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► **To cite this version:**

Johan Cassirame, Hervé Sanchez, Julien Frère. Why pole vaulting at 6.50 meters seems possible but remains improbable. 2024, pp.236, v1. hal-04717694

**HAL Id: hal-04717694**

**<https://hal.science/hal-04717694v1>**

Submitted on 8 Oct 2024

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# Why pole vaulting at 6.50 meters seems possible but remains improbable

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Track and field | Pole vault | Prediction | Performance analysis

## Headline

When a world record is broken, an important question often arises, particularly in athletics due to the measurable nature of performance: have we reached the limit of human capability? In pole vaulting, an analysis of the annual top 25 world performances from 1948 to 2012 by Haake et al. (2015) showed that performance had increased by approximately 34%, with 99.9% of the predicted limit expected to be reached by 2026. The authors estimated that about 8% of this performance increase could be attributed to the use of composite vaulting poles, while around 21% came from other improvements such as coaching, nutrition, and training methods. To surpass this predicted limit, Haake et al. (2015) suggested three main possibilities: a change in the rules, the introduction of new technology, or the emergence of a new generation of athletes.

A brief retrospective shows that since Sergei Bubka's last world record of 6.15 meters in 1993, the rules have changed, but not necessarily in ways that benefit performance (e.g., the reduction in peg length, semi-circular end pieces for the crossbar, and a decrease in the time allowed for trials). Additionally, today's vaulting poles remain largely similar to those used in the 1980s and 1990s. As a result, it appears that the recent improvements in the men's pole vault world record are largely due to the emergence of a new generation of athletes, such as Renaud Lavillenie (6.16 meters in 2014) and Armand (Mondo) Duplantis (6.17-6.26 meters, 2020 to present).

Currently, with the remarkable domination of Mondo, one can reasonably state that the limit of men pole vault performance essentially relies on his own limits. That's why many speculations emerged regarding his potential maximum performance. These speculations appear serious, often based on various calculations, experiences, and increasingly, on AI analyses. However, despite the apparent credibility of these predictions, no clear explanations regarding the data used or the methodologies employed by the authors have been provided, making it difficult to understand the results obtained. The latest popular speculation was made before the Olympics by Ather Gattami, an expert in AI, using data (though it is unclear which data) from 14 other world champion athletes or record breakers, as well as from Mondo himself (Hernandez, 2024).

Beyond these speculations, numerous publications have been produced to describe and explain pole vault performances (Adamczewski & Perlt, 1997; Cassirame et al., 2024; Frère et al., 2010; Linthorne & Weetman, 2012; Schade et al., 2000). By combining various approaches from the literature with the available real data, it seems possible to investigate this question in a rational and explainable manner. This allows us to identify potential weaknesses in the methodologies or approaches used.

Since 2011, we have been collecting data during national and international pole vault competitions to provide feedback to athletes and coaches from the French Federation. Whenever

possible, we also publish scientific papers to share knowledge with both the scientific and pole vaulting communities (Cassirame et al. 2022a, 2022b, 2024). Thanks to this project, our database of biomechanical data has reached 18,000 analyzed jumps, including run-up analysis, take-off and jump phase analysis, and metadata (athletes' and poles' information).

## Aim

The aim of this paper is to investigate the plausibility of the speculated maximum performance of Mondo Duplantis (6.51 meters) using different methodologies informed by our data. First, we will assess the performance using the principle of conservation of mechanical energy. Second, we will use our dataset, particularly the take-off speed ( $TK_s$ ), which is the strongest predictor of performance, to estimate potential performance (Arampatzis et al., 1999; Cassirame et al., 2019; Frère et al., 2010). Finally, we will evaluate the maximum performance based on video analysis of previous world record jumps (6.22 m).

