

The Relativistic Runner: An LLM Challenge

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Six frontier large language models (LLMs), each running in an agentic harness, were tasked to calculate the differential aging of a marathon runner's head and feet due to relativistic effects and to create infographics of their findings. This tested each LLM's ability to research, reason, and create.

1. Introduction

Bob is a marathon runner. During a marathon, Bob's head ages more than his feet. The two largest factors are general relativity which says that a clock at Bob's head runs faster because of the difference in gravity between his head and feet, and special relativity which says that his feet age slower because of the speed of their movements in a running gait.

We challenged three Anthropic LLMs and three OpenAI LLMs to estimate the differential aging of Bob's head and feet due to relativistic effects. Each LLM ran in an agentic harness that gave it access to the web for research and access to local programming tools for running simulations. We also asked each LLM to generate an infographic of its findings.

The prompt was intentionally unspecific in certain details, requiring each LLM to research, estimate, or simulate missing information such as track altitude, race duration, foot speed, and even Bob's posture during the race.

Each LLM was instructed to create an infographic in SVG format, convert to PNG and inspect it, then reiterate until the infographic is of a quality suitable for an undergraduate physics textbook. The infographics are displayed in [Appendix B](#).

2. The Models

We tested the models shown in [Table 1](#).

Table 1: Models evaluated, reasoning levels, and prices per million output tokens in US dollars.

Model	Reasoning level	Cost per million output tokens (US\$)
OpenAI GPT 6 Luna	high	0.50
OpenAI GPT 6.1 Sol	high	10.00
Anthropic Claude Sonnet 5.5	high	10.00
OpenAI GPT 5.6 Terra	high	12.00
Anthropic Claude Opus 5.5	high	20.00
Anthropic Fable 5.1	medium	50.00

3. The Agentic Harness and Prompt

We used the Pi Coding Agent harness¹ with the following extensions:

- **pi-subagent** – Allows the parent LLM to orchestrate worker sub-agents. In all cases, the sub-agents were pinned to GPT-6 Luna.
- **pi-web-access** – Allows the parent LLM and sub-agents to search the web and access web pages.
- **pi-ask-user** – Allows the LLM to interrupt progress to ask the user a multiple-choice question.

Each agent began its test in a directory configured with a Python virtual environment and a directory named `./media/` containing the three SVG icons of a runner that the model could use in an infographic if it wanted to.

All models were given the same prompt which described the task and required output format. The complete prompt is reproduced in [Appendix A](#).

4. Results

All of the LLMs estimated gravitational effects using different ways to estimate the head-foot altitude difference. All of the models calculated time dilation effects from Bob’s moving feet, but only three of the models included that calculation in their final result.

All the models investigated additional correction factors, all of which were several orders of magnitude smaller than the principal effects.

¹<https://pi.dev/>

The LLMs’ calculations are shown in [Table 2](#). The row “Headline total” shows each LLM’s preferred final answer for the number of picoseconds that the runner’s head ages more than his feet during the marathon. (One picosecond is roughly the time it takes for light to travel the distance equal to the thickness of a sheet of office paper.) Sol reported a time dilation calculation from the runner’s gait as a separate calculation that it did not include in its headline total. Terra reported a height-only differential assuming simplified motion. Some of the calculations in the table are unsigned magnitudes or upper bounds.

The LLMs used their web-access capabilities to search the web and retrieve several source documents. The documents downloaded by the LLMs are listed in [Appendix D](#).

The winning LLM was Anthropic Claude Opus 5.5. The LLM ranking is shown in [Section 5](#). Opus generated a formal report of its calculations, reproduced in [Appendix C](#).

The next subsections provide further commentary on the results.

4.1. Marathon race parameters

The prompt specified that Bob was an Olympic-qualifying marathon runner and ran at Valencia, Spain. All the models made similar estimates of the track altitude. The track at Valencia is well known and regional data seemed to be well represented a priori in the LLMs’ training data. Sonnet, Opus, and Fable retrieved the Wikipedia page for the Valencia marathon containing track data. Opus additionally downloaded detailed track profile data for the Valencia course.

Four of the models cited historical winning times at the Valencia track and used those times for Bob’s race duration. Luna and Sol mentioned that the winning time might not represent Bob’s actual race time but used record time anyway. Sonnet and Fable cited Paris 2024 men’s Olympic marathon entry standard and assumed it was more appropriate for Bob who is “training for the Olympics.”

Winners: Sonnet and Fable for noticing that Bob is in training.

4.2. Gravitational effects

The prompt specified Bob’s height. All the models knew that the gravitational term is linear in height. All of the models selected or estimated a representative head-foot separation and used essentially the same gravitational accelerations ($9.80\text{--}9.807\text{m/s}^2$) and race duration ($7308\text{--}7690\text{s}$). The models differed slightly in their choice for the Δh height difference. The three OpenAI models (Luna, Terra, and Sol) treated Bob as a rigid object and estimated the height difference between the top of Bob’s head and the ground, although Sol mentioned that the clocks could be located inside the head and feet. The three Anthropic models (Sonnet, Opus, and Fable) placed the clocks in the centers of mass of Bob’s head and feet (Fable specified the ankle joint) instead of at the extreme points. They

Table 2: Head-minus-feet clock offset by physical effect as estimated by six LLMs, along with various secondary calculations.

Effect	Head-minus-feet offset (ps)					
	Luna	Sol	Sonnet	Terra	Opus	Fable
<i>Principal effects</i>						
Gravitational ^b	1.4	1.4	1.3	1.4	1.1	1.2
Kinematic ^c	—	—	1.0	—	0.80	0.80
<i>Secondary corrections and upper bounds</i>						
Earth rotation ^d	-2.9×10^{-3}	-2.9×10^{-3}	—	—	—	—
Sagnac cross term ^{a,e}	6.1×10^{-5}	9.4×10^{-5}	4.6×10^{-5}	—	9.0×10^{-8}	4.0×10^{-7}
Course curvature ^f	—	-7.6×10^{-7}	—	—	—	—
Start/finish posture ^{a,g}	—	—	4.0×10^{-4}	—	1.2×10^{-3}	—
Simultaneity ^{a,h}	—	—	1.1×10^{-4}	—	—	—
Free-air gravity gradient	—	-4.0×10^{-7}	—	—	3.0×10^{-7}	—
Course elevation ^{a,i}	—	—	—	—	8.0×10^{-6}	—
Sun/Moon tides ^a	—	1.0×10^{-7}	3.0×10^{-14}	—	3.0×10^{-7}	—
Self-gravity ^a	—	4.0×10^{-9}	8.0×10^{-10}	—	3.0×10^{-10}	5.0×10^{-10}
<i>Illustrative gait model (not in headline total)</i>						
Gravitational	—	1.3	—	1.4	—	—
Kinematic	—	0.70	—	0.90	—	—
<i>Totals</i>						
Headline total	1.4	1.4	2.3	1.4	1.9	2.0
Incl. illustrative gait model	—	2.0	—	2.3	—	—

^a Magnitude only; sign not reported (exception: Fable's Sagnac entry).

