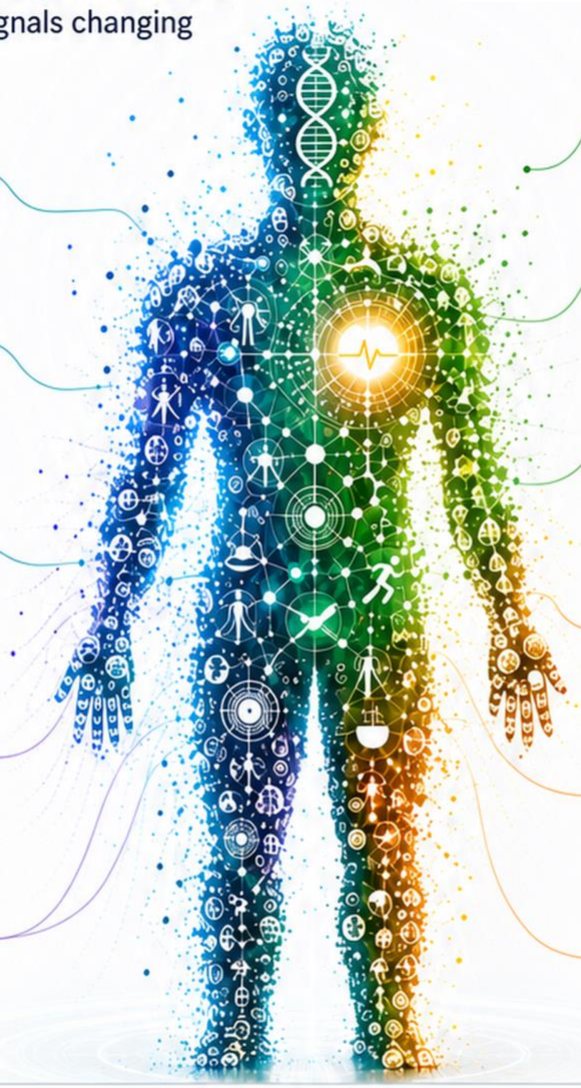
HEALTHSPAN BEFORE IT'S OVER

Your health is not one measurement.
It is the **integration** of thousands of biological signals changing through time.

Nathan D. Price, PhD



GENETICS
Your biological blueprint

PHYSIOLOGY
How your body functions

BRAIN & COGNITION
Clarity, memory, resilience

IMMUNE SYSTEM
Your defense network

MICROBIOME
Trillions of partners

MOVEMENT
Activity, strength, mobility

SLEEP & RECOVERY
Restorative renewal

NUTRITION
Fuel, nutrients, metabolism

STRESS & EMOTIONS
Balance, calm, adaptation

CONNECTION
Relationships, belonging, purpose

ENVIRONMENT
Air, water, light, toxins, climate

1 MEASURE
Understand the health you've already lived.

2 FORECAST
Project a range of possible futures.

3 MODIFY
Take action to improve your trajectory.

Act. Then re-measure.
Learn. Adapt. Improve.

Thousands of signals.
Countless possibilities.
One you.

HEALTHSPAN HORIZONS
healthspanhorizons.org

CONTENTS

What's inside

The final count of healthy years can be known only in hindsight. A useful science of healthspan needs to measure the health already lived, forecast where the current path and credible alternatives may lead, and determine which changes can responsibly be put into practice.

Healthspan has become a central goal of aging science: not simply more years, but more years with health, function, independence, and the capacity to live a life that still feels like one's own. The Roman philosopher Seneca captured the distinction two thousand years ago. In his Moral Letters, he wrote that "it makes a great deal of difference whether a man is lengthening his life or his death."[1] More years are not automatically more life; a longer decline is still a decline.

> " It makes a great deal of difference whether a man is lengthening his life or his death.
>
> — *Seneca, Moral Letters*

Yet healthspan is less settled than the word suggests. Researchers have defined it in many different ways: years free from major chronic disease, disability, frailty, functional limitation, or some combination of them. A 2025 systematic review identified 187 publications that provided a definition of healthspan. Most definitions centered on the absence or onset of chronic disease or disability, or on performance limitations; only two included subjective measures such as quality of life.[2] Everyday health is not binary, either. A person can live actively and independently with a well-managed diagnosis, while someone with no diagnosis may already be losing strength, cognition, or resilience. We also feel that difference vividly: some days are filled with energy and curiosity; others are marked by fatigue and listlessness.

Whatever definition of healthspan we choose, a person's final, realized healthspan is backward-looking. It can be counted with confidence only after the life course has unfolded. As a tool for guiding a life still in progress, conventional healthspan is closer to an epitaph than an instrument.

