DISSERTATION

THE COMPLEXITY AND DYNAMICS OF ENHANCING ENDURANCE PERFORMANCE

Submitted by

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ABSTRACT

THE COMPLEXITY AND DYNAMICS OF ENHANCING ENDURANCE PERFORMANCE

Enhancement of endurance performance has been a longstanding goal for professional athletes, military personnel, as well as health-conscious individuals. Traditional methods to improve endurance primarily focus on individual changes in physiology with training. Recent trends generally recognize that mental stress affects endurance and that psychological interventions can affect behaviors that sustain activity. Current methods treat physiological and psychological factors separately in different disciplines as linear processes with one-size fits all solutions. This representation fails to capture the evolving dynamic interactions and feedback loops between physical and mental endurance attributes over long duration sustained activity which vary with individuals. This mental model could be why the United States civilian and military population suffer from higher rates of obesity and mental health diagnoses than many global peers, despite spending the most on fitness and wellness. The gap in research is that there are no combined behavioral, mental, and physical system dynamical models for endurance.

This dissertation develops new Systems Dynamical models that combine behavioral, mental, and physical aspects of endurance. These models account for individual variability in physical, mental and behavioral factors that affect endurance and capture the dynamic feedback loops between them that result in the evolution of physical and mental endurance over time. To accomplish this, the research applied a Model Based Systems Thinking (MBST) approach that utilizes a suite of tools including causal loop diagrams, agent-based modeling, system dynamical causal modelling as well as rigorous analyses to simulate the complex, evolving interactions between physical, mental and behavioral factors that affect endurance. The primary contribution of this research is a set of Endurance models that enable understanding and predicting how changes to activity affect physical and mental endurance over time. This enables tailoring training methodologies to individual physical and mental factors allowing for a balance between physical and mental endurance enabling sustained activity. This research provides an Endurance Power(EP) metric that captures the effect of perception of effort on ability to perform an activity. This can prevent overtraining and stopping an activity due to mental stress. The dissertation provides strategies based on model insights that enable tailoring training for civilian and warfighter groups and individuals to optimize endurance enhancement over time.

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DEDICATION

To my parents who taught me that dreams are achievable with hard work and perseverance.

To my daughter (Megan Chappell) who inspires me to be the best version of myself

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NOMENCLATURE AND KEY DEFINITIONS

Acronyms

- ABM: Agent-Based Model
- SDM: System Dynamical Model
- MBST: Model Based Systems Thinking
- MTQ: Mental Toughness Questionnaire
- DOW: Department of War
- PFA: Physical Fitness Assessment
- BCA: Body Composition Assessment
- RPE: Ratings of Perceived Exertion
- Vensim: Visual Enumeration and Simulation (The software used for SD modeling)

Key Definitions

- Endurance: The ability to sustain moderately intense activity over long periods of time by balancing the complex, dynamic interaction between mind and body during the activity.
- Psychobiological: The study of how physical /biological processes influence mental states and behavior
- Psychosociophysical: The study that involves the constant interaction between your mind (psycho), your relationships and environment (socio), and your actual body (physical).
- Mental Fatigue: A temporary, "psychobiological" state of tiredness, caused by prolonged, intense cognitive activity.

- Perception of Effort(Perceived Exertion): The subjective feeling of how hard, heavy, or strenuous a physical task feels to you while you are doing it.
- Subjective Norms: Perception of social pressure. It is what you believe "important" people in your life (family, friends, peers, or society) think you should do.
- Intrinsic Beliefs: Personal feelings about the outcome of an action. It’s based on whether you think the behavior is "good" or "bad" for you.
- Control Belief: Perceived power over a situation. Beliefs about the presence of factors that may facilitate or hinder your ability to perform the behavior.
- VO2max: A measure of the maximum amount of oxygen your body can utilize during exercise to burn calories to fuel endurance activities.
- EPower: A metric that evaluates the joint effects of the physiological and psychological variables at a given time on a runner’s expected performance.
- Novice – low fitness/unfit
- Average – medium fitness/ fit
- Elite – high fitness/super fit

Systems Modeling

- Agent-Based Modeling (ABM): It is a bottom-up computational simulation technique used to model the actions and interactions of individuals or entities within a complex system. The agents interact among themselves and their environment by following defined rules that can lead to emergent, often unexpected, collective behaviors.
- Reinforcing & Balancing Feedback Loops: Reinforcing loops occur when a change in one direction leads to more change in that same direction. It drives exponential growth or

collapse. Balancing loops (B) occur when a system tries to resist change and return to a stable state.

CHAPTER 1.0 INTRODUCTION

1.1 What is Endurance?

Enhancement of endurance performance has been a longstanding goal for professional athletes, military personnel, as well as health-conscious individuals. The classic definition of endurance is the ability to sustain prolonged physical or mental effort, resisting fatigue, stress, or hardship over time (*Merriam-Webster.Com Dictionary*, 2026). It describes long-duration activities such as training for or running a marathon, cycling the Tour de France, swimming the English Channel, military training and combat situations. Endurance, stamina, and resilience are often used interchangeably and relate to sustained performance but describe distinct ways the body and mind handle stress and activity. Endurance is focused on duration and describes the maximum amount of time you can sustain an activity. Stamina is focused on intensity and describes the ability to perform at peak or near-peak effort for as long as possible. Stamina is typically used in the context of having the ability to maintain high-intensity effort for a short period of time or repeating an intense activity many times, combining physical energy and mental focus like sprinting or powering through a demanding task. Resilience is focused on recovery and describes the ability to bounce back or adapt after a setback or hardship. Stamina and endurance are focused on delaying fatigue and stopping an activity whereas resilience is about how to bounce back from the activity or recover from fatigue. All three require effort from the body and mind in different ways.

From a cardiovascular system perspective, endurance focuses on the amount of oxygenated blood the heart can pump per beat. High endurance is marked by a lower resting heart rate and efficient delivery of oxygen to muscles. Stamina involves the ability of the heart to work at nearmaximum heart rates for extended periods. It is limited by how long the heart can fuel intense activity. Resilience in this context is the cardiovascular systems ability to recover from intense exercise and return to a normal heart rate quickly after a spike in stress.

From a pulmonary system perspective, endurance relies on the lungs' ability to steadily intake oxygen and expel carbon dioxide during prolonged, moderate activity. Stamina relies on Maximum Voluntary Ventilation (MVV) which measures the maximum volume of air a person can breathe in and out over a 12–15 second interval, usually extrapolated to a 1-minute rate. It determines how long you can sustain the "heavy breathing" required for high-intensity bursts. Resilience relies on respiratory muscle strength (diaphragm and intercostals) that resists fatigue. It also includes the lungs' ability to maintain function despite environmental stressors like cold air or pollutants.

From a muscular system perspective, endurance is driven by mitochondrial density and capillary growth in the muscles. Endurance utilizes primarily type 2 (slow twitch) muscle fibers. Stamina provides the ability to delay lactic acid buildup during high-power tasks. It is the capacity of a muscle to perform at its peak force repeatedly. It relies on type1 muscle fibers (fast twitch). Resilience in this context is about durability which is the muscle's ability to resist functional decline as fatigue accumulates. It involves repairing "micro-tears" efficiently through hormesis, a beneficial adaptation to stress (Peake et al., 2015). Research has shown that although the initial number of these muscle fibers is determined by genetics, a person's type of activity over time determines which ones grow more (Marsh et al., 2020).

From a psychological perspective, endurance requires the ability to stay in a repetitive state without stopping and ignore discomfort, stamina requires the ability to ignore the burn of maximum exertion and resilience requires psychological flexibility to recover from stress, trauma, or failure. Common terms that represent these desired mental abilities are mental endurance, mental toughness and mental resilience. They are typically used interchangeably but represent distinct psychological constructs related to how a person handles stressors, physical or mental setbacks, over time. Mental endurance focuses on sustainability and continuously maintaining performance over long periods. It is the psychological capacity of persistence to maintain and improve performance in challenging or fatiguing situations over time (Lorist et al., 2000). Mental toughness focuses on performance under pressure before or during an activity. For instance, if a person has experienced a traumatic situation before attempting an endurance activity, mental toughness could determine how well they perform that activity. It is a measurable personality trait that determines how a person responds to stressors and challenges regardless of the circumstances(Lin et al., 2017). This is a trait commonly seen in Olympic athletes. Mental resilience is focused on recovery, reacting, and returning to an original mental stable state after a setback or adversity. It is the psychological ability to survive and adapt to significant stress or trauma (Qiu et al., 2025; Toth et al., 2024).

This dissertation defines endurance as the ability to sustain moderately intense activity over long periods of time by balancing the complex, dynamic interactions between mind and body during the activity. This research aims to understand the complexity of the dynamics of enhancing endurance which relies on efficient cardiovascular, pulmonary and muscular systems as well as staying mentally engaged during the activity. Building endurance inherently involves all the previous factors discussed and cultivating specific behaviors to overcome challenges and achieve desired goals.

1.2 Why is building endurance important?

The benefits derived from improving endurance are dependent on the initial physical and mental fitness state for an individual. Benefits range from improvements in movement, weight management, and strengthening of bones and muscles, managing diseases and reducing risk for diseases, improved mental health to completing a marathon, cycling a 100miles or being combat ready for months-years (Hughes et al., 2018). Research has shown that increasing endurance can not only improve cardiovascular, pulmonary and muscular efficiencies by making them more durable under stress but also helps maintain the increased capabilities for weeks after stopping endurance type exercise (Ashcroft et al., 2024; Farrell & Turgeon, 2021). Studies have shown a direct correlation between higher endurance and increased longevity and lower mortality risk (Kalogerakou et al., 2022; Reimers et al., 2012). Improvements in endurance are scientifically linked to disease prevention and management including lower blood pressure, improved lipid profiles, a delayed onset of Type 2 diabetes and improved immune response (Mrówczyński, 2019; Nieman & Wentz, 2019; Teixeira-Lemos et al., 2011). Recent papers highlight the role of endurance exercise in the growth of new neurons and improves synaptic connectivity in brain regions responsible for memory and learning and as a treatment for depression and anxiety (Jachim et al., 2020a, 2020b; Ma & Mumtaz, 2025; Saraulli et al., 2017; Singh et al., 2026; Solmi et al., 2025; Vancampfort et al., 2025). Research from the University of Pennsylvania suggests that successful endurance depends on a collaboration between muscle fibers and specific neurons in the hypothalamus, which also helps regulate energy and weight (Kindel et al., 2026). This highlights the endurance brain-body dynamic connections.

For an athlete, different levels of endurance can make the difference between completing a race, reaching a personal best time or winning the race or medal. The implications of achieving improved endurance for a warfighter are significant. During peacetime operations, starting with endurance of a novice athlete can make the difference between qualifying for service in bootcamp or placement in special teams. Endurance at certain levels is required for staying qualified for military service. In combat situations, endurance can be a matter of life or death since it enables combat readiness which requires both physical and mental endurance. This is why new standards for military fitness have been enacted by the Department of War (DoW). Achieving the benefits of different levels of endurance requires sustained activity as part of a person's lifestyle and is a function of both mind and body (CDC, 2025; HHS, 2018; Reiner et al., 2013; Warburton et al., 2006). Conventional methods to improve endurance primarily focus on individual changes in physiology with training, blood volume enhancements, steroids, or other medications. Mental wellness is typically treated using meditation, yoga, etc. and measured separately using questionnaires and surveys.

1.3 The U.S. Fitness Paradox and Military Readiness Gap

Extensive research has led to an awareness of the immediate and long-term health benefits of exercise which has resulted in enthusiastic spending on fitness globally. The United States leads the world in physical activity and wellness spending. However, it suffers from higher-than-average rates of mental illness and lower physical fitness compared to global peers. The U.S. physical activity market is valued at $265 billion, accounting for nearly one-third of the global total (McGroarty Beth, 2025). Americans spend an average of $810 per person annually on fitness and more than 50% own fitness trackers (Nagappan et al., 2024). In 2025 the U.S. had one of the highest adult obesity rates among high-income nations at 47%, surpassing peers like the UK (28%), Australia, and Chile (OECD, 2025). Inadequate physical activity is estimated to cost the U.S. $117 billion in annual healthcare costs Nearly 48% of Americans reported being more stressed at the start of 2026 than in the previous year compared to global peers (Allianz, 2025). The “Fitness Paradox” depicted in figure 1, highlights how the U.S. population has lower physical and mental fitness than global peers despite spending the most on health and fitness(Newsome et al., 2024).

While the U.S. remains the world's top-ranked military power, it faces higher internal rates of obesity and mental health diagnoses than many global peers. The U.S. military is undergoing a major fitness overhaul to address a growing "readiness gap”.

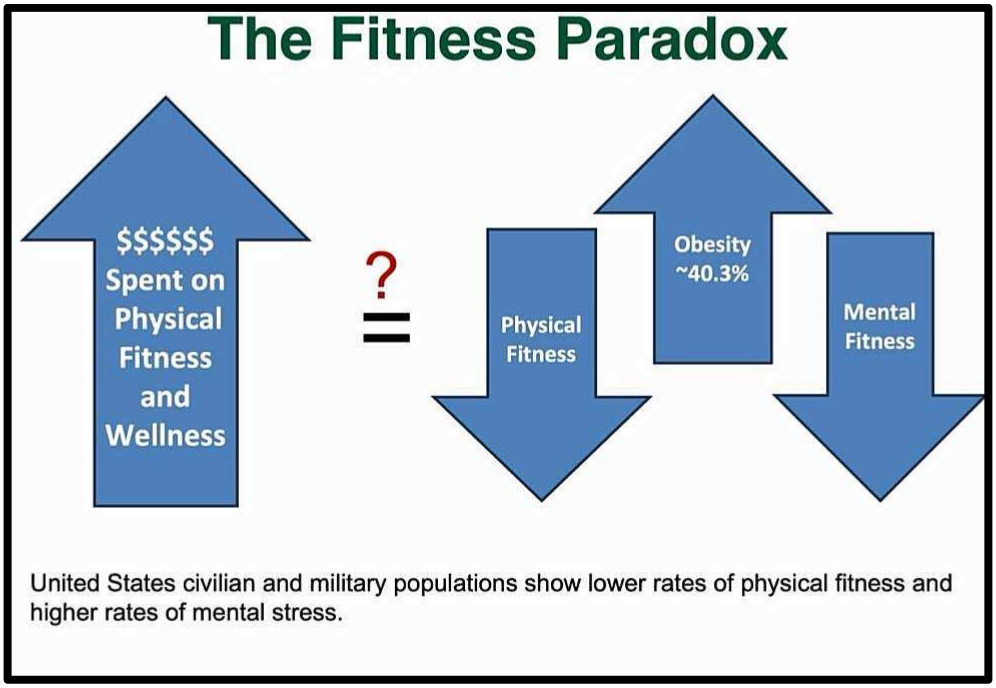


Figure 1: The U.S. Fitness Paradox. Physical and mental fitness dropping despite increased spending on fitness by U.S. population

An examination of the fitness paradox and military readiness gap, points to a problem with current mental models of endurance. Endurance is seen only from the lens of physiology which can be accomplished through rigorous training activities. This perspective came from the seminal work by AV Hill which provided an understanding that a person's physiology is dynamically changing during a training period and is affected by other parameters such as age, gender, physiology, and altitude. Although the original paper refers to a mental component, it was subsequently dropped by researchers using this work presumably due a lack of research quantifying its role in affecting fitness.

Typical methods for improving fitness and endurance involve creating and following training plans. Most training plans are generic and not tailored to a person's initial level of fitness unless prescribed by a physician for specific therapy activities. Most plans created by coaches or personal trainers for a client, only adjust a premade recipe for training to a few specific parameters such as gender, age, or injury. After the advent of the artificial intelligence revolution, planning methods and apps utilize machine learning techniques to learn previous behavior patterns from biometric data from wearables and come up with training plans that are followed. The top-rated apps attempt to incorporate weather and terrain into prescribing training and reevaluate based on recent performance. However, they are still causing subscribers to overtrain resulting in injury and stopping the activity.

Recent trends acknowledge the positive effect of physical training on mental stress of an individual. A recent national survey found that 78% of exercisers cite mental or emotional well-being as their top reason for working out, ahead of physical fitness or appearance goals (MindBody, 2022). Mindfulness training, yoga, etc. are other typical methods used to reduce mental stress. The effect of mental stress on physical endurance has been researched in terms of mental fatigue causing a perception of effort. Existing theories/models attempt to explain the physical mechanisms connecting the intensity of exercise to mental fatigue. This is based on the premise that exercise-induced muscle fatigue triggers mental fatigue and perception of effort.

This does not quantify the contribution to mental fatigue (Pattyn et al., 2018; Meeusen et al., 2021). Evaluations of mental stress are typically accomplished through questionnaires and surveys typically after cessation of a specific activity.

The current mental models of endurance treat physical and mental endurance training and evaluation separately. A systems perspective is necessary that looks at the problem as a dynamic interaction with feedback loops between mind and body over the duration of the activity that affect endurance. This requires incorporation of all the key physiological, psychological, and exogenous attributes that change over time and interact among themselves to affect endurance. This dynamic, evolutionary perspective is supported by research (Jones & Jones, 2024, Van Cutsem et. al, 2017) that highlights the fact that factors involving cardiovascular and muscular efficiencies change continuously during endurance activities/training depending on the intensity of exercise and affect physical endurance; and that mental endurance (in terms of perception of effort) may possibly contribute to physical fatigue.

Another key aspect of enhancing endurance is recovery. Recovery is recognized as an essential component to building physical and mental endurance. It is responsible for not only repairing tissues but also beliefs about what can be accomplished. The training stimulus creates stress, but the subsequent recovery period is when the physical and mental attributes get stronger. The complex recovery process happens via dynamic interactions between recovery strategies and fatigue, physical and mental endurance over a period of time through feedback loops. While endurance performance has been studied, significant research gaps exist on how individual recovery varies according to individual attributes.

This dissertation challenges the conventional focus on physical endurance and recognizes the contributions and interaction of both physical and mental endurance. It employs a model-based systems thinking approach to defining and modelling the endurance system. Enhancement of endurance varies by individual and requires both physical and mental endurance to sustain intense physical activity over a long period of time.

The ability to sustain continuous, strenuous, physical activity that is repeated over a period of time is a function of a homeostatic balance of individual physical and mental capability. The main idea of this research is that homeostasis (in the context of endurance), is the trend toward a balance between its interdependent elements of physical and mental endurance to sustain an activity over time. This balance does not imply a static state. It means that the contribution from physical and mental endurance is interconnected and constantly changing. It need not be equal at any given time but it should be balanced enough to sustain endurance. An imbalance between physical and mental endurance is expected at any time instant during an active period and can result in both positive and negative effects on overall endurance.

Endurance during sustained activity depends on the interaction between physical capacity and mental capacity. Each can support the other when one becomes limited. When the combined effect of both capacities is sufficient to sustain performance, the system maintains a positive balance. Performance continues because the individual can compensate for temporary weaknesses in either domain.

A negative balance occurs when the combined levels of physical and mental endurance are insufficient to sustain the activity. In this state, the body and/or mind cannot maintain the required effort. The system begins to fail under the accumulated demands of the task. This imbalance can lead to injury during prolonged physical exertion. Marathon events provide a clear example. Some participants continue to push beyond their physiological limits despite insufficient physical preparation. Mental drive sustains effort temporarily, but the physical system cannot support the demand. The result can be collapse, medical emergencies, or hospitalization. This example interaction shows that endurance is not purely physical or purely psychological. Sustained performance emerges from the balance between both systems. When that balance breaks down, risk increases and performance cannot be maintained. An example of negative imbalance is when reduced mental endurance due to mental strain can cause elite athletes to stop training or performing even though they were physically in top condition. e.g. Simone Biles (gymnastics), Naomi Osaka (tennis), Michael Phelps (swimming).

Achieving a positive imbalance that optimizes individual performance can be used to achieve performance higher than expected in a competition or warfighter setting. For example: Eluid Kipchoge who achieved a sub-2-hour marathon finish which was deemed impossible. Other examples of positive imbalance are Rose Harvey who completed the 2024 Paris Olympic marathon in under three hours despite sustaining a stress fracture in her femur just two miles into the race. She battled severe pain for 24 miles to finish the event. Military examples include several Medal of Honor recipients ranging from World War I (Sgt. Henry Johnson) to Afghanistan(Cpl. Dakota Meyer(2009), Staff Sgt. Ryan Pitts (2008), who despite being wounded saved numerous lives and held off enemy fire singlehandedly for a long time.

1.4 Problem Statement and Research Gaps

Health improvement requires sustained physical activity. Repeated exercise leads to adaptation in the body and the mind. These adaptations increase endurance and support continued performance.

Sustained strenuous activity depends on several physiological and psychological systems that interact over time. These systems regulate energy use, fatigue, recovery, and stability. Neural feedback supports homeostasis and maintains balance between mental and physical states. Endurance emerges from this interaction between body and mind.

Most conventional approaches to endurance improvement focus on physiological training. Training programs target cardiovascular capacity, muscular strength, and metabolic efficiency. These approaches treat endurance primarily as a physical property that can be improved through repeated physical stress.

Recent research in psychobiology shows that mental states also influence endurance performance. Mental fatigue can reduce physical output even when physiological capacity remains available. Psychological interventions can also change behavior and influence the willingness to sustain effort during demanding activity.

Current research does not fully explain how physical and mental endurance interact during prolonged exertion. The mechanisms that link physiological systems, cognitive states, and behavior remain unclear. The contribution of each domain to sustained performance over time is not well defined.

A unified framework is needed to study endurance as a dynamic adaptive system. Such a framework must integrate physiological, psychological, and behavioral processes. A combined dynamical model can capture how these elements interact over time to sustain or limit performance during prolonged activity.

1.5 Dissertation Approach, Research Questions with Outputs

This dissertation uses a Model Based Systems Thinking(MBST) approach to develop systems models of the complex, dynamic physical and mental interactions that affect endurance performance over a period of time. It applies Systems Principles to frame the problem and combines System Dynamical Causal Modeling (SDM) and Agent-Based Modeling (ABM) to provide a holistic methodology to enhance endurance for individuals and groups tailored to their specific physical and mental fitness levels.

Main Research Question: Can endurance performance be characterized as a function of mental and physical attributes?

A: Yes: It is possible to set up all the relevant feedback loops to represent complex interactions between those systems that occur synergistically and evolve over time.

RQ1: Can the relevant physical and mental attributes that affect endurance be identified and the causal connections between them captured?

A1. Yes: Observational data and literature search were used in a systems thinking framework to identify attributes and causal connections between them.

The data was used in development of tools such as causal loop diagrams(CLD) and holistic System Dynamical Models of endurance that explain the interplay and contribution of physical and mental endurance on sustaining, strenuous activity for periods of time. These include:

1. Endurance Agent Based Model with associated CLD
2. Endurance System Dynamical Causal Model with associated CLD
3. Recovery for Endurance System Dynamical Causal Model with associated CLD

RQ2: Can the combined dynamics and interaction of physical and mental aspects be modelled?

A2. Yes: Using the data and causal loop diagram, a holistic Endurance System Dynamical Causal Model was developed that explains the interplay and contribution of physical and mental endurance on sustaining, strenuous activity for periods of time.

Key Findings:

- Confidence and motivation act as a bridge between Mental and Physical endurance
- Physical attributes such as weight, body fat percentage, BMI and training intensity have an impact on physical and mental endurance.
- Initial Physical and mental endurance with physiology affect outcomes
- Mental stress affects endurance and the motivation to sustain activity
- Increasing training intensity will increase physical and mental endurance to a point but motivation drops-dependent on initial physical fitness

RQ3:Does performing an activity with others change physical and mental endurance?

A3:Yes: A novel Endurance Agent Based Model which captures peer group effects and a new behavioral model for endurance were developed to incorporate the effects of physical and mental changes and decisions made during an activity to sustain that activity.

Key Findings:

- Running with others can contribute to improvements in physical endurance.
- Initial physical and mental fitness of interacting runners(type of runner) affects the physical and mental endurance of the runners.
- Motivation and confidence change dynamically over time, and both affect and are affected by mental and physical endurance.
- Novice runners may need to ramp up their training pace slowly and build up their confidence to gain physical endurance

- Average runners are likely to stop running if they are pushed too hard to increase their pace to match a running buddy
- Elite runners are motivated by the improvement in pace and the increased perception of effort, which drives their perceived value and intention to keep running

RQ4: Can changes in mental models that affect behavior and recovery choices be modeled?

A4: Yes: A novel Recovery for Endurance Systems Dynamical Model was developed that shows the inter influence of recovery methods on fatigue, physical and mental endurance.

Key Findings:

- Mental recovery is affected by physical strategies
- Physical & mental endurance and training intensity affect overall recovery
- Timing of recovery methods affects how quickly and how much a person recovers
- Combining recovery strategies is critical to reduce fatigue since time constants for recovery strategies are different
- Sleep has a cumulative effect on recovery
- Active recovery (stretch, walk, run) must match fitness level of runner otherwise can cause overtraining specially in lower fitness
- Mental stress reduces recovery effect on physical and mental endurance
- Delayed hydration and diet slow down recovery
- Model integration of individual physical and mental endurance with recovery strategies explains real world individual variability of response to recovery methods

RQ5: How can we rigorously gain confidence in model-based findings?

A5. The system dynamical models utilize and build on knowledge gained from actual experimental and survey results for short duration exercise on athletes of varying fitness levels. The causal connections in the causal loop diagram and equations which characterize the relationships between parameters were developed from insights gained from actual data. Data from literature reviews reflect the ranges used for initial values for physical, mental, and behavioral parameters, and the rules used to update the agent attributes at every time step. This research combined multiple analytic approaches to provide empirical validation of the model outcomes with real-world data. These approaches were used for both individual behaviors as well as the aggregate patterns produced by the model. Sensitivity analysis was employed to explore how sensitive the model's outputs were to changes in its input parameters and assumptions. Detailed sensitivity and individual analysis were conducted to test for robustness. Validity assessments by domain experts were conducted to determine if the model and its outputs appear plausible and reasonable.

RQ6: How do you practically use the dynamic models to implement strategies for different types of individuals and groups?

A6: An Endurance Implementation Framework was developed that utilizes the insights gained and the models and metrics developed in the research. Models and analyses can be used to develop training strategies for civilian and military individuals and groups of various physical and mental fitness

- Sensitivity, Exploratory, and Correlation analyses provide insight into key areas to focus on for groups and individuals.

  - Endurance Agent Based Model: Elite runners need to be challenged to improve endurance
  - Endurance System Dynamical Causal Model: Increasing intensity for average fitness individuals can increase physical endurance but reduces motivation over time that can result in cessation of activity
- The dynamic models can be used to provide the best points of leverage and conduct predictive analysis and optimize training for individuals and groups.
  - Endurance System Dynamical Causal Model: Change in pace/intensity over time is best leverage for physical endurance
  - Recovery for Endurance System Dynamical Causal Model: Timing of recovery methods affects how quickly and how much a person recovers
- Metrics such as resting heart rate over time and EPower can be easily used to assess the effect of changes to physical and mental endurance as well as power needed to accomplish an activity
  - Endurance Agent Based Model-EPower metric incorporates the effect of perception of effort to calculate power needed prior to activity
  - Endurance System Dynamical Causal Model- Demonstrates how change in resting heart rate over time can be used to gauge gains/losses in endurance for various fitness levels.
- The relationship between research questions and models is shown in Figure 2. The models and metrics have value by themselves in understanding endurance. Interconnecting them adds even more value since it provides cross correlation and validation. In literature, researchers who have modelled individual aspects show certain

results for their specific focus and discipline. In this research, the integrated attributes and models show the results seen in many past different, disparate research experiments and studies. This provides confidence in the structure of the modelled system. The implementation framework provides even more value since it can be utilized by practitioners beyond just this research.