^b Head–feet altitude difference in the gravitational potential.

^c Time dilation from the feet moving faster than the head during the gait cycle.

^d The head, farther from Earth's rotation axis, co-rotates faster.

^e Cross term between Earth's rotation and the running velocity (Sagnac-type).

^f Eötvös-type term from the changing local vertical along a curved course.

^g Boundary term from the start/finish posture offset.

^h Relativity of simultaneity between head and feet.

ⁱ Variation of gravity with course elevation.

Note: Values in picoseconds to two significant figures. An em dash indicates that a model either did not report the effect or did not quantify it. Totals are the models' own reported totals, rounded independently, so the listed components might not sum exactly.

also assumed that Bob's running feet, on average, are above the ground, and assumed that his head is slightly lowered by a few centimeters because of his posture while running.

Winner: Opus wins this one. It searched the web and found motion-capture foot height data from movement studies² and derived a gait model from that. The others made simpler models of foot stride.

4.3. Kinematic effects

Time dilation depends on the average of the squared speed. The head moves at a relatively constant speed, while the feet, at times, move up to twice that speed.

Luna used simplified kinematic assumptions. Sol and Terra made simplistic models of foot movements and calculated the relativistic effects but didn't include them in the final answer (shown separately in the row "Incl. illustrative gait model" in Table 2).

The three Anthropic models (Sonnet, Opus, and Fable) calculated and included kinematic effects in their final answer. Sonnet assumed a parametric swing model and ran a Monte Carlo to measure its characteristics. Fable found some gait data on the web and extrapolated from that to run a Monte Carlo.

Winner: Opus wins this one by finding detailed motion-capture data on the web³ and using that data in a clear and reasoned way in its Monte Carlo. Fable was a close second using clear reasoning but less specific empirical data.

4.4. Sagnac effect

The Sagnac effect is related to clock speed differences when signals travel around a path on a rotating body like the Earth. The correction factor has opposite signs for clocks displaced east vs west.

Terra did not quantify a direction-specific correction. Luna calculated an upper bound with some ambiguity about its relation to the gravitational constant. Sonnet, Sol, and Fable made some estimates of the magnitude.

Winner: Opus obtained actual data for the Valencia marathon track from a GPX file online.⁴ Its calculation used a 52.5 m start-to-finish displacement, smaller but more accurate than the guesses made by the other models.

²Fukuchi RK, Fukuchi CA, Duarte M. A public dataset of running biomechanics and the effects of running speed on lower extremity kinematics and kinetics. PeerJ. 2017 May 9;5:e3298. doi: 10.7717/peerj.3298. PMID: 28503379; PMCID: PMC5426356.

³<https://bmclab.pesquisa.ufabc.edu.br/datasets/rbds/>

⁴https://www.goandrace.com/gpx/2025/12/07/gpx_20251207_id10637_race1_20251126173357.gpx

4.5. Sun and Moon effects

The difference between the gravitational pull of the Sun and Moon affects the gravitational gradient along Bob's vertical axis. Sonnet's calculation carelessly used assumptions that were off by many orders of magnitude. Sol and Opus made estimates but without rigorously explaining their methods.

Winner: Sol cited a source and computed a physically correct magnitude with clear explanations of its methods.

4.6. Posture and relativity of simultaneity

Sonnet mentioned a simultaneity term. In special relativity, what appears to be simultaneous to one observer might not be simultaneous to another. The canonical example is a train with clocks at each end passing by an observer on the ground who sees the clocks as synchronized, but a passenger on the train sees an offset of $\Delta t \approx vL/c^2$. Sonnet assumed that Bob leans slightly forward while running, so that a clock at his head reaches a point slightly ahead of when a clock at his feet reaches the same point. It's not clear to me how Sonnet quantified the magnitude of this effect.

There is a similar posture-related calculation that Sonnet mentioned and Opus calculated for changes in the clock endpoint positions due to an Earth-rotation cross term, resulting in a slightly different average velocity of his head vs his feet, listed in [Table 2](#) in the row labeled "Start/finish posture."

4.7. Free-air gravity gradient

All of the models calculated a gravitational potential difference due to the height difference of Bob's head and feet using a constant gravitational term g . However, g gets a little weaker with altitude. Three of the models calculated a correction factor for that gradient.

Winner: Sol's calculation was most complete, with clear explanations for the gradient's sign and units and how a change in track elevation would change the result. Opus is a close second and applied the correction to its more refined estimate of foot-head height difference.

4.8. Course elevation change

Some of the models mentioned that some of their calculations would be affected by an elevation change along the track. Opus gathered actual course elevation data from an online GPX file.⁵

Winner: Opus for using actual data.

⁵Ibid.

4.9. Self-gravity

The principal head-foot gravitational differential can be corrected by considering the effects of Bob's own body mass distribution. Sol, Sonnet, Opus, and Fable made similar estimates of the effect, all of which are orders of magnitude smaller than the principal effects.

Winner: Opus made the most careful calculation by modeling Bob's body as mass segments in which his head sits near the trunk. The others estimated similar amounts but with a rougher model of Bob's body mass distribution.

5. The winners

The LLMs were judged for robustness, completeness, and accuracy. Their ranking in decreasing order is shown along with their total token cost in [Table 3](#). Anthropic Claude Opus 5.5 was the winner. Its summary report is reproduced in [Appendix C](#). Its infographic is shown in [Appendix B](#).

6. The infographics

[Appendix B](#) shows the infographics produced by each LLM in the order they are ranked in [Table 2](#). They are reproduced without analysis or comment.

Table 3: LLM ranking (highest to lowest), total token costs (US\$), and assessment.

Model	Cost (US\$)	Assessment
Opus 5.5	4.31	Heavily relied on published sources, clearly stated its extrapolations, tabulated local gravity, and used actual GPX course data. Quantified all small effects, including the route-specific Sagnac term, and reported defensible uncertainty bounds.
Table 5.1	5.68	Applied sound physics and used a rigorous Cauchy–Schwarz bound to identify and correct its own error. Gait inputs were based on literature averages rather than raw data. Its total (+2.03 ps) agrees with Opus’s result; tidal, Sagnac, and gravity-gradient terms were also checked.
Sol 6.1	0.84	Strong theoretical treatment of rotating-frame proper time and effective gravity. Its +1.42 ps headline is a conditional height-only reference. A separate, hypothetical gait gives +2.03 ps; Bob’s actual gait correction remains unknown.
Sonnet 5.5	1.52	Included gravitational and kinematic contributions, a full budget of small effects, and Monte Carlo analysis, yielding a plausible total (+2.29 ps). However, key gait inputs were extrapolated from cited sources for population estimates.
Terra 5.6	0.36	Obtained the correct height-only result and recognized the importance of foot motion. Its gait correction used a crude illustrative model and was excluded from the headline result. Earth-rotation, Sagnac, and tidal terms were not quantified.
Luna 6	0.70	Calculated an approximate rotation correction and bounds for a heading-dependent correction, but assumed identical head and foot motion and therefore omitted the kinematic contribution. Its headline result (+1.418 ps) is approximately 25–40% too low for a running body.