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So when we say that Healthspan Horizons aims to make healthspan measurable, predictable, and modifiable, we are not claiming that a person's ultimate healthspan can already be read directly from a test. That isn't possible. We are proposing a three-part learning system. First, measure the state of health now and estimate

[1] Seneca. Epistles, Volume I: Epistles 1–65. Translated by Richard M. Gummere. Loeb Classical Library 75. Cambridge, MA: Harvard University Press; 1917. Letter 58, §33.

[2] Masfiah S, Kurnialandi A, Meij JJ, Maier AB. Definitions of healthspan: a systematic review. Ageing Research Reviews. 2025;111:102806. doi:10.1016/j.arr.2025.102806.

the health already experienced. Second, forecast where the current path may lead and—where causal evidence permits—how plausible changes might alter it. Third, determine which changes are genuinely available and responsible, put one or more into practice, and measure again.

> **These are not three separate ambitions. They are three parts of one loop that makes healthspan actionable now.**

SECTION 01

A Learning System for Healthspan

The human aim is simple to state and hard to deliver: as many years of healthy, vibrant life as possible for each of us. Not merely years survived, but years lived with energy, clarity, strength, connection, and agency.

The scientific logic is iterative: observe, model, act, then observe again. Systems biologists will recognize the pattern. It is how we learn about and steer any complex system. The challenge is to apply that discipline to one human life without pretending that a human life is fully knowable—or that health is fully controllable.

Healthcare is increasingly moving toward prevention and well-being, with real-time monitoring and more proactive interventions.[3] But much of its architecture remains episodic and threshold-based. Measurements may be months apart, and action often begins when a value crosses a clinical boundary or symptoms become unmistakable. Those thresholds are important for diagnosis and treatment. But health is also shaped in the long interval before a threshold is crossed, when smaller changes may be visible and some trajectories may still be easier to alter.

This is the shift Lee Hood and I called Scientific Wellness in our book, The Age of Scientific Wellness: health understood not merely as the absence of a diagnosis, but as a changing state that can be observed over time and managed proactively.[4] The promise is not continuous surveillance for its own sake. It is earlier, more useful understanding—insight when it matters, while health can still be preserved or improved.

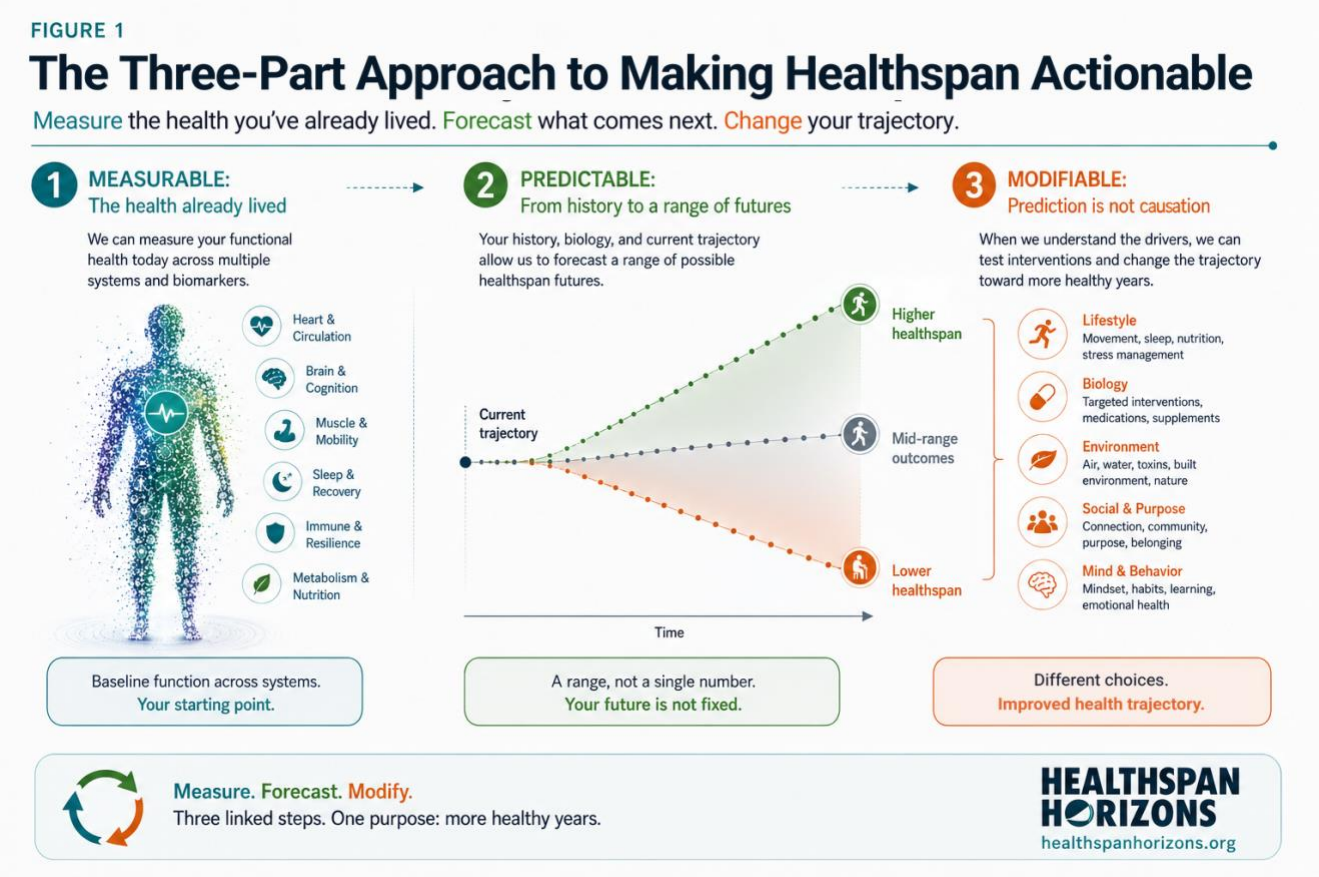
The rest of this perspective follows that loop. Measurable gives us something real to stand on: the health already lived, the state now, and health in motion. Predictable uses that history to estimate both the current path and—where causal evidence permits—credible alternatives. Modifiable then asks two linked questions:

[3] Shukla M, Davis A, Batra N, Gilbert F. Digital disruption for health plans: it isn't coming, it's here. Deloitte Insights. March 29, 2022. https://www.deloitte.com/us/en/insights/industry/health-care/digital-health-plan.html

[4] Hood L, Price ND. The Age of Scientific Wellness: Why the Future of Medicine Is Personalized, Predictive, Data-Rich, and in Your Hands. Belknap Press of Harvard University Press; 2023.

Which alternatives are causally credible, safe, feasible, and accessible? And what happens when one is put into practice?

FIGURE 1



SECTION 02

Can Healthspan Be Measured?

Lived Healthspan and the Health Already Lived

Begin with the part of the story that has already happened.

Imagine a person's state of health plotted against time. The curve might be stable, volatile, interrupted by illness, or different across physical, cognitive, and emotional domains. The area under that curve up to today would represent the healthy life accumulated so far. We call this proposed Healthspan Horizons research construct Lived Healthspan.

If the health-state scale were normalized so that a year in full health contributed one health-adjusted year, then a year lived at a lower health state would contribute proportionally less. Such weighting would describe health and functional state alone, not the worth of a person or the value of a life. And there could be many ways to

define this scale of health, as we will explore in a later essay. Lived Healthspan would be a running total rather than an endpoint: the health-weighted years already lived, updated as life unfolds.

" Lived Healthspan would be a running total rather than an endpoint: the health-weighted years already lived, updated as life unfolds.

For most people, earlier portions of that history would initially have to be reconstructed imperfectly from clinical records, major health events, functional history, and self-report; confidence would increase as prospective longitudinal measurements accumulate.

The underlying mathematics is not new. Health economics and population health already use related ideas, including quality-adjusted life years and healthy life expectancy.[5] The proposed difference is in purpose and resolution. Lived Healthspan is intended not primarily to compare treatments or summarize populations, but to follow an individual longitudinally, across multiple domains, as part of a measure–predict–modify loop. These measures become increasingly informative as prospective longitudinal data accumulate.

The distinction between Lived Healthspan and Healthspan matters—but it does not make the measurement easy. The integral is the simple part. The hard part is the vertical axis: what, exactly, counts as health?

A credible health-state measure cannot be a single biomarker, wearable score, or diagnosis. It must combine several kinds of evidence: physical function, cardiometabolic and immune health, cognition, sleep, symptoms, mental well-being, and the ability to carry out valued activities. Depending on the purpose, useful measures might include strength, gait, cardiorespiratory fitness, glucose regulation, sleep continuity, cognitive performance, inflammatory activity, and self-reported health. Each signal has limitations. Some are noisy, some are context-dependent, and some are better supported than others.

The goal is not to collect everything that can be measured. It is to identify a compact set of measurements that are reliable, interpretable, and prospectively associated with outcomes that matter.

Two views are needed at once. The first is decomposed: which domain is changing, and what might be driving it? That is where action becomes possible. The second is integrated: what do those domains mean for the quality and durability of the life as a whole?

Integration requires care. A simple average can hide a serious weakness; excellent results in several domains should not erase a major loss of function in another. But whole-person health is not always identical to the single lowest score, either. The way domains are weighted—and the way severe deficits are prevented from disappearing inside an average—is a modeling choice that must be explicit and tested.