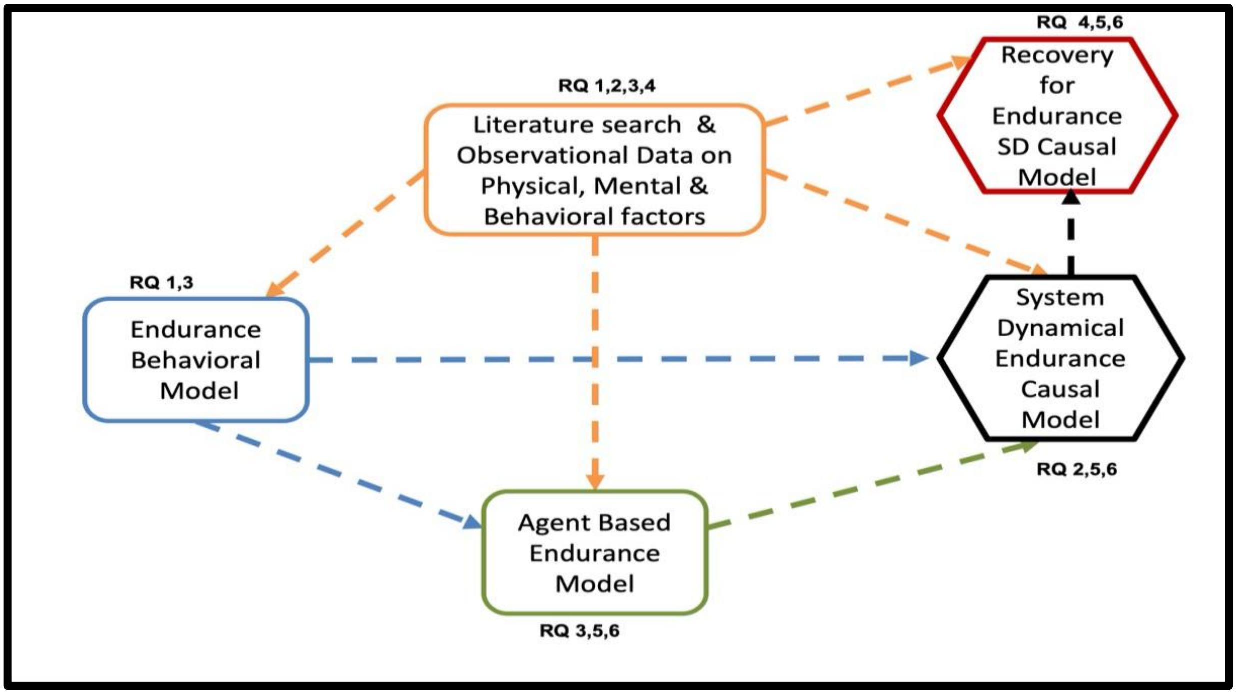


Figure 2: Relationships between key research models and research questions. Integration of models and methods provides greater cross validation of outcomes

1.6 Research Contributions

This dissertation advances the field of endurance and systems dynamics science by extending Model-Based Systems Thinking (MBST) into the domain of human endurance, a complex, multi-scale, physical and psychological phenomenon not traditionally modeled using formal system dynamics architectures. The research conducted in this dissertation is the first application of Model Based Systems Thinking (MBST) to the non-traditional problem of enhancing endurance. It utilizes a cross disciplinary, holistic approach to fuse and leverage the body of knowledge in exercise science related physiology, psychology, and psychobiology, with behavioral science and systems dynamics and systems thinking to develop a model-based solution to the problem.

The research contributes a rigorous cross-disciplinary modeling framework that integrates physiology, psychology, psychobiology, and behavioral science within a coherent system structure. Utilizing a systems approach enables examination of the problem from multiple perspectives to extract causal connections and patterns of behavior across disciplines and time. The framework created uses rigorous systems thinking tools such as multidisciplinary Body of knowledge(Bok) exploration, systems principles, causal loop diagrams, systems dynamical causal and agent-based modelling coupled with various analysis methods to validate the model structure and results and gain insights into leverage points and strategies to solving the problem. The research conducted developed new causal loop diagrams based on extensive literature search that capture physical and mental attributes and causal connections. Examination of the problem from a practitioner's perspective, resulted in exploration of how social interactions affect physical and mental endurance. Investigation into existing behavioral models and theory resulted in the realization that a single theory in its typical context would be inadequate to represent this unique problem. This led to the development of a new behavioral model of endurance that combines behavioral theories such as Theory of Planned Behavior(TPB) and Prospect theory with physical inputs which has not been done before.

This research provides novel insights in the area of endurance enhancement and Systems Dynamics that have not been fully explored. It contributes to the field of Systems Engineering by demonstrating that the thought processes and tools can be applied to other disciplines. This research expands the application of model-based systems thinking to health, sport and military science which spans both civilian and warfighter domains. The models can be scaled to other endurance sports such as long-distance cycling and swimming and extended to include other areas such as strength conditioning and weightlifting. This research contributes to the systems engineering field both methodologically as well as technically. It advances the area of uncertainty quantification analysis in agent-based modelling by developing a new method to conduct a Monte Carlo simulation of an agent-based model. The method enables exploration of sensitivity to multiple variables with random initial values that change simultaneously, which has not been done before.

This research has developed an agent-based model of endurance that combines and connects physical, mental and behavioral attributes for sustainment of long duration activities. It utilizes a new set of coupled equations based on the literature search to describe causal connections between physical, mental and behavioral attributes and implement them as agent-model rules. The Endurance Agent Based Model (ABM) shows the impacts of running with others on physical and mental endurance for individual and groups with various initial physical and mental fitness levels. The introduction of a formal methodology for conducting multivariate Monte Carlo sensitivity analysis on an agent-based endurance model addresses a known gap in ABM validation practice. The analysis provided insights that the fitness level of the runner and who they run with and how often they run with them affects endurance. This can be used to tailor training strategies for runners of different fitness levels by pairing them up to optimize both their endurance. Detailed correlation analysis provided insights into how coaches and trainers should train runners of various fitness levels since they are motivated by and respond differently to training.

An Endurance System Dynamical Causal Model was developed that demonstrates the interaction and effects of physical and mental attributes on endurance. The model was used to explore two domains: enhancing civilian endurance and enhancing warfighter endurance. The model demonstrates the impact of physical attributes such as weight, body fat percentage and BMI and training intensity on physical and mental endurance. Model insights can be used to tailor training strategies to individual attributes to enable novice runners and trainees at bootcamp to increase endurance, resulting in fewer overtraining injuries and dropouts. It can enable warfighters to maintain fitness levels to meet new Department of War (DoW) physical fitness requirements and enable them to sustain operations while carrying gear averaging from 50-120 pounds during peacetime and combat. The model show how mental stress affects endurance and the motivation to sustain activity.

The holistic approach used in this dissertation revealed the importance of recovery which is another key aspect of building endurance. While endurance performance is studied, significant research gaps exist on how individual recovery varies according to individual attributes. This dissertation developed a novel Recovery for Endurance System Dynamical Causal model that shows how specific recovery methods evolve with feedback to produce better endurance performance depending on the initial physical and mental fitness of the individual. By modeling recovery as a feedback-governed stock rather than a passive rest interval, the work formalizes recovery as a structural determinant of long-term performance trajectories. This can be used to reduce the effects of overtraining and failure to achieve endurance goals due to physical problems from inadequate recovery and/or mental stress.

A new Endurance Power(EP) metric was developed that captures the effect of perception of effort on ability to perform an activity. It combines simple physics equations with the questionnaire-based Borg Rate of Perceived Exertion(RPE) scale assessment to determine the amount of power needed to perform a run at a certain intensity given a runners physical and mental attributes. This can be used by individuals and trainers to determine realistic strategies to build up training intensities to enhance endurance by incorporating the current physical and mental state of the runner. The Endurance System Dynamical Model incorporates a resting heart rate(RHR) metric that was implemented as a stock in the model. It captures the pattern of behavior of an individual's resting heart rate as it responds to changes in endurance over time based on their specific physical and mental attributes.

This dissertation contributes to the physiological community by providing a shift from single static performance metrics toward integrative dynamic modeling of endurance. Traditional endurance research isolates variables, like cardiovascular efficiency, lactate threshold, muscular strength, or psychological motivation. This research instead shows how endurance emerges from the coupled dynamics of these attributes over time.

The dissertation provides strategies based on model insights that enable tailoring training for groups and individuals to optimize endurance enhancement over time to gauge gains/losses in endurance for various fitness levels. It describes future applications of this work in both the civilian and military domains.

CHAPTER 2: LITERATURE REVIEW & SYSTEMS FOUNDATIONS

A diagnostic literature review of empirical data from disciplines ranging from physiology, psychology, sociology, behavioral science, psychobiology to systems science was conducted. This included a broad swath of information derived from observation, experience, or experiment, focusing on measurable evidence. The experimental empirical research is useful in determining cause-and-effect whereas observational data was better for identifying correlations or patterns. Data from literature was used to identify the key physical, mental and behavioral attributes that affect endurance, their patterns of behavior and the causal relationships between them.

2.1 Existing Physiological Research

Conventional ways to improve endurance focus on physiology and emphasize training to sustain moderately strenuous activities. The predominance of exercise research is focused on the physical state due to the significant contributions by AV Hill and Otto Meyerhof, who were jointly awarded the 1922 Nobel Prize for Physiology or Medicine for discovering the distinction between aerobic and anaerobic metabolism (Jones & Poole, 2008; Clark et al., 2019). It describes physiological changes that affect physical endurance that are a function of pulmonary, cardiovascular, and muscular efficiencies for an individual. The existing body of research is focused on the contribution of specific physical factors such as age, body composition, weight, height, gender and genetics that affect these efficiencies. Research has shown that the factors involving cardiovascular and muscular efficiencies change continuously during endurance activities/training depending on the intensity of exercise and affect physical endurance; and that mental endurance (in terms of perception of effort) contribute to physical fatigue. Lower-intensity activity, such as walking, does not increase endurance as much as a higher-intensity activity, such as running or cycling (Wang & Wang, 2023; Rognmo et al., 2004). Endurance performance is directly impacted by the intensity and duration of the activity(Seiler & Tønnessen, 2009). The intensity and duration are a function of an individual's fitness state, mental state, and physiology, and they impact the improvement of endurance (Schiphof-Godart et al., 2018). The fitness state is the individual's current physical capability to perform the activity, the mental state is their mental model towards performing the activity, and physiology is their cardiovascular, pulmonary, and muscular systems that respond to the activity. For someone starting from a lower fitness state, walking or just moving can be physically and mentally exhausting. This causes them to stop or at best conduct low intensity activities periodically

For a low-fitness individual, running a mile in 20 minutes is an endurance activity, whereas for a highly fit individual, running 26 miles in 2 hours is an endurance activity. For lower fitness individuals, this creates a reinforcing loop between initial lower physical and mental endurance resulting in reduced intensity and duration which maintains the lower fitness. This could explain why despite being enthusiastic about fitness and wellness and tracking their fitness, a predominant portion of the U.S. population has low physical activity and higher mental stress.

In long distance running, pace is an indicator of both intensity and duration of activity which can exhibit physical endurance at an individual level(Abbiss & Laursen, 2008; Roelands et al., 2013; Pageaux, 2014). For example, an individual with a running pace of 7 minutes per mile for 10 miles has a higher physical endurance than a person with a pace of 15 minutes per mile for the same distance. The adjustment of pace to optimize the sustainment of activity has been shown to be a function of both physical and mental endurance (Skorski & Abbiss, 2017).The dynamical models developed in this dissertation use pace and change in pace to represent the training load on an individual during a run/activity.

Endurance arises from physiological adaptation across several body systems. The pulmonary, cardiovascular, and muscular systems interact through continuous feedback. These interactions regulate oxygen delivery, energy production, and waste removal. Endurance develops as these systems adapt to sustained activity.

Figure 3 illustrates the interconnections among these systems. Understanding the figure requires a clear view of the processes within each system and the boundaries that define them. Each system performs a specific function. Sustained performance depends on how these functions operate together.

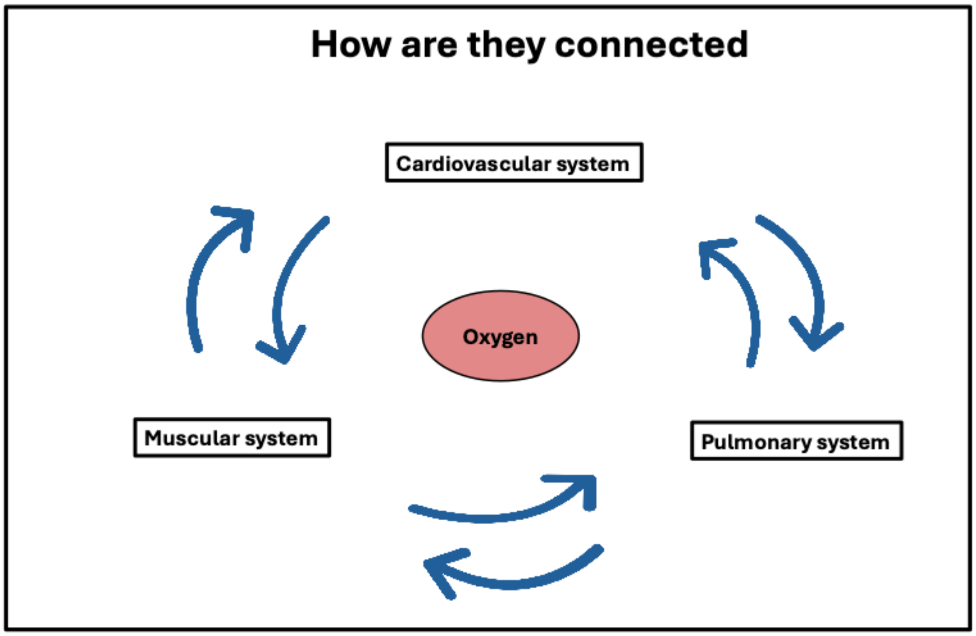


Figure 3: Feedback between Cardiovascular, Pulmonary and Muscular Systems. Dynamic interactions between these systems affect physical endurance

Pulmonary respiration begins the process. Oxygen enters the lungs during inhalation. Carbon dioxide leaves the body during exhalation. Oxygen diffuses into the bloodstream and becomes available for transport through the circulatory system.

The cardiovascular system distributes this oxygen throughout the body. The heart pumps blood to the lungs to receive oxygen. Oxygenated blood then travels through the arteries to active tissues. This circulation supports metabolic activity during exercise. At the cellular level, muscles convert energy through aerobic metabolism. Mitochondria use oxygen to produce adenosine triphosphate (ATP). ATP provides the energy required for muscular contraction and mechanical work. This process produces carbon dioxide and water as metabolic by-products. Skeletal muscles use the available oxygen to sustain repeated contractions. These contractions generate movement and physical work. Muscle tissue also uses metabolic energy to repair fibers that experience strain during exercise.

Exercise produces metabolic waste. Lactate, often called lactic acid, forms when cells break down energy sources during activity. Red blood cells and muscle cells contribute to this process. During lower intensity aerobic exercise, oxygen supports the breakdown of lactate within muscle tissue. This reaction converts lactate into carbon dioxide and water, which the body can remove through normal physiological processes. This enables sustaining exercise. The exercise intensity in which blood lactate levels start rising above resting levels is known as aerobic threshold and is the point where fat is broken down as fuel. As exercise intensity increases, the body does not have as much available oxygen for the muscles which causes lactate to build up. This causes a person to have a burning sensation and feel sore and fatigued. When blood lactate levels increase faster than the body can remove them, causing fatigue, a person reaches their lactate threshold. This is where the body starts relying on glucose for fuel instead of fat. A person can exercise for

30-45 minutes in this state. When the muscles run out of oxygen, the body reaches the anaerobic threshold and starts breaking down glucose that's already in muscles for energy. This can only be sustained for a few minutes before a person feels muscle cramps and has to stop or slow down exercise. This is important to understand because increasing a persons' aerobic, lactate and anaerobic threshold will cause them to have increased endurance. Although there are several types of physical endurance such as aerobic endurance, anaerobic endurance, speed endurance and strength endurance, aerobic endurance is the foundation for all of them.

A diagnostic literature survey was conducted to explore aerobic endurance in runners and the factors that affect them. The research in this thesis is based on the premise of low to moderate intensity exercise loads to sustaining an activity. Based on available data, common practice, and the practicality of measurements, this research uses VO2max as a primary metric of aerobic endurance and fitness (Wasserman et al., 2011). It incorporates running economy as a factor that improves endurance. VO2max is a measure of the maximum amount of oxygen your body can utilize during exercise to burn calories to fuel endurance activities. It is measured as maximum milliliters of oxygen consumed in 1 minute per body weight in kilograms. The more efficiently your body utilizes the oxygen the more energy is produced and the longer you can sustain exercise. Improved pulmonary function will increase the oxygen supplied to the muscles but if its utilization is not optimized then the athlete will not be able to sustain the exercise for long. Increasing VO2max with training increases not only the oxygen uptake in all muscle fibers but also increases leg muscle strength and power which improves running economy. Another important benefit of higher V02max is that it impacts the rate at which lactate can be oxidized and cleared during moderate to high intensity exercise. The longer the distance, the more important VO2max becomes. This is because fuel burning efficiency increases as type of muscles used for endurance activities become stronger and increase, so they require less energy expenditure to maintain a pace. For shorter endurance distances, this efficiency can translate to higher power and therefore faster speeds and reduced times for the same distance.

In endurance performance, VO2max, lactate threshold, and running economy are the three key variables that interact to determine an athlete's sustainable running speed. VO2max is the maximum rate at which your body can consume oxygen and defines the absolute upper limit for aerobic metabolism (Ranković et al., 2010). Lactate threshold is the exercise intensity at which lactate accumulates in the blood faster than it can be removed. It is expressed as a percentage of VO2max and determines how much of a person’s metabolic ceiling can actually be used for an extended period without fatigue. Common percentages are ~50–60% of VO2max for untrained athletes and 85–90% of VO2max for elite athletes (Kelly, 1989; W. D. McArdle, 1996).

The physiological factors that determine lactate threshold are extremely complex and include density of mitochondrial efficiency that affects oxidative capacity of skeletal muscles, muscle fiber type, ability of the heart, liver, and non-active muscles to uptake and remove lactate from the blood, density of capillarization and enzymatic levels and pathways (Alvero-Cruz et al., 2019; Joyner & Coyle, 2008). Running economy is the oxygen cost required to run at a specific submaximal speed and dictates the actual running speed produced for a given level of oxygen consumption. The physiological determinants of running economy are very complex and include neuromuscular efficiency, elasticity of muscle-tendon connection, body mass and body fat quantity and distribution, heart rate and breathing efficiency and capacity to oxidate fat (Barnes & Kilding, 2015; Joyner & Coyle, 2008). Since running economy is the energy cost of running at a speed, it can be considered as a way to fine tune performance. So, the lower your VO2 is at a certain pace, the better your running economy. Running efficiency, or economy, is determined by a combination of biomechanical techniques such as gait, physiological factors and training habits that minimize energy expenditure at a given pace. Key factors include low vertical oscillation, faster cadence, increased tendon stiffness, and improved aerobic capacity (VO2 max). It is heavily influenced by genetics, body composition, and, importantly, consistent, high-volume training. Running Economy can be improved over time through various training mechanisms to achieve better running form to reduce vertical oscillation, shorten ground contact time, increase stride rate to ideally 180+ steps per minute, maintain an upright posture with minimal trunk movement and small amplitude arm swing motions. Consistent training volume and intensity, strength training, lightweight footwear can improve running efficiency whereas environmental factors such as high temperatures, humidity and wind can negatively affect efficiency and performance (Cheung & Ngai, 2016; Fuller et al., 2015; Hottenrott et al., 2012; Lee & Kwon, 2025; Llanos-Lagos et al., 2024; Segreti et al., 2024). VO2max can be considered as endurance potential, whereas lactate threshold and running economy are considered predictors of performance of actual race times.

Another performance measure that is used to evaluate performance in high to severe intensity domains of athletic performance is Critical Power (Galán-Rioja et al., 2020). It is the greatest average effort that can be sustained for a period of time without fatigue. The Critical Power concept was extended to cycling by Moritani, T., et al. in 1981. The extension of the Critical Power(CP) model to running where it is specifically referred to as Critical Speed (CS) or Critical Velocity (CV) is primarily attributed to Hughson et al. in 1984 and is used to predict race performance. CP and the finite work capacity above CP (W') can be derived from mathematical models based on the power-duration relationship within the severe intensity domain (Hill et al., 2002; Poole et al., 2016). Critical Power is an individual metric derived from personal testing and involves 2-3 maximal, exhaustive efforts and the use of power meters (Burnley et al., 2006; Triska et al., 2015). Critical Power (CP) for running represents the highest sustainable, steady-state intensity (roughly a 40–60-minute maximal effort) that separates heavy from severe exercise domains, acting as a fatigue threshold. It is defined as the power-asymptote of the hyperbolic power-time relationship, with power output above this limit causing rapid exhaustion (Poole et al., 2016). Its relationship to VO2max is the intensity boundary above which VO2 maxes out. typically falling around 85–90% of VO2max. It is traditionally determined through 3 to 5 constant-work-rate or time-trial tests to exhaustion on separate days. Other high intensity Critical Power related measures are W' (W-Prime) and Functional Threshold Power (FTP). W' is the curvature constant of the power-duration relationship, representing a fixed amount of work that can be performed above Critical Power. It represents a finite energy reserve and is measured in kilojoules (kJ). It has been linked to high-energy phosphate depletion, glycogen availability, and the accumulation of fatiguing metabolites. Once W' is depleted, the athlete must drop below CP to recharge. FTP is the highest mean power an athlete can maintain in a quasi-steady state for approximately 60 minutes. FTP is estimated often as 95% of a 20-minute maximal effort (A. M. Jones et al., 2010).

The diagnostic literature search provided an understanding of key physiological dynamical variables and their causal feedback along with realistic initial and change expected values for them. For example, males of a specific fitness level typically have higher starting VO2max values versus females with similar fitness level due to differences in physiology (Cureton, 1981; Sharma & Kailashiya, 2016; Weiss et al., 2006). The increase in VO2max with training is also expected to be lower and take longer in females based on extensive studies and data from experiments. Similarly, training at different intensities will affect subjects at varied starting fitness levels differently. Nominal values of VO2max for novice, average and elite runners of all ages range from 30-60 mL/kg/min for men and 20-50 mL/kg/min for women. However, elite runners can reach VO2max levels as high as 90 mL/kg/min (Joyner & Dominelli, 2021; Santisteban et al., 2022a). Typically beginning runners with lower VO2max will see the most improvement with training. Elite runners typically show smaller increases in VO2max with training since they have already optimized it.

If a person gets injured and has to stop exercising, their VO2max will decrease with time and their training heart rate will increase. This is known as the detraining effect on $\dot{V}$O2max and is categorized as a short-term (less than four weeks) or long-term (more than four weeks) period of training cessation (Barbieri et al., 2023; Mujika & Padilla, 2000; Zheng et al., 2022). Studies show that $\dot{V}$O2max for highly trained athletes decreased by 4-14% after short-term detraining but decreased by 6-20% after long-term detraining. After 3 months, the drop in VO2max plateaus. The studies also showed that elite runners with high VO2max values tend to see more dramatic drops in VO2max with cessation of training whereas novice runners show a slower drop. These reductions can be restored when training is resumed (Bosquet et al.,2012 ; Klausen et al., 1981).

A diagnostic literature search revealed a summary of the factors that affect VO2max and their causal relationships. These are listed below:

- Age: Data shows that VO2max declines with age due to decreased heart and muscle function and strength and reduction in lean body mass (Betik & Hepple, 2008; Kim et al., 2016; Tanaka & Seals, 2008; Wiswell et al., 2001.)The rate of decline is approximately 10% per decade after the age of 25 years, and about 15% between the ages of 50 and 75 years. (ASTRAND, 1960; Hawkins & Wiswell, 2003; Robinson, 1938). VO2max age related declines for sedentary, active, and trained males were documented to be approximately 0.40, 0.39 and 0.46 ml/kg/min per year and for sedentary, active, and trained females were 0.35, 0.44, 0.62 ml/kg/min per year (Brown et al., 2007; Fitzgerald et al., 1997; Pimentel et al., 2003). Studies have shown that the decline is slower in athletes who continue to exercise, and training can slow the rate of decline in VO2max but becomes less effective after the age of about 50 (T. M. Wilson & Tanaka, 2000)

- Gender: Data shows that men have approximately (5-15%) higher VO2max than their female counterparts. In general, for similar fitness levels, men have higher VO2max levels than women due to difference in body composition including muscle mass, body fat amount and location in body, and heart size (Santisteban et al., 2022b; Sparling, 1980)
- Genetics/physiology: Several studies attribute the variations in VO2max in elite athletes to difference in genetics and physiology (Bassett & Howley, 2000; Bouchard et al., 1992; Wilmore & Costill, 2005). A person can inherit larger lung capacity, more efficient cardiovascular and muscular system which will affect their body's ability to use oxygen.
- Weight/Body Mass Index/Body Composition: In general, relative VO2max is inversely proportional to body mass index which is a function of weight and height and is used to determine a person's body fat percentage. Data suggests that decreased muscle mass and increased percent body fat in young adults as well as excess weight have a detrimental effect on aerobic capacity and VO2max (Mondal & Mishra, 2017; Rickta et al., 2024; Sun et al., 1998). Elite endurance athletes have a higher proportion of muscle mass which corresponds to aerobic endurance (E. R. Burke et al., 1977; Costill et al., 1976).
- Altitude: Training at altitude is used by elite athletes to boost overall VO2max levels. Studies have shown that maximal oxygen uptake increases by 5-7% overall for elite athletes after altitude training(Chen et al., 2023; Wilhite et al., 2013). However, the

increase in overall VO2max is not evident till after the training is completed since the athlete will experience a drop in VO2max while training. Training at altitude for untrained and moderately trained athletes may not provide as much of a benefit since their initial VO2max is lower which means it will be utilized to support resting oxygen requirements at altitude and could even impair cardiovascular function (Bailey & Davies, 2000; Constantini et al., 2017; Deng et al., 2025; Wolski et al., 1996).

- Training and Exercise Intensity: In general, higher intensity exercise with adequate rest and recovery exercises are attributed to higher VO2max. Various studies have shown a significant increase in VO2max with duration of intense training. This is caused by increased efficiency of oxygen transport within the body, increased oxygen extraction capability and other physiological changes. Data shows that training at any intensity above approximately 60% of VO2max is likely to improve maximal oxygen uptake in healthy adults (Brooks & Mercier, 1994; Dudley et al., 1982; Scribbans et al., 2016; Wenger & Bell, 1986).

2.1.1 Physiological Recovery

Most literature on endurance enhancement states that a key component to endurance is recovery. Effective recovery is a complex multidimensional process that happens via dynamic interactions between recovery strategies and fatigue. Recovery involves physiological, psychological, emotional, social, and behavioral aspects that interact together to combat fatigue (Braun-Trocchio et al., 2022). Recovery includes not only physical adaptations such as repairing tissues but also positive beliefs about what can be accomplished. The training stimulus creates stress, but the subsequent recovery period is when the physical and mental attributes get stronger. The complex recovery process happens via dynamic interactions between recovery strategies and fatigue, physical and mental endurance over a period of time through feedback loops. Recovery strategies are focused on replenishment of fuel, repair of muscles and restoration of endurance. Literature commonly divides strategies into proactive recovery techniques, passive and active recovery techniques. Proactive recovery requires individuals to choose activities prior to an activity that they determine will best help them recover and implement them based on preference. Proactive techniques include activities conducted hours to weeks prior to performing an activity such as extra sleep and rest, energy producing diet such as carbohydrate loading, sustained hydration, tapering training loads, monitoring biometrics using wearables, and social activities. Passive techniques range from external methods such as massage, rolling, cryotherapy to internal methods such as diet, hydration, sleep and inactivity. Active recovery techniques are physical activities aimed at compensating for the metabolic responses of physical fatigue such as stretching, walking, jogging and running (Braun-Trocchio et al., 2022; Crowther et al., 2017; Venter et al., 2010). While endurance performance has been studied, significant research gaps exist on how individual recovery varies according to individual attributes.

Recovery in endurance training occurs along a continuum. This continuum reflects increasing levels of fatigue and dysfunction. The recovery states range from overreaching to staleness to burnout. Each stage represents a different level of strain on the physical and psychological systems that support sustained activity.

Overreaching represents the mildest state in this continuum. Training load accumulates and produces a short-term decline in performance. The condition remains manageable. Athletes often experience muscle soreness, mild fatigue, and small reductions in performance. The time scale is usually a few days. Adequate rest allows the body to recover within two to fourteen days.

Recovery often leads to supercompensation, where performance improves beyond the previous level.

Staleness represents a deeper level of fatigue. Performance begins to decline even when training volume remains constant or increases. Athletes often report persistent fatigue, reduced motivation, and difficulty sleeping. Performance plateaus become common. The time scale extends over several weeks. Recovery requires longer periods of reduced training and rest. Full restoration may take weeks or several months.