## Methods

### Measurements process

During competitions, biomechanical measurements were conducted to collect a variety of kinematic and technical variables. A 20-meters Optojump Next system (Microgate Srl, Bolzano, Italy) was installed along the run-up lane to record the spatiotemporal parameters of the approach run. Additionally, a radar gun (Stalker Pro II, Stalker Ltd, Plano, TX) was positioned behind the landing mat, aligned with the run-up direction at a height of 1.4 m, to ensure a clear line of sight to the athletes' torsos as they approached the runway. The radar gun recorded horizontal speed at a sampling rate of 46.875 Hz, with the data being collected by MookyStalker software 2.0.22 (Mtraining, Ecole Valentin, France). Both systems were synchronized using an external trigger to enable precise calculations, such as take-off speed ( $TK_s$ ), based on the last ground contact time.  $TK_s$  was calculated as the average speed over the 0.2 seconds prior to the last ground contact time, using the speed data from the radar gun.

All vaults were recorded using a high-speed video camera (100 Hz, Panasonic, Kadoma, Japan) positioned perpendicular to the runway, either on the left or right side, depending on the competition venue. The camera was placed approximately 25 m from the runway's midline, 5 m above ground level, and 2.5 m in front of the planting box. This setup allowed for the capture of the athlete's last two steps during the run-up, as well as the entire pole interaction phase, including bar clearance, all within the camera's central focal range (1920 × 1080

pixels). Calibration was performed using a  $2 \times 2$  m square and additional markers positioned on the runway, 4.5 and 5.5 m in front of the planting box. For this experiment, the video setup enabled us to estimate the pelvis altitude at take-off and at maximal elevation, as well as the horizontal speed at maximal elevation, using Kinovea software 0.9.5 (Joan Charmant & Contributors, Bordeaux, France).

### Athletes and jumps selections

The measurements used in this study included data from 200 athletes whose vaults were collected during the following competitions: Allstar Perche, Rouen Perche Elite, Meeting Indoor de Paris, and Mondo Classic. Except for the Mondo Classic competition, all other events were conducted on an artificial elevated track (Cassirame et al. 2017b). For our analysis, only the best vault of each athlete from our database was selected. To ensure relevant predictions regarding performance outcomes, we included only male data in our calculations (Adamczewski & Perlt, 1997; Cassirame et al., 2017a; Cassirame et al. 2024). The vaulters chosen for this study

represented 16 different nationalities, ranging in age from 18 to 38 years, with performances spanning from 3.82 to 6.22 m.

### Approach using principle of conservation of mechanical energy

Pole vault performances have been studied through biomechanical analysis, focusing on energetic calculations at both the take-off and at the point of maximal elevation (Gros & Kunkel, 1990; Schade et al., 2004). At these two key moments, the energy of the vaulter center of mass can be determined by the sum of kinetic energy ( $E_k$ ) and gravitational energy ( $E_g$ ) (Figure 1.)

$$E_k = \frac{1}{2} \cdot m \cdot v^2$$

$$E_g = m \cdot h \cdot g$$

Where  $m$  is the mass of the subject,  $v$  the velocity, and  $g$  the acceleration due to gravity ( $9.81 \text{ m}\cdot\text{s}^{-2}$ ).

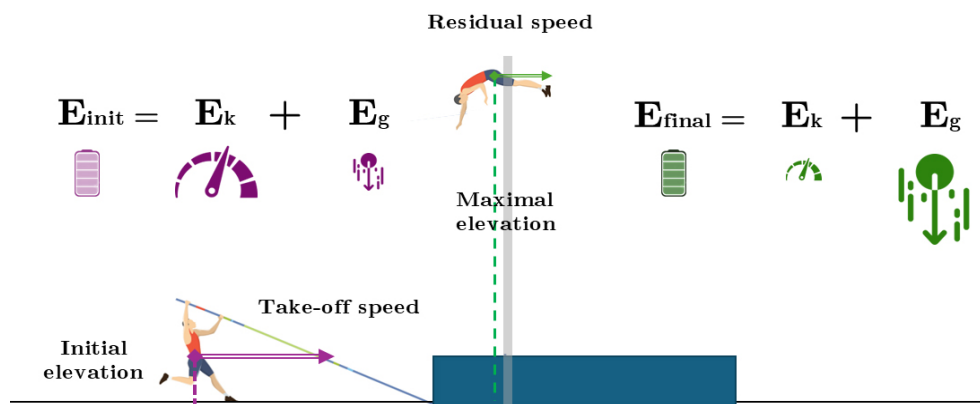


Fig. 1. Illustration of energy calculations at take-off and maximal elevation.