Reference frames also answer different questions. A personal baseline can reveal change from an individual's earlier state. A population or clinical reference can reveal that a stable personal baseline is nevertheless

[5] Gold MR, Stevenson D, Fryback DG. HALYs and QALYs and DALYs, oh my: similarities and differences in summary measures of population health. Annual Review of Public Health. 2002;23:115–134. doi:10.1146/annurev.publhealth.23.100901.140513.

associated with substantial risk. Neither should replace the other. The most useful system asks both: How have you changed? and What does your current state mean in the wider evidence?

This is why Lived Healthspan should be understood, at present, as a proposed research construct—not a finished or validated clinical score. To become trustworthy, it would need prospective validation against future function, independence, disease burden, and lived well-being; it would need to handle missing and noisy data; and it would need to perform across ages, sexes, ancestries, disabilities, and social contexts rather than mistaking unequal access or measurement for biology.

> **The domains are where we act. The integral is what we are acting for.**

SECTION 03

Resilience:

Measuring Health in Motion

Most health measurements are snapshots. Resilience adds dynamics.

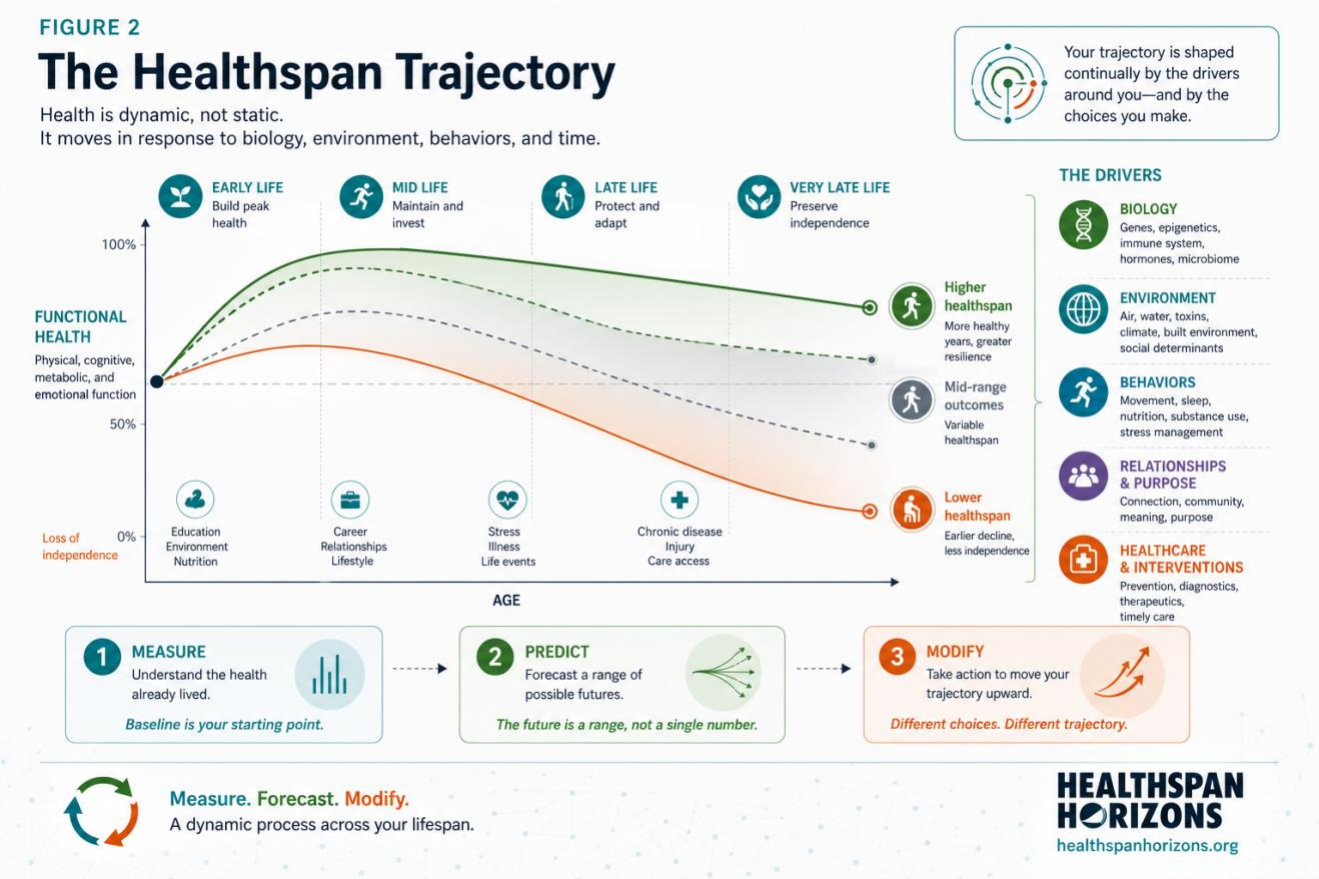
Resilience is the capacity to absorb a perturbation and recover toward baseline. It can be examined after a standardized challenge or a naturally occurring event: how heart rate settles after exertion, how glucose regulation responds after a meal, how function returns after an infection, or how inflammatory markers resolve after surgery. In each case, the trajectory of recovery may reveal information that a resting measurement misses. In a 2022 retrospective analysis of hospitalized patients recovering from surgery, infection, or ischemia, deviations from a characteristic white-blood-cell and platelet recovery trajectory were associated with markedly higher risks of prolonged hospitalization or death.[6]