Burnout represents the most severe condition in the recovery spectrum. The individual experiences chronic physical, emotional, and mental exhaustion. Training becomes difficult or impossible to sustain. Signs include severe performance decline, emotional fatigue, loss of interest in the activity, and symptoms of depression. The immune system may also weaken. Recovery requires extended withdrawal from intense training. The process may take several weeks or many months before normal function returns.

A well-known sports science phenomenon is the supercompensation effect which describes how a body adapts to and surpasses previous performance capability after physical training. The stimulus of a training load is applied, causes stress on the body leading to temporary fatigue and a decline in performance capacity. The body then recovers by repairing tissue and replenishing energy stores like glycogen and ATP. Depending on the level of recovery and adaptations by an individual’s body, their performance returns to the initial baseline. In the case of full recovery, the body continues to adapt and , reaches a peak where performance and energy levels exceed the starting point. This is considered as the optimal point to continue training to achieve performance enhancements. No further training will cause the body to eventually return to its original base level. Achieving the benefits of this effect is dependent on balancing the training intensity for an individual so that it is challenging enough to trigger adaptation but not so much that the body cannot recover. As training intensity increases, the amount of time to achieve supercompensation increases.

Another factor is the timing of subsequent training loads which can cause injury or overtraining if conducted too soon or no adaptation if too late (Kowalski et al., 2025; Nuuttila et al., 2021) This timing issue is compounded by the fact that different physical and mental systems recover at different rates and are dependent on individual physical factors such as diet, sleep, age, physiology, fitness level. For example, a high fitness older persons muscle glycogen may replenish in a day but their tendons could take longer due to age, whereas for a low fitness person younger person the recovery could be the opposite (Doering et al., 2016; Ivy, 1991; Kjaer M et al, n.d.; Tuite et al., 1997)

Research indicates that functional performance gains from supercompensation can require anywhere from a week to a month to fully manifest depending on intensity and timing of training and the fitness level of the person. Observations of VO2max show that it may remain stable or even slightly decrease immediately after a high intensity training period and then overshoot the baseline after a week of recovery. This is supported by studies which showed that structural muscle adaptations (fiber cross-sectional area) did not peak until 10 days post-stimulus (Bosquet Laurent et al., 2007; L. Wang & Wang, 2023). The Recovery for Endurance SD model developed in this dissertation spans a 30-day timeline to account for this window of recovery.

This research models the effect of passive recovery techniques as diet, hydration, and sleep duration and quality and active recovery techniques that range from stretching to running on various fitness levels. Proactive recovery effects are consolidated as initial recovery which is the starting point for all other recovery effects.

2.1.2 Passive Recovery

Diet or nutrition is a key enabler for recovery and its effect is dependent on the timing of intake, specifically protein and carbohydrates. Traditional research centered on elite athletes has shown that consuming these nutrients within the “anabolic window of opportunity” which is approximately 30 min to two hours post-exercise aids rapid recovery. This recovery practice supports multiple training sessions of elite athletes who are trained to maximize muscle protein synthesis and glycogen replenishment (Alghannam et al., 2018; Beelen et al., 2010; L. M. Burke et al., 2017; Margolis et al., 2021; Wang et al., 2024). Recent research has shown that average and novice athletes can meet recovery needs through a balanced diet without strict adherence to this specific timeframe. Novice or untrained individuals may experience more muscle damage initially and benefit from stable protein intake to support muscle repair and adaptation (Arent et al., 2020; Reljic et al., 2022; Zhang et al., 2025)

Inadequate nutrient intake can have adverse effects on an athlete performance, resulting in a reduction of fat-free mass, compromised immune function, decreased bone mineral density, heightened susceptibility to injuries, and an elevated occurrence of symptoms related to overtraining (Kerksick et al., 2018; Mountjoy et al., 2023).Vitale & Getzin, 2019 recommend that endurance athletes optimize performance by consuming 8–12 g/kg/day of carbohydrates, ensuring adequate protein (1.3–1.8 g/kg/day) for repair, and utilizing strategic hydration with electrolytes. In general, a 3:1 or 4:1 carbohydrate-to-protein ratio is recommended for post-exercise recovery. Recommended amounts of carbs and proteins for various intensity levels have been documented by observational studies(Evans et al., 2017)

Adequate recovery is contingent on fluid intake during, before, and after exercise. Proper hydration maintains cardiovascular health, aids nutrient transport, and accelerates muscle repair which is crucial for recovery across all fitness levels. Water transports essential nutrients to muscle cells, speeding up repair and reducing soreness and prevents excessive heat strain, allowing the body to recover faster. Hydration maintains blood volume, prevents high heart rates that slow down recovery, and helps flush out metabolic byproducts like lactate. Dehydration exceeding 2% of body mass significantly affects cognitive function and impairs performance, causing fatigue and slowing recovery and decreases power/strength by 3–6%, especially in high-intensity athletes. Average and novice individuals are typically less susceptible to rapid severe dehydration unless they have a high sweat rate. They can still suffer reduced performance and delayed recovery with increased soreness if hydration is neglected, especially in hot conditions. Elite athletes have higher sweat rates and lose more electrolytes as they train at high intensities. They typically need 100–150% of weight loss replaced to recover within 4 hours. (Pałka et al., 2023).Adequate and timely rehydration between training sessions is important when the period to rehydrate is brief or during hot conditions (Evans et al., 2017).

A recommended pre-training regimen for a well-hydrated state is ingestion of 500 to 600 mL of fluid (water or a sports beverage), 2 to 3 hours before engaging in exercise and an additional intake of 200 to 300 mL of water or a sports drink is recommended 10 to 20 min before the onset of exercise. During training fluid replenishment recommendations include ingestion of 200 to 300 mL of fluid at intervals of approximately 10 to 20 min depending on sweat levels. The focus of post activity hydration should be on rectifying any fluid deficits incurred during the activity. Research has shown that thirst may not be an effective indicator of dehydration since 1.5 L can be lost before thirst perception (Bergeron, 2007; Elliott et al., 2024; Judge et al., 2021). Research has shown that physically active individuals should eat and drink within 2 hours of physical activity to replace fluid, electrolytes, carbohydrates, and protein (Bergeron, 2007; Kaczmarek et al., 2025).

Sleep is the key restoration and regeneration element of recovery. It is a fundamental biological requirement which impacts individuals at all fitness levels. It facilitates hormone release which facilitates tissue repair through increased protein synthesis. Sleep is needed for psychological restoration as well as to replenish muscle glycogen stores, which are depleted during exercise. Insufficient sleep can reduce the body's ability to restore these energy reserves by up to 50%. Lack of sleep is strongly associated with higher injury rates and can affect sustainment of an activity. Fatigue from sleep loss reduces reaction time, coordination, and decision-making, which can lead to mistakes during training and further increase injury risk (Charest & Grandner, 2020). Sleep deprivation elevates the Rate of Perceived Exertion (RPE), making workouts feel significantly more difficult and saps motivation. Sleep quantity and quality are key factors that affect endurance. Sleep quality affects the production of cytokines that support immune function and can delay tissue repair and prolong soreness. The volume of sleep needed increases with physical demand. Novice or average individuals who typically have moderate activity levels should recover with consistent 7-9 hours of sleep. Elite athletes typically require 9–10 hours of sleep to fully recover due to higher training volumes and physiological stress. Research has shown that a reduced sleep duration of 4–6 hour, can cause decrease in endurance performance by 10–20% and maximal strength by 8–12% (Craven et al., 2022). Performing intense exercise less than four hours before sleep affects quality of sleep and recovery (Leota et al., 2025).

2.1.3 Active Recovery

Active recovery is low-intensity exercise performed after strenuous activity. The effects of different intensities of active recovery such as stretching, walking and jogging vary with individual fitness in both short-term and long-term endurance adaptations. Research shows that active recovery after strenuous exercise clears accumulated blood lactate faster than passive recovery in an intensity-dependent manner and that active recovery should be performed just below the individual's lactate threshold roughly 55–60% of heart-rate reserve(max heart rate minus resting heart rate), to achieve maximum effectiveness (Menzies et al., 2010). Observational studies have shown that recovery performance boosts even with active recovery sessions lasting 6-10 minutes (Ortiz Jr et al., 2018). For all fitness levels, active recovery improves mood and perceived recovery better than total rest. This is due to the triggering of endorphin release and reduction of the lethargy and inertia related to complete inactivity. The primary physiological difference between fitness levels is the Metabolic Clearance Rate (MCR) of lactate, which is significantly more efficient in trained athletes. In less fit individuals, low-intensity active recovery methods often will maintain a higher heart rate compared to athletes which can have the effect of increasing total cardiorespiratory demand instead of aiding recovery. This can slow down muscle glycogen replenishment because the body continues to oxidize lactate for fuel instead of converting it back to stored energy. High fitness individuals are sensitive to intensity of active recovery and get the most benefit when it is performed at 80–100% of their lactate threshold. Research has shown that for lower fitness individuals there is no significant difference in power output between active and passive modes. A key benefit of active recovery is reduced perception of muscle soreness and a higher clearance rate of lactate than passive rest for very lower absolute workloads. For elite athletes, active recovery maintains peak power output during repeated sprints significantly better than passive rest, can achieve greater gains in "critical power" and incremental power output over short timeframes, and increases the rate of return of blood lactate to baseline at moderate intensities (Gmada et al., 2005; Toubekis et al., 2005). A general rule of thumb for all fitness levels is to base the choice of activity recovery intensity on an activity that keeps your heart rate between 30–60% of your maximum. For lower fitness individuals, this will translate to stretching, leisurely swimming and walking whereas for higher fitness levels it could translate to jogging or cycling.

2.1.4 Physiological Systems Modelling:

A review of literature shows that systems dynamics modeling has been applied to several areas of health care and exercise physiology. Researchers have used tools such as system dynamics models, causal loop diagrams, flow association models, mathematical equations, transfer functions, and agent-based models. These approaches often examine individual components of health or performance. Most studies treat these components as separate systems rather than parts of a larger integrated structure.

Evidence of a Systems of Systems approach in this area is limited. Existing work focuses on system dynamics models of health care delivery and public health systems. Prior studies developed causal loop diagrams and simulation models to study disease epidemiology, substance abuse dynamics, patient flow in emergency and extended care, and health care capacity planning within population-based health organizations. Other research examined system behavior in dental care and mental health services. These models also explored interactions between health care capacity and patterns of disease spread (Homer & Hirsch, 2006).

Research in sports medicine has begun to apply system thinking to injury dynamics. A causal loop model of lower extremity injuries identified nonlinear relationships among several risk factors. These factors include biomechanical and neuromuscular quality, accumulated fatigue, and psychological influences. The model revealed the complex feedback processes that influence injury development in athletes. Insights from this work informed the development of the endurance recovery model presented in this research (Liveris et al., 2023). Another example is a systems equations model for cardiovascular, strength, skills and psychological aspects in the context of comparing the effect of different forms of training on performance provided insight into causal links and development of equations (Calvert & Banisteb, 1976; Taha & Thomas, 2003). Various first order and second order mathematical models have been developed to represent VO2 kinetic response to different exercise training intensities (de Lima et al., 2020). System Dynamical models for specific subject areas related to exercise and diet in the context of obesity treatment have been developed and provided insights into the relationship between weight and training (Abdel-Hamid, 2002, 2003).

(Abbiss & Laursen, 2005) developed an overall causal association model that links previous models for specific subject areas of cardiovascular/anaerobic, energy supply/energy depletion, neuromuscular fatigue, muscle trauma, biomechanical in the context of fatigue during prolonged cycling. Insights include recommendations to take a holistic approach and looking at interactions of developed linear fatigue models concurrently to evaluate effects on fatigue due to long distance cycling. Systems modeling is an effective approach to analyze the body's response to exercise and providing insights for training methodology and exercise medicine. Specific physiological parameters of heart rate kinetics and oxygen consumption during workloads of time-varying intensity can be simulated by a set of differential and state space equations (Stork et al., 2017).

Bioenergetic mathematical model for specific mechanisms related to contributions of the lactic, and aerobic systems as well as different sources of the total metabolic demand for cyclists have been proposed. They describe a non-linear grey-box parameter estimation method for individualizing bioenergetic model formulations to reflect an individual athlete's bioenergetic systems (Lidar, 2023).These models informed the development of the Endurance SD model.

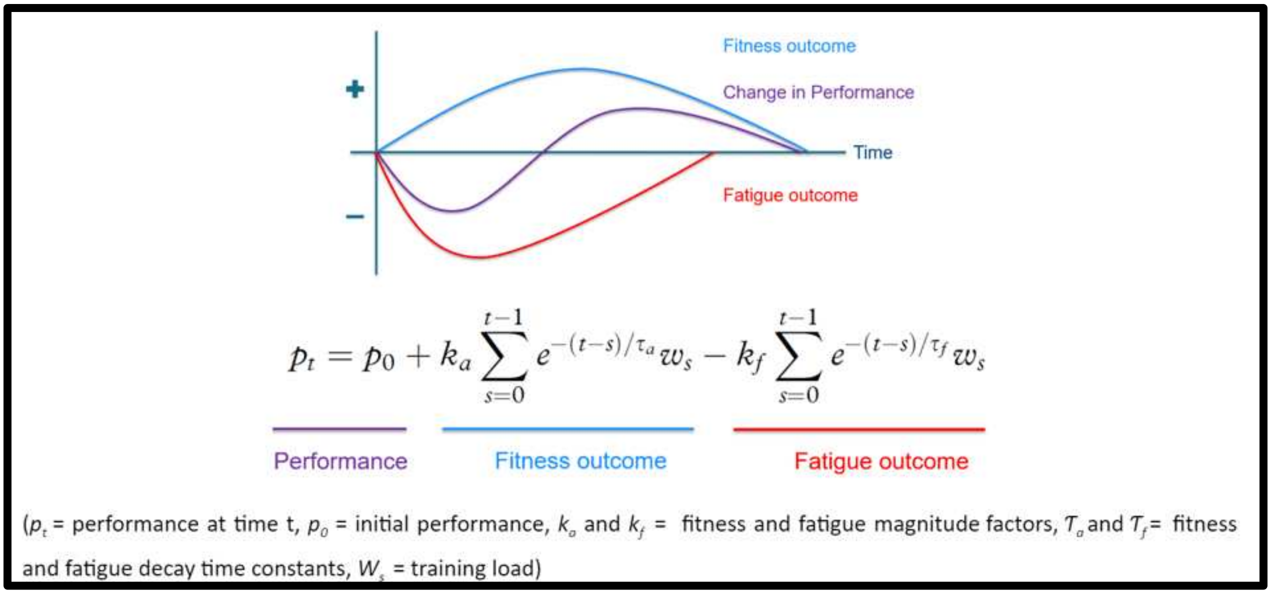
Flow causal models of exercise-induced central fatigue based on interoception (the ability to be aware of internal sensations in the body such as heart rate, respiration, hunger, fullness, temperature, emotion, and pain) and motivation have been proposed. They provide insight into the roles of brain catecholamines in decision making concerning if and when to stop exercising (McMorris et al., 2018).

Endurance exercise has been modelled as the physiological integration of cardiovascular, respiratory, metabolic-endocrine, and neuromuscular functions during endurance activities. This schematic model explores control of physiological responses by the central nervous system during endurance exercise using feedforward and feedback mechanisms in response to increased oxygen demand based on a set of equations. The interaction between these mechanisms allows precise control of the variables to attain a state of homeostasis during endurance exercise (Calderón-Montero et al., 2021)

Nonlinear mathematical models for heart rate response as well as dynamic system mathematical models (DSM), genetic algorithms (GA) and Artificial Neural Networks(ANN) have been used for predicting Heart Rate(HR) max and VO2max, as well as VO2 kinetics during walking and running at varied intensities on a treadmill. The ANN model could predict general VO2 responses from measured HR data for lower intensities fairly well but could not predict maximal values (Borror et al., 2018; Cheng et al., 2007). Machine Learning based models have been developed to analyze individual responses to different endurance training distributions (e.g., polarized vs. pyramidal) to identify the most effective strategy based on an athlete's unique characteristics and experience level. Results identified substantial inter-individual variability, with four distinct responder clusters comprising the study population, demonstrates that optimal training methodology selection depends critically on individual athlete characteristics rather than universal prescriptions. Another ML model developed to determine if machine learning models could predict the perceived morning recovery status (AM PRS) and daily change in heart rate variability (HRV change) of endurance athletes based on training, dietary intake, sleep, HRV, and subjective well-being measures was more effective in predicting recovery measures at the group level than individual level due to inter-individual variability (Rothschild et al., 2022.) Agent-Based Modeling of physical activity behavior and environmental correlations has been used to predict sustained walking behavior (Zhu et al., 2013). Agent-based models (ABMs) have provided a novel framework for investigating both tissue adaptations and cellular interactions in skeletal muscle during disease atrophy for elderly communities (K. S. Martin et al., 2015). Another example is an exercise physiology agent model developed to help understand the factors involved in generating the appropriate hormonal balance required to develop muscle from weightlifting. It showed that all five factors (frequency, sleep, intensity, genetic, and diet) must be understood and put into balance with one another in order to achieve optimal muscular development. The appropriate combination is highly dependent on the individual and their current, unique state which will change over time (Wilensky, 1999).

ABMs have been used to simulate a synthetic population of distance runners to study the relationship between weekly distance and injury. This research found that even staying within the recommended norms can eventually lead to injury as athletes hit individual physical ceilings (Hulme et al., 2019).

Systems models for recovery exercise recovery provide mathematical and theoretical frameworks to predict how an athlete's performance fluctuates based on the balance between training stress causing fatigue and subsequent adaptation improving fitness. Foundational systems models for exercise recovery are the simplified Banister systems model and the Fitness-Fatigue Model(FFM) which are based on the premise that every training session creates a negative fatigue effect and a positive fitness effect, which oppose each other and affect an athlete's actual performance at any time (Banister E et al et al., 1985; Calvert & Banister, 1976). The magnitude and rate for both effects are assumed to decay exponentially over time with fitness lasing longer than fatigue. Performance is defined as the difference between the fitness and fatigue modeled as two simple first order transfer functions. As seen in figure 4, the duration and intensity of a training load were modeled as an impulse with an exponential coefficient to model weighting factors. The TRIMP (Training Impulse) metric shown in equation 1, was defined to quantify the dose/ internal load due to physiological stress of a training session. It integrates workout duration and intensity via heart rate into a single numerical value to help predict an athlete's fitness and fatigue.



$$p_t = p_0 + k_a \sum_{s=0}^{t-1} e^{-(t-s)/\tau_a} w_s - k_f \sum_{s=0}^{t-1} e^{-(t-s)/\tau_f} w_s$$

(p_t = performance at time t, p_0 = initial performance, k_a and k_f = fitness and fatigue magnitude factors, T_a and T_f = fitness and fatigue decay time constants, W_s = training load)

Figure 4: Representation and equation of Banister Fitness Fatigue Model (Top Sports lab, 2020)

$$\text{TRIMP} = \text{Duration} * \text{HeartRate Ratio} * \text{Genderfactor}. \tag{1}$$

Where:

Duration = training time in minutes

$$\text{HeartRate Ratio} = \frac{\text{Average HR} - \text{Resting HR}}{\text{Max HR} - \text{Resting HR}}$$

Gender factor=accounts for gender differences in lactate response

$$Men = 0.64 * \text{e}^{1.92 * \text{HeartRate Ratio}}$$

$$Women = 0.86 * \text{e}^{1.97 * \text{HeartRate Ratio}}$$

There have been several alternative Heart Rate(HR)-based TRIMPs proposed including Edward's TRIMP which is calculated as a sum of time spent in five HR zones multiplied by zone-specific weighting factors; Lucia's TRIMP in which weighting factors are based on ventilatory thresholds instead of HR zones, and Session RPE that multiplies perceived exertion by duration which has been shown to correlate well with heart-rate-based TRIMP. Multiple improvements to the FFM ranging from alternative mathematical equations, statistics, and regression models to utilizing machine learning and data science methodologies have been proposed to improve its accuracy, overcome its simplification of physiological processes involved by exercise and account for individual variability of multiple factors responsible for an athletic performance (Busso et al., 1994; Imbach et al., 2022; Marchal et al., 2025; Pritchard et al., 2015). The fitness-fatigue model and its variants continue to play a role in sports performance science, providing foundational framework for quantifying the effects of training on athletic performance (Kontro et al., 2025).

While the various FFM and TRIMP models provide a mathematical framework for supercompensation, the equations and models used do not account for the inter-individual variability of recovery amounts and timelines. Gaps in research include assumptions of fixed recovery windows, lack of consideration of sleep quality or nutritional status in the recovery equation, psychological stress, heterogeneity of physical systems responses, and individual factors such as age, genetics and physical and mental fitness levels (Doherty et al., 2021; Halson, 2014; Herold et al., 2019; Minett & Costello, 2015; Stults-Kolehmainen & Bartholomew, 2012)

2.2 Existing Psychobiological and Behavioral Research:

Recent research has highlighted that a person's mental state contributes to the overall change in fitness and affects/modifies the physical state(McCormick et al., 2015a). Existing theories/models attempt to explain the physical mechanisms connecting the intensity of exercise to mental fatigue with the premise that exercise-induced muscle fatigue triggers mental fatigue and perception of effort but do not quantify the contribution (Pattyn et al., 2018; Meeusen et al., 2021). The terms mental endurance, mental toughness, and mental stamina are used synonymously in literature. The community acknowledges that mental endurance, in terms of persistence, may play a role in endurance enhancement. Although there is some research showing a general correlation between mental fatigue and decreased physical endurance, it does not examine the interaction between mental and physical endurance for long duration sustained activity (Marcora, 2019; Noakes et al., 2004; Slimani et al., 2018; Teixeira et al., 2012a) . The key contributor to mental endurance is motivation, with confidence as a second key factor (Konopka et al., 2022). (Mouratidis et al., 2008)showed that a lack of motivation and reduced performance are correlated. Current research on improving motivation explores exercising with others (Kohler effect) , self-talk/entertainment, having plans/goals, continuous training, and tracking progress (Duncan et al., 2010; Feltz et al., 2011; Meeusen et al., 2021b; Meijen et al., 2023). However, all of them are short-duration and focused on a specific contributor to motivation(Samendinger et al., 2019). Motivation differs between short-term (hours–days) and long-term (months–years) endurance exercise. Throughout prolonged activity, individuals continually assess their intent to persist, which influences behavior and varies with fitness level (Micklewright et al., 2017; Smits et al., 2014). In short-duration activities, physical (muscular) endurance dominates the motivation to stop the exercise (Gandevia, 2001),whereas in long duration exercise mental fatigue affects the motivation to stop exercising(Martin et al., 2018). Mental fatigue affects physical performance even in short duration (less than 2 hours) (M. R. Smith et al., 2015). The extent of the impact of mental fatigue is determined by the duration and intensity of activity (Van Cutsem, De Pauw, et al., 2017a). Older adults often report lower levels of chronic mental fatigue than younger adults. However, during sustained, high-difficulty tasks, older adults show a sharper decline in "responsivity," indicating they may disengage sooner as effort expenditure becomes too high.

In some studies, women and men experience similar levels of mental fatigue from prolonged cognitive tasks. However, women frequently report higher subjective levels of fatigue despite performing as well as or better than men on objective measures.

Research on elite athletes indicates that male athletes (ages 26–33) often show higher scores in mental endurance and emotional intelligence, while female athletes (ages 21+) tend to score higher in "mental training" (using techniques like self-talk).

Research shows that a person who is mentally stressed will feel a greater perceived exertion for an action compared to a less stressed one (M. R. Smith et al., 2016).This causes a reduction in physical ability even though their body may be physically able to carry out or sustain an action (Pageaux, 2014; Van Cutsem, Marcora, et al., 2017).

2.2.1 Psychological Recovery

Research on the psychological effects of training on recovery has shown that increased emotional and mental fatigue hinders recovery, increases injury risk and reduces overall well-being (Balk & Englert, 2020; Farahani Faezeh et al., 2026).New models and frameworks such as the Demand-Induced Strain Compensation Recovery (DISC-R) Model hypothesize that mental detachment (psychological recovery) is essential to prevent injury and restore mental energy and that recovery from a specific type of strain(physical or mental) requires a matching recovery activity of the same functional domain (Balk & Englert, 2020).Observational studies have shown that physical and mental fatigue alter decision making which has direct implications for sustainment of activity and sports performance (Farahani Faezeh et al., 2026). There is increasing awareness of the effect of cognitive load on physical performance and recovery. Although significant amount of research on recovery methods on physiology and psychology (especially injury) has been conducted separately, there is a paucity of interdisciplinary approaches that treat mental and physical recovery as one unit (Brooks Toby et al., 2022).

2.3 Metrics and Measures:

2.3.1 Physiological Metrics:

Physical endurance and fitness are typically assessed through a combination of physiological, performance-based, and subjective metrics. These measures evaluate the efficiency of the cardiorespiratory system and the stamina of specific muscle groups. Cardiorespiratory fitness (CRF) measures the ability of the circulatory and respiratory systems to supply oxygen to skeletal muscles during sustained physical activity. VO2max determines aerobic capacity and measures the maximum amount of oxygen the body can utilize during exercise in units of milliliters of oxygen per kilogram of body weight per minute. It is measured directly and indirectly though calculated methods.

Current Methods of VO2max Estimation:

There are three common ways VO2max is estimated.

- Direct Laboratory Tests: Elite athletes typically measure VO2max in a laboratory or clinic on a treadmill or bike. This is the most accurate way to measure and is typically used to baseline VO2max. The test uses a mask and heart rate monitor worn by the athlete to measure their oxygen/carbon dioxide exchange and heart rate. The protocol is after a 5-minute warm-up at 3-5 mph the speed or resistance is increased by 1-2 mph or 1-2% incline every 1-2 minutes until the person cannot carry on exercising.
- Indirect Tests: These are tests that can be carried out at home or by certified fitness instructors by walking or running and are more widely used by coaches as they require

little or no expensive equipment. Some are more reliable and accurate than others, but none are as accurate as direct testing. Commonly used equations to estimate VO2max for running include the American College of Sports Medicine (ACSM), Fitness Registry and the Importance of Exercise National Database (FRIEND), Léger and Mercier Equation (ACSM, 2021; Bosquet et al., n.d.; Foster et al., 1984; Jurov et al., 2023; Kokkinos et al., 2017; Léger & Mercier, 1984).

- Common tests are:
    - The Bruce Protocol Treadmill test: This test is often used for testing VO2 max in athletes or for signs of coronary heart disease in high-risk individuals. The test involves increasing both the speed and incline of the treadmill at 3minute intervals. The test starts at 2.74km/hr at a gradient or incline of 10%. At minute 3 the speed is increased to 4.02km/hr and the gradient increased to 12%. This data is used to calculate VO2max (ACSM, 2021).
    - The Cooper run test is carried out over 12 minutes and requires you to run or walk as far as you can in 12 minutes (Cooper, 1968). Distance covered is in kilometers for 12 minutes VO2max is calculated using eq 2 or 3.

$$VO2\,max = (22.351 \times distance\,covered) - 11.288 \tag{2}$$

$$VO2\,max = (35.97 \times distance\,covered) - 11.29. \tag{3}$$

    - The Rockport 1-mile walk test is similar to the Cooper run test but the calculation accounts for weight and age (Ashfaq et al., 2022; Kline G M et al, 1987)The test requires you to walk for exactly 1 mile on a level track/level surface as fast as you can and record your heart rate and walking time in minutes. VO2max is calculated using equation 4:

$$V02\max = 132.853 - (0.0769 \times weight) - (0.3877 \times age) + (6.315\ if\ male\ or\ 0\ if\ female) - (3.2649 \times walking\ time) - (0.1565 \times heart\ rate) \tag{4}$$

where: weight is in pounds, age is in years, time is in minutes, heart rate is in beats per minutes.

Other submaximal tests and their validity are documented (Bennett et al., 2016; Noonan V et al., 2000)

- Calculating VO2max from Wearable data.

