of about 36° to the left, with an initial velocity of about 1 m/s. All signs indicate, therefore, that the woman's fall from height leading to her death could not have occurred entirely in the manner and under the circumstances described in the preliminary data, that is, practically vertically hanging from the window. So what is the possible explanation? In expert practice, such a degree of lateral displacement primarily occurs when the victim actively defends herself, trying to prevent her body from falling out against an external force (e.g., push, thrust, throw) by bracing or holding on, but falls despite all this. Consequently, the relative location and distance of the fall and impact point are characteristic of a thrust during a struggle. The telltale signs of this seemed to be supported by the limb injuries and bilateral bruising of the facial soft tissues described in the medical expert's opinion, as well as the partial palm print belonging to the victim recovered from the window's glass surface. Another hypothesis is that the cause of the anomalous displacement could be a low-force collision with the roller shutter box located 120 centimetres below the incriminated windowsill, occurring almost immediately after release. The physical effects of impact and push are indistinguishable from each other, but with a detailed and thorough examination of the circumstances of the fall and the method of the rescue attempt, a physicist expert could not confirm the woman's intentional fall, her active resistance to rescue, or the attempt to pull her up from the window. In fact, from the established facts, external intervention became increasingly likely among the possible explanations. Accordingly, the opinion, or conclusion: the suspect's intentional action may have contributed to the victim's position outside the window, may have played a role in her fall, and may even have played a significant role in it.

Summary

One common feature of the film and a real case is that until the last minute, all participants in the proceedings are plagued by doubts about what happened. Will the truth be revealed, can it be revealed at all? Can the truth be

learned from expert opinions? Although experts only play a minor role in the film, we can still see some scenes where the expert and expert work appear (e.g. the lawyer's site visit reminiscent of an expert inspection, model experiments, expert hearings, etc.). They give meaning to the traces, reveal possible mechanisms of injury formation, explain the absence of traces, check, refute, confirm, and make hypotheses probable. Clarifying the circumstances of falls from height - whether in general administrative or criminal proceedings - is not solely the task of the physicist expert, but their work can still be crucial from the point of view of evidence. They can contextualize the findings of other specialties, such as medical, trace, in our case dactyloscopic experts or polygraph specialists, synthesize data by connecting the specialties, and fit them into a possible motion process. Objective data and conclusions that can be drawn from them using the laws and theorems of physics can reveal additional "hidden" information, facts, and connections for the prosecution, which can lead to successful indictment and ultimately accountability, or conversely, to the acquittal of the accused.