But resilience is not yet one universally validated number. It is likely to be domain-specific, and even within the physical resilience literature, definitions, operationalizations, and measurement approaches remain inconsistent.[7] A slower or less complete recovery may indicate vulnerability, but claims that any one recovery metric can forecast whole-person healthspan years in advance require prospective testing.

That caveat does not weaken the idea. It identifies the work. Resilience is promising precisely because it connects state to trajectory: not only where the system is, but how it responds when pushed.

[6] Foy BH, Sundt TM, Carlson JCT, et al. Human acute inflammatory recovery is defined by co-regulatory dynamics of white blood cell and platelet populations. Nature Communications. 2022;13:4705. doi:10.1038/s41467-022-32222-2.

[7] Manning J, Morales B, Yentes J. Building an ontology of resilience: insights from the physical resilience literature. Ageing Research Reviews. 2026;119:103155. doi:10.1016/j.arr.2026.103155.



SECTION 04

Can Healthspan Be Predicted?

Forecasting the Current Path and Alternative Futures

A person's complete healthspan trajectory is not directly observable in advance. It can only be forecast—and every forecast is conditional on a path.

Lived Healthspan supplies the measured history. Prediction extends the health curve forward from today. It can address two questions: What is likely if the current path continues? And—where the evidence allows—how might the distribution shift under specific alternative decisions, treatments, or conditions?

These are two different prediction tasks. Current-path prediction asks what is likely to happen given the present state, direction of change, and resilience. Alternative-path prediction asks what is likely under a specific change—for example, if a sleep disorder is treated, activity is restored, a medication is changed, or an environmental exposure is reduced. The second task is harder because it requires causal evidence about the effect of the change, not merely an association that predicts risk. That evidence turns a speculative what-if into a decision-relevant forecast—and helps establish whether the proposed lever is genuinely modifiable.

The word distribution matters. For each path, a healthspan forecast should not be a single line pretending to be fate. It should be a range of possible futures that widens with time and reflects several kinds of uncertainty: imperfect measurement, limitations of the model, uncertainty about the effect of an intervention, changes in behavior or environment, and events no model can foresee.

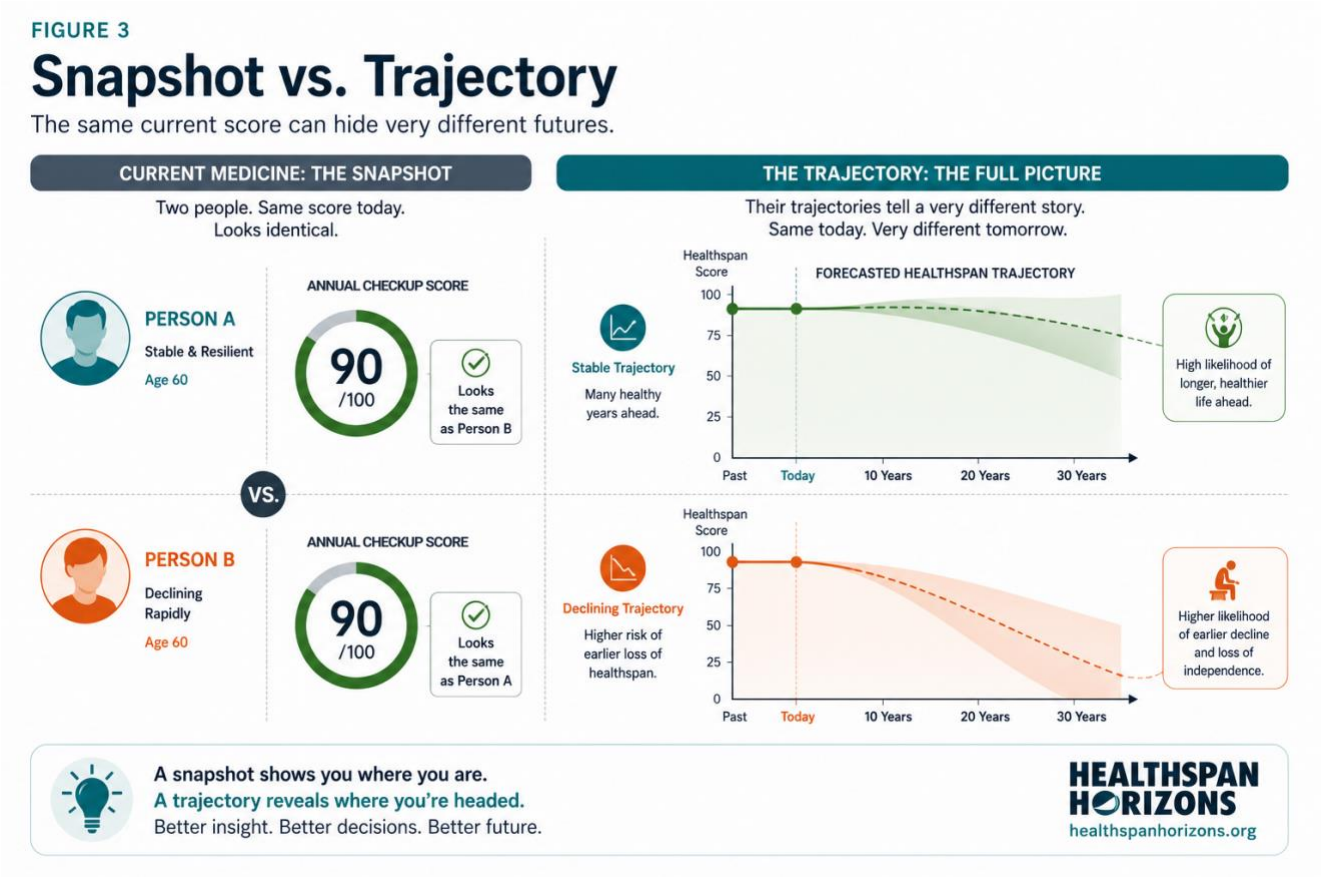
> " A healthspan forecast should not be a single line pretending to be fate.