Recent studies show that data from wearables can be used to calculate VO2maz just as well as direct measurements (Helgerud et al., 2022; Molina-Garcia et al., 2022)

VO2max can be calculated from heart rate in beats per minute, time in minutes and velocity in meters per second, by either equation 5 or equations 6-8.

$$VO2\ max = 15.3 \times (maxumum\ heart\ rate + resting\ heart\ rate) \tag{5}$$

$$\%VO2max = 0.8 + 0.1894393 \times e(-0.012778 \times time) + 0.299558 \times e(-0.1932605 \times time) \tag{6}$$

$$VO2 = -4.60 + 0.182258 \times velocity + 0.000104 * velocity2 \tag{7}$$

$$VO2max = Vo2/\%Vo2max \tag{8}$$

Recent advances in artificial intelligence and machine learning have provided another way to calculate and predict VO2max from indirect tests and health data (ACSM, 2021; Foster et al., 1984; Jurov et al., 2023; Kokkinos et al., 2017; Léger & Mercier, 1984). Common predictive machine learning methods used are support vector machines, multiple linear regression, artificial neural networks and multilayer perceptron. Of these methods artificial neural networks provided the best accuracy. These methods used a variety of different, specific datasets and parameters and typically only looked at healthy people, which makes it hard to correlate and generalize the findings. Another popular study used deep learning with feature extraction of wearable heart rate and accelerometer data from the Fenland study of over 12000 healthy subjects to predict VO2max and compared to submaximal/indirect test data and non-exercise models. The model overestimated VO2max when compared to a dataset of direct VO2max test subjects and had similar limitations for sedentary subjects. This is a common problem with machine learning based models which do well if new data fits within the scope of training data but do not generalize well. Indirect/calculated methods consider more parameters but are typically only accurate for a specific dataset and do not generalize well (Ashfaq et al., 2022; Spathis et al., 2022).

Heart Rate (HR) metrics include resting heart rate, heart rate variability and target heart rate zones. A lower Resting HR typically indicates superior cardiovascular efficiency. Heart Rate Variability (HRV) measures the variation in time between heartbeats where higher values are associated with better fitness and recovery. Target Heart Rate Zones are defined based on a percentage of Maximum Heart Rate (MHR) and used to monitor and prescribe exercise intensity. Lactate Threshold (LT) and Functional Threshold Power (FTP) are physiological markers used to determine the highest intensity an athlete can maintain for a prolonged period (usually 60 minutes) without excessive fatigue.

Muscular endurance is the ability of a muscle or group of muscles to perform repetitive contractions against a force for an extended period (Schoenfeld et al., 2021). Common metrics include counting the maximum number of repetitions of a specific exercise performed with proper form to failure such as push-up test (upper body), sit-up/curl-up test (core), and bodyweight squat test (lower body), Isometric Hold Times which measure how long a specific position can be maintained against gravity such as Prone Plank Test (core endurance), and Fixed-Percentage Loading which involves performing as many repetitions as possible using a set percentage of an individual's one-repetition maximum (1-RM) (Kaminsky et al., 2023; Strand Sarah L. et al., 2014).

Performance tests include Timed Distance Tests to estimate aerobic capacity in field settings such as the 1-mile run/walk, Cooper 12-minute run, or the PACER (Progressive Aerobic Cardiovascular Endurance Run) (Mahar et al., 2018).

2.3.2. Mental Metrics:

Metrics to measure psychological and behavioral attributes are subjective. They are in the form of questionnaires or surveys that map them to mental categories and/or provide a combined score(scale). Common measures aim to capture mental toughness and mental fatigue. Mental toughness (MT) is typically viewed as a stable, measurable psychological trait whereas Mental Fatigue(MF) is a transient psychobiological state resulting from prolonged cognitive demand. Both are measured using a combination of psychometric scales, behavioral tasks, and physiological markers.

Mental Toughness is assessed through self-reporting questionnaires with questions in four categories designed to capture Control, Commitment, Challenge, and Confidence. The Mental Toughness Questionnaire 48 (MTQ48) is the most widely used standard measure based on the 4Cs model. Mental Toughness Index (MTI) is an 8-item unidimensional scale focusing on the ability to consistently perform at the upper range of one's skills. The Sport Mental Toughness

Questionnaire (SMTQ) is a 14-item scale measuring confidence, constancy, and control specifically in athletic contexts. The Mental Endurance Inventory in Sport (MES) is a 14-item scale specifically for athletes that measures Confidence, Persistence (determination to continue despite obstacles), and Control (emotional regulation). The Psychological Performance Inventory (PPI) which is one of the earliest measures (Loehr, 1986), is also often used in sports.

Other alternatives used in professional workplace environments are the Psychological Endurance Scale which measures an individual's capacity to withstand mental stress, adversity, maintain motivation and assess resilience and persistence and the Adversity Quotient (AQ) which measures an individual's ability to handle, persist through, and navigate challenging situations.

Mental Fatigue is currently measured for a variety or sports and non-sports related assessments using subjective, physiological, and behavioral or performance-based methods. Endurance activities relate to active mental fatigue that is induced by prolonged sustained activity that require continuous effort (Desmond & Hancock, 2020). Subjective Measures include the Visual Analogue Scale (VAS), NASA Task Load Index and Mental Fatigue Awareness Scale in Athletes (MFASA). The most common tool used is the VAS where individuals rate their perceived level of fatigue on a 100mm horizontal or vertical line as little to extreme. The NASA Task Load Index (NASA-TLX) assesses mental workload across six domains, including mental demand and frustration across a multidimensional scale (Hart, 2008; Hart & Staveland, 1988)The Mental Fatigue Awareness Scale in Athletes (MFASA) assesses an athlete's awareness of fatigue symptoms on a 25-item scale (Johansson et al., 2010). Behavioral Measures used in psychobiological experiments such as the Stroop Attention test and Psychomotor Vigilance Task track changes in cognitive or motor performance following a demanding task. The Stroop Attention Test (SAT) measures change in attention and executive function (Stroop, 1935).

Sustained Attention Response Task (SART) measures the ability to maintain attention over time(Robertson et al., 1996) . The Psychomotor Vigilance Task (PVT) measure’s reaction time and lapses in attention (Basner et al., 2011). Physiological Measures are used in research settings to find correlations of fatigue with biological functions and include Electroencephalography (EEG) which measures increases in theta and alpha power, Eye Metrics which measure changes in pupil diameter and blink rate, and Heart Rate Variability (HRV) which if decreased indicates increased mental stress and workload (Chua et al., 2014; Lecomte & Juhel, 2011).

To evaluate current mental stress and recovery balance, subjective tools like the RESTQ-76 Sport and Proof of Mood States (POMS) that employ detailed questionnaires with Likert scales are used. RESTQ-76 Sport is widely used to assesses the frequency of current stress and recovery states in athletes to monitor training load, prevent burnout, and manage overtraining syndrome (Kellmann & Kallus, 2024)The Profile of Mood States (POMS) is used in clinical, medical, and sports settings to measure mental health and recovery from exercise. It measures transient emotional mood states to characterize overtraining and burnout in athletes. The Iceberg Profile shown in Figure 5 is a visual representation of the ideal mental state for peak performance as measured by the Profile of Mood States (POMS). It is characterized by low raw scores on the tension, depression, anger, fatigue, and confusion, and above norms (the “water line”) on vigor which is a positive state. Effects have been shown to be larger in short duration exercise where it is useful in the prediction of performance outcomes (Beedie Christopher J. et al., 2000; Lochbaum Marc et al., 2021; Renger, 1993).

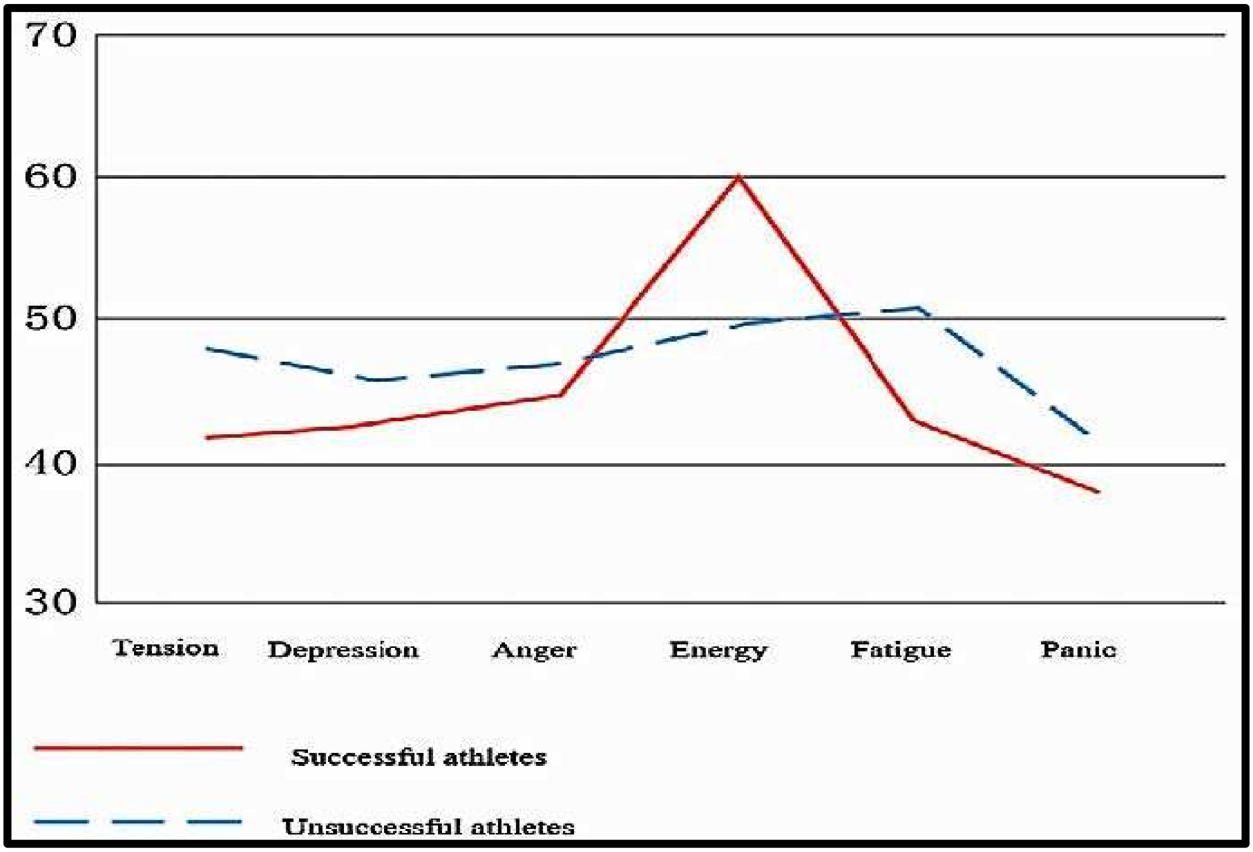


Figure 5: POMS Iceberg representation of mood (Gai, 2024). Provides a visual representation of the ideal mental state for peak performance

2.3.3 Combined Psychophysiological Metrics

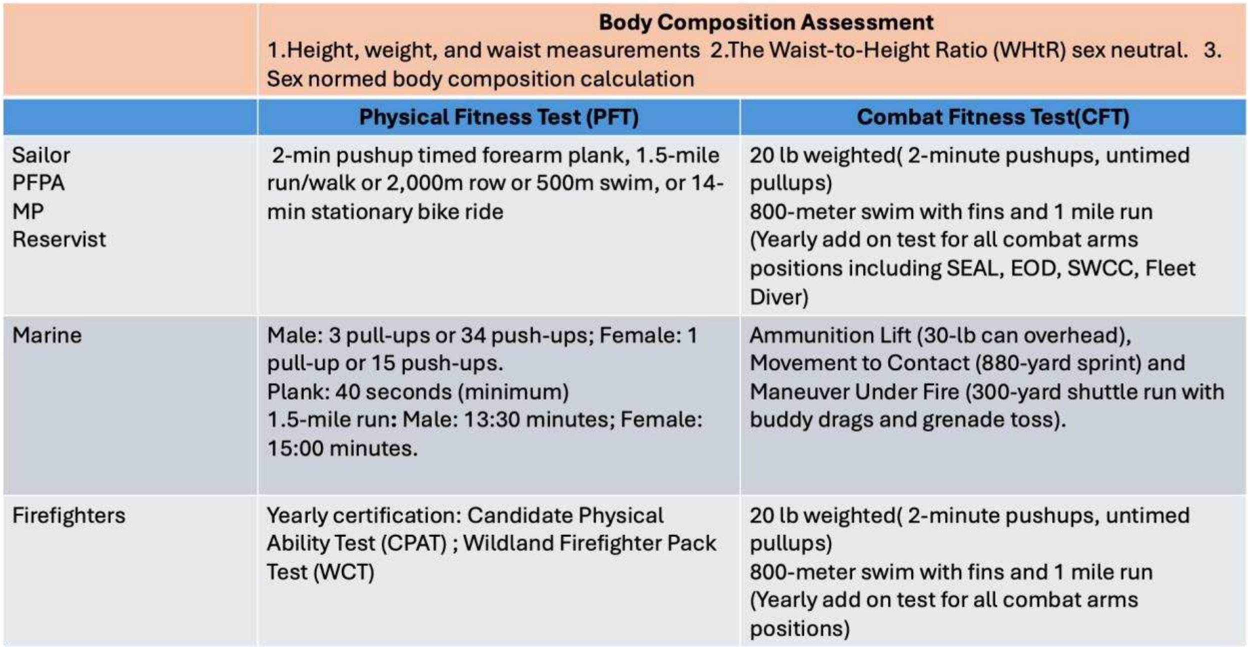
These metrics measure the interaction between the mind and body during exercise. Subjective performance assessments include Rate of Perceived Exertion (RPE) which is a subjective 0–10 or 6–20 scale (Borg Scale) used to quantify an individual's perceived effort during exercise and Session-RPE (sRPE) which is a subjective measure of training load calculated by multiplying the session RPE by the duration in minutes. Another type of assessment is the Cognitive Cost of Effort which is calculated by tracking the increase in RPE or decrease in power output when a cognitive task is added to physical training. The cognitive cost of effort scale measures an individual's, or a task's, perceived, or actualized, willingness to exert mental energy, often using tools like the C-EEfRT (Cognitive Effort Expenditure for Rewards Task) and N-back task that measures working memory capacity and attentional control and acts as a metric for mental workload.

This dissertation utilizes Rate of Perceived Exertion (RPE) since these assessments are standardized psychophysical scales used to measure the subjective intensity of physical activity in medical and sports fields. Rate of perceived exertion (RPE) refers to a subjective measure of how hard you think you're pushing yourself and can be used before, during or after exercise. The Borg Rating of Perceived Exertion (RPE)Scale (6–20) was developed by Dr. Gunnar Borg to correlate with heart rate. A rating of 12–14 typically corresponds to a heart rate of approximately 120–140 bpm in healthy adults. The scale corresponds to 6: No exertion at all (at rest); 13: "Somewhat hard" (target exercise zone) and 20: Maximal exertion (Borg, 1998; Borg Gunnar, 1982) To measure specific sensations like breathlessness (dyspnea) or localized muscle pain beyond overall exertion, the Borg CR10 Scale (0–10 scale was developed. The scale corresponds to 0: Rest; 5: Strong perception (aerobic threshold) and 10: Maximal effort. Other scales used are the OMNI Scale (0–10) which uses both numerical and pictorial descriptors to help individuals rate effort (Utter et al., 2004). Various versions exist for walking/running, cycling, and resistance exercise. The Session-RPE (sRPE) method provides a single RPE score by an athlete for an entire training session approximately 30 minutes after completion. Total training load is calculated as RPE × duration (minutes) (Egan et al., 2006; Falk Neto et al., 2020; Ozeas de Lins-Filho et al., 2012; Yang et al., 2024). Subjective measures have been shown to reflect acute and chronic training loads with superior sensitivity and consistency than objective measures (Saw et al., 2016).

2.4 Military Research Literature Search

The Department of War (DOW) emphasizes “Warrior Ethos”, a core mindset and belief system, as the cornerstone of a tough and lethal fighting force. It is the motivation for the Warrior Toughness Program, which is a Navy-developed, Navy-focused initiative for its sailors that incorporates concepts from Naval Special Warfare (SEALs) to build mental, physical, and spiritual resilience for peak performance under pressure (Directives, 2021; Navy Fitness, 2018). This program develops a lethal and resilient force by providing Sailors with mind and body skills to manage stress and perform under pressure to execute missions. This is accomplished through total fitness programs that incorporate physical exercise, stress management programs such as Mindfulness-Based Attention Training (MBAT) and Expanded Operational Stress Control (E-OSC) from Fleet & Family Support for stress resilience. In 2026, the updated Navy Physical Readiness Program (PRP) includes daily physical training, a new Combat Fitness Assessment (CFA) and changes body composition standards to include sex neutral, waist-height ratio and sex normed, body composition tests (Physical Readiness Program Office, 2025; Undersecretary of War, 2025) . Active-duty sailors in combat arms positions(e.g. SEALs, special warfare combat crewmen, explosive ordnance disposal and fleet diving positions) now take both the Physical Fitness Assessment (PFA) composed of the Body Composition Assessment(BCA) and Physical Fitness Test (PFT) and the CFA composed of the BCA and Combat Fitness Test(CFT) which includes 20lb weighted push-up, pull-up and run requirements (Physical Readiness Program Office, 2025). These requirements have been summarized in Table 1.

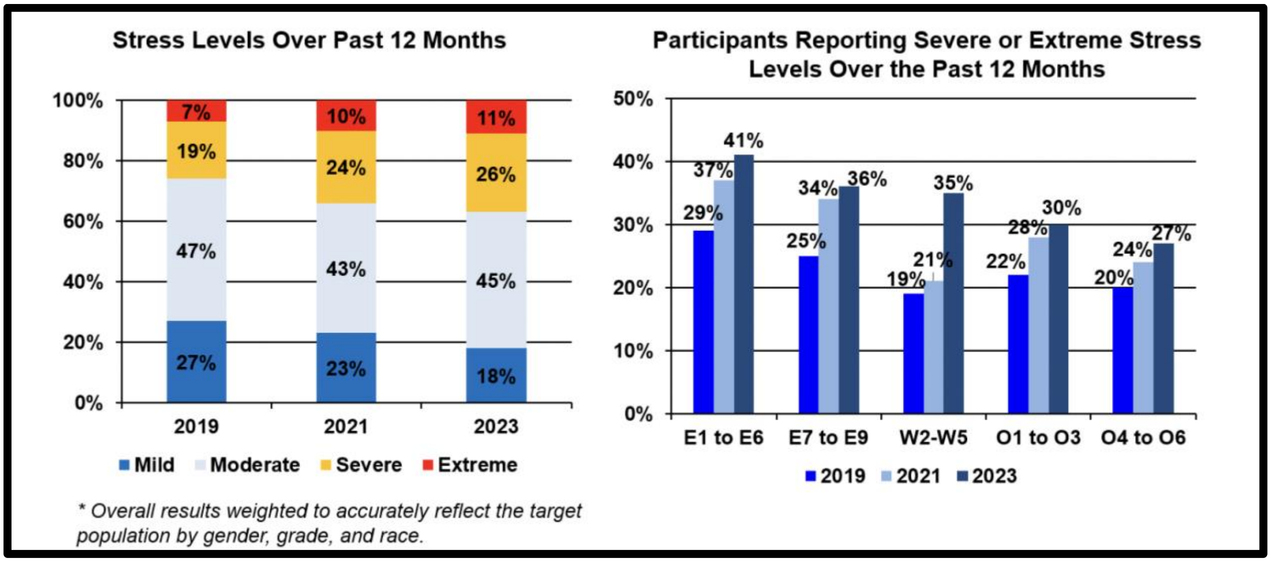
Table 1: Summary of fitness requirements for Navy



	Body Composition Assessment 1.Height, weight, and waist measurements 2.The Waist-to-Height Ratio (WHtR) sex neutral. 3. Sex normed body composition calculation	
	Physical Fitness Test (PFT)	**Combat Fitness Test(CFT)**
Sailor PFPA MP Reservist	2-min pushup timed forearm plank, 1.5-mile run/walk or 2,000m row or 500m swim, or 14-min stationary bike ride	20 lb weighted(2-minute pushups, untimed pullups) 800-meter swim with fins and 1 mile run (Yearly add on test for all combat arms positions including SEAL, EOD, SWCC, Fleet Diver)
Marine	Male: 3 pull-ups or 34 push-ups; Female: 1 pull-up or 15 push-ups. Plank: 40 seconds (minimum) 1.5-mile run: Male: 13:30 minutes; Female: 15:00 minutes.	Ammunition Lift (30-lb can overhead), Movement to Contact (880-yard sprint) and Maneuver Under Fire (300-yard shuttle run with buddy drags and grenade toss).
Firefighters	Yearly certification: Candidate Physical Ability Test (CPAT) ; Wildland Firefighter Pack Test (WCT)	20 lb weighted(2-minute pushups, untimed pullups) 800-meter swim with fins and 1 mile run (Yearly add on test for all combat arms positions)

The EOSC program is health-focused and emphasizes recovery and adapting to adversity to maintain long-term well-being and readiness through peer and family support and stress management (CNO, 2019). The Marine Warrior Athlete Readiness and Resilience (WARR) program supports the Marine Corps Total Fitness (MCTF) strategy by focusing on four primary domains of physical, mental, social and spiritual to enhance combat readiness and durability (Marine Corps, 2026).

Although the programs and requirements for sailors, Marines, and Special Operations Forces(SOF) are different, they all incorporate physical and mental conditioning, since the Navy views physical and mental fitness as equally crucial for service readiness. Training is used to build both stamina and mental fortitude to manage warfighter-specific stressors such as bootcamp, combat, and peacetime operations as well as civilian transition. A recent health of force survey comprising 19,380 active-duty sailor responses, reported that 40% of enlisted sailors felt severely or extremely stressed (Mongilio, 2024). The amount and type of stress in the seafaring communities is occupation dependent and response to stress varies by individual and needs to be studied and modelled for specific interventions .



** Overall results weighted to accurately reflect the target population by gender, grade, and race.*

Figure 6: U.S. Navy survey results on mental stress of active-duty Naval personnel (Mongilio, 2024). 40% of enlisted sailors felt severely or extremely stressed.

Military research has shown evidence that a warfighter’s physical and psychological performance in battle situations was affected by strenuous physical activity during prior combat operations (Jensen et al., 2013). Recent research demonstrated that wearing military equipment during high-intensity tasks significantly increases both perceived stress and Rate of Perceived Exertion(RPE) compared to civilian gear(Curiel-Regueros et al., 2024). This stress coupled with combat stress could reduce endurance performance significantly during combat. A warfighter’s inaccurate perceived exertion can cause them to overextend themselves in combat or stop an operation even though they are physically capable (Stergiou et al., 2024). Prolonged mental exertion can induce battle fatigue and reduce mission effectiveness (Rabat et al., 2025).

During sustained military operations warfighters experience high levels of physical and mental stress without having the ability to fully recover. They have to conduct military work with little or no rest or sleep which can range from a minimum of 36 hours to a maximum of a warfighter's abilities. They also experience long periods of inactivity in between demanding situations which requires them to stay alert. Their vigilance, reaction time, and working memory are affected after only a few hours which can be restored with little recovery time. However, their reasoning ability is affected for longer durations and has been shown to require longer times to return to baseline values than is available during sustained operations (Vrijkotte Susan et al., 2016). This has implications for combat readiness, which requires focus, quick decision-making, and physical fitness.

Previous exercise research has shown that stress generates mental fatigue which affects overall fitness and modifies physical performance even in short duration (less than 2 hours) (Smith et al., 2015, McCormick et al., 2015). The negative effects of combat related stress on cognitive performance of soldiers have been documented (Harris et al., 2005; Lieberman H et al, 2002; Lieberman et al., 2002, 2016). Mental fatigue has been observed during long cognitive tasks as a function of time on task or in subsequent cognitive or physical tasks in a sequential task protocol (Pattyn et al., 2008; Brown et al., 2020).

Warfighters typically carry heavy loads ranging from 40-120 lbs. in depending on their role(e.g. sailor vs. marine) and whether they are operating in peacetime to combat scenarios. Nominal loads carried range from approach loads which are ≤ 45% of body weight (approx. 72–84 lbs.) to fighting loads which are ≤ 30% of body weight (approx. 48–55 lbs.). Mission specific gear such as ammunition, batteries, and other equipment adds even more weight. During short mixed terrain marches, military personnel can maintain similar pacing while carrying either fighting or approach loads if they have been trained. During longer distance marches their cardiorespiratory demands have been shown to be greatly elevated with the approach load and will increase with longer distances (Looney et al., 2018). Wearing standard military equipment during high-intensity interval training (HIIT) significantly increases both perceived exertion and overall stress perception compared to civilian athletic wear (Stergiou et al., 2024). Using military equipment during a high intensity training session has been shown to increase stress perception and perceived exertion. This can be attributed to a psychophysiological response to mechanical difficulty and the lack of operability in movements due to the equipment (Curiel-Regueros et al., 2024). Sex differences in training loads could contribute to the greater injury risk for women during basic training (O'Leary et al., 2018). Experienced, high fitness warfighters demonstrate better self-confidence and more consistent motor skills despite high perceived exertion. Research has shown that adrenaline and intense focus may cause soldiers to underestimate their actual level of physical exhaustion so that they report lower rates of perceived exertion despite showing extreme physiological stress markers like elevated heart rate and lactate. RPE was measured using the original Borg scale (Stergiou et al., 2024). Another study on military personnel found that stress-induced changes in cognition may not initially be detected through decrements in performance, but instead through decreased efficiency (Flood & Keegan, 2022). This has significant implications for combat readiness.

A lethal fighting force requires top performance during combat operations which necessitates the ability to tolerate and use strength, endurance, and speed while performing demanding physical tasks. The military understands that mental fitness is imperative to excel in demanding and unpredictable combat situations and affects overall readiness for war (Army, 2020; Directives, 2021).

Psychological stress affects “Functional Motor Competence”, which is required for physical fitness including muscular strength and endurance and cardiorespiratory endurance and performance-related outcomes for military fitness in peacetime and combat situations (Leone et al., 2025). In recognition of this effect, military programs consider both physical and psychological aspects in military training to optimize performance and decision-making in combat situations (Army, 2020; Navy Fitness, 2018). Recent research shows that Mental fatigue (MF) monitoring and management bolsters military performance in continuous operations and extreme environments by directly reducing or managing risk related to physical and mental lapses (Rabat et al., 2025). A longitudinal survey-based, U.S. Millennium Cohort Study tracks the physical and mental health of over 77,000 service members over a 20-year span providing a baseline for military health status compared to the general population (Belding et al., 2022). The Pentagon has launched the Cognitive Monitoring program in 2024 to baseline and track the brain health of all warfighters every five years to look at how daily cognitive function is maintained or degraded during a military career and to identify interventions. Prior research suggests that mental skills or mindfulness-based training can reduce the negative effects of stress and improve physical performance by reducing the cognitive interference of fatigue-related thoughts (B. J. Jones et al., 2020; Nien et al., 2020). A study of Marines who practiced mindfulness for just 8 weeks showed improved cognitive performance compared to those who did not (Jha et al., 2010). A study on basic military training recruits showed that recruits in the mental toughness group showed improved physical performance, better results in final training exercises, and reduced stress, and they graduated on time more often, with 63.5 on-time graduates per division compared with 55.75 in the control groups (Saul et al., 2024). Physiological and psychological measures include TotalRelVO2 which is average relative VO2 over time, sum HR which is calculated by multiplying time spent in each of the five heart rate zones by a multiplier factor for each zone, RPE using the Borg 6-20 scale and session RPE(sRPE) which is RPE over time (Jha et al., 2025).

Brain endurance training research at the Walter Reed Army Institute of Research is a cognitive-physical training method to increase tolerance to fatigue and enhance physical performance by forcing the brain to operate under stress. It involves performing mentally demanding tasks such as memory or reaction-time tests during or immediately after strenuous physical exercise. Results show that integrating low to moderate memory tasks into rest periods during high-intensity interval training (HIIT) displayed twice the improvement in endurance performance and twice the reduction in perceptions of exertion compared to the control group following the six-week training (Johnson, 2023).

The Department of War has Mindfulness-Based Attention Training (MBAT) programs in the Army, Navy and AirForce which are tailored to focus on the needs of warfighters in those services. The Army MBAT emphasizes ground combat and aims to reduce mind-wandering and improve working memory. The Navy MBAT focuses on maritime operations for resilience against isolation experienced in underwater and at at-sea long duration deployments. The Air Force MBAT prioritizes technical skills and, a higher quality of life. Research conducted under the U.S. Army Mindfulness-Based Attention Training (MBAT) showed that soldiers who complete the full 4-week MBAT protocol rather than 2 weeks, experience significant benefits in working memory and decentering of stressful thoughts. The Army MBAT program aims to enhance focus and cognitive control under high-stress military environment pressure for improved mental strength. The program uses mindfulness techniques, such as meditation and focus exercises, to improve attention, emotional regulation, and stress management (Nassif et al., 2023; C. D. Smith et al., 2023; Zanesco et al., 2019). It is possible that long term training could enable warfighters to push closer to their physiological limits because they no longer interpret the physical lactate burn as a signal to quit immediately. These observational studies highlight the fact that mental training is a core component of physical fitness and that a warfighter's brain and body must train together to achieve optimal readiness.