A. The complete prompt

This prompt was given to each LLM:

Task

Summary

Bob is 30 years old, 5 ft 10 inches tall, and weighs 158 pounds. Bob just finished a marathon
 ↳ race in Valencia, Spain, training for the Olympics. He completed the race in a very
 ↳ favorable time. Owing to relativistic effects, his feet and head aged slightly different
 ↳ amounts during the race. Calculate the differential aging of his head and feet. Then create
 ↳ an infographic named "./infographic.svg" that summarizes your results of the relativistic
 ↳ effects.

Important Notes

- Use web access to find reliable data as needed, and record your sources.
- Record your modeling assumptions and rationale.
- Delegate tasks to efficient sub-agents as needed.
- Ask the user a question only if an ambiguity prevents completion; otherwise proceed until
 ↳ finished.
- Show enough intermediate work to make the results reproducible.
- Make your relativistic model as detailed and reasoned as possible.
- Use `uv` if you need to install any Python packages.
- You may use assets in `./media/`, but inspect any asset before using it and ensure the final
 ↳ SVG is self-contained or has no broken references.
- Rasterize the SVG to a PNG and inspect the rendered image with available tools. Check factual
 ↳ accuracy, legibility at ordinary viewing size, clipping, contrast, and layout. Revise
 ↳ identified defects and reiterate until the infographic is suitable for publication in an
 ↳ undergraduate-level physics textbook. Do not claim visual inspection or upload if the tools
 ↳ did not actually permit it.
- You may use `cairosvg` or `inkscape` to rasterize the SVG file with a command line like this
 ↳ example:

```
"inkscape infographic.svg --export-type=png --export-filename=infographic.png
↳ --export-width=512"
```

- Deliverables: ./infographic.svg and a summary of your research, sources, assumptions, and
 ↳ calculations.

B. Infographics

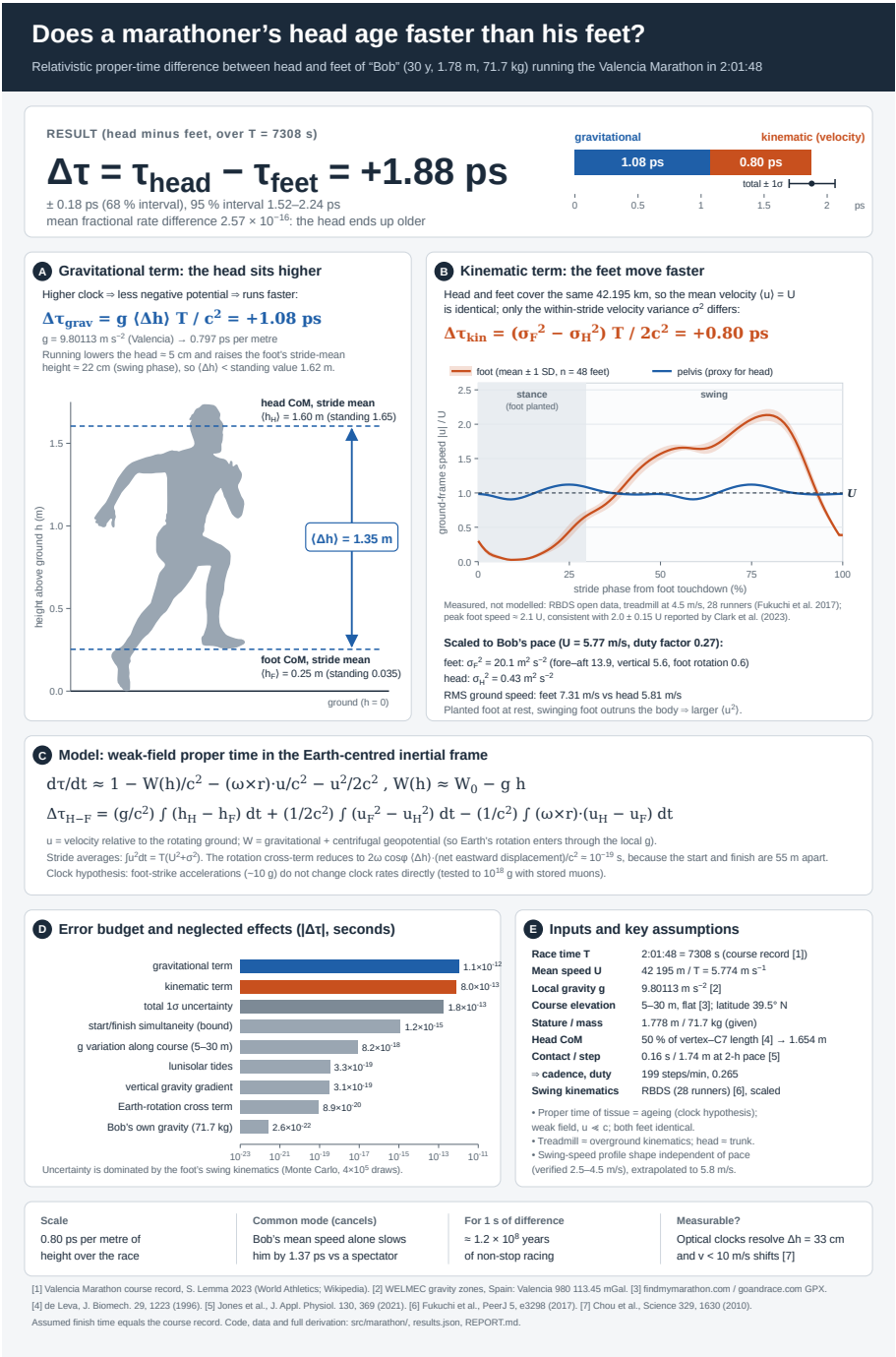


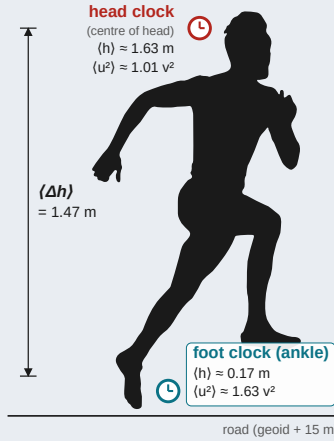
Figure 1: Winner – Infographic by Anthropic Claude Opus 5.5

Relativistic ageing of a marathon runner: does the head age more than the feet?

Bob (30 y, 1.778 m, 71.7 kg) runs the Valencia Marathon, 42.195 km, in 2:08:10 (the Paris-2024 Olympic entry standard): mean speed $v = 5.49$ m/s, $T = 7690$ s.

1 Two clocks on one runner

A higher clock ticks faster (gravity); a faster-moving clock ticks slower (motion). () = average over a gait cycle. Both effects favour the head: $\Delta\tau = \tau_{\text{head}} - \tau_{\text{feet}} > 0$.