A snapshot tells us position. A trajectory tells us velocity—the speed and direction of change over time. Resilience tells us something about how the system may handle shocks. Together, they inform the current-path forecast; causal evidence is what allows the model to estimate how a different path might change it.

Consider two people who are both fifty-two. Their current integrated health scores are nearly identical, but their resilience differs. One has been stable for years and tends to recover fully from illness and exertion. The other has declined more rapidly over the past eighteen months, and each disruption takes longer to recover from.

They occupy the same position today, but they do not have the same velocity. A responsible model would not give them identical current-path forecasts, nor assume that the same intervention would shift their futures by the same amount. The second person's projection might shift downward and become more sensitive to future shocks. The example is illustrative, not a claim that current models can already estimate those differences—or intervention effects—with clinical precision. Its point is that longitudinal pattern can contain information that a one-time score cannot.

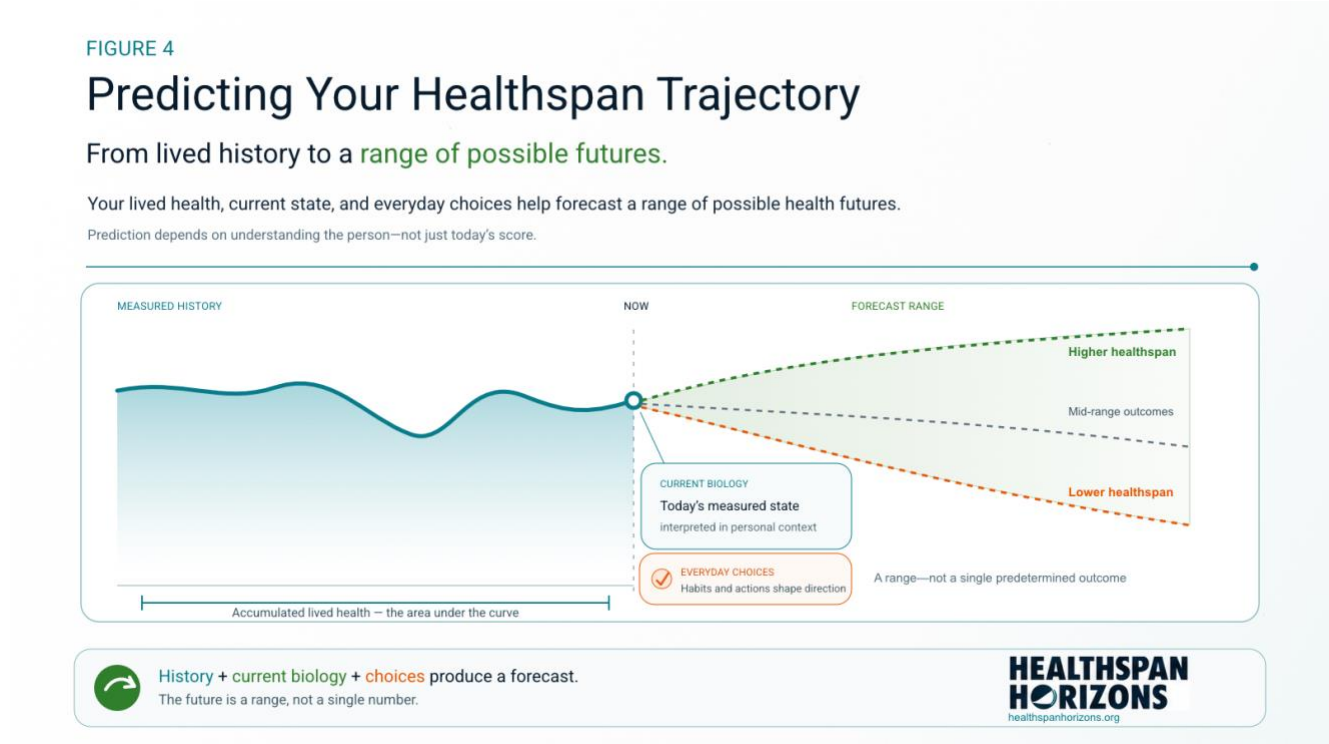
FIGURE 3



A sufficiently validated model could then compare credible alternatives. Preserving existing routines may be the highest-value path for the first person, while treating an unrecognized sleep disorder or restoring activity may matter more for the second. These comparisons remain part of Predictable—but only when they are anchored in causal evidence. Modifiable asks the next question: Is the better path actually available and responsible to take?

This leads to two central scientific difficulties. First, prediction is generally easier for groups than for individuals. A model may estimate average outcomes accurately across thousands of people while being badly wrong for the person sitting in front of it. Good performance at the population level does not automatically translate into a trustworthy personal forecast. Second, forecasting the effect of an intervention is harder than forecasting the current path: a model can predict risk well and still be wrong about what will change it.

Closing those gaps requires more than denser data. Models must be tested in populations not used to build them, checked for systematic error across subgroups, and evaluated for calibration: when a model says an outcome has a 20 percent probability, does that outcome occur about 20 percent of the time in comparable people? Alternative-path forecasts must also be tested against observed responses to interventions, not merely fitted to historical associations. Every personal forecast should be presented as provisional and updated as the individual record grows and the science improves.