Individual differences in physical fitness and mental state can be responsible for variability in mental fatiguability (Habay et al., 2023; Jaydari Fard & Lavender, 2019; Skau et al., 2021). Compounding the variability caused by the initial state effects, research has shown that during sustained long term activity, the person's physical and mental state changes as their physiology responds to physical exercise [Van Cutsem et al., 2017, Jones and Jones,2024). An approach and model are needed to capture the variability in initial states and the dynamic changes to physical and mental endurance due to the complex interactions between them. Studies on the interconnected contributions of physiological, psychological and environmental aspect of endurance highlights the need for an interdisciplinary, integrated approach to understand and build resilience to enhance military performance (Nindl et al., 2018).

2.4.1 Military focused Research Modelling:

Some military research system models exist that view endurance as a dynamical system. The models investigate how physical capacity, psychological state, and environmental stressors interact through complex feedback loops to account for how performance degrades and recovers over time. These models examine specific aspects of endurance and range from systems frameworks to equation-based models.

The Maximal Adaptability Model is a foundational framework of the impacts of stress on performance and proposes that humans can maintain stable performance over a wide range of stress levels by utilizing psychological and physiological reserves, only failing when those, maximum adaptive capacities are exceeded. The model proposes that stress response follows an extended-U shape where it remains stable for a long period before declining steeply, unlike the popular theory that stress results in a simple linear decline of performance. It proposes that when training load intensity and fatigue stressors reach extremes, the system's homeostatic control fails, leading to dynamic instability and rapid performance collapse (Hancock, 2022; Hancock P et al, 1989). This framework has been modelled with equations and software by many researchers. The SAFTE Model (Sleep, Activity, Fatigue, and Task Effectiveness) is a biomathematical model developed by Johns Hopkins APL and used by the DoD to predict cognitive endurance and task effectiveness based on sleep debt and circadian rhythms. It serves as a dynamical tool for Fatigue Avoidance Scheduling in operational planning. (Hursh et al, 2004).

The Allostasis Model which is a framework that predicts long-term endurance failure or burnout by tracking the cumulative "wear and tear" on the body (allostatic load) has been applied to the military. It describes the dynamical nature of physiological response such as the hypothalamic-pituitary-adrenal (HPA) axis to unpredictable acute stressor as they adapt to shifting demands (Feigal, 2025). The Critical Power (CP) and W' (W-prime), Power law and hyperbolic models of the bioenergetic property of endurance can be used to quantify a soldier's sustainable intensity (CP) and their finite anaerobic reserve (W') that is depleted during high-intensity bursts. The Critical Speed concept has been proposed to help tactical commanders estimate how fast a squad can move over a set distance without exhaustion before reaching the objective (Dicks et al., 2025; Dicks & Pettitt, 2021; Lipková et al., 2022). System Dynamics Models and Simulations have been developed to simulate the dynamic relationships between a soldier's physical condition, psychological state, and leader behavior which interact to influence mission completion. The model highlights the relationship between adaptable and non-adaptable leadership on subordinates and responses to praise or criticism and how it impacts physical fitness performance on the Army Combat Fitness Test. These models use Causal Loop Diagrams to show how feedback such as a leader's perception of a subordinate's fatigue impacts unit-level endurance. The models show how adaptive leadership by providing encouragement to suit an individual soldiers can mitigate a soldier’s exhaustion needs and improve sustainment of long-term effort. Another systems dynamics model and simulation studies a four-rank military closed loop workforce training management system. The model explores the causality and information feedback loops to understand system behavior over time. It shows how the intention to expand the Combat Force (CF) could lead to its temporary reduction; and an increased training demand at a lower rank can, in principle, cause training demands to increase at higher ranks (J. Wang, 2007).

CHAPTER 3: METHODOLOGY

This research in this dissertation is based on a Model Based Systems Thinking (MBST) method (Eftekhari Shahroudi, 2025) to shed light on the complexity of interaction between changes in physical endurance due to mental aspects related to exercise or physical training. Figure 7 shows the incremental rigorous steps of the method that integrate applying Systems principles, literature search, Causal Loops Diagrams, Systems Dynamical Agent Based and Causal Modeling, and multiple analysis methods to analyze and model endurance.

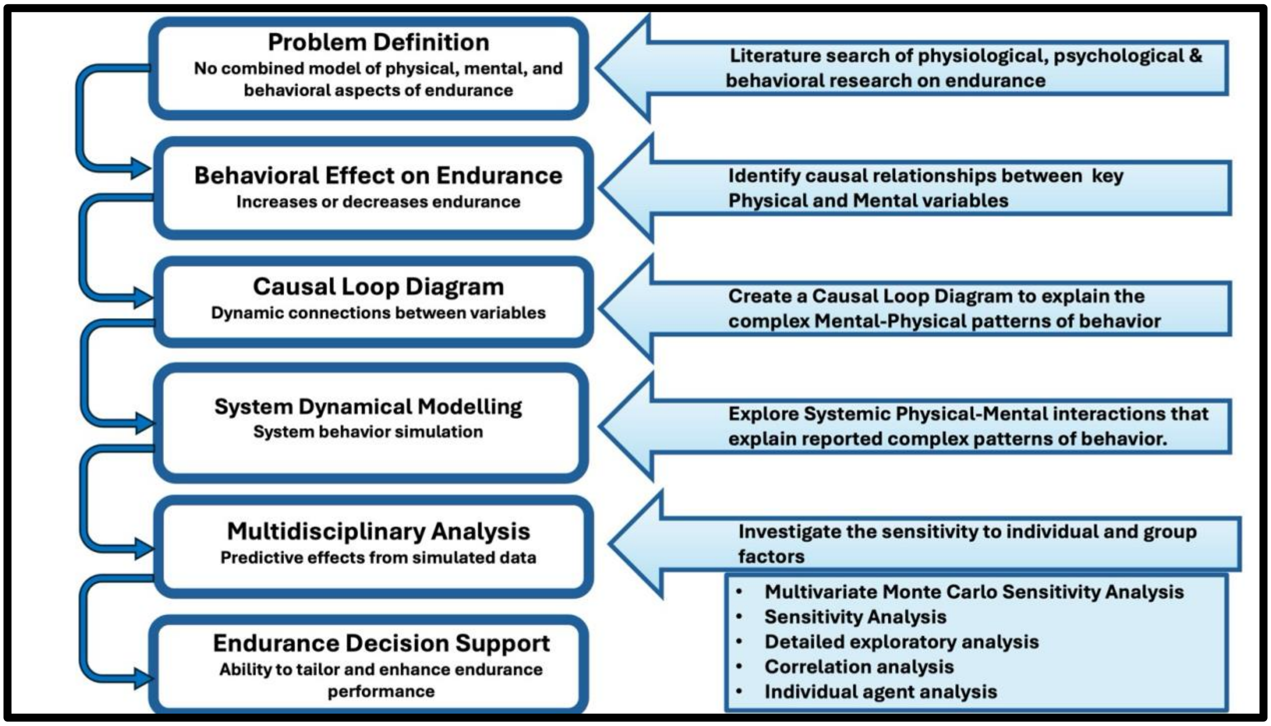


Figure 7: Overall Methodology used in dissertation. Utilizes Model Based Systems Thinking methods and tools to define and analyze problem and results. The multi-model approach was necessary to capture the complex dynamic relationships between mental and physical endurance factors, parameters and variables for individuals and groups.

The application of the eight systems principles enabled inclusion of perspectives from multiple disciplines including systems dynamics, physiology, psychology, and behavioral science. A corresponding literature search of the physiological, psychological and behavioral research on endurance was conducted. Investigation into existing behavioral models and theory resulted in the realization that a single behavioral theory in its typical context would be inadequate to represent this unique problem. This led to the development of a new behavioral model of endurance that starts with foundational behavioral theories and augments them with physical and mental variables to captures the dynamics. Identification of the causal relationships between the physical and mental variables led to the creation of three Causal Loop Diagrams (CLD) which explain the complex patterns of behavior from various perspectives. The Endurance Agent Based Model CLD captures the relationships between the physical, mental and social behavioral attributes of each runner as they dynamically evolve over a year in response to runner interactions. The Endurance System Dynamical Causal Model CLD captures the relationships between the physical and mental attributes of an individual as they dynamically evolve over two months. This was developed from a warfighter and individual perspective but represents groups within a fitness level. The Recovery for Endurance System Dynamical Causal Model CLD was developed from the perspective of how recovery strategies affect physical and mental fatigue to enhance physical and mental endurance. For the Agent Based Model(ABM), the causal relationships between attributes were captured in the form of coupled equations with constants, grounded in observational data from short duration experiments. The equations were used as rules in an agent based behavioral model which was chosen to enable exploration of the systemic interactions that explain the patterns of behavior. It allowed evaluation of the extensive possibilities of runners physical, mental, and behavioral parameters changing with interactions over a year. The Endurance and Recovery SDMs choice of stocks, flows and variables and the equations used to describe their relationships were derived from the observational studies and research. The multidisciplinary analysis methods enabled investigations of the sensitivity to group and individual factors. For the ABM, a new method to conduct Monte Carlo sensitivity analysis was developed that provided the key input parameters that affect runners of different initial physical, mental and behavioral initial parameters. Using this data, a detailed sensitivity analysis was carried out for the primary factors that affected physical and mental endurance. Correlation analysis provided further insight into how the various factors are correlated for a type of runner which could inform future ways to tailor endurance gains. Individual analysis of agent behaviors provided insights into effects of interactions with different classes of runners. The ABM and Endurance and Recovery SD models were developed with the combined civilian and military perspective of enhancing endurance. The Endurance SDM, was anchored with data from the agent model as well as observational studies. It will enable identification of the specific leverage points in the endurance system that can help an individual gain endurance tailored to their specific initial physical, mental and behavioral values. The Recovery SDM utilized data from literature search as well as insights from the ESDM. The suite of endurance models provides insights into developing customized training and recovery strategies for individual and group to enhance endurance.

3.1 Systems Foundations and Applications of Systems Principles

To enable a holistic and comprehensive view of endurance, the problem was analyzed using Systems Thinking. This approach provided the understanding that the various components of the endurance system are interconnected and that changes in one area can ripple through others, often in unpredictable ways. Adopting a systems thinking mindset enabled identification of leverage points to enhance endurance, development of strategies that consider the broader context rather than just isolated parts such as group vs. individual behaviors and anticipation of the potential consequences of actions such as training and social interaction. Systems thinking enabled a shift in perspective from a linear, cause-and-effect to an understanding of the dynamic, evolutionary nature of the endurance system that includes feedback loops and delayed effects between elements. Applying eight systems principles (Eftekhari Shahroudi, 2025), enabled fusion of perspectives from multiple disciplines, including systems dynamics, physiology, psychology, and behavioral science.

1. Holism Principle: This principle is at the crux of the research gap. There are varied amounts of research on physiology of physical endurance, psychological aspects of mental endurance, psychobiology between physical endurance and mental stress, exercise behaviors, general behavioral models, systems dynamical causal models, and agent-based models unrelated and related to endurance. However, the gap is that the problem is not viewed as a dynamic interconnected system of systems which has resulted in a lack of understanding, models and metrics to enhance endurance in a tailored manner. An endurance system is more than the sum of physical, mental, and behavioral elements, interconnects, and their purposes.
2. Architecture Principle: This principle provides insight into the development of the endurance system models. The purpose, structure, and behavior of systems related to endurance such as cardiovascular, muscular, pulmonary, mental, and social systems influence each other continually. Separately they can explain a small piece of how they contribute to endurance but show emergent behaviors due to interconnections between the systems. For example, mental stress can cause a person to stop an activity even though they may be physically capable of performing it.
3. 3-Systems Principle: Identifying the three systems is essential to defining the problem to be solved. In terms of endurance training, the three systems are context system(long duration

activities that require persistent physical and mental resilience), system of interest (person's mind and body together), and enabling systems(recovery, coaches, wearables, running group). Changing even one of the three systems can change the problem. For example, if the context was short-duration intense activity such as weightlifting, the model attribute ranges and causal connections would be different and there may be additional attributes to consider. This is because the approach to building a model for stamina will be different from building a model for marathon-like endurance.

4. Boundaries Principle: Defining the boundaries of the endurance system will directly affect the physical and mental attributes and strategies used to solve the problem. The boundaries for the Endurance system depend on whether an individual or a coach/trainer (role) is aiming to enhance endurance for a person or group and goals for enhancement (perspective) depend on whether it is for recreational purposes, military, or work such as firefighting, police, etc.

5. Evolution Principle: Endurance is a dynamically evolving system with a life cycle based on initial conditions. The physical and mental attributes are constantly changing as they interact with each other over time through dynamic feedback loops over a time period.

6. Emergence Principle: Interactions(including feedback loops) within and between the three systems cause (sometimes unwanted) emergent behaviors. For example, inadequate rest/recovery can increase mental fatigue and decrease physical performance. High mental resilience can overcome physical fatigue and lead to increased physical performance. Difficult terrain or excess heat during an activity can affect mental endurance and physical performance.

7. Learning Principle: Techniques like positive self-talk, visualization, mindfulness,
and chunking the distance, practicing with challenging workouts and developing pre-run routines are commonly used to build mental strength that helps overcome discomfort and maintain focus

during tough runs. A person’s mental model continually influences their decisions to continue to run.

8. Human Principle: A person’s physical and mental state impact their future state and is affected by their environment as well as other humans (social norms, running with others, etc.).

3.2 Identification of Key Physical, Mental, Behavioral, and Exogenous Factors Affecting Endurance

This methodology establishes a structured, cross disciplinary framework for understanding endurance as a multi-factor adaptive system influenced by physiological capacity, psychological resilience, behavioral consistency, and environmental conditions. By integrating these domains, the study provides a robust foundation for predictive modeling, intervention design, and performance optimization. This study adopts a systems-based approach to identify and categorize the primary factors influencing physical and mental endurance. Endurance is conceptualized as a dynamic, multi-dimensional construct shaped by interacting physiological, psychological, behavioral, and environmental variables. These factors are grouped into four major domains: physical, mental, behavioral, and exogenous. Understanding how these domains interact provides a foundation for modeling endurance adaptation and performance improvement.

3.2.1 Physical Factors

Physical factors represent the biological and physiological attributes that directly influence endurance capacity. These variables determine an individual’s baseline performance and adaptation potential and are:

- Age – Endurance capacity changes across the lifespan due to hormonal shifts, muscle mass decline, and cardiovascular efficiency.
- Gender – Differences in hemoglobin levels, muscle fiber composition, and hormonal profiles influence aerobic capacity and fatigue resistance.
- Body composition – Ratios of lean mass to fat mass affect oxygen utilization and movement efficiency.
- Height and weight – Influence biomechanics, stride length, and energy expenditure. In general, relative VO2max is inversely proportional to body mass index, which is a function of weight and height, and is used to determine a person's body fat percentage.
- Resting heart rate (RHR) – Lower RHR typically indicates higher cardiovascular efficiency.
- Maximum heart rate (HRmax) – Used to define training zones and intensity thresholds.
- VO2max – Primary indicator of aerobic endurance and oxygen uptake capacity.
- Current fitness level – Baseline endurance determines training response and progression rate.
- Pace and speed – Reflect efficiency and energy management.
- Training intensity – Percentage of HRmax or VO2max used during exercise.
- Training duration – Length of exercise sessions.
- Training frequency – Number of sessions per week.

These variables collectively determine cardiorespiratory efficiency, muscle fatigue resistance, and metabolic capacity, which directly impact endurance performance.

3.2.2 Mental and Behavioral Factors:

Mental and behavioral variables influence an individual's ability to sustain effort over time and adhere to training regimens. These factors affect perception, motivation, and decision-making during exertion.

Key mental and behavioral factors include:

- Mental endurance – Ability to sustain focus and effort during prolonged activity.
- Mental fatigue – Cognitive exhaustion that reduces motivation and performance.
- Confidence – Belief in personal capability to complete endurance tasks.
- Motivation – Internal and external drivers that sustain training adherence.
- Perception of effort (Rate of Perceived Exertion) – Subjective assessment of physical strain.
- Self-efficacy – Belief in one's ability to overcome challenges.
- Intrinsic beliefs – Internal satisfaction derived from exercise.
- Normative beliefs(subjective norms) – Social expectations influencing behavior.
- Control beliefs – Perceived ability to influence outcomes.
- Perceived value of training – Expected benefits of endurance improvement.

These variables shape training consistency, pain tolerance, and goal persistence, directly influencing long-term endurance development.

3.2.3 Exogenous Factors

Exogenous factors represent external influences that modify endurance outcomes by affecting recovery, performance conditions, and training quality.

Key exogenous variables include:

- Diet and nutrition – Macronutrient balance, caloric intake, and timing affect energy availability and muscle recovery.
- Hydration – Fluid balance influences thermoregulation and cardiovascular efficiency.
- Sleep quality and duration – Critical for muscle repair, hormonal balance, and cognitive function.
- Exercising Recovery strategies – Stretching, foam rolling, cold therapy, and active recovery.
- Weather conditions – Temperature, humidity, wind, and altitude affect performance.
- Terrain & Altitude– Hills, trails, and surface types of influence energy expenditure.
- Training partners – Social support and competition affect motivation.
- Fitness level of peers – Influences training intensity and pacing.
- Wearable technology – Heart rate monitors, GPS, and sleep trackers improve feedback and self-regulation.
- Footwear and equipment – Shoe cushioning, support, and traction affect biomechanics and injury risk.

These variables modify external load, recovery efficiency, and training quality, indirectly shaping endurance progression.

3.2.4 System Interaction and Dynamic Adaptation

Endurance is not governed by a single factor but emerges from continuous interaction between all four domains of physiological capacity, psychological resilience, behavioral consistency, and environmental conditions. In one instance, high training intensity (physical) combined with poor sleep (exogenous) may lead to overtraining where in another instance strong motivation (mental) can offset temporary fatigue (physical). Proper nutrition (exogenous) enhances training adaptation (physical) while in another instance confidence(behavioral) gained by a trainer's encouragement can lead to endurance gains (physical and mental). This study models endurance as a dynamic adaptive system, where inputs such as training load (intensity & duration), nutrition, and recovery lead to states such as fitness level, fatigue, and motivation, resulting in outputs such as endurance performance, change in pace, and completion time. Feedback loops exist where performance outcomes and confidence influence motivation, which in turn affects future training behavior.

3.2.5 Measurement and Operationalization

The metrics shown in table 2 enable data-driven modeling of endurance adaptation over time.

Table 2: Operational metrics for each domain of endurance

Domain	Sample Operational Metrics
Physical	VO2max, HR zones, pace, distance, critical power
Mental	RPE scales, confidence, motivation, toughness/resilience questionnaires and surveys
Behavioral	Training adherence, session frequency
Exogenous	Sleep hours, caloric intake, hydration
Overall	EPower, Resting Heart Rate

3.3 Causal Loop Diagrams

Empirical experimental and observational data on the relationships between physical and environmental factors that affect physical fitness, mental factors that affect mental fitness and physical performance for short duration activities, and behavioral impacts on performance were used to develop the causal loop diagrams. Each of the three System Dynamical models developed utilized a causal loop diagram(CLD). For the Endurance Agent Based Model, a causal loop diagram (CLD) shown in Figure 8 was developed to understand how physical, mental, and behavioral parameters influence one another as runners exercise/interact with each other over a year.

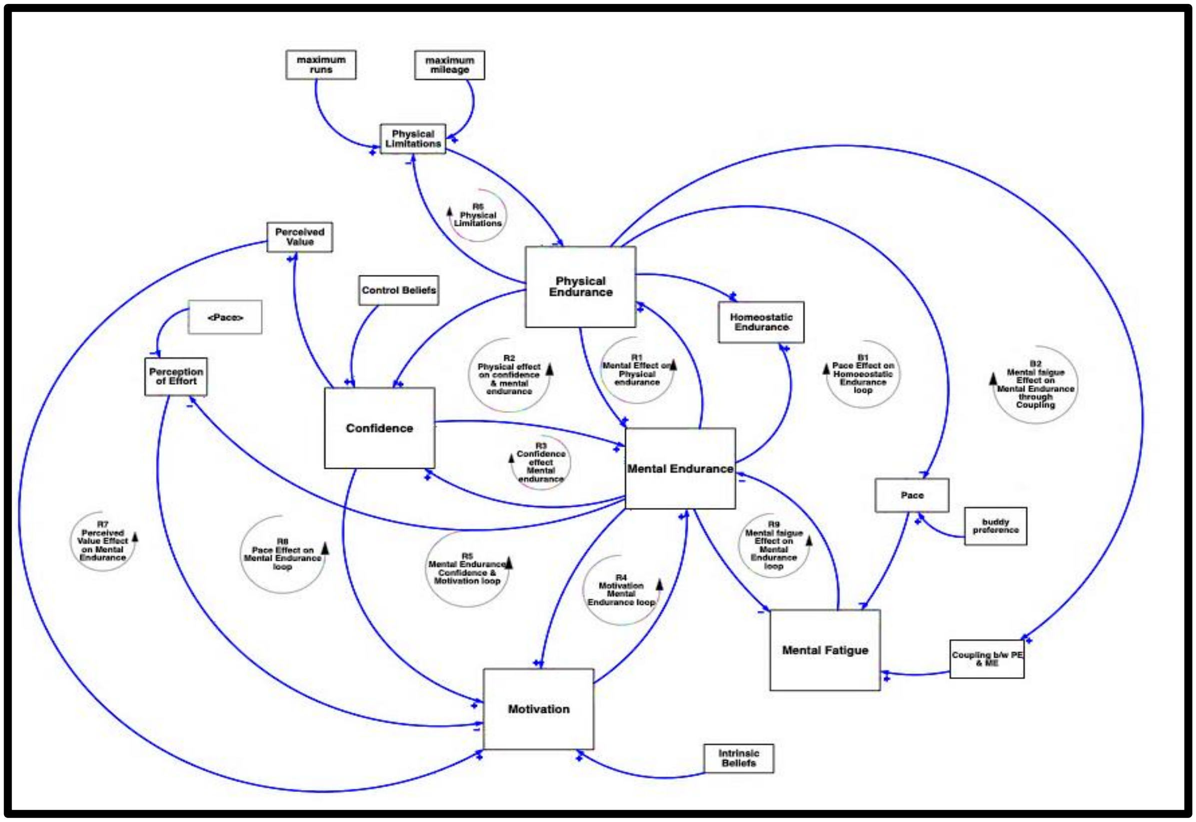


Figure 8: Causal Loop Diagram of Endurance Agent Based Model. This simplified helicopter view shows how major endurance concepts are inter-related. Each box contains detailed ABM sub models.

The modeled endurance system is designed to maintain homeostasis, enabling sustained activity and, ultimately, the improvement of endurance over time. The diagram includes seven reinforcing loops and four balancing loops that collectively influence increases or decreases in both physical and mental endurance. The diagram highlights that as confidence, motivation, mental fatigue, belief in running, and physical endurance change, they have a reinforcing effect on the mental endurance of a runner. Change in pace which is based on intensity and duration of a run, directly impacts how a runner perceives how much effort is required to conduct the run. This is based on their current mental endurance which affects their motivation and has a reinforcing effect (R8) on mental endurance and physical endurance. The balancing loop (B2) for mental fatigue effect on mental endurance through the coupling between physical and mental endurance will affect the gains in physical and mental endurance.

Figure 9 depicts the Causal Loop Diagram for the Endurance SD causal Model. The CLD highlights the reinforcing and balancing loops between the key elements that represent the interaction between physical and mental attributes. The individual attributes such as height, weight, body fat percentage, age, gender, body composition assessment that are unique to a warfighter and define their physical capabilities are those recorded as part of a physical fitness assessment. The reinforcing loops characterize relationships that cause a pattern of behavior between elements to consistently increase or decrease.

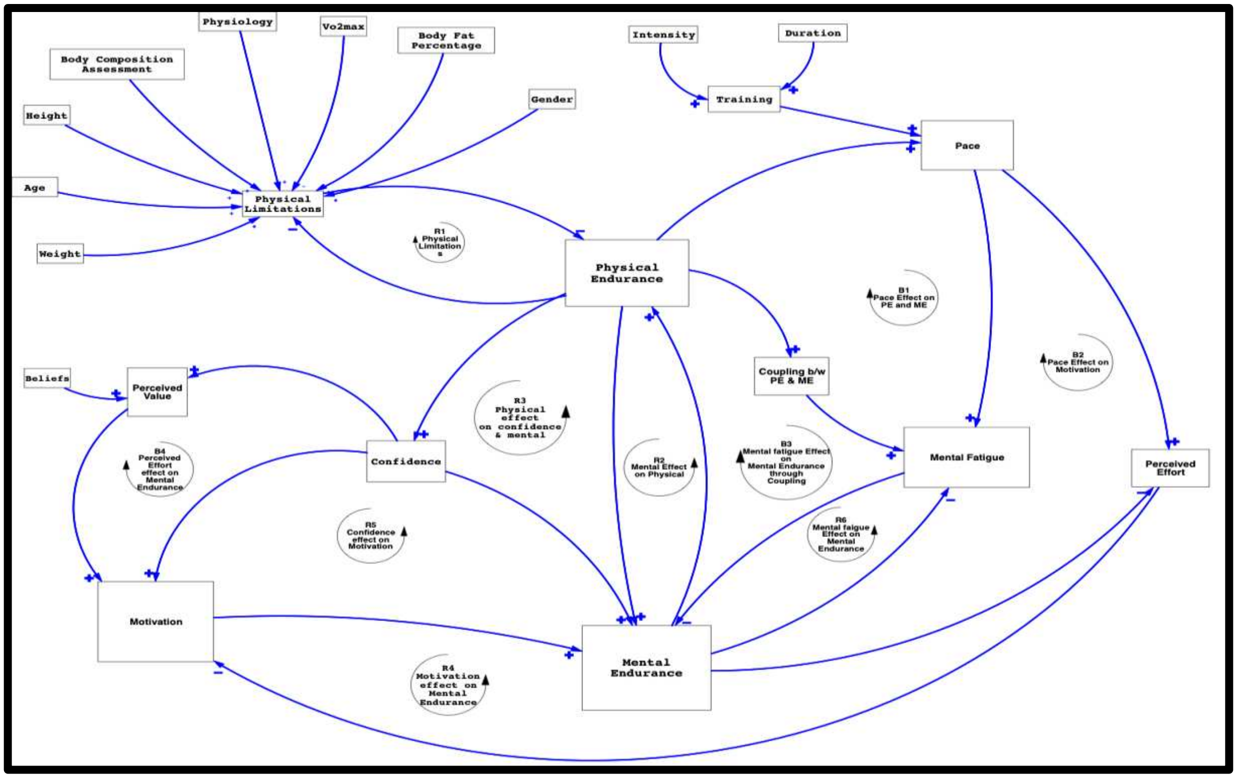


Figure 9: Causal Loop Diagram for Endurance SD Causal Model. This simplified helicopter view shows how major endurance concepts are inter-related. Each box contains detailed SD sub models.

For example, the R1 loop in figure 9 describes the relationship where physical limitations increase, a person's physical endurance drops which causes a corresponding increase in physical limitations. Similarly, the R5 loop captures how increase in a person's confidence about an activity, causes them to be motivated to sustain an activity that in turn causes them to increase their confidence in performing the activity. Balancing loops characterize relationships between elements that are opposing resulting in rebalancing effects. For example, in B1, when a person increases their pace, their mental fatigue increases, which causes their mental and physical endurance to drop which causes them to slow down their pace.

A Causal Loop Diagram of Recovery for Endurance SD Model shown as figure 10 was developed to understand the effects of recovery strategies on physical and mental endurance.