2 Model (weak-field GR, Earth-fixed frame)

Proper-time rate of a clock at height h , ground speed u :

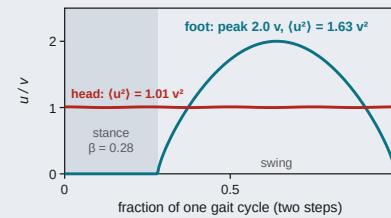
$$dt/d\tau = 1 + U(h)/c^2 - u^2/(2c^2) - (\omega \times r) \cdot u/c^2$$

$U(h) = U_0 + g h$ (gravity + centrifugal potential); ω = Earth spin

Integrate head minus feet over the race (coordinate time T):

$$\Delta\tau = [g(\Delta h) + \frac{1}{2}(\langle u_f^2 \rangle - \langle u_h^2 \rangle)] T/c^2 + \text{Sagnac}$$

Sagnac term = $-(\Delta h) \omega \cos\phi \cdot (\text{net eastward displacement})/c^2$
= $+4 \times 10^{-7}$ ps here: start and finish are ~ 0.4 km apart (loop course).



3 Result: head minus feet over the race

Head ages more than feet by ($\Delta\tau = \tau_{\text{head}} - \tau_{\text{feet}}$)
 $\Delta\tau \approx +2.03 \pm 0.1$ ps

(1 ps = 10^{-12} s; + means the head clock runs ahead)

Gravitational $g(\Delta h)T/c^2$

+1.23 ps

head higher → head clock faster

Kinematic $\frac{1}{2}(\langle u_f^2 \rangle - \langle u_h^2 \rangle)T/c^2$

+0.80 ps

feet move faster → feet clock slower

Sagnac (Earth rotation)

0.00 ps

= $+4 \times 10^{-7}$ ps for this loop course

Total

+2.03 ps

± 0.1 ps (1 σ , Monte-Carlo over gait inputs)

Naive estimate $g \cdot (1.778 \text{ m}) \cdot T/c^2$ (standing height, no gait):

1.49 ps

• Light travels only 0.6 mm in 2.0 ps.

• $\Delta\tau$ is 2×10^{-24} of Bob's 30 years.

• Bob as a whole ages 1.29 ps less than a spectator at the finish line ($v^2 T^2/c^2$).

• Over his 30 years (upright ~ 16 h/day) his head has already aged ≈ 110 ns more than his feet.

Inputs (race, place, Earth)

$T = 2:08:10 = 7690$ s; $v = 42\,195 \text{ m} / T = 5.487$ m/s
 $v^2/2c^2 \approx 1.67 \times 10^{-16}$ (Bob's own Lorentz factor ~ 1)
Valencia: $\phi = 39.47^\circ$ N; course 2–30 m above sea level, flat loop
 $g = 9.8012$ m/s² (WGS-84 Somigliana formula at ϕ , +15 m free-air)
 $\omega = 7.292115 \times 10^{-5}$ rad/s; $c = 299\,792\,458$ m/s (exact)
Bob: 5 ft 10 in = 1.778 m; 158 lb = 71.7 kg. His mass is irrelevant:
his own gravitational field contributes $\sim 5 \times 10^{-20}$ ps.
Race time chosen = Paris-2024 Olympic entry standard ("very favourable").
Steady pace assumed (v = mean speed); pace variation is not in the ± 0.1 ps.
Result scales: gravitational $\propto T$, kinematic $\propto v^2 T \propto 1/T$.

Gait model & assumptions ($\pm 1\sigma$, Monte-Carlo)

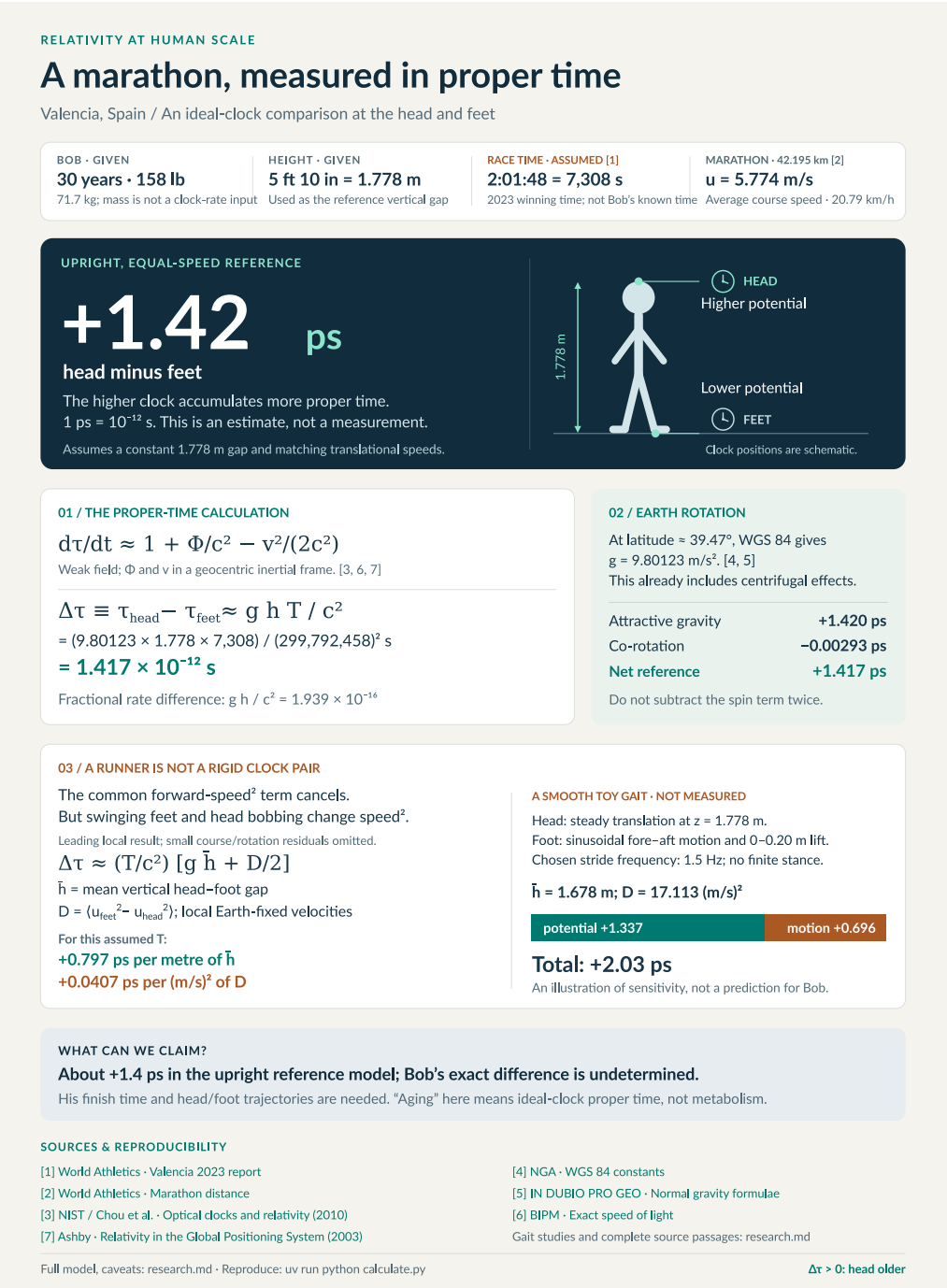
Head clock = centre of head, 0.115 m below vertex; lowered a further
 0.03 ± 0.02 m by running posture; vertical oscillation 7.6 ± 1.5 cm p-p.
Foot clock = ankle: 0.08 m high in stance, 0.20 ± 0.06 m mean in swing.
Step rate 3.3 ± 0.15 Hz, contact 170 ± 15 ms → duty factor $\beta \approx 0.28$.
Foot speed: 0 in stance; swing profile $\propto \sin^2(\pi t/T_{\text{swing}})$, peak 2.0 ± 0.15 v,
cycle-mean $v \rightarrow p \approx 0.74$, ($u^2 = 1.63$ v² (bound $\geq v^2(1-\beta) = 1.39$ v²)).
Neglected: tidal potentials (10^{-7} of g), gravity gradient across Δh ,
 $O(1/c^4)$ terms, head not exactly above the feet, Sagnac term ($\sim 10^{-7}$ ps).
Uncertainty is dominated by (u^2) of the foot and the mean ankle height.