Using  $10.3 \text{ m}\cdot\text{s}^{-1}$ , the best take-off speed ( $TK_s$ ) observed for Mondo in our records over the last six years, and the associated pelvis elevation of 1.13 m, we calculated a total energy at take-off of 5066.3 Joules. By applying the law of conservation of mechanical energy with this input, we can determine the theoretical elevation by subtracting the residual kinetic energy at the maximal elevation position ( $0.6 \text{ m}\cdot\text{s}^{-1}$ ), which amounts to 14.2 Joules.

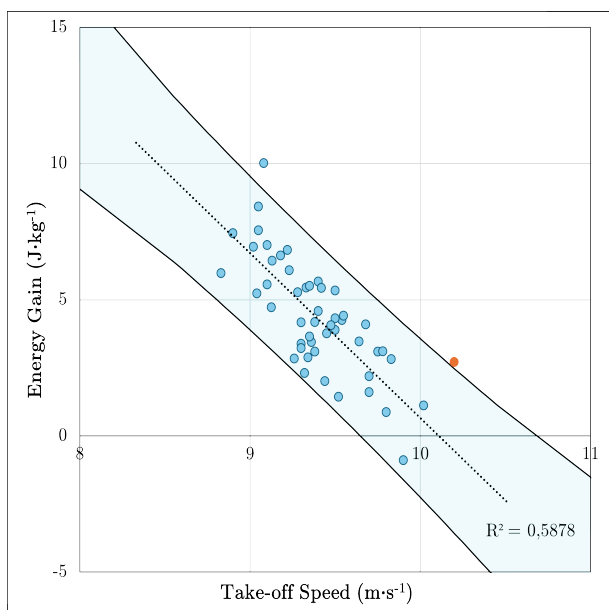
This leaves 5052.1 Joules as gravitational energy, which corresponds to an elevation of 6.52 m. This approach is one of the typical calculations that can yield a value of 6.50 m or even higher if the  $TK_s$  used in the model is greater.

However, this approach is a theoretical approximation that includes several simplifications and a violation of physical laws. First, we made our calculations based on the center of mass and its maximum elevation. It's possible that the maximal elevation is not reached directly over the bar but slightly before or after, meaning the parabolic trajectory of the athlete's flight (while in the air and not in contact with any element) could intersect the bar. Secondly, in our calculations, the athlete is simplified as a point located at the center of mass, but in reality, athletes have arms, trunks, and legs that need to be carefully managed to clear the bar.

Moreover, this approach relies on the law of conservation of

energy, which holds true for isolated systems subjected only to conservative forces. During the pole support phase, athletes are in contact with the pole, which is itself in contact with the ground. Interactions with the pole allow athletes to transfer the kinetic energy acquired during the run-up and to add extra elastic energy through muscle work, i.e. by applying push/pull forces on the pole with both arms to enhance pole bending (hanging at and swinging around the pole) and further elevating their center of mass while the pole is recoiling (inversion position). It has already been demonstrated that the extra energy of vaulters can be beneficial for elite athletes, enabling them to achieve elevations higher than those predicted by theoretical models (Arampatzis et al., 2004; Frère et al., 2012; Schade et al., 2004). To illustrate this point, the energy balance of our top 50 athletes is shown in Figure 2. This is crucial for pole vaulters because, even though speed is the major determinant of performance (Cassirame et al., 2019; Cassirame et al., 2017a; Frère et al., 2018), pole vault performance is not solely dependent on  $TK_s$ . For example, we have observed that an athlete with a  $TK_s$  of  $9.15 \text{ m}\cdot\text{s}^{-1}$  cleared 6.0 m, and similar phenomena, as displayed in Figure 3, will be detailed in the second approach. The techniques used by pole vaulters are not completely uniform, and different methods add more energy during the support phase to maximize performance (Cassirame et al., 2024).