Genetics belongs in that forecast, but not as destiny. The genome can inform inherited predisposition; current state, exposures, behavior, treatment, environment, and chance all shape what happens next. In a four-study analysis involving 55,685 participants, genetic and lifestyle factors were independently associated with coronary disease. Among participants at high genetic risk in the three prospective cohorts, a favorable lifestyle

was associated with a 46 percent lower relative risk of coronary events than an unfavorable lifestyle.[8] In two large U.S. cohorts, men with four or five of the study's low-risk lifestyle factors were estimated at age fifty to have about eight more years free of cancer, cardiovascular disease, and type 2 diabetes than men with none; the corresponding estimate for women was about eleven years.[9]

Those findings are observational associations, not guarantees for an individual, and they do not show that lifestyle outweighs genetics in every person or every disease. They can identify plausible factors to investigate at the population level, but they do not by themselves support a causal estimate of how much a particular choice will shift one person's forecast. They do show that inherited risk and modifiable risk can coexist—and that meaningful room to move often remains.

> **A current-path forecast is therefore not a sentence, but one conditional hypothesis. Alternative-path forecasts are additional hypotheses about what may happen if a specific, causally supported change is made.**

SECTION 05

Can Healthspan Be Modified?

Identifying Real Levers and Putting Them Into Practice

The Modifiable part of the framework also has two linked tasks. Modifiability asks whether a better path is real and responsibly available: Is the lever causally credible, safe, feasible, accessible, acceptable, and within someone's power to act? Modification is what follows—choosing a path, putting it into practice, measuring the response, and learning from what happens. Together, they form the third part of the loop.

A variable can predict decline without causing it. A smoke alarm contains information about a fire, but silencing the alarm does not put the fire out. In the same way, lowering a predictive biomarker will not necessarily improve health unless that biomarker lies on a causal pathway—or reliably tracks something that does.

> " A smoke alarm contains information about a fire, but silencing the alarm does not put the fire out.

[8] Khera AV, Emdin CA, Drake I, et al. Genetic risk, adherence to a healthy lifestyle, and coronary disease. New England Journal of Medicine. 2016;375(24):2349–2358. doi:10.1056/NEJMoa1605086.

[9] Li Y, Schoufour J, Wang DD, et al. Healthy lifestyle and life expectancy free of cancer, cardiovascular disease, and type 2 diabetes: prospective cohort study. BMJ. 2020;368:l6669. doi:10.1136/bmj.l6669..