Sources

World Athletics / olympics.com – Paris-2024 marathon entry standard 2:08:10.
Wikipedia "Valencia Marathon"; findmyrun.com – loop course, 2–30 m
a.s.l., men's course record 2:01:48 (S. Lemma, 2023).
Clark et al., J. Hum. Kinet. 87 (2023) – peak forward foot speed
= $2.00 \pm 0.15 \times$ running speed (154 trials, 3–10 m/s).
Kong & de Heer, J. Sports Sci. Med. 7 (2008) – elite runners: contact
time 174 ms, 3.26 steps/s at 5.4 m/s.
Cavanagh, Pollock & Landa (1977) – elite vertical oscillation ≈ 7.6 cm.
NIMA TR8350.2 (WGS-84 gravity); IERS Conventions (ω); SI (c).
Silhouette: ./media/running-man-2.svg (asset supplied with the task).

Model: first-order post-Newtonian proper time in the Earth-centred Earth-fixed frame; numbers generated by src/marathon/relativity.py

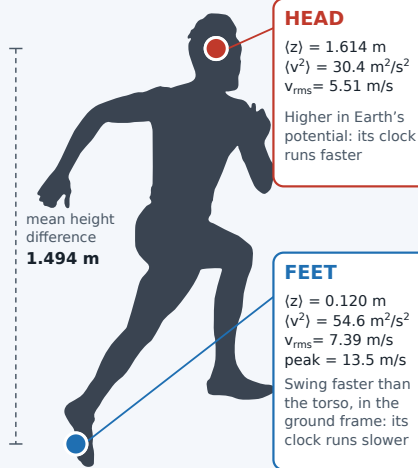
Figure 2: Runner up – Infographic by Anthropic Claude Fable 5.1



Head vs. Feet: Relativistic Differential Aging of a Marathoner

Bob · 30 y · 5'10" (1.778 m) · 158 lb (71.7 kg) · Valencia, Spain · 42.195 km in 2:08:10 (Olympic entry standard) · mean speed 5.487 m/s

A · Two clocks, one body



Result: differential aging over the whole race

$$\tau_{\text{head}} - \tau_{\text{feet}} = +2.29 \pm 0.23 \text{ ps}$$

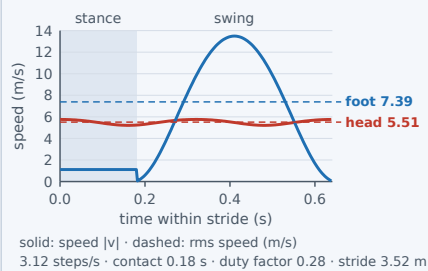
fractional rate difference $\Delta\tau/T = +2.98 \times 10^{-16}$, 95 % interval [1.89, 2.71] ps

$$\Delta\tau = (T/c^2) [g \Delta\langle z \rangle + \frac{1}{2} (\langle v_f^2 \rangle - \langle v_h^2 \rangle)]$$

The head ages more: higher in Earth's potential, slower in the ground frame.

Ranges: 1 σ and 95 % from a Monte Carlo over gait parameters (panel D).

B · Speed vs. time, one stride



C · Budget (head – feet)

Gravitational
 $g \Delta\langle z \rangle / c^2$
+1.25 ps

Kinematic (SR)
 $\frac{1}{2}(\langle v_f^2 \rangle - \langle v_h^2 \rangle) / c^2$
+1.04 ps

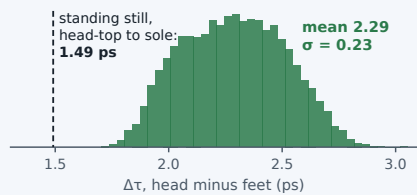
Net (whisker: 95 % interval)
+2.29 ps

Versus a clock at rest on the ground:

head +0.05 ps feet –2.23 ps

The feet are the “young” end.

D · Gait uncertainty (20 000 draws)



E · Model & assumptions

Rate: $d\tau/dt = 1 + (W - \frac{1}{2}v^2)/c^2$, Earth-fixed frame
 W : geopotential incl. centrifugal; $g = 9.8012 \text{ m/s}^2$
 Head, feet: worldlines of head / foot centroids
 Head: 1.664 m upright, 5 cm running crouch, 7 cm peak-to-peak vertical bounce
 Foot: stance ≈ 0 speed, then min-jerk swing (25 cm rise); same distance per stride
 Body mass drops out (equivalence principle)

Both effects push the same way.

F · Scale & checks

Light crosses 0.69 mm in 2.29 ps
 1 s offset $\approx 106 \text{ Myr}$ of running
 $\Delta\tau$ scales linearly with race time T

Neglected, as fraction of $\Delta\tau$:

Earth-spin cross term 2×10^{-5}
 Simultaneity $v/c^2 \times 10^{-5}$
 Sun and Moon tides 1×10^{-14}
 Bob's self-gravity 4×10^{-10}

Sources: World Athletics Paris 2024 entry standard (men's marathon 2:08:10) · IAAF 2017 World Championships marathon biomechanics report (step rate, step length) · Kenyan distance-runner gait, J. Sports Sci. Med. 7:499 (contact time) · NGA WGS84 / Somigliana normal gravity · Chou et al., Science 329:1630 (2010) · Valencia Marathon course (flat, near sea level). Gait parameters are literature-typical values, not measurements of Bob; the interval reflects gait uncertainty only. Full derivation, sources and code: REPORT.md, src/marathon/model.py.