Beyond this basic model, our work currently focuses on the initial energy at take-off, its transfer to pole, elevation gain or loss, and how athletes generate extra energy during the support phase. But this amount of extra energy is a net value and can be seen as a "black box" hiding the work done by the athlete and sources of energy loss. For instance, during load-deformation experiments, vaulting poles lost few amount of strain energy (Warburton et al., 2015), and our recent calculations (Figure 2.) indicate that athletes do not exhibit the same efficiency in providing extra energy during this phase. It appears that faster athletes experience lower energy gains than slower ones, suggesting potential higher energy losses for faster athletes (Frère et al., 2018). Additionally, we observe significant variability in the energy gain among athletes within the same speed range, with a confidence interval of approximately  $\pm 2 \text{ J}\cdot\text{kg}^{-1}$ . Incorporating this trend into predictive models based on energetic approaches seems feasible, but the variability in athletes' ability to convert energy introduces an uncertainty of  $\pm 0.2 \text{ m}$ . Moreover, Mondo's speed is often cited as the reason for its performance. However, this graph shows that he also possesses excellent technique, enabling him to transfer speed perfectly and to add extra energy after take-off.



**Fig. 2.** Energy balance from the top 50 male athletes in our database (with performances over 5.50 m). The orange point represents Mondo Duplantis, while the blue dots display the entire group. The blue shaded area shows the 95% confidence interval.

### Approach using relationship between speed and performance

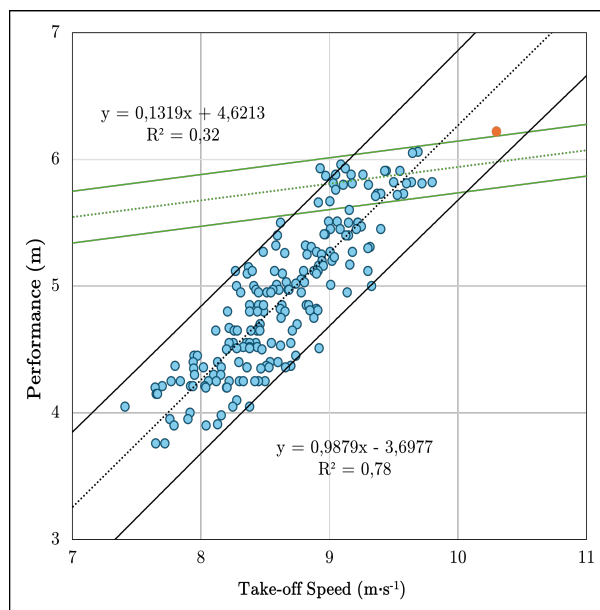
Many studies have highlighted that speed is the major determinant of performance (Cassirame et al., 2019; Cassirame et al., 2017a; Frère et al., 2010), and some have used the mathematical relationship between take-off speed (TKs) and performance to generate formulas for predicting outcomes (Adamczewski & Perlt, 1997; McGinnis, 2004). Based on our database, we can relate the speed to the performances of the top 200 male athletes using the following formula:

$$\text{Performance} = 0.9879 \cdot \text{TK}_s - 3.6977.$$

This strong relationship ( $R^2 = 0.78$ ) (Figure 3) gives us high confidence in this prediction, suggesting a reliable estimation of performance when using Mondo's speed in the model. Applying the formula with a take-off speed of  $10.3 \text{ m}\cdot\text{s}^{-1}$ , we obtained an output of 6.48 m. This prediction aligns with results from AI-based and energetic approaches.

However, this prediction has several limitations. First, the strength of the relationship, as indicated by the Pearson correlation, does not necessarily guarantee a high level of individual prediction accuracy. It's important to note that  $10.3 \text{ m}\cdot\text{s}^{-1}$  represents a near "no man's land," where only Mondo is living. Consequently, the relationship established from the entire dataset becomes highly uncertain at this extreme level (Coles, 2001). For example, the relationship between the two variables is heavily influenced by the input data, especially the range of the data. The broader the range, the more generalized the relationship between parameters becomes, making the prediction more vulnerable to confounding factors like athlete size, technical skills, grip length, pole stiffness, and other variables (Ameringer et al., 2009).