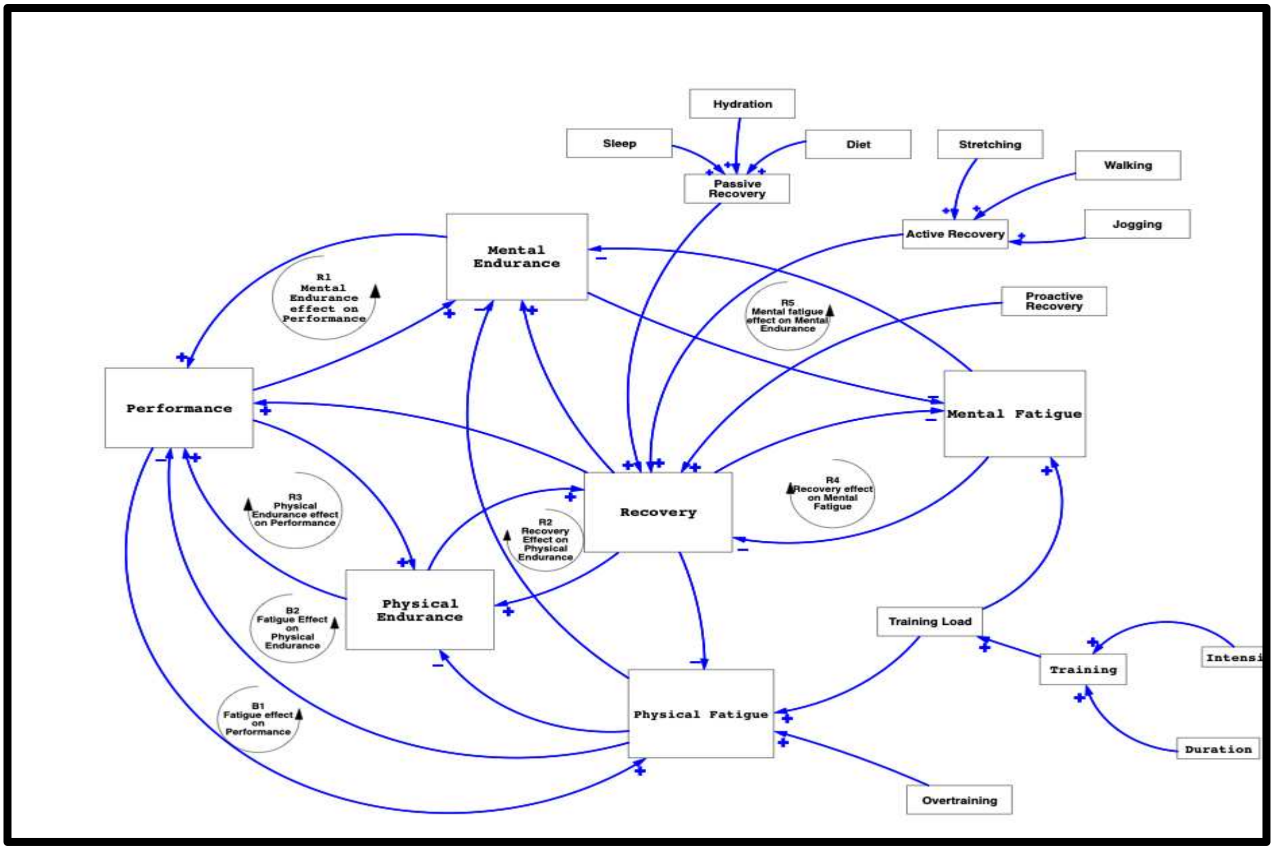


Figure 10: Causal Loop Diagram for Recovery for Endurance SD Causal Model. This simplified helicopter view shows how major endurance concepts are inter-related. Each box contains detailed SD sub models.

The CLD in figure 10 shows six key reinforcing loops and two key balancing loops. Recovery affects physical and mental fatigue, performance, and physical and mental endurance. The recovery strategies cumulatively affect the magnitude and timing of recovery. The R1 loop shows how mental endurance increases performance which in turn increase mental endurance. The R2 and R3 loops together show how recovery affects performance through physical endurance. The R4 and R5 loops together show recovery affects mental endurance through mental fatigue. A key balancing loop is B1 which depicts how an increase in fatigue decreases performance which causes fatigue to increase. The B2 balancing loop shows how as endurance increases, performance improves which increases fatigue which reduces performance. Initially the B1 loop dominates but as recovery increases over time, the B2 loop takes over and reduces fatigue.

3.4 Endurance Behavioral Model

A new Endurance Behavioral Model was proposed that combines Prospect theory and Theory of Planned Behavior (TPB) in a novel way and adds additional factors related to perceived value and physical effects. A key component of the mental influence on endurance is behavior, which affects sustainment of activities and often overrides physical abilities. People often start exercising with the best of intentions but stop due to physical and/or mental fatigue or injury after a period of time. Other methods such as exercise groups and buddies are very commonly used motivators for sustainment of exercise. Runners often train with others or in groups, where it has been observed that peer behavior can influence motivation, adherence, and training intensity. This is validated in observational studies that show how social interaction contributes to positive exercise behavior and greater performance outputs (A. J. Davis et al., 2021). Recent studies on the use of wearables for motivation show that they only work in short term, are dependent on social support and do not provide lasting effects on sustainment of an activity (Han et al., 2025; Steel, 2024).

Throughout prolonged activity, individuals continually assess their intent to persist, which influences behavior and varies with fitness level. This highlights the fact that physical, mental, and behavioral factors and their dynamic interactions need to be considered simultaneously to understand their joint, evolving impact on endurance performance.

A behavioral model framework, grounded in existing behavioral theories, is proposed to design an agent model that identifies the factors contributing to mental endurance and its influence on physical endurance. The proposed behavioral model shown in Figure 11 is tailored to endurance and incorporates additional physical and mental factors that affect behaviors that improve endurance.

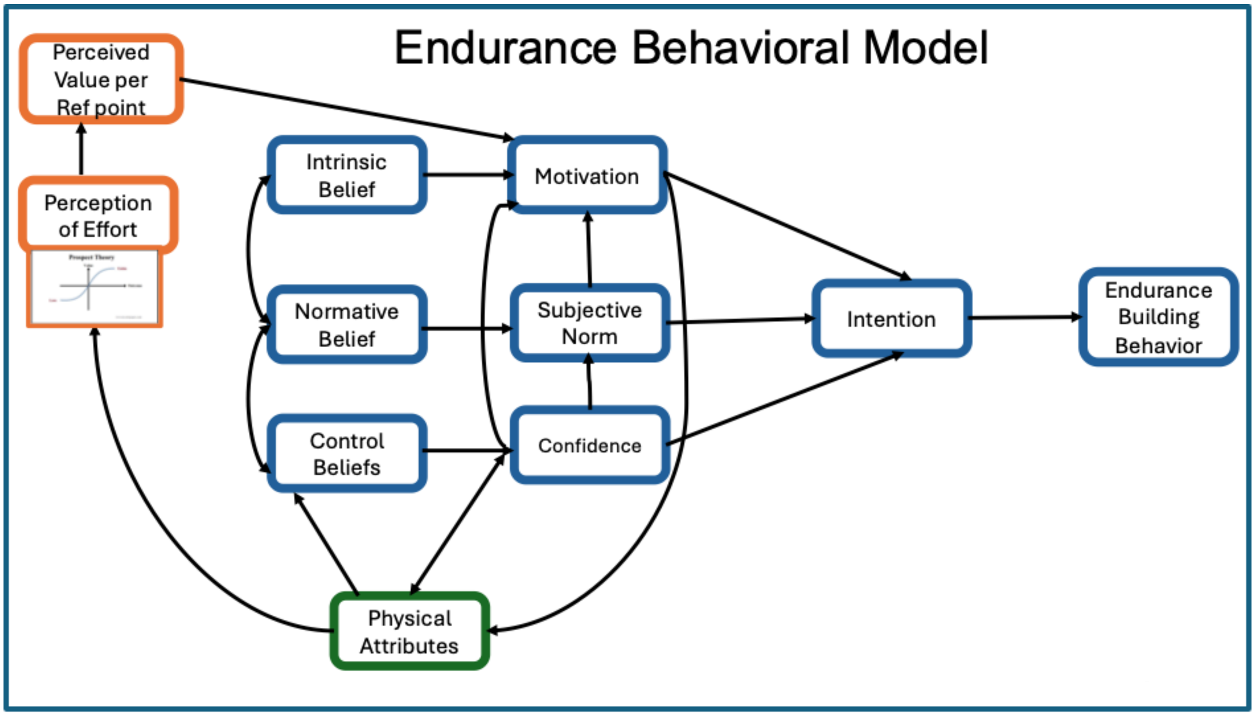


Figure 11: Proposed Endurance Behavior Model. Combines Theory of Planned Behavior (TPB) (blue) and Prospect theory(orange) with physical attributes(green).

Physical endurance, mental fatigue, perception of effort, and perceived value all impact the perceived value of sustaining an activity which directly impact confidence and motivation. Prior research has identified a potential correlation between mental fatigue in one week and physical injury risk in the subsequent week, but long duration effects have not been explored (von Rosen & Heijne, 2021).Work related to Motivational Intensity Theory in the context of fatigue has theorized that the intention to sustain an activity is dependent on perception of effort, a decision-making process, and motivation (Pattyn et al., 2018b). The key factors that affect motivation in the context of endurance are based on physical attributes as well as the perceived value of performing the activity to accomplish an increase in endurance, which is informed by their perception of effort. This perceived value is shaped by an individual's perception of effort, which depends on their personal history and current physical and mental condition (Pageaux, 2016; Pageaux & Lepers, 2016). In endurance activities, this is constantly being evaluated and changed, and affects motivation, which affects the performance of the physical activity. The endurance activity explored in the proposed experimental framework is running but the framework is general enough that it can be applied to other endurance activities.

This research combines Prospect theory and Theory of Planned Behavior (TPB) in a novel way and adds additional factors related to perceived value and physical effects to develop a behavioral model for endurance. Prospect Theory describes how people make reference-dependent, rational decisions that are aimed at max (Hensher et al., 2015; Kahneman & Tversky, 1979). The Theory of Planned Behavior provides the link between prediction of a behavior and intention which is influenced by attitude towards a behavior, social pressures and belief in the ability to perform the behavior Existing theories applied to the domain of exercise adherence have explored the Theory of Reasoned Action (TRA), TPB, Self Determination Theory, and Social Cognitive Theory for general exercise behavior, but the research has been on specific populations and issues for short durations and does not factor in the effects of intensity (Courneya et al., 1995; Teixeira et al., 2012; Godin Gaston & Kok Gerjo, 1996). In general, they show correlations between attitude/motivation and perceived behavioral control to intention to continue exercising. In the domain of exercise, Prospect theory has been explored in terms of exercise messaging(Latimer et al., 2008;More et al., 2024). Applying TPB, an individual's motivation/attitude towards a behavior, belief/subjective norms, and confidence/perceived behavior control on performing a behavior contribute to the intention to perform that behavior. Motivation in this context, is a function of intrinsic beliefs for conducting the behavior, perceived value of the behavior as well as confidence that they can perform the behavior. Intrinsic beliefs may include enjoyment of exercise or exercising for health benefits. The subjective norms of body image (how people perceive them), family/friends who want them to exercise, and also exercise themselves with normative beliefs of how important others think they should or shouldn't exercise affect the intention to perform endurance activities (K. Wilson, 2021). Confidence and perceived behavioral control are a function of a person’s physical fitness. Control belief is their belief that they have the ability and means to change their fitness by performing the activity. (André et al., 2024) showed that perceived value can create the cognitive dissonance/motivation necessary to sustain activity even if the perception of effort is high. A person will change their attitude ahead of time to enable performance of intense activity even when they perceive it to be difficult.

The behavioral model evaluates the mental and physical factors that contribute to sustaining endurance activities, aiming to achieve a state of endurance homeostasis. This behavioral model builds upon existing work on short duration intense activity contribution to mental fatigue and impacts on physical endurance. Behavioral studies show that less fit athletes have lower motivation and do not sustain activities as well as elite athletes for the same task (Hallderson, 2009). However, too much motivation can cause mental fatigue that can lead to overtraining injuries and declines in endurance (Mageau et al., 2009;Vallerand, 2012; Schiphof-Godart & Hettinga, 2017).

The behavioral model theorizes a series of coupled equations for mental and physical endurance shown below that capture the nonlinear dynamics of the feedback between all the salient factors that affect mental and physical endurance during sustained intense physical activity. The values for the dynamics are based on observational data and survey data. The values and equations are used in the agent model rules to update the state of the agent’s attributes. The model couples the TPB with Prospect theory to include the effect of physical attributes, perceived value of sustaining the activity using confidence to weigh the effect of perception of effort, to calculate the intention to perform the activity. It introduces a coupling coefficient between physical and mental endurance based on the physical and mental state of an individual, which affects how much the intensity of exercise affects mental fatigue. It extends individual-focused models of endurance training to include social interaction effects over time. Incorporating social interaction mechanisms enhances our understanding of fitness development and can guide more effective training interventions for improved adherence. This research frames physical endurance in terms of physical performance of endurance activities. A decrease in physical performance is seen as the effect of physical fatigue.

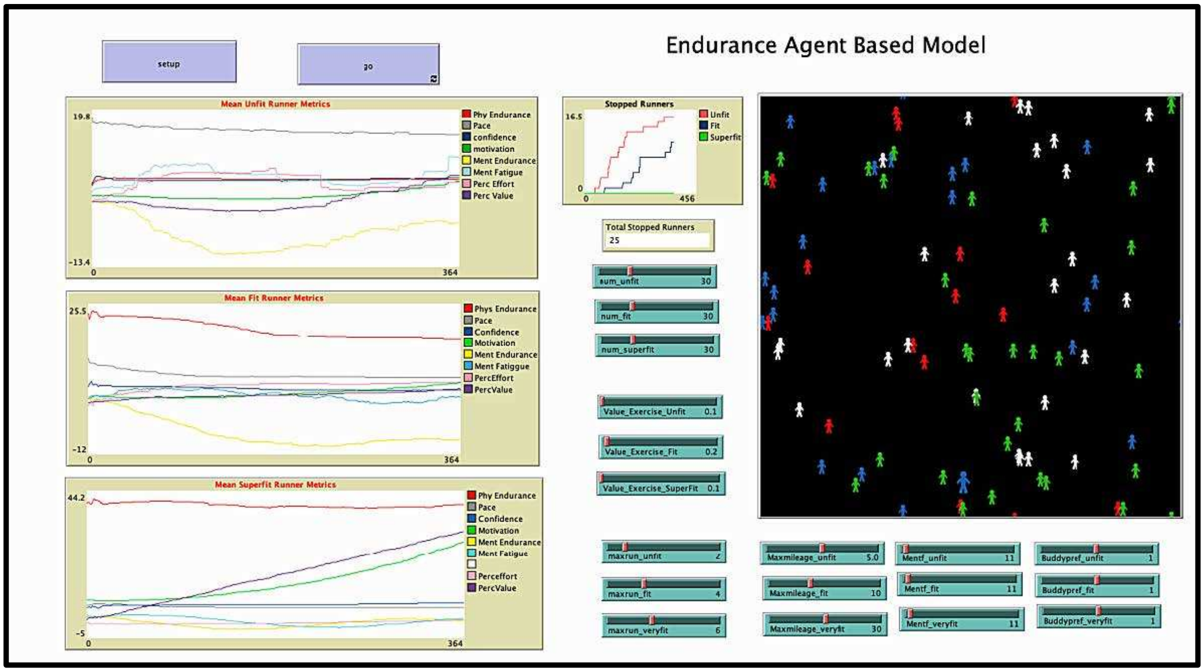
CHAPTER 4: COMPUTATIONAL SIMULATIONS OF EVOLVING DYNAMICS

This dissertation developed three different computational simulations of the evolving dynamics of endurance enhancement. The first was an agent-based model to capture the behavioral effects of social interactions on the evolving dynamics of physical, mental and behavioral attributes as they affect endurance. It provided an understanding of group and individual effects. The second and third models are system dynamical causal models of physical and mental attributes of endurance and recovery effects on endurance.

4.1 Agent-Based Model and Simulation (ABM)

Runners often train with others or in groups, where it has been observed that peer behavior can influence motivation, adherence, and training intensity. The Agent based model explores how the physical and mental endurance of runners of different initial physical and mental fitness levels is affected if they run with others of different fitness levels or if they run alone. It enables exploration of a wide range of values for physical and mental parameters and provides reference modes for SD model.

Social psychology and behavioral research based on surveys has shown that people who exercise with others felt increased bonding that led to improved exercise ability (A. Davis et al., 2015; A. Davis & Cohen, 2018; Sullivan & Blacker, 2017). Group running has been shown to improve motivation and adherence to exercise. This research utilizes an agent model to explore how the endurance of runners of different initial physical and mental fitness levels is affected if they run with others of different fitness levels or if they run alone. The model shown in Figure 12 was developed with “Netlogo 6.4.0 agent modeling software” (Wilensky, 1999). It classifies runners as novice runners in red, average runners as blue, elite runners as green and all stopped runners as white. The interface allows varying the input parameters including number of runners, maximum number of runs, maximum mileage, belief in running, buddy preference (choice to run alone or with someone) for each fitness group. It also shows the number and type of stopped runners. The rules for the agent model are listed in Appendix A.



Total Stopped Runners 25

num_unfit 30
num_fit 30
num_superfit 30
Value_Exercise_Unfit 0.1
Value_Exercise_Fit 0.2
Value_Exercise_SuperFit 0.1
maxrun_unfit 2
maxrun_fit 4
maxrun_veryfit 6
Maxmileage_unfit 5.0
Maxmileage_fit 10
Maxmileage_veryfit 30
Mentf_unfit 11
Mentf_fit 11
Mentf_veryfit 11
Buddypref_unfit 1
Buddypref_fit 1
Buddypref_veryfit 1

Figure 12: Endurance Agent Based Model. Management Flight Simulator ABM as modelled with Netlogo software

The core behavior modeled in the agent-based simulation is the change in runners' endurance within a community as they train and interact with one another over the course of a year. Information that can be gained from the model are:

O1: Do people improve endurance if they train with more people?

O2: Does the fitness level of the person they train with affect endurance?

O3: Does change in physical endurance affect motivation through confidence?

To develop the endurance-focused agent-based behavioral model, a simulated group of runners with varying levels of initial physical and mental fitness is created. The environment is represented by a 50-by-50-mile grid, modeling a community with a large running population. This population consists of three types of agents:

Novice – low fitness/unfit

Average – medium fitness/ fit and

Elite – high fitness/super fit

The model assumes that each runner completes one run per day and that changes in physical and mental endurance occur immediately afterward. All agent types share the same set of attributes, differing only in their initial values. Appendix B lists the parameter ranges used for the model. Initial ranges of values for physical endurance are based on typical VO2max but other metrics such as critical power could be used. Initial ranges for mental endurance are based on mental toughness measure Mental Toughness Questionnaire(MTQ48) but other metrics such as Mental, Emotional, and Bodily Toughness Inventory (MeBTough) or Mental Toughness Index (MTInd) could be used (Clough et al., 2017; Gucciardi et al., 2015; Mack & Ragan, 2008). The average pace for an individual runner for a up to a 3-mile run for low fitness, up to a 5-mile run for an average fitness runner and up to 8 miles for an elite runner will be used to assess fitness level (Ristanović et al., 2023; Myrkos et al., 2020). The model does not differentiate between age and sex at birth. Initial mental endurance was assigned randomly within a range for each type of agent.

The model rules for updating physical and mental endurance, confidence, motivation, mental fatigue, and perception of effort are based on the series of coupled equations shown in section 4.1.1. Prospect Theory was used to evaluate the perceived value of sustaining an activity. A weighting function was used to calculate the perceived value of each outcome based on the reference point (perception of effort), which is weighted based on confidence that the individual feels based on their current physical and mental state.

As the agents interact with the environment, they randomly encounter runners with different fitness levels, paces, mental state, running buddy preferences, motivation, and confidence. Building on previous research that shows that pace is an indicator of both intensity and duration of activity, the model uses pace coupled with duration to assess the change in physical and mental endurance. Each runner is randomly assigned an initial number of miles within a range typical of their fitness type and runs that number of miles for every run at varying paces based on who they are running with. For example, lower fitness runner can run anywhere between 0.1 miles and 3 miles per run. The maximum mileage per week and number of runs parameters are used to determine the volume of running. The parameter “running buddy preference” was used to explore solo and group running behaviors for the same runner. Depending on a match between running buddy preference, intensity/pace, run completed for the day, and time interval(within a week), an agent will choose to run with another agent. When agents interact with another agent who has a pace within a 1-4 minutes per mile difference, they will choose to run with them since it is advantageous to them and feasible, and if they meet the agent's preferences and have not run that day. The physical endurance, motivation, and confidence of an agent will be affected positively or negatively depending on the fitness level of the agent and the pace difference. The model does not specify interactions based on agent breed type but instead just on the difference in pace and willingness to run(buddy preference). The higher pace, slower runner will reduce their pace based on the pace of the faster runner and run their miles at that pace. If the difference in pace is less than or equal to 1 minute per mile, the slower runner will adopt that pace and run with the faster runner. If the pace difference is between 1-4 minutes per mile, the faster runner will slow down by one minute per mile and the slower runner will increase their pace by 2 minutes/mile. The change in pace triggers updates to physical, mental and behavioral parameters for each runner via the rules that implement the equations at each time step. This will affect the motivation, confidence, and perception of effort of both runners resulting in a change to physical and mental endurance. The model assigns a higher coupling between mental and physical endurance to lower fitness runners and a higher belief in the value of running to high fitness individuals. Once a run is completed, the agent can run with a different agent till the end of the week or eighth tick. If an agent exceeds the maximum mileage per week their physical endurance will decrease slightly. The model changes pace, mileage, and confidence for both agents when an agent encounters another agent positively or negatively, depending on the fitness level of the agent and the change in pace and mileage. If a runner exceeds their maximum allowed mileage or number of runs during a given week, they stop participating in group runs and rest for the remainder of the week. For a solo/no-buddy runner, the agent will run and continue not to run with other agents despite interaction. If the cumulative interactions deplete motivation to less than 0.5, the agent will stop running permanently. Future work that incorporates age, rest, recovery, and detraining will look at stopping the agent from running temporarily to recover and start back up. Future work will explore the effect of added mental stress and how frequency and volume of running affects runners of varying physical and mental endurance as they run with others.

4.1.1 Coupled differential equations:

The behavioral to physical attributes relationships for each individual agent in the model were implemented as coupled differential equations. These were implemented as rules that incrementally modify/update the values of the agent's attributes at each timestep

Specific outcomes are not predetermined and can vary each time it is applied due to random initial values for each individual agent's attributes. Equations 9-16 describe the relationships between the dynamic variables in which:

CPace =change in pace; PHE=Physical endurance; ME=Mental Endurance; Conf=Confidence; Mot=Motivation; Peff=Perception of Effort; MF=Mental Fatigue; PV=Perceived Value

The change in pace occurs when a runner adopts a new pace based on the interaction with another suitable running buddy/group and is shown in equation 9.

$$CPace(t) = \frac{dPace}{d(t)} = Pace(t) - Pace(t-1) \tag{9}$$

This change in pace coupled with the runner's current physical and mental endurance, affect the new physical endurance of the runner as seen in equation 10.

$$\frac{dPHE}{d(t)} = PHE(t-1) + k1 * CPace(t) * k2 * ME(t-1) * k3 * PHE(t-1) \tag{10}$$

The runner's confidence is dependent on their current confidence levels modulated y their physical and mental endurance as shown in equation 11.

$$\frac{dConf}{dt} = Conf(t-1) + \; k4 * PHE(t) + k5 * ME(t-1) \tag{11}$$

The runner's perception of effort is related to their current perception of effort and motivation balanced by their physical and mental endurance as shown in equation 12

$$\frac{dPeff}{dt} = Peff(t-1) + k6 * Mot(t-1)/(PHE(t) + ME(t-1)) \tag{12}$$

Their mental fatigue is affected by their mental endurance, change in pace, coupling and perception of effort as seen in equation 13.

$$\frac{dMF}{dt} = MF(t-1) + k7 * (ME(t-1) + k8 * (CPace(t) * CC * Peff(t)) \tag{13}$$

where CC = coupling constant between physical and mental endurance assigned randomly to each runner within a range for each fitness group.

At each time instant, the runner makes a value decision on whether they want to keep running based on their confidence in their ability to continue, their belief in the value of running, their perception of effort required to continue running and their current physical state as shown in equation 14

$$\frac{dPV}{dt} = PV(t-1) + k9 * Conf(t) + B + k10 * PHE(t) - Peff(t) \tag{14}$$

where B=belief in value of running assigned randomly for each runner within a range for each fitness group

The motivation to run is dependent on their confidence at that time, their perception of effort, and perceived value of continuing to run as seen in equation 15

$$\frac{dMot}{dt} = Mot(t-1) + k11 * Conf(t) - k12 * Peff(t) + k13 * PV(t) \tag{15}$$

A runner's mental endurance is affected by their motivation, confidence and mental fatigue as they run as seen in equation 16.

$$\frac{dME}{dt} = ME(t-1) + k14 * Mot(t) + k15 * Conf(t) - k16 * MF(t) \tag{16}$$

All initial values were assigned randomly for each runner within a range expected for their fitness group.

4.2 System Dynamical Causal Simulations

Two System Dynamical (SD) Causal simulations were developed. The Endurance System Dynamical simulation models the dynamical interaction between physical, mental and behavioral attributes for an individual. The Recovery for Endurance SD Causal Simulation models the interaction between physical and mental endurance, fatigue in response to recovery strategies.

4.2.1 Endurance System Dynamical Causal Model

An Endurance System Dynamical Causal model was developed that captures the key physical and mental attributes that affect endurance and explores their dynamic interactions over a long period of time for an individual. The model structure which includes internal logic and equations were developed using known real-world physical and causal relationships based on empirical experimental and observational data. Key dynamic parameters include physical endurance, mental endurance, weight, resting heart rate, confidence, motivation, mental fatigue, perceived effort and perceived value. These parameters are dimensionless quantities and are represented by stocks that accumulate or deplete over time. Flows that represent the rates of change of these stocks cause increases or decreases of the amount that stock represents. As seen from figure 13, the overall model is extremely complex and has multiple reinforcing and balancing feedback loops between physical and mental attributes of the endurance system. The balancing loops cause the inherent delays observed in empirical literature that exist between physical and mental attributes of the endurance system in response to adaptations to training. A key insight gained from the model is that the endurance system behaves like an underdamped oscillator where physical endurance directly affects mental endurance which takes time to damp out in an overshoot and collapse pattern. The changes in physical and mental endurance are the result of the body and mind adapting to training. When a person starts training, they gain efficiency in breathing, their muscles build up and strengthen, and they get mentally stronger. Training consistently does more than just make muscles look different; it rewires a body’s internal systems to handle stress more effectively. A person’s breathing muscles get stronger, allowing them to take deeper, more controlled breaths with less effort. Their body sees tiny muscle tears as "damage" that needs to be fixed, which results in stronger muscles. Exercise triggers the release of endorphins and dopamine, which improve mood and focus. As a person’s physical abilities increase with training, their confidence increases along with mental endurance.