Figure 4: 4th place – Infographic by Anthropic Claude Sonnet 5.5

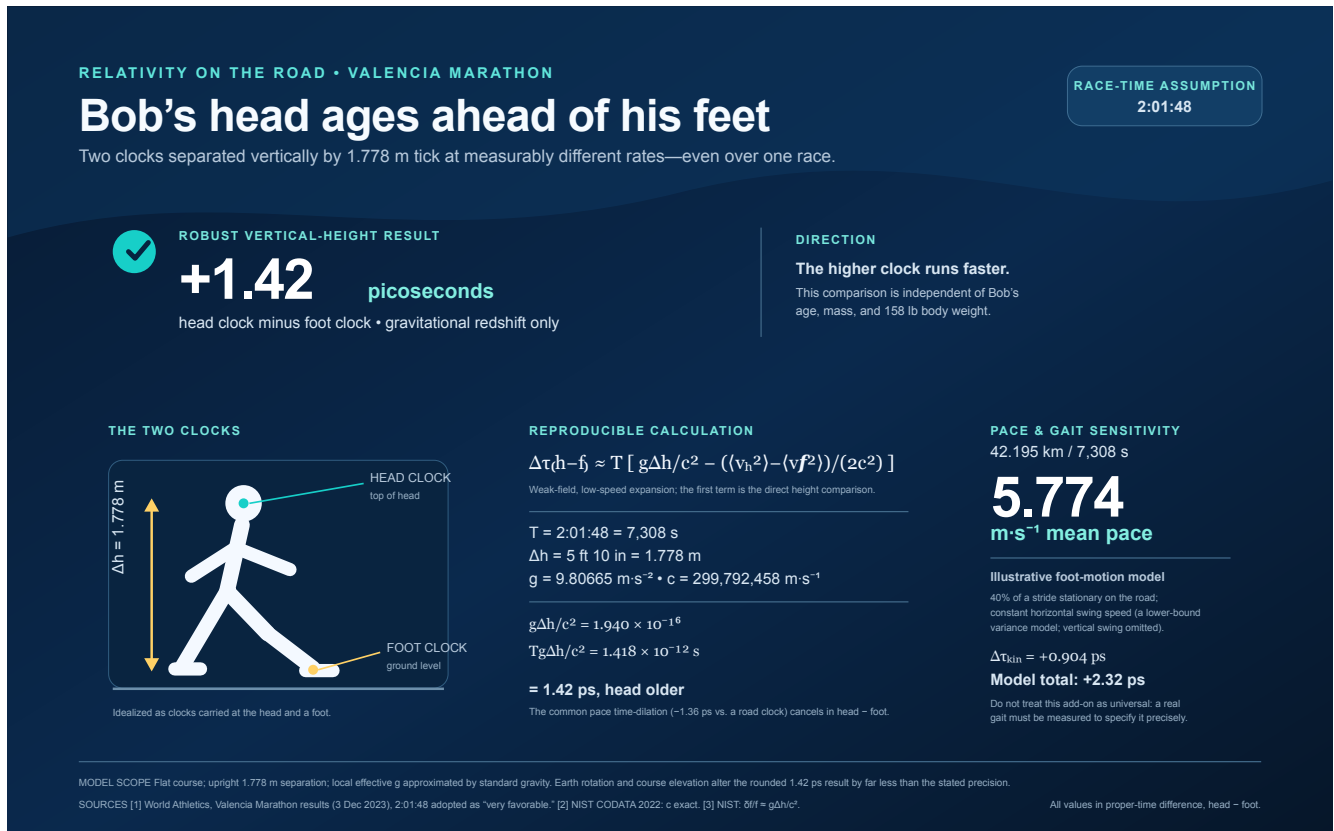


Figure 5: 5th place – Infographic by Anthropic Claude Terra 5.6



Figure 6: Last place – Infographic by OpenAI GPT-6 Luna. The SVG file is ill-formed, so this is a raster reconstruction.

C. Summary report by Claude Opus 5.5

Claude Opus 5.5 wrote the following summary of its methods, assumptions, calculations, and conclusions, reproduced here in blue.

Differential ageing of a marathoner’s head and feet: research summary

Result. During a 2:01:48 Valencia Marathon, Bob’s head accumulates

$$\Delta\tau = \tau_{\text{head}} - \tau_{\text{feet}} = +1.88 \text{ ps} \text{ } (\pm 0.18 \text{ ps at } 68 \text{ } \%; \text{ } 95 \text{ } \% \text{ interval } 1.52\text{--}2.24 \text{ ps})$$

more proper time than his feet. That is a mean fractional rate difference of 2.57×10^{-16} . The total has two parts:

term	physical origin	value
gravitational	head is on average 1.35 m higher in Earth’s potential	+1.08 ps (68 %: 1.04–1.11)
kinematic	feet have a larger mean-square ground speed (7.31 vs 5.81 m/s RMS)	+0.80 ps (68 %: 0.63–0.98)

Both effects make the head older. Every other effect checked is at least ~150× smaller than the 1σ uncertainty (see §5).

Deliverables: infographic.svg (self-contained; the only reference is an internal url(#ah arrow marker), infographic.png (a 1200 px rasterisation made with Inkscape). Reproducible code is in src/marathon/, and numbers are in results.json / results.txt.

Interpreting the question and the “very favorable time”

- Bob is a hypothetical 30-year-old male, 1.778 m (5 ft 10 in) and 71.67 kg (158 lb). Assumption: his “very favorable time” is the Valencia men’s course record, 2:01:48 (Sisay Lemma, 2023; still the record after the 2024 and 2025 editions, which were won in 2:02:05 and 2:02:25). So $T = 7308 \text{ s}$ and the mean speed is $U = 42\,195 \text{ m} / 7308 \text{ s} = 5.774 \text{ m/s}$.
- “Ageing” here means elapsed proper time along each body part’s worldline. This assumes biological processes run like ideal clocks, which is the clock hypothesis. “Head” is the head centre of mass (CoM). “Feet” is the mass-averaged foot tissue: foot CoM motion plus a rotational correction.
- Age and mass do not affect the main result. Mass is used for the self-gravity estimate. Age is used only for a lifetime context number.

Relativistic model

Weak field and slow motion in the Earth-centred inertial frame (GCRS). The rate of an ideal clock is

$$d\tau/dt = 1 - U_E/c^2 - v^2/(2c^2), \text{ where } U_E > 0 \text{ is the Newtonian potential depth.}$$

Split the inertial velocity as $v = \omega \times r + u$, where u is the velocity relative to the rotating ground. Define the geopotential $W = U_E + |\omega \times r|^2/2$, which includes the centrifugal part. Then

$$d\tau/dt = 1 - W/c^2 - (\omega \times r) \cdot u/c^2 - u^2/(2c^2), \text{ with } W(h) \approx W_0 - g h + \frac{1}{2} \gamma h^2.$$

Here g is the local effective gravity, which already contains Earth's rotation, and $\gamma = 3.086 \times 10^{-6} \text{ s}^{-2}$ is the free-air gradient. For head (H) minus feet (F):

$$\Delta\tau = (1/c^2) \int [g(h_H - h_F) - \frac{1}{2}\gamma(h_H^2 - h_F^2)] dt + (1/2c^2) \int (u_F^2 - u_H^2) dt - (1/c^2) \int (\omega \times r) \cdot (u_H - u_F) dt.$$

Key simplification. Head and feet travel the same 42.195 km in the same time, so their stride-averaged velocity $\langle u \rangle$ is the same. Hence $\langle u^2 \rangle = U^2 + \sigma^2$, where σ^2 is the within-stride velocity variance: the internal kinetic energy per unit mass in the runner's mean frame. The kinematic term depends only on $\sigma_F^2 - \sigma_H^2$:

$$\Delta\tau = g(\Delta h)T/c^2 + (\sigma_F^2 - \sigma_H^2)T/(2c^2).$$

Head and feet share the net displacement, so the rotation cross term integrates exactly to boundary terms plus $2\omega \cos\phi \langle \Delta h \rangle D_{\text{east}}/c^2$. D_{east} is the net eastward start-to-finish displacement: 52.5 m from the course GPX.