When examining the linear regression of the overall dataset, we see a strong correlation and a steep slope (coefficient 0.9879), demonstrating the significant impact of speed on performance. However, when we narrow the focus to a smaller sample of athletes who perform above 5.70 m ( $n = 29$ ), the correlation diminishes significantly ( $R^2 = 0.32$ ), and the slope becomes much less steep (coefficient 0.1319). Both predictions are flawed, and the truth likely lies somewhere in between. As it is often the case, predictions are completed with confidence intervals that provide a wide range of possibilities, not all of which are equally plausible. Given the substantial differences in speed, pole characteristics, and techniques compared to the rest of the sample, the accuracy of this prediction is clearly questionable. Mondo is an outlier in terms of  $\text{TK}_s$ , making any extrapolations highly uncertain.

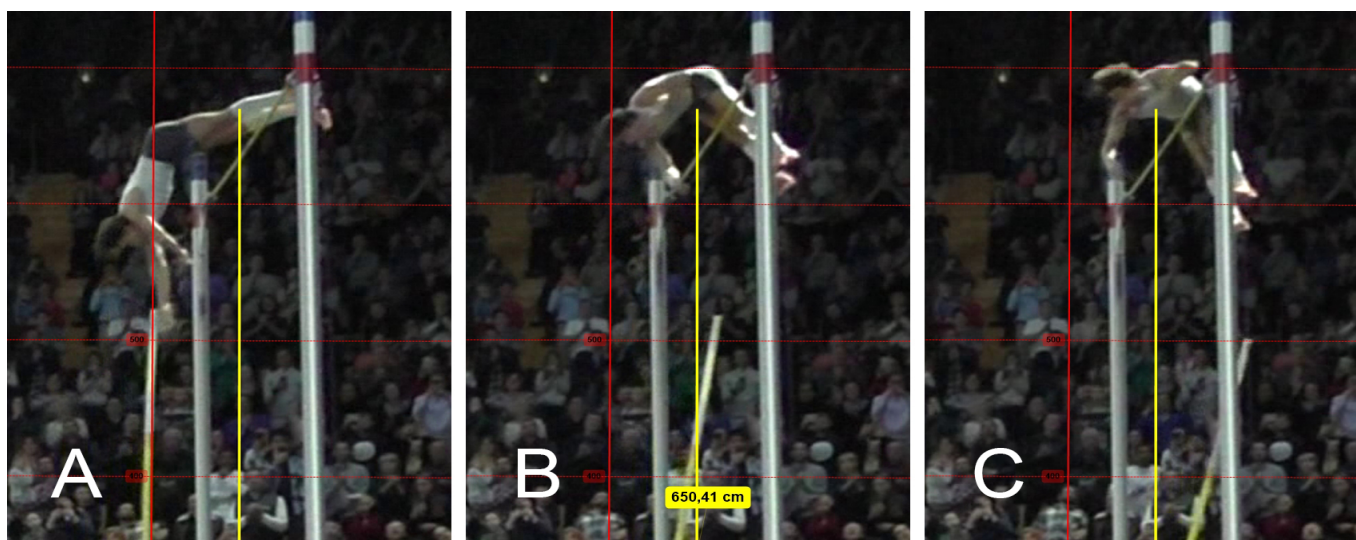


**Fig. 3.** This figure illustrates the relationship between performance and take-off speed for 200 athletes, with performances ranging from 3.82 m to 6.22 m. The orange point represents Mondo Duplantis. The dotted black line shows the overall relationship between take-off speed and performance for the entire dataset, while the green dotted line highlights the same relationship specifically for athletes performing over 5.70 m. Solid lines display the 95% confidence intervals.

### Video based measurements estimations

The final approach available based on our materials is the estimation through video analysis, utilizing calibration made in the environment prior to the competition. We selected a video from our database in which the pelvis was measured at its highest position, specifically during the world record performance of 6.22 m at the All Star Perche 2023 in Clermont-Ferrand (France). In this performance, at the point of maximal pelvis elevation, we measured the distance between the floor and his body at the bar plane, which reached 6.50 m

(Figure 4.B, with an accuracy of 0.02 m). Despite this impressive elevation at that moment, we observed that earlier in the jump, his feet and legs cleared the bar with a smaller margin (Figure 4.A), and a similar observation can be made for his chest later in the jump (Figure 4.C). Pole vaulting remains a sport where the entire body must clear the bar set at a specific height and at a chosen horizontal position from the planting box. In our video analysis, we can evaluate the highest virtual bar cleared by Mondo in this performance is around 6.30 m.