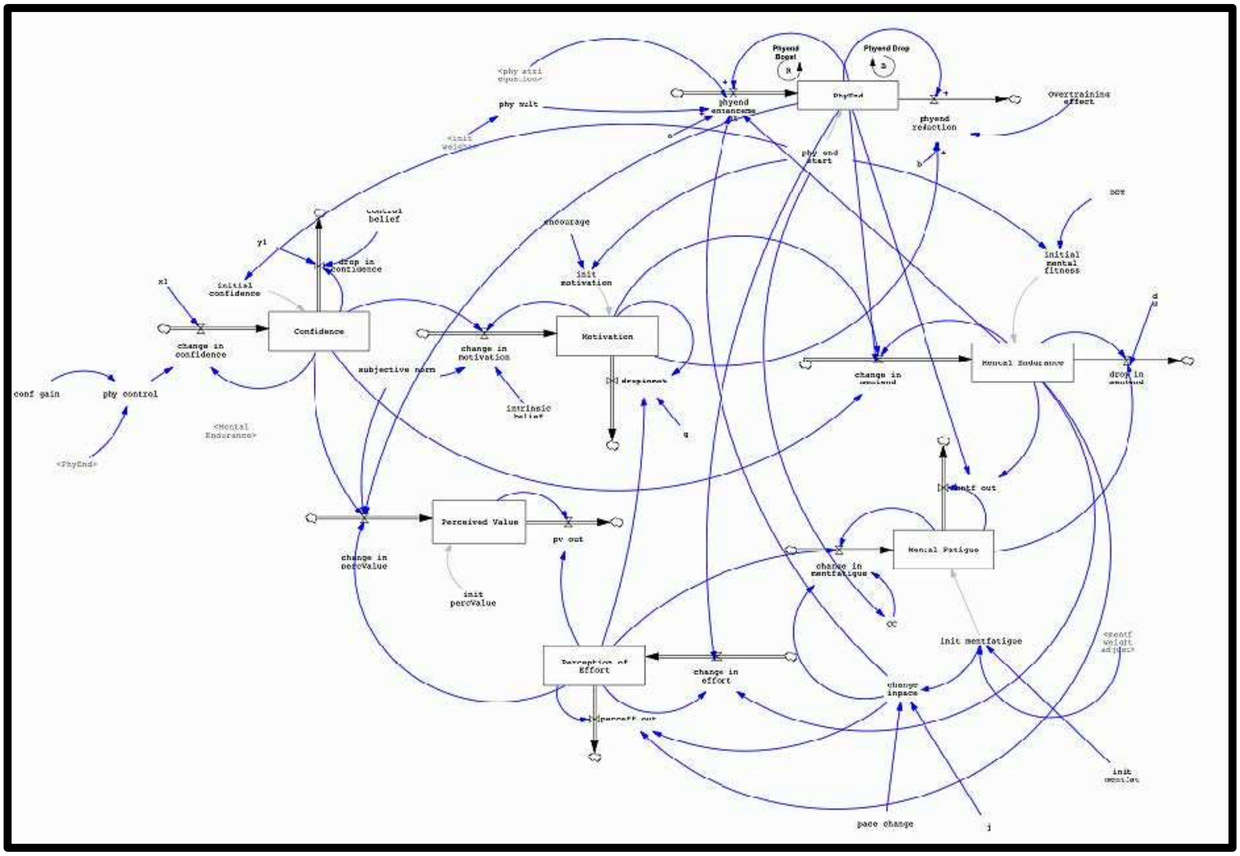


Figure 13: Endurance System Dynamical Causal Model. Extremely complex model with multiple reinforcing and balancing feedback loops between physical and mental attributes

For ease of understanding, the overall model was broken into sub models for each of the key attributes represented as stocks. The Physical Endurance sub model shown in figure 14 represents how physical endurance dynamically changes over time. It has two basic feedback loops-one reinforcing that results in enhancement of physical endurance and another balancing loop that reduces physical endurance. The structure and equations of the Physical Endurance sub model were defined based on the causal relationships between key attributes such as mental endurance, change in physical endurance, change in pace and physical attributes/exogenous variables such as age, weight, body fat percentage which is impacted by age, gender and BMI, body composition, physiology, training type, initial VO2max, and altitude/terrain. Based on literature search of studies and observational data and SME input, the S shaped logistic archetype was chosen to represent the stock dynamics.

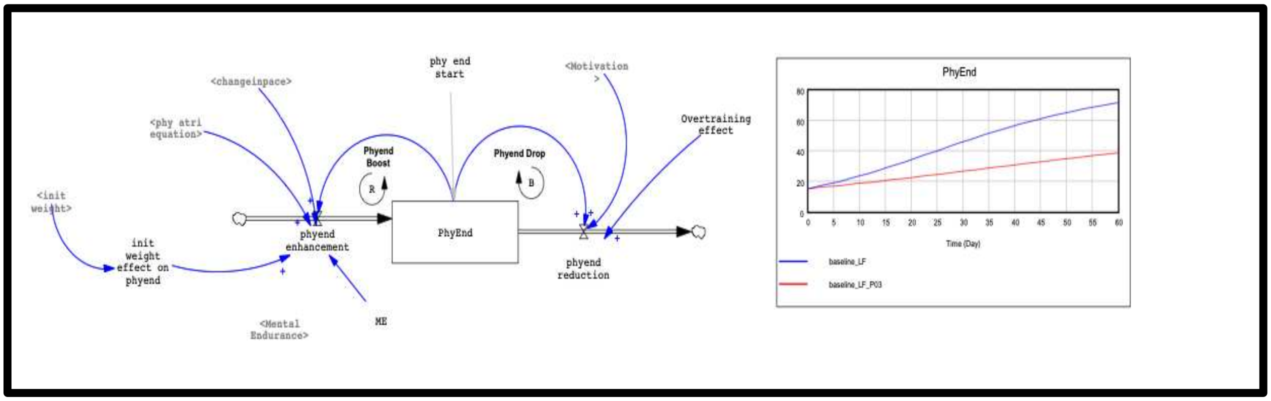


Figure 14: Physical Endurance Sub Model. Simplified view includes complex dynamic variables that affect growth and drop in physical endurance. Low fitness individual shown: Red =Physical endurance baseline and Blue = Physical endurance growth with increased training intensity

A primary driver for change in physical endurance is pace which reflects the change in intensity and duration of training. Change in pace acts as a stimulus and is affected by initial mental fatigue which increases with mental stress due to physical exertion. This can be environmentally induced, increased by carrying weight or due to combat stress. Mental Endurance which is a stock in the overall model has a positive causal relationship with physical endurance which means that changes in mental endurance positively(negatively) affect physical endurance positively(negatively) over time. A person's physical attributes interact with external variables to collectively affect physical endurance over time. As a person gets older, their physical endurance responds slower to training. VO2max is considered an indicator of physical endurance and so has a positive causal relationship with physical endurance. As altitude increases, physical endurance grows slower which implies a negative causal relationship. Body composition, which is a function of BMI, height, weight and body fat percentage directly affects physical endurance. As BMI and height/waist ratio improves(decreases), physical endurance grows(declines). A person with higher body fat percentage will have lower physical endurance. This attribute is affected by weight(stock), age, gender, height, and BMI. As a person trains their weight changes in response to the exercise and affects their body fat percentage. This affects their overall composition which affects physical endurance. This change is mediated by gender. A person's physiology which is based on genetics affects physical endurance in a positive causal relationship. When a person trains at altitude, their cardiopulmonary system has to work harder due to lower levels of oxygen. As altitude increases, physical endurance grows slower but ends up contributing to physical endurance over time. Overtraining has a negative causal relationship with physical endurance. As training intensity increases beyond the physical capabilities of a person, it has a detrimental effect on physical endurance. Motivation which is a stock that changes over time directly impacts physical endurance. The physical endurance stock integrates the two flows which include feedback from the stock. At the beginning of a training period, the reinforcing loop dominates initially but as a person gets physically tired and mentally fatigued which causes motivation to drop, the balancing loop activates and limits physical endurance growth and in some cases a drop in physical endurance.

The Mental Endurance sub model shown in figure 15 represents how mental endurance dynamically changes over time. It has two basic feedback loops-one reinforcing that results in enhancement of mental endurance and another balancing loop that reduces mental endurance.

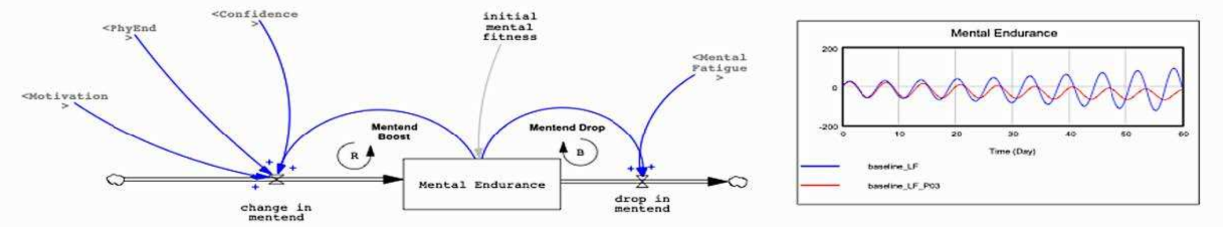


Figure 15: Mental Endurance Sub Model. Simplified view of extremely dynamic variable. Oscillations caused by push-pull between complex dynamic variables that affect growth and drop in mental endurance. Low fitness individual shown: Red =Mental endurance baseline and Blue = Mental endurance growth trend with increased training intensity

The structure and equations of the Mental Endurance sub model were defined based on the causal relationships between key attributes such as confidence, motivation, physical endurance, mental fatigue, initial physical endurance. Based on literature search of studies and observational data and SME input, the S shaped logistic archetype was chosen to represent the stock dynamics. As seen from figure 15, mental endurance is a dynamic attribute that continuously changes in response to physical and mental stimuli. The pattern of behavior of this stock is the key point of interest, not the actual values of this dimensionless attribute. The system dynamics model shows the interactions over time that affect mental endurance. The oscillations represent the natural ups and downs of a person's mental state. The model shows two main loops fighting for control. The inflow factors like motivation, physical endurance, and confidence act like a faucet, pouring energy into the mental endurance tank. The outflow factor mental fatigue acts like a drain, pulling energy out of that same tank. Because these two forces aren't constant, fatigue builds up as a person trains, and confidence grows as a person meets physical goals, creating a cycle. The circular arrows in the center represent feedback. As a person's endurance goes up, their "Mentend Boost" gets stronger and they feel good, so they do more. The balancing loop controls that eventually so that high endurance or high activity leads to a "Mentend Drop" and fatigue kicks in to prevent burnout. The oscillations occur because there is a time delay between these factors. A person doesn't feel tired the second they start running. Fatigue builds up slowly over time. Similarly, a person doesn't recover instantly. It takes time to refill the tank. In the chart in figure 15, the blue line shows a wider oscillation while the red line shows a much more stable, controlled rhythm. The blue line corresponds to the greater intensity of training and the corresponding effort and resulting mental fatigue experienced by a person. This suggests that for lower intensity levels, the baseline mental fitness helps dampen these swings, keeping energy more consistent.

The structure and equations of the Confidence sub model shown in figure 16 were defined based on the causal relationships between physical endurance stock, initial confidence, and control belief. Based on literature search of studies and observational data and SME input, the S shaped logistic archetype was chosen to represent the stock dynamics.

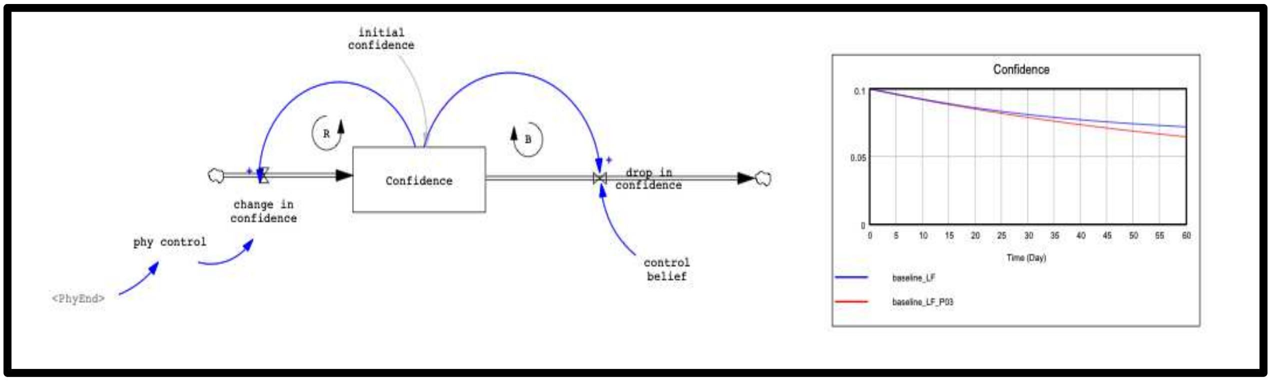


Figure 16: Confidence Sub Model. Simplified view includes complex dynamic variables that affect growth and drop in Confidence. Low fitness individual shown. Red =Confidence baseline and Blue = Confidence growth with ability to handle increased training intensity

Initial physical endurance affects confidence where a more fit person has higher confidence. As physical endurance increases(decreases), their confidence in performing the activity grows(depletes). Self-efficacy or perceived behavioral control will directly impact confidence. The more control a person believes they have over changing their endurance, the higher their confidence in performing the activity.

The structure and equations of the Motivation sub model in figure 17 were defined based on the causal relationships between key attributes such as confidence, intrinsic belief, subjective norm, perception of effort, initial physical endurance. Based on literature search of studies and observational data and SME input, the S shaped logistic archetype was chosen to represent the stock dynamics. As confidence increases(decreases) in performing an activity, a person's motivation to sustain that activity increases(decreases). A person who believes in the value of performing an activity(intrinsic belief) is more motivated. A person who believes that their peers/family value them performing an activity (subjective norm) is more motivated. These are typically affected by social influences such as praise or criticism by peers or trainers. A person who perceives an activity to be difficult is less motivated regardless of whether they are physically capable of performing the activity. The dynamic model seen in Figure 17 shows that as physical fitness decreases, a person is less motivated.

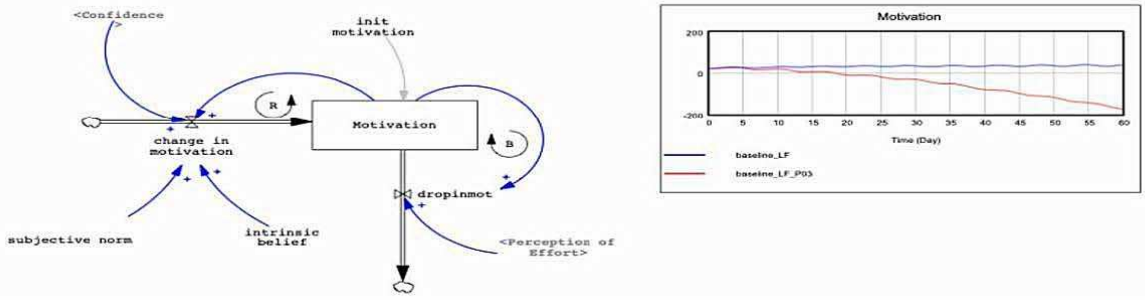


Figure 17: Motivation Sub Model. Simplified view includes complex dynamic variables that affect growth and drop in Confidence. Low fitness individual shown. Red =Motivation baseline and Blue = Motivation sustainment with ability to handle increased training intensity

Perception of effort is the primary driver of the balancing loop that reduces motivation. The model shown in figure 18 describes several causal relationships that shape perception of effort, perceived value, and mental fatigue during sustained activity. Perception of effort is influenced by both physical and mental endurance. Higher physical endurance reduces perceived effort because the body can sustain work with less strain. Higher mental endurance also lowers perceived effort because the individual can tolerate stress and discomfort more effectively. Changes in pace increase perceived effort. A faster pace requires greater exertion to maintain the activity.

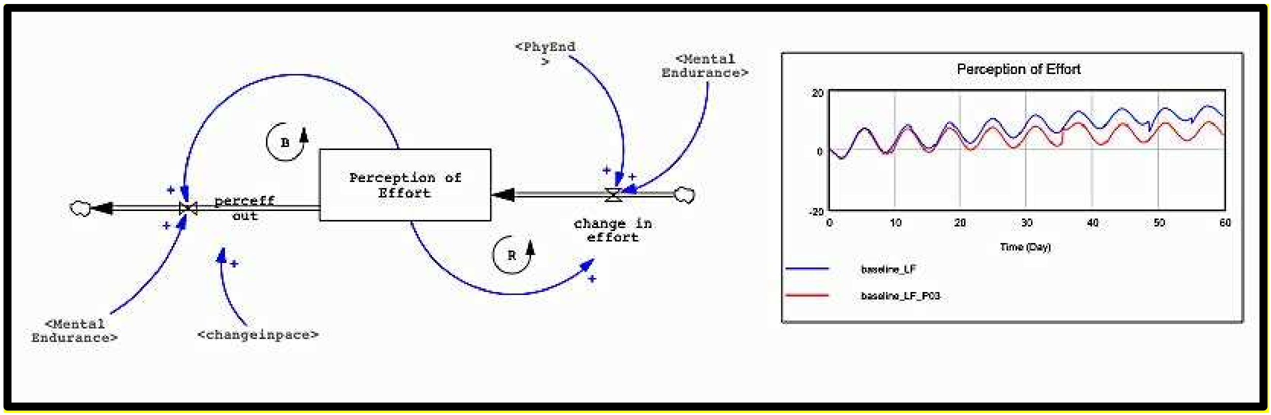


Figure18: Perception of Effort Sub Model. Simplified view includes complex dynamic variables that affect growth and drop in Perception of Effort. Low fitness individual shown. Red =baseline and Blue = Perception of Effort growth with increased training intensity

This figure also shows oscillatory behavior. The reinforcing loop suggests that as a person feels they are working harder, their body or mind may signal a need for even more effort to maintain the same pace. It’s a snowball effect. The balancing loop acts as a check. Factors like mental endurance and change in pace help drain the perceived effort. If you have high mental endurance, the task "feels” easier, effectively lowering the perceived effort. The oscillations represent the daily or session-based cycle of exertion. The up swings are the moments during training or work where the task feels harder and harder as you push through. The down swings represent the recovery phase or the moments where your mental endurance kicks in to make the task feel manageable again.

The Perceived Value dynamic model reflects how worthwhile the activity feels to the individual and is shown in figure 19. Confidence plays an important role in shaping this perception. Greater confidence in performing the activity increases its perceived value. Perception of effort influences value in the opposite direction. When the effort required to perform the activity increases, the perceived value tends to decline. Physical endurance also affects value. Individuals with greater endurance tend to view the activity more positively because they expect successful performance. Social influences contribute as well. When individuals believe that peers or family value their participation, the perceived value of the activity increases.

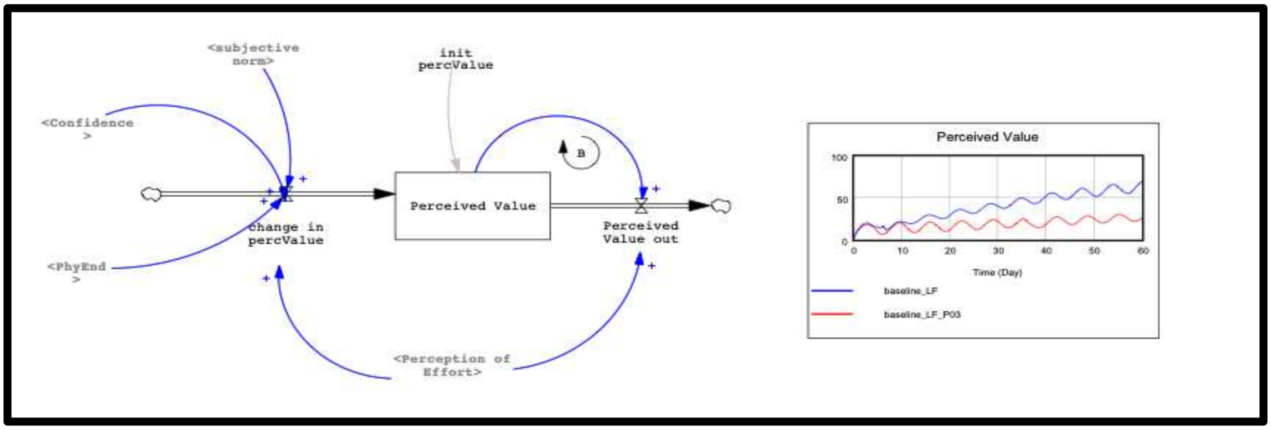


Figure 19: Perceived Value Sub Model. Simplified view includes complex dynamic variables that affect growth and drop in Perceived Value. Low fitness individual shown. Red =baseline and Blue = Perceived Value grows with ability to handle increased training intensity

Mental fatigue develops through several interacting factors as seen from the dynamic model shown in figure 20. Perception of effort is a strong driver. As effort feels higher, mental fatigue increases. Physical endurance reduces mental fatigue because stronger physiological capacity lowers the strain associated with activity. Mental endurance also reduces fatigue by improving tolerance to cognitive and emotional stress. Changes in pace increase fatigue because sustaining a higher pace requires greater concentration and effort. The coupling between physical and mental endurance also affects fatigue levels. Strong coupling means that strain in one domain quickly affects the other. Individuals with lower initial fitness often experience stronger coupling, which leads to greater mental fatigue. Initial mental fatigue also influences the system. Individuals who begin activity under psychological stress, physical load, or other strain experience higher levels of mental fatigue during the activity.

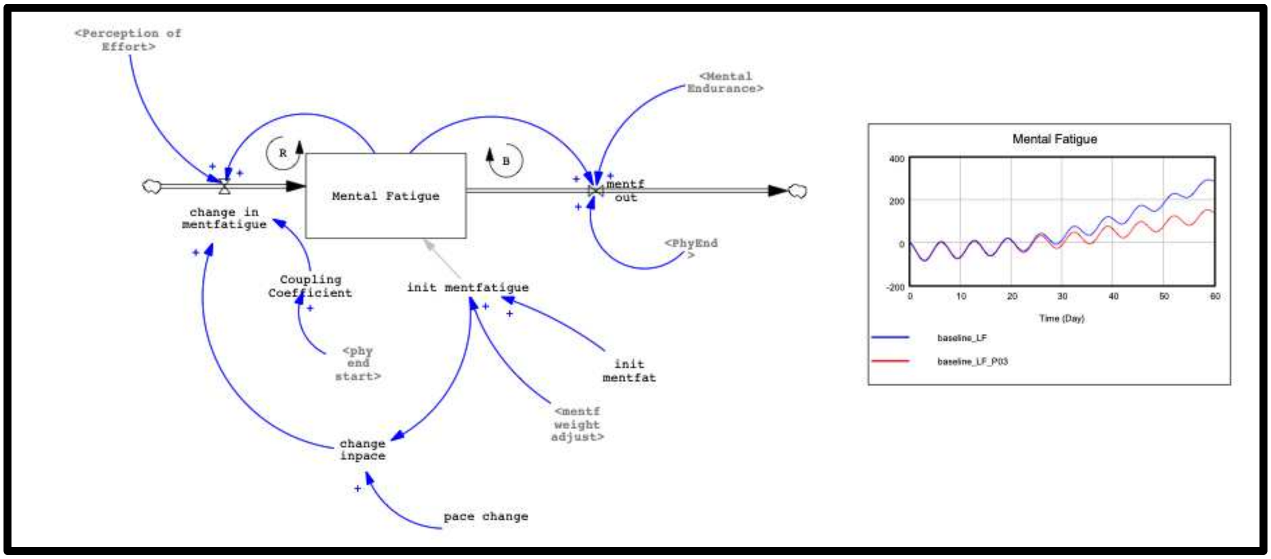


Figure 20: Mental Fatigue Sub Model. Simplified view includes complex dynamic variables that affect growth and drop in Mental fatigue. Low fitness individual shown. Red =baseline and Blue = Mental Fatigue grows with increasing training intensity

The drivers of the inflow are Confidence (the more capable you feel, the more you value the work), Physical Endurance (as your body gets stronger, the "value" of the session increases because you feel the results), and Subjective Norm, (doing what you think you should be doing). The oscillations are caused by the Perception of Effort, the factor in the previous model. The blue arrow from Perception of Effort goes into both the "change" (inflow) and the "out" (outflow). The inflow represents the effort that makes a task feel more valuable, the "I worked hard for this" effect. But, if the effort feels too high, it starts "draining" the perceived value affecting the outflow. The oscillations represent this constant mental negotiation; the satisfaction of a hard workout versus the exhaustion that follows.

Based on literature survey and observational data, the change in resting heart rate over time is a great indicator of how a person’s physical fitness is changing. Resting Heart Rate was implemented as a stock shown in figure 21, to be used as a metric to gauge how a person’s physical endurance changes over time. The stock is affected directly by the physical endurance stock and indirectly by the other stocks in the model. The starting values of maximum heart rate and initial resting heart rate are dependent on initial physical fitness. These are measured by most fitness trackers and smart watches. The better a person’s physical endurance, the faster the drop in their resting heart rate. An increase in resting heart rate over time is an indicator of a decrease in physical endurance. It can also indicate, overtraining, injury or sickness. This sub model as well as the perception of effort sub model can be used as inbuilt metrics to gauge the change in a person’s endurance over time.

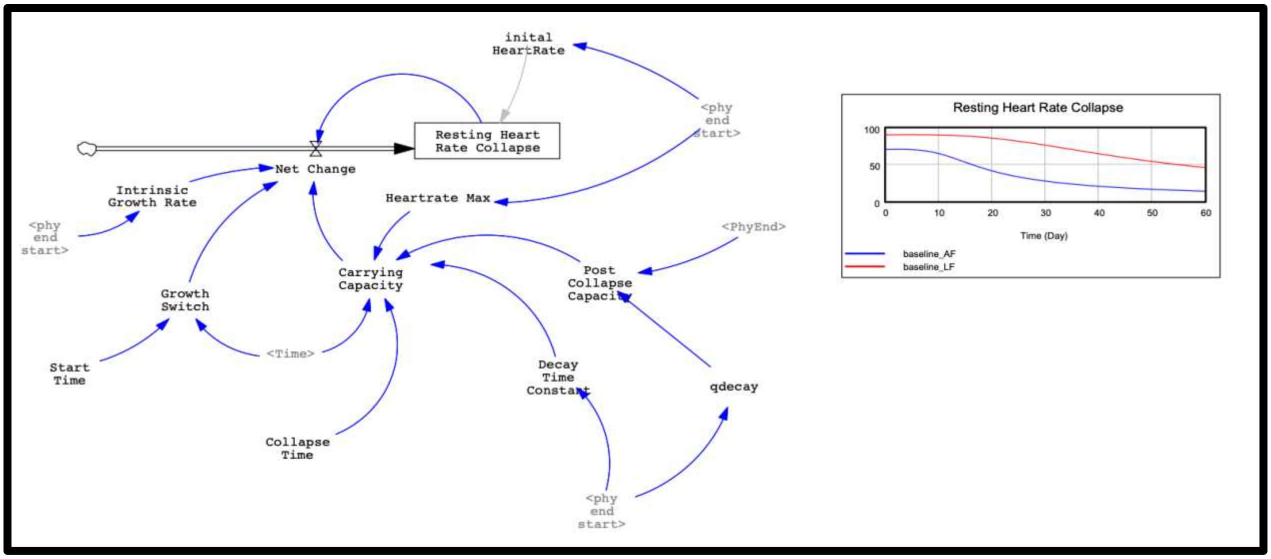


Figure 21. Resting Heart Rate Sub Model. Shows how initial fitness and dynamically varying Physical endurance affect resting heart rate. Comparison of Low and average fitness individuals shown. Red =Low fitness and Blue = Average fitness individual's resting heart rate improves faster with training

The oscillation patterns in four of the models occur because the body and mind do not exist in a steady state; they operate through a series of delayed feedback loops. The mechanics of the oscillations are primarily driven by balancing (negative) feedback loops. When you train, your body consumes resources. This creates a "drain" on your system. The brain perceives this drain as fatigue or effort. To protect the body, the brain signals you to slow down or rest. There is a lag between the action (training) and the sensation (fatigue). Because you don't feel the full weight of the effort instantly, you often "overshoot" your limit, leading to a sharp drop in energy, followed by a recovery period. This overshoot and recovery create the wave pattern. The mind and body push-pull effect also influences each other's frequency and amplitude. The waves become smaller and more stable because the body isn't sending "signals" to the brain as quickly. When your "Perceived Value" or "Confidence" is high, you can override the physical signals of fatigue. This allows you to maintain a higher baseline, even when the body is demanding rest.

4.2.2 Recovery for Endurance System Dynamical Causal Model

A System Dynamical causal model of performance, physical fitness, fatigue, and recovery mechanisms and their impact on endurance was developed. This is a complex model with multiple reinforcing and feedback loops between attributes. For ease in understanding the model, it was broken into three sub models: the fatigue, performance and physical endurance sub model, the mental attributes sub model ,and the recovery sub model.

The Predator Prey archetype was used to model the dynamics between Fatigue, Performance and Physical endurance as shown in figure 22. Fatigue is the predator, performance is the prey, mental and physical endurance is grass. Endurance during sustained activity emerges from the interaction of competing forces inside the human system. Physical effort supports performance. Fatigue accumulates as activity continues. The balance between these forces determines whether performance can be maintained or begins to decline. Many complex adaptive systems show similar dynamics. Predator prey models provide one example. These models describe how one population grows while another consumes it. The interaction produces oscillations, limits, and periods of recovery. The same logic can help explain the behavior of endurance during prolonged activity. In this analogy, activity performance functions as the prey. It represents the visible output of sustained effort such as running, cycling, or other prolonged physical work. Performance grows when sufficient internal resources are available. It declines when opposing forces increase. Fatigue functions as the predator. It accumulates through metabolic demand, neuromuscular strain, and psychological effort.