Inputs and sources

quantity	value	source
Race time	2:01:48 (7308 s), course record	Wikipedia "Valencia Marathon" (World Athletics results cited there)
Local gravity	$g = 980\,113.45 \text{ mGal} = 9.8011345 \text{ m s}^{-2}$ at $39^\circ 28' 36''\text{N}$, 11 m	WELMEC gravity zone table, Spain (welmec.org/.../gravity_info_Spain.pdf)
Course	flat, 2–30 m elevation; start and finish 55 m apart; lat $39.457\text{--}39.494^\circ \text{ N}$	findmyarathon.com; 2025 course GPX from goandrace.com (data/valencia_marathon_2025.gpx)
c, ω_E, G	$299\,792\,458 \text{ m/s}$; $7.292115 \times 10^{-5} \text{ rad/s}$; 6.674×10^{-11}	SI, IERS/WGS-84, CODATA

Continued on next page

(Continued)

quantity	value	source
Head CoM	50.02 % of the vertex-C7 length from the vertex. Length 24.29 cm at 1.741 m stature, scaled to Bob: 24.8 cm, so CoM is 12.4 cm below the vertex and 1.654 m above the sole	de Leva (1996) J. Biomech. 29:1223, adjusted Zatsiorsky-Seluyanov parameters (the head CoM fraction was checked against the Visual3D documentation table)
Foot CoM height (standing)	0.035 ± 0.010 m, about half of the ankle height 0.039 H	assumption based on Winter/Drillis-Contini proportions; not verified by a primary source
Foot radius of gyration	$0.257 \times$ foot length (0.264 m) = 0.068 m	de Leva (1996)
Elite gait at 2-h pace (21.1 km/h)	contact 0.16 ± 0.01 s; step length 1.74 ± 0.06 m (the paper calls it “stride length” but defines it as the distance to the next contralateral step)	Jones et al. (2021) J. Appl. Physiol. 130:369, “Physiological demands of running at 2-hour marathon race pace” (Breaking2 athletes)
Derived gait for Bob	step 0.301 s, cadence 199 min^{-1} , stride 0.603 s, duty factor $D = 0.16/0.603 =$ 0.265 , swing 0.443 s, mean swing speed $U/(1-D) = 7.86$ m/s	computed
Foot/pelvis marker kinematics	28 runners, treadmill at 2.5, 3.5 and 4.5 m/s, 150 Hz, 30 s trials	Fukuchi, Fukuchi & Duarte (2017) PeerJ 5:e3298; figshare doi:10.6084/m9.figshare.4543435 (RBDS)
Validation: peak foot speed	$2.00 \pm 0.15 \times$ running speed	Clark et al. (2023) J. Hum. Kinet. 87:1
Experimental context	clock rate shifts measured for $\Delta h < 1$ m (33 cm) and $v < 10$ m/s	Chou, Hume, Rosenband & Wineland (2010) Science 329:1630
Clock hypothesis test	muon lifetime unaffected by $\sim 10^{18}$ g acceleration	Bailey et al. (1977) Nature 268:301

A separate literature brief from a delegated research sub-agent is in research/biomechanics_brief.md. It records the parameters that could not be verified, notably elite heel clearance and head oscillation.

Calculations

Empirical stride kinematics (src/marathon/rbds_analysis.py)

For each RBDS trial I built a foot centroid (mean of the heel-marker cluster and the MT1/MT5 midpoint) and a pelvis centroid (6 pelvic markers). I low-pass filtered them (4th-order Butterworth, 15 Hz, zero-lag) and differentiated. On a treadmill the lab-frame mean velocity is about 0, so the lab-frame velocity variance equals the ground-frame σ^2 . This is a Galilean change of frame; treadmill kinematics are assumed to match overground running. Stance was detected as the forefoot moving with the belt while near its lowest height.

U (m/s)	n	σ_{F^2} (m ² /s ²)	σ_{F^2}/U^2	duty D	S = (1+ σ_{x^2}/U^2) (1-D)	σ_{pelvis^2}	mean Δh of foot vs standing	pelvis drop
2.5	31	5.61 ± 0.50	0.90	0.377	1.066	0.405	+0.091 m	-0.030 m
3.5	39	9.33 ± 1.29	0.76	0.331	1.066	0.430	+0.133 m	-0.035 m
4.5	31	13.42 ± 2.96	0.66	0.285	1.049	0.414	+0.168 m	-0.043 m

Suppose the foot is at rest in stance and moves in swing with a normalised speed profile $B(s)$ with mean 1. Then $\sigma_{x^2}/U^2 = \langle B^2 \rangle / (1-D) - 1$, so $S = \langle B^2 \rangle$ is a **shape factor**. The data show S is essentially constant over the whole speed range (1.05–1.07). That justifies extrapolating to Bob with his elite duty factor. The RBDS peak foot speed at 4.5 m/s is 2.07 U, which agrees with Clark et al.'s 2.00 ± 0.15 U.

Bob's velocity variances (src/marathon/model.py)

I used linear-in-U regressions over all 101 trials, evaluated at $U = 5.774$ m/s: * fore-aft: $\sigma_{x^2} = U^2[S/(1-D) - 1] = 33.34 \times (1.0417/0.7345 - 1) = 13.94$ m²/s² * vertical: $\sigma_{y^2} = 0.167$ U² = **5.56** m²/s²; medio-lateral 0.04 m²/s² * foot rotation (tissue averaging): $r_g^2 \langle \omega^2 \rangle = 0.068^2 \times 124 \text{ rad}^2/\text{s}^2 = 0.57$ m²/s² * $\sigma_{F^2} = 20.11$ m²/s², so the foot's RMS ground speed is $\sqrt{U^2 + \sigma_{F^2}} = 7.31$ m/s * head: $\sigma_{H^2} \approx$ pelvis value **0.43** m²/s², so RMS 5.81 m/s. The head is assumed to move like the trunk; its rotation adds < 0.01 m²/s².

Kinematic term: $(\sigma_{F^2} - \sigma_{H^2})T/(2c^2) = 19.69 \times 7308 / (2 \times 8.98755 \times 10^{16}) = 8.00 \times 10^{-13}$ s.