This is the distinction between a risk marker and a lever. Prediction can identify where risk is concentrated and, when causal evidence exists, estimate how outcomes might differ under alternative paths. Modifiability asks whether the proposed lever is both causally credible and practically usable.

For alternative paths, the same causal evidence serves both Predictable and Modifiable. In Predictable, it supports an estimate of what may happen under a different path. In Modifiable, it helps establish that the factor is a genuine lever rather than merely a marker. Evidence may come from randomized trials where feasible; convergent mechanistic, quasi-experimental, and longitudinal studies where trials are impractical or unethical; and carefully designed within-person experiments when the question is individual and the intervention is safe. But practical modifiability requires more than evidence: the option must also be safe, feasible, accessible, acceptable, and within the authority or capacity of someone who can act. The target is not merely a better number on a dashboard. It is better function, lower disease burden, greater resilience, or a longer period of life lived well.

Return to the two fifty-two-year-olds. Prediction may suggest that the best alternative for the person with a stable trajectory is protective: preserve strength, sleep, social connection, cardiovascular fitness, and the routines that support recovery. For the person with accelerating decline, it may point instead toward finding and addressing the drivers of that change—perhaps a treatable illness, medication effect, sleep disorder, loss of activity, metabolic deterioration, depression, environmental stress, or some combination. Modifiability asks whether the most promising alternative is actually appropriate and available; modification begins when it is chosen and acted upon. The same current score does not imply the same forecast, and the same forecast does not imply the same feasible action.

Modification should be treated as a structured learning process: choose an evidence-based intervention, define what improvement should look like and over what period, put the intervention into practice, measure adherence along with benefits and harms, and update the forecasts. Act, re-measure, re-predict.

Not every turn will narrow uncertainty. A null response may suggest that the presumed lever was wrong—or that the dose, duration, adherence, or measurement was inadequate. Conflicting signals may widen the range of possibilities. That, too, is learning. The observed response becomes new measurement, helping the model estimate more accurately how this individual responds to particular choices. The value of the loop is not that it always confirms the model, but that it gives the model repeated chances to be corrected by reality.

Modifiable must not be confused with personally controllable. The category includes levers at multiple levels: individual action, clinical care, institutional practice, community conditions, and public policy. Air quality, work conditions, chronic stress, income, neighborhood design, discrimination, access to care, and social support all shape health trajectories. The relevant actor may be the individual, a clinician, an employer, a community, or a policymaker. A useful healthspan framework should identify changeable conditions without turning risk into blame.

SECTION 06

Making Healthspan Actionable:

The Measure–Predict–Modify Loop

Measurement without prediction becomes a static dashboard. Prediction without a modifiable path becomes fatalism. Modification without measurement becomes guesswork.

Taken together, the three linked parts create a learning system that connects the retrospective concept of healthspan to a trajectory we can begin to measure, compare across possible paths, and influence while life is still unfolding. Measurable establishes what has happened and what is happening now. Predictable estimates what is likely under the current path and credible alternatives. Modifiable determines which alternatives are real and responsible, then puts one into practice and returns the result to measurement.

That system must remain modest about what it knows. Lived Healthspan is a proposed construct that must be defined and validated. Current-path and alternative-path predictions will always contain uncertainty, and the latter require causal evidence, not just pattern recognition. A modeled alternative may still fail the modifiability test because it is unsafe, inaccessible, infeasible, or beyond the control of the relevant actor. And no amount of data eliminates biology, circumstance, or chance. Life is for the living, and no model can fully account for all that lies ahead.

But uncertainty is not the same as helplessness. A forecast on the current path may be the least interesting future a model can show, because it is the one future that new evidence and effective action may allow us to refuse. Alternative-path forecasts can show where the trajectory might bend; the Modifiable part of the loop determines whether a path is real and then puts it to the test.

> " A forecast on the current path may be the least interesting future a model can show, because it is the one future that new evidence and effective action may allow us to refuse.

Aging remains inevitable, and it will likely never be fully predictable or controllable. But it need not remain wholly opaque. We can create enough visibility, early enough, to make better decisions while they can still matter: measuring the health already lived, forecasting both the current path and plausible alternatives with honesty, and acting on the levers that can responsibly bend the trajectory toward more life in those years.

By learning across many personal trajectories—and from the interventions and conditions that do or do not shift them—we can deepen our understanding of which levers can extend healthspan and make that knowledge more useful to everyone.

ABOUT THIS RESEARCH

This perspective was developed by Healthspan Horizons, a research initiative led by Nathan Price and Yi Sherry Zhang at the Buck Institute for Research on Aging.

Healthspan Horizons advances a federated, AI-enabled framework for integrating multi-omic, clinical, behavioral, and environmental data in service of longer, healthier lives.

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