**Fig. 4.** Video extractions of Mondo Duplantis's bar clearance during the World Record of 6.22 meters at the AllStar Perche 2023 in Clermont-Ferrand, (France).

### Discussion

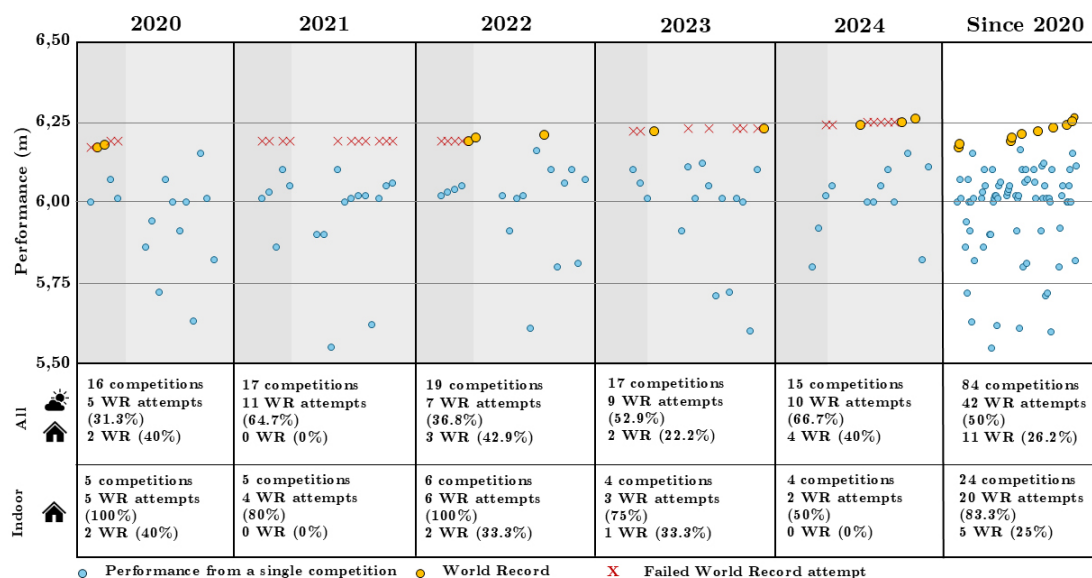
Based on the approaches described above, we can observe that achieving a height of 6.50 m in pole vaulting is possible, but the probability of reaching this performance is currently low. To achieve this height, it would be necessary to attain higher take-off speeds (between 10.5 and 10.6 m·s<sup>-1</sup>) while maintaining the same efficiency in energy transfer and/or maximizing the extra energy provided by his muscular system. Our data displayed in the Figure 2, showed that Mondo is already above the trend of this parameter when associated with take-off speed. From a technical standpoint, an increase in TKs would require adjustments to the characteristics of the pole used (such as upgrading stiffness) and changes in the athlete's technique to synchronize maximal elevation with the vertical plane of the bar. We have previously demonstrated that these parameters can be associated with an increased risk of injury, particularly when athletes use a technical approach involving the upper hand position behind the take-off foot during pole planting (negative under) (Edouard et al., 2019b). Careful and precise adjustments would be necessary to effectively accommodate such a speed progression.

From a factual analysis of the situation, it is evident that pole vaulters traditionally attempt to break world records incrementally, centimeter by centimeter, as Sergei Bubka did when he set most of his 35 world records (both indoor and outdoor), up to 6.15 m. When Mondo Duplantis cleared 6.17 m in 2020, surpassing Renaud Lavillenie's previous record of 6.16 m, he began an impressive streak of 11 world records over nearly five seasons (Figure 5). Since 2020, Mondo par-

ticipated in 84 official competitions, both indoor and outdoor. He cleared  $\geq 6$  m 62 times and attempted to break the world record at 42 events (50%).