Heights

- Standing: head CoM 1.654 m, foot CoM 0.035 m, so $\Delta h = 1.619$ m. Shoe stack raises both equally and cancels.

- Running (RBDS regressions extrapolated to 5.77 m/s): the trunk and head drop 0.050 m, and the foot's stride-mean height rises 0.218 m because of swing-phase heel recovery. So $\langle h_H \rangle = 1.604$ m, $\langle h_F \rangle = 0.253$ m, and $\langle \Delta h \rangle = 1.351$ m.
- Gravitational term: $g\langle \Delta h \rangle T / c^2 = 9.80113 \times 1.351 \times 7308 / 8.98755 \times 10^{16} = 1.077 \times 10^{-12}$ s. The rate is 1.47×10^{-16} , or 0.797 ps per metre of height over the race.

Uncertainty (Monte Carlo, 4×10 draws)

The parameters were varied as follows: * contact time and step length: Jones et al. SDs * S, vertical ratio, foot height gain, pelvis drop, pelvis σ^2 and foot ω^2 : regression SE combined with the inter-individual SD, because Bob is one individual * foot radius of gyration: ± 10 % * head $\approx$ pelvis: ± 25 % * standing foot CoM: ± 1 cm * head CoM: ± 1.5 cm * elite-transfer uncertainty on the foot height: ± 2 cm

Results: total median 1.88 ps, 68 % interval [1.70, 2.06] ps, 95 % interval [1.52, 2.24] ps. The swing kinematics of the foot dominate the uncertainty.

Finish time sensitivity: gravity scales with T, and kinematic $\propto U^2 T \propto 1/T$. So the total is nearly independent of pace. A 2:10 finish gives about $1.15 + 0.75 \approx 1.9$ ps.

Effects checked and found negligible ($|\Delta \tau|$ over the race)

effect	estimate	reasoning
start/finish simultaneity (boundary term)	$\leq 1.2 \times 10^{-15}$ s	$v_{\text{rot}} (359 \text{ m/s}) \times \text{posture offset } (\leq 0.3 \text{ m}) / c^2$
g variation along the course (5–30 m)	8×10^{-18} s	$\gamma \Delta z / g \approx 8 \times 10^{-6}$ relative
lunisolar tides	3×10^{-19} s	tidal $\Delta g \lesssim 3 \times 10^{-6} \text{ m/s}^2$ ($\approx 3 \times 10^{-7} g$)
vertical gravity gradient over $\langle \Delta h \rangle$	3×10^{-19} s	$\frac{1}{2} \gamma (h_H^2 - h_F^2)$
Earth-rotation cross term	9×10^{-20} s	$2\omega \cos \varphi \langle \Delta h \rangle \times 52.5 \text{ m} / c^2$
Bob's own gravity (71.7 kg)	3×10^{-22} s	segmental rod model with de Leva masses; the head sits slightly deeper, near the trunk
foot-strike accelerations ($\sim 10 g$)	0	clock hypothesis (tested to $10^{18} g$)
$O(c^{-4})$ terms	$(v/c)^4 \sim 10^{-31}$; $(w/c^2)^2 \sim 5 \times 10^{-19}$ absolute, common mode	negligible

Common-mode effects are identical for head and feet, so they cancel in the difference but matter in absolute terms. Relative to a spectator standing at the start, Bob's mean speed alone slows his head by 1.37 ps. His time-averaged course elevation (0.3 m above the start) adds +0.26 ps. The Sagnac term for the course loop, closed finish→start (projected equatorial area 4.87 km²), is −0.008 ps. These numbers show that the head–feet difference comes from *internal* motion and posture, not from Bob's overall speed.

Assumptions and limitations

1. Bob runs exactly the course-record time at an even pace. The result is almost pace-independent (§4.4).
2. The weak-field, slow-motion metric is adequate, as it is for GPS/TT. Tissue ages with proper time.
3. Treadmill and overground kinematics are equivalent at constant belt speed. RBDS runners are recreational or competitive, not elite. The elite transfer uses the published elite duty factor, and the speed-invariant swing shape factor S is extrapolated from 4.5 to 5.8 m/s.
4. Head velocity variance is taken from the pelvis: small, 2 % of the foot term. The standing foot CoM height is an anthropometric estimate (± 1 cm $\rightarrow \pm 0.008$ ps).
5. Both feet are identical. A stride average represents the whole race, including the first and last few seconds.

Context

- Present-day optical clocks resolve rate differences of this size ($\sim 10^{-16}$ – 10^{-17} ; Chou et al. 2010 measured 33 cm). Integrated over a single race, though, the difference is only about 2 ps.
- 1 s of head–feet difference would take about 1.2×10^8 years of non-stop racing.
- Over Bob’s 30 years of ordinary life (roughly 6 h/day standing, 10 h sitting, 8 h lying, time-averaged $\Delta h \approx 0.92$ m), gravity alone has made his head about $0.1 \mu\text{s}$ (≈ 95 ns) older than his feet. The marathon adds about 2×10^{-5} of that.

Reproduction

```
uv sync                                # numpy, scipy
# download RBDS *markers.txt, *static.txt, RBDSinfo.txt from figshare 4543435 into data/rbds/
uv run python src/marathon/rbds_analysis.py # -> data/rbds_summary.json
uv run python src/marathon/stride_profile.py # -> data/stride_profile_45.json
uv run python src/marathon/model.py        # -> results.json (printed log in results.txt)
uv run python src/marathon/infographic.py   # -> infographic.svg
inkscape infographic.svg --export-type=png --export-filename=infographic.png --export-width=1200
```

D. LLM citations

The LLMs had access to the web and used it to download various resources. Some of the LLMs also cited additional references but did not attempt to download them. The following is a list of documents downloaded or cited by one or more LLMs. The list is categorized into three parts; documents successfully downloaded by one or more LLMs; citations that are legitimate (at the time of this writing) but not downloaded; and legitimate documents cited accurately except for the title.

D.1. Downloaded, verified

These are the online resources downloaded by the LLMs. All are accessible as of the date of this report.

- BIPM, “A concise summary of the International System of Units, SI,” <https://www.bipm.org/documents/20126/41483022/SI-Brochure-9-concise-EN.pdf>.
- BIPM, “SI base unit: metre,” <https://www.bipm.org/en/si-base-units/metre>.
- BIPM, “SI defining constants,” <https://www.bipm.org/en/measurement-units/si-defining-constants>.
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D.2. Cited, not downloaded, verified to exist

These are references cited by one or more LLMs but not downloaded. They are legitimate references, verified at the time of this report.

- Bailey et al., “Muon lifetime / clock-hypothesis experiment,” *Nature* **268** (1977), 301.
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D.3. Cited, not downloaded, ambiguous reference

These resources were mentioned but not downloaded by any LLM. The citations are ambiguous; similar, relevant resources exist online with the same authors but with different titles.

- Drillis–Contini, “Anthropometric body-segment proportions.”
- Winter / Dempster, “Anthropometric body-segment proportions.”

Acknowledgements and disclosures

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