It is noteworthy that Mondo participates in fewer competitions (16 to 19 per season) compared to other athletes like Lavillenie or Kendricks, who might compete in over 25 events in a full season. Due to his extensive technical background in pole vaulting, Mondo does not need to jump as frequently to improve or maintain his skills. This gives him a dual advantage: he can invest more time in speed development while reducing the number of impacts caused by high-speed take-offs with stiff poles, as confirmed by Mondo himself (Meurisse, 2023). Indeed, our research has shown that factors such as speed, the number of jumps, pole stiffness, and certain technical behaviors can be associated with a higher injury risk, necessitating longer recovery periods between competitions to manage the mechanical stress incurred (Edouard et al., 2019b). It is also worth noting that his indoor season is particularly short, with only 4 to 6 competitions, yet it has yielded 5 world records and 20 world record attempts out of 24 competitions (83.3%). If we project based on past seasons and assume that Mondo has the potential to reach around 6.30 m, he could potentially achieve 6.34-6.37 m by the end of the next five seasons, considering his improvement of +11 cm over the last five seasons. However, several aspects of this projection remain uncertain.

First, it is important to recognize that as the bar height increases, the difficulty of clearing it will also rise, and the margin for error in technique will become smaller. Perfect execution, combined with maximum speed, will be crucial for setting new world records. As a result, the success rate may decline further (Figure 5).



**Fig. 5.** Performances and World Records attempts of Mondo Duplantis since 2020 done during indoor or outdoor competitions. The darker grey sections indicate the indoor season whereas lighter sections indicate outdoor competitions

Secondly, our previous analysis of pole vaulters’ career progressions demonstrated that the prime years for male athletes performing over 6 m typically occur between 26 and 28 years old (Cassirame et al., 2021; Haugen et al., 2018). Born in 1999, Mondo is currently in his third senior season, suggesting that he could potentially improve his performance over the next 2 to 3 seasons if his trajectory follows that of other world-class athletes. On the other hand, we have also observed that Mondo is smartly managing his career by reducing the number of events he participates in and adjusting his technical approach to lessen the impact at take-off (Cassirame, 2024). Then, his training program is primarily focused on sprint training, with only a few vaulting sessions each week (as discussed in his coaches’ presentation during the Padova Pole Vault Convention 2024). Sprint training offers a dual advantage: it directly enhances performance by effectively transferring speed from sprinting to sprinting with the pole, and it optimally integrates with the take-off (Cassirame et al., 2022). Additionally, it provides a protective effect against muscular injuries, particularly hamstring injuries (Edouard et al., 2019a). So far, his strategy has proven to be highly effective in terms of performance and in preventing significant injuries.

Pole vaulting, especially outdoors, is a highly challenging discipline where performance can be significantly impacted by environmental factors. Weather is the primary factor that can affect athletes’ performance. Rain can make the pole slippery and the vault dangerous, while wind whether a headwind that slows the athlete down or a wind from any direction can complicate the take-off preparation. To consistently attempt world records without taking unnecessary risks, favorable weather conditions are crucial.

Moreover, Mondo is currently dominating the discipline, creating a noticeable gap between himself and his competitors. This dominance presents two challenges for the future. First, his competition routine typically involves a light warm-up, followed by a long wait while other athletes compete. After just one or two jumps, Mondo often remains the last athlete and has the freedom to set his own bar height. This rhythm is not ideal for him, as the extended cooldown period after the warm-

up may hinder his performance and generate injury. Additionally, being alone without direct competition means he has less recovery time between jumps. Second, the lack of rivalry may slightly diminish his motivation over time, which could affect his focus, engagement, and consequently, his speed.

### Conclusion

- Based on data collected in pole vaulting over the past decade, we can hypothesize that a height of 6.50 m is a highly improbable prediction.
- Despite Mondo Duplantis’s exceptional talent and speed, the weaknesses and shortcuts in the established prediction models lead us to have only modest confidence in such a performance expectation.
- Considering the traditional approach of breaking the world record centimeter by centimeter, and with an average of 2.2 world records per year, it would take 11 more seasons at this pace for Mondo to reach 6.50 m. In this scenario, Mondo would be 35-36 years old.
- It is well established that speed (Suominen, 2011), and even more so pole vaulting performance, typically begin to decline before this age (Careau & Wilson, 2017; Cassirame et al., 2021).

### Acknowledgment

The authors would like to thank Greg Duplantis for his valuable comments, which helped refine this article.

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