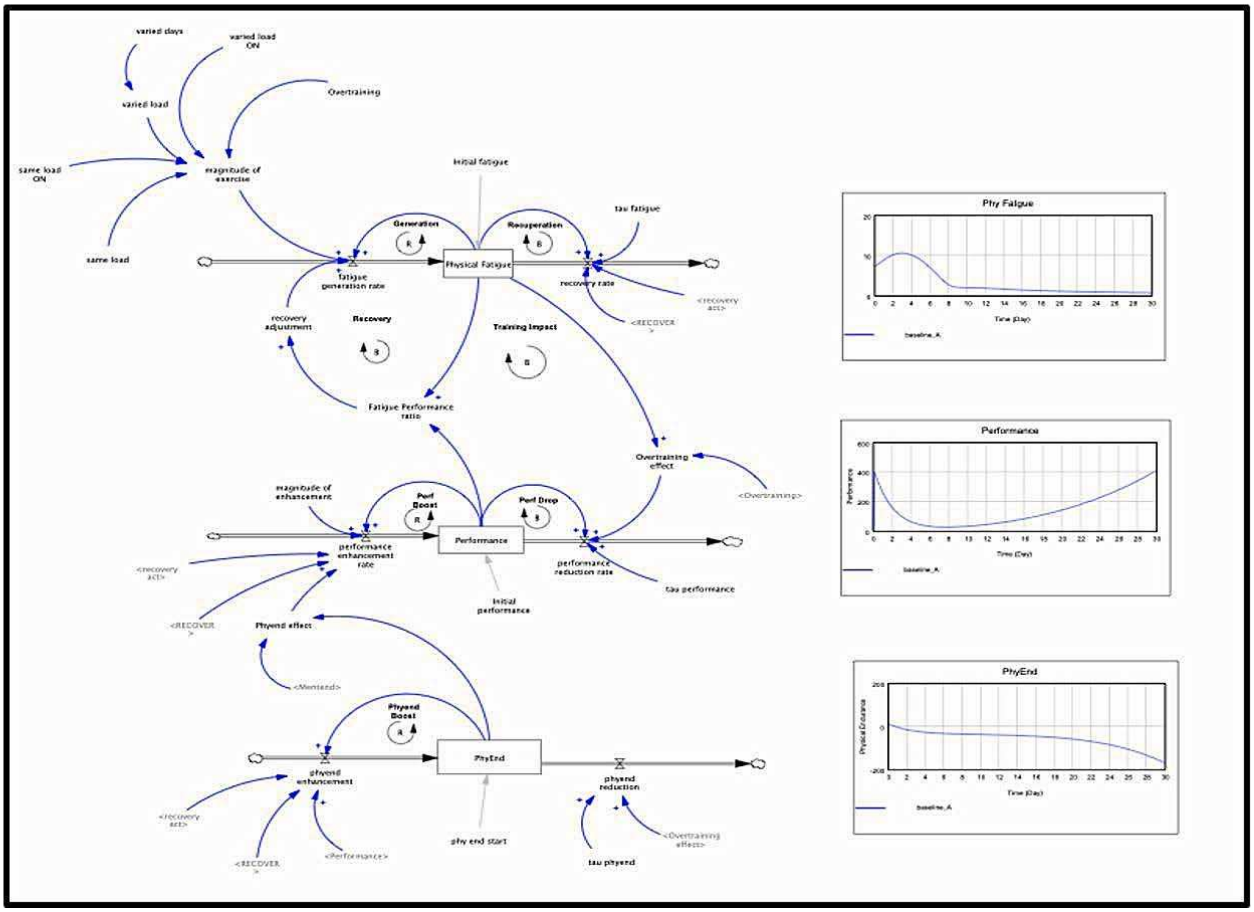


Figure 22: Fatigue, Performance and Physical Endurance Sub Model. Used Predator (Fatigue), Prey (Performance) and Food (Physical and Mental endurance) archetype. Simplified view includes complex dynamic variables that affect each other.

Fatigue reduces the capacity to sustain activity. As fatigue grows, it begins to consume performance in the same way a predator consumes prey. Rising fatigue leads to declining activity output. Endurance functions as the resource that sustains performance. In ecological systems, prey populations depend on available food such as grass. In the endurance system, physiological capacity and psychological resilience provide the energy that supports activity. Performance draws from this resource as activity continues.

The interaction between endurance, performance, and fatigue forms a dynamic system. Endurance supports performance. Sustained performance increases fatigue. Fatigue suppresses performance and eventually forces reduction or cessation of activity. Recovery restores the endurance resource and reduces the influence of fatigue. Current research often treats endurance, fatigue, and performance as separate variables. The dynamic relationship between them remains poorly understood. A predator–prey analogy provides a structured way to model these interactions over time. Such a framework allows endurance systems to be studied as complex adaptive systems where competing forces regulate sustained performance.

Mental endurance provides the energy needed for performance. It improves as a person's performance improves, which is affected by physical endurance. As shown in figure 23, the rate of replenishment of the mental endurance stock is affected by their performance, how well a person recovers and by initial mental fatigue. Mental fatigue decreases as a person recovers and their mental endurance improves over time.

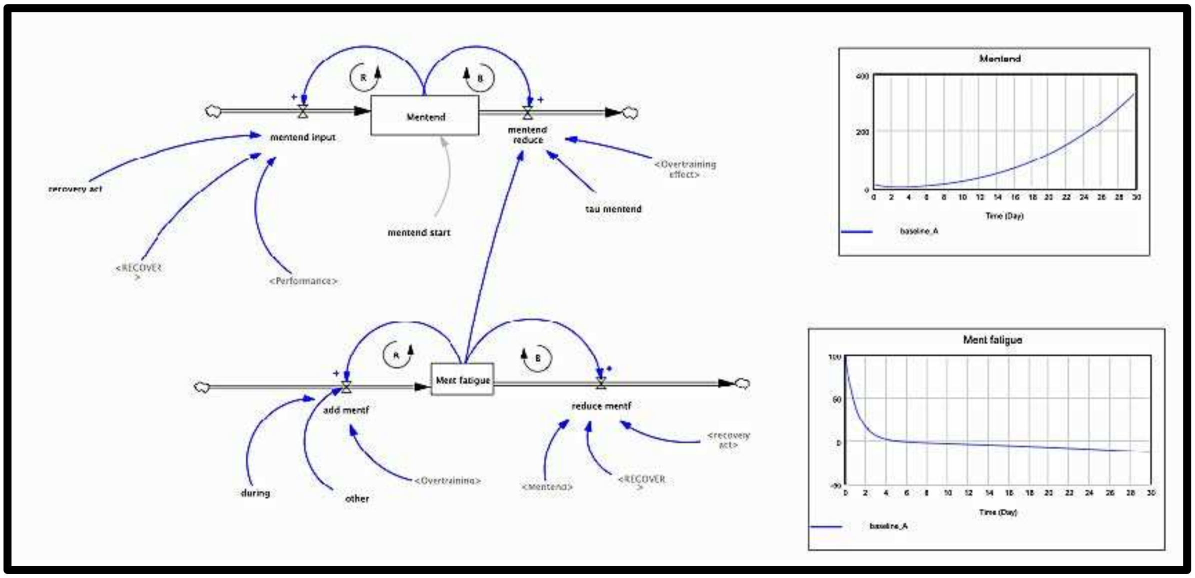


Figure 23: Mental Effects Sub Model. Simplified view includes complex dynamic variables that affect growth and drop in mental endurance and fatigue.

The recovery strategies were modelled by the Recover stock and related flows which are impacted by the various recovery strategies and other attributes such as physical endurance and mental fatigue. As seen in figure 24, the sleep, diet, hydration and active recovery strategies cumulatively add to recovery. Each of them has a magnitude and a duration determined by start and end time for the variables. The diet and hydration strategies can have different magnitudes when they are employed effectively and not effectively. The sleep strategy was modelled as a ramp function with a corresponding start and end time. The slope of the ramp determines the restorative effect of sleep(quality coupled with quantity).

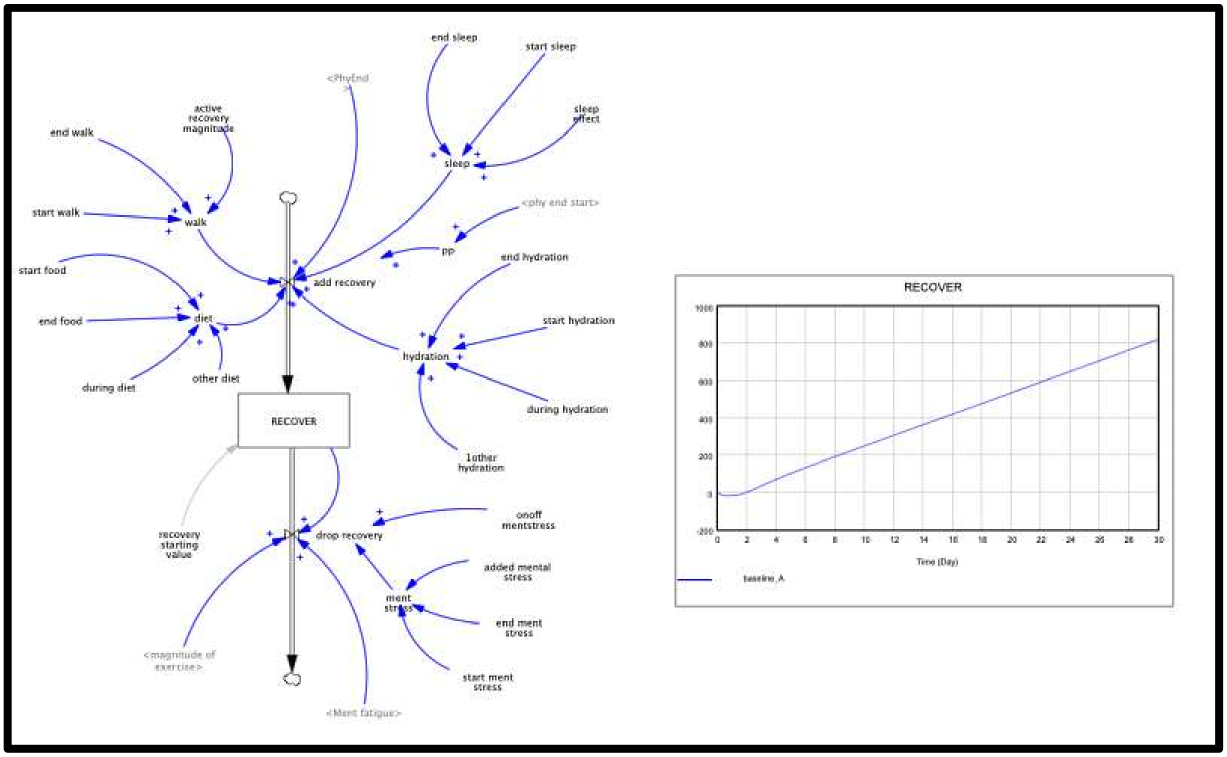


Figure 24: Recovery Sub Model. On-off implementation. Simplified view includes proactive, active(stretching, jogging, walking) and passive recovery(sleep, diet, hydration) strategies for recovery enhancement and mental stress for recovery drop -all have magnitude and duration(start and end times)

The active recovery strategy magnitudes represent the range from stretching, walking, jogging to running. This strategy was also modelled as a ramp to reflect its cumulative effect. This strategy can be overused and end up hurting physical endurance. For example, if an elite runner decides to run instead of walk for active recovery and their body has not adapted to the training stress, their physical endurance will decrease. Initial physical endurance affects how well a person recovers. For the same training intensity, a more fit person will recover much faster than a less fit person. Mental stress and fatigue will also affect the time it takes and how much you recover. The magnitude of exercise variable represents the intensity and duration effect of training that modulates the amount of recovery for a person, given their physical and mental endurance. In the overall Recovery for Endurance model, the recovery sub model is employed through an on-off recovery activation switch to enable comparisons with or without recovery for the different strategies.

CHAPTER 5. MULTIPLE ANALYSIS METHODS AND RESULTS

This dissertation combined multiple analytic approaches to provide empirical validation of the model outcomes with real-world data for both individual behaviors as well as aggregate patterns produced by the model. Sensitivity analysis was employed to explore how sensitive the model's outputs were to changes in its input parameters and assumptions. Detailed sensitivity and individual analyses were conducted to test for robustness. Validity assessments by domain experts were conducted to determine if the model and its outputs appear plausible and reasonable.

5.1 Agent Based Model Analyses & Results

The Endurance Agent Based Model (ABM) was exercised by varying the number of agents of a particular fitness level running solo, running only with their type of fitness level runners, and running with runners from a higher fitness level. The model rules did not allow runners to run together if the difference in pace was greater than 4 minutes per mile, since it would not be realistic to do so. When agents interact with agents who have a pace within a 4 minute per mile difference, they will choose to run with them since it is advantageous to them and feasible. The model only allows one run per day per agent for realism. Agents who exceed their maximum mileage per week showed a slight decrease in physical endurance. The ABM models the effect of interactions between agents so that when a person of lower fitness runs with a person of higher fitness, they will change their behavior and run faster. When the difference in fitness is too large, the novice person will run some fractional amount faster, and the average person will run some fractional amount slower, which affects their motivation, confidence, and physical endurance.

This change can also cause the person to stop exercising due to demotivation by overtraining. The model assigns a threshold minimum value for endurance so that the agent stops due to physical inability or lack of motivation. The model does not model recovery, or the effect of diet or temperature on behavior, physical, and mental endurance.

5.1.1 Sensitivity Analysis

To explore the aggregate effects for each population of runner type interacting with other runner types, a Monte Carlo sensitivity analysis of the agent model was conducted. The model was exercised with 5000 runs in Netlogo Behavior Search software to explore the long-term behaviors and identify which parameters affect the physical and mental endurance of 50 low fitness, 50 average fitness and 50 high fitness runners' as they interact with each other. All initial values were assigned randomly within the range for each type of runner as shown in Appendix B. Figures 25, 26, and 27 show the mean physical and mental endurance for a group of 50 novice, 50 average and 50 elite runners respectively for 5000 runs. All data was normalized using min-max -1 to 1 normalization and analyzed in MATLAB software (Mathworks, 2025). The novice physical and mental endurance plot show a lot of variability due to the large range of initial conditions for this group. The initial downward trend demonstrates that the sustained interactions with other runners initially cause them to push themselves, resulting in endurance levels decreasing. Due to the delayed effects of exercise training, the physical and mental endurance eventually show an increase and then plateaus. Another subtle effect that can be seen by comparing the physical and mental endurance is that a physical endurance increase lags the mental endurance increases since it is affected by the change in mental endurance. Novice runners have a higher coupling between physical and mental endurance and are more affected by interactions since they have initial lower physical and mental endurance. For average and elite runners, their physical and mental endurance is more correlated and follows a similar trend with the increase in physical endurance being affected by the earlier increase in mental endurance but with a longer delay. This can be explained by the reduction in coupling between physical and well as higher initial mental endurance which is seen in fitter runners. This enables fitter runners to maintain the cognitive dissonance needed to complete longer runs at a faster pace.

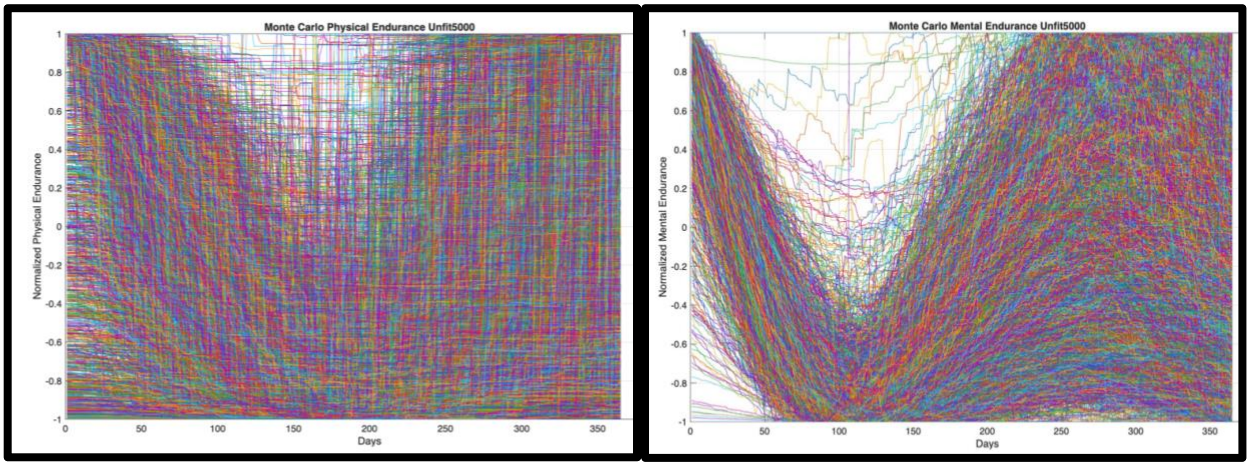


Figure 25: Physical Endurance and Mental Endurance of Novice runners Monte Carlo. Each line is mean value of 50 novice runners interacting with 50 average and 50 elite runners for 5000 runs

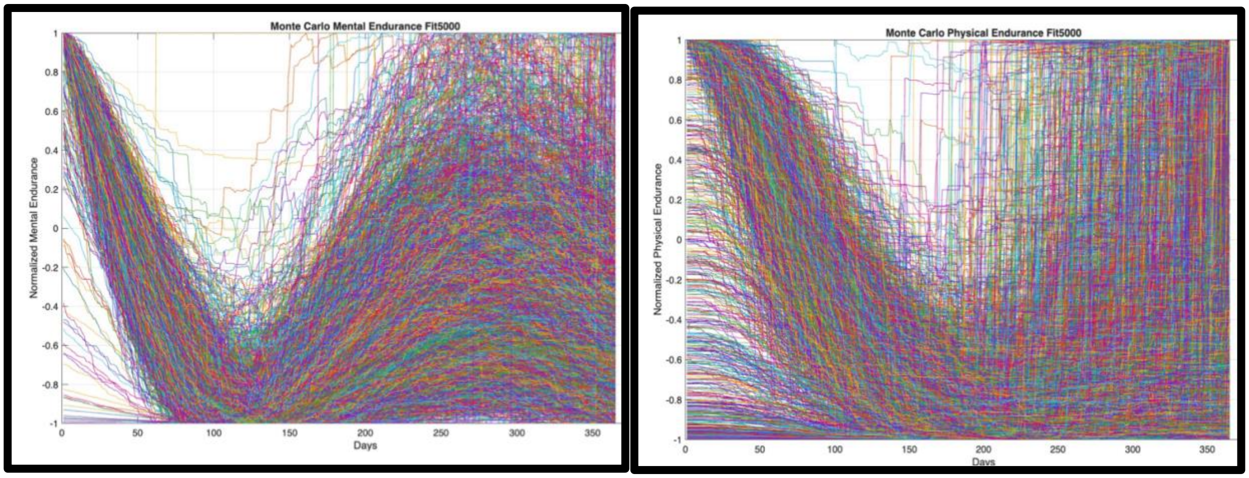


Figure 26: Physical Endurance and Mental Endurance of Average runners Monte Carlo. Each line is mean value of 50 average runners interacting with 50 novice and 50elite runners for 5000 runs

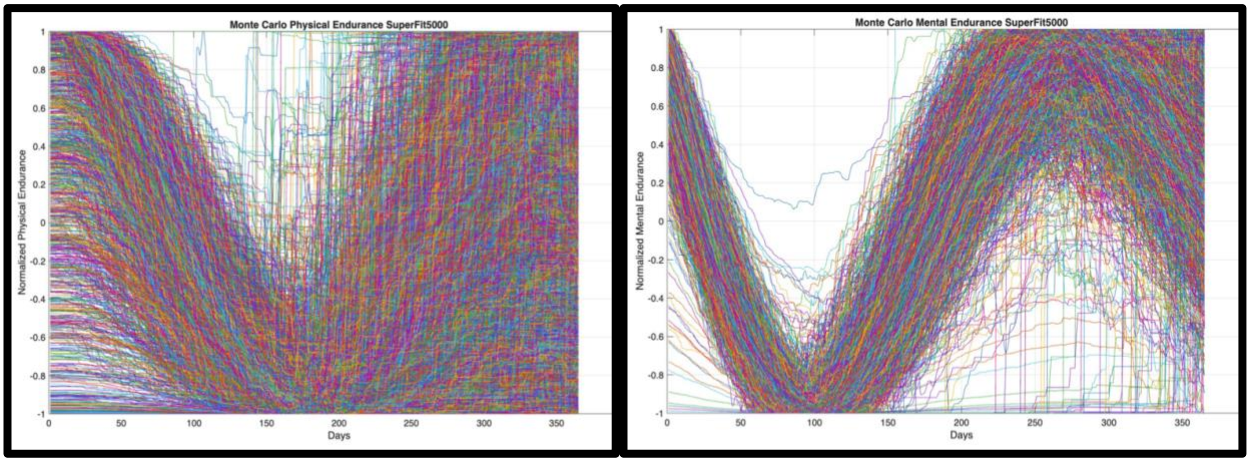


Figure 27: Physical Endurance and Mental Endurance of Elite runners Monte Carlo. Each line is mean value of 50 elite runners interacting with 50 novice and 50 average runners for 5000 runs

The Monte Carlo data was used to generate tornado plots for the sensitivity of physical and mental endurance of the three types of runners to the input parameters. The parameters varied were number of runners, initial mental fatigue, maximum number of runs, maximum mileage, coupling between physical and mental endurance and belief in the value of running. Figures 28 shows tornado plots of the factors that show the most increase and reduction in physical and mental endurance of novice runners compared to the baseline with minimal change from beginning to end of exercise timeline. For novice runners, the maximum number of runs per week affected their physical endurance and initial mental fatigue affected their mental endurance the most. Maximum mileage per week was the second largest contributor to change in physical endurance which is due to their lower physical and mental endurance. Maximum runs per week was the second largest contributor to change in mental endurance for novice runners.

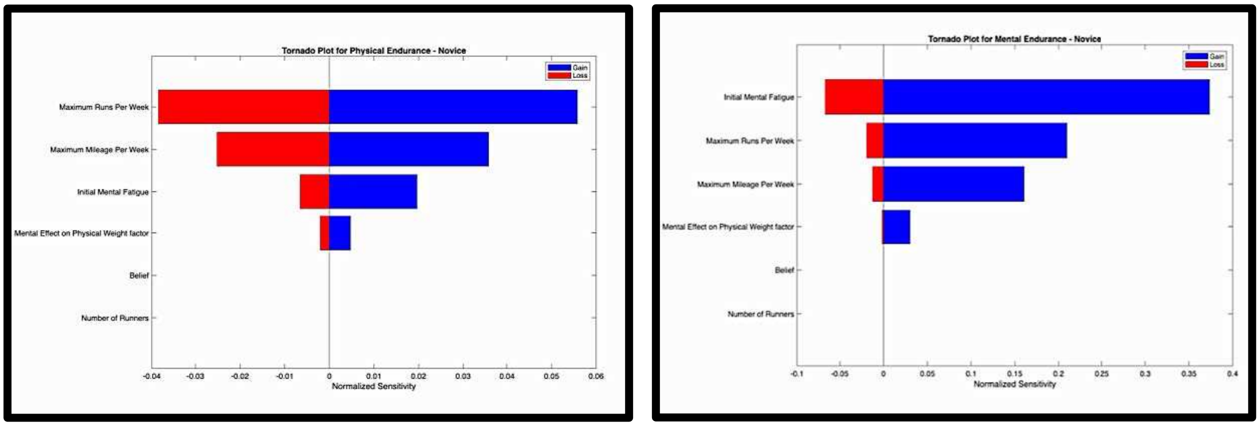


Figure 28. Sensitivity of Physical and Mental Endurance of Novice runners to Input Parameters.
Left graph: Max runs and Max miles affect physical endurance of novice runners
Right graph: Initial Mental Fatigue and Max runs affect mental endurance of novice runners

Figures 29 shows tornado plots of the factors that show the most increase and reduction in physical and mental endurance of average runners compared to the baseline with minimal change from beginning to end of exercise timeline. For average runners, initial mental fatigue was the key factor that affected both physical and mental endurance. For average runners the second most impactful parameter for physical endurance was number of runners and for mental endurance was maximum number of runs. Figure 30 shows tornado plots of the factors that show the most increase and reduction in physical and mental endurance of elite runners compared to the baseline with minimal change from beginning to end of exercise timeline. For elite runners, maximum mileage per week affected both their physical and mental endurance the most. Initial mental fatigue was the second most impactful parameter for physical and mental endurance. These sensitivities have implications on how to train runners of different initial physical and mental fitness to improve endurance.

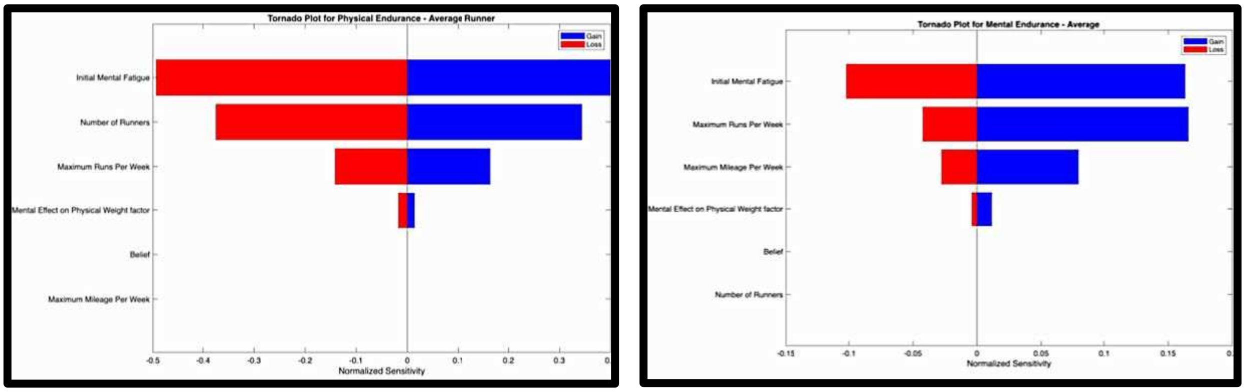


Figure 29. Sensitivity of Physical and Mental Endurance of Average runners to Input Parameters
Left graph: Initial Mental Fatigue and number of runners affect physical endurance of average runners. Right graph: Initial Mental Fatigue and Max runs affect mental endurance of average runners

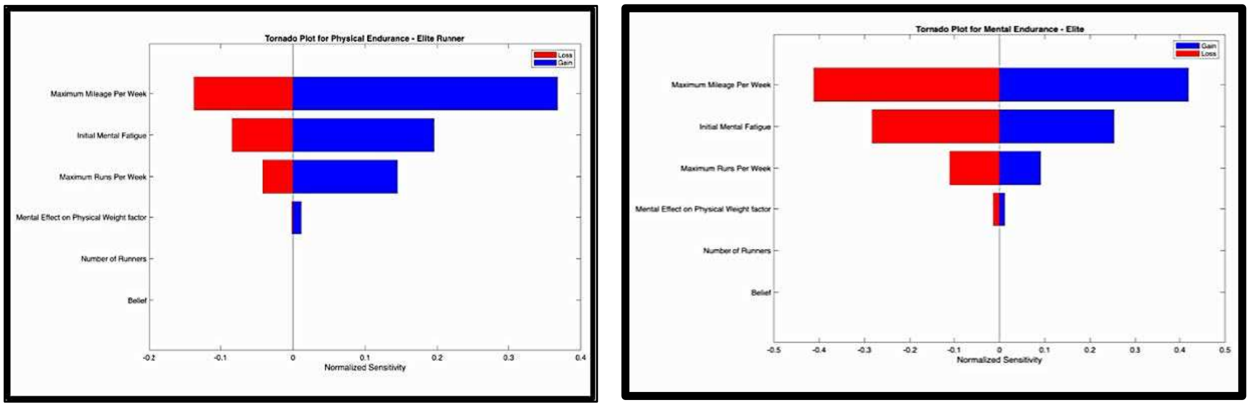


Figure 30. Sensitivity of Physical and Mental Endurance of Elite runners to Input Parameters
Left graph: Max miles and Initial Mental Fatigue affect physical endurance of average runners
Right graph: Max miles and Initial Mental Fatigue affect mental endurance of average runners

5.1.2 Detailed exploratory analysis:

Exploratory analysis included one factor at a time sensitivity analysis and inter group analysis. The one factor at a time sensitivity analysis investigated the relationships between the top two attributes for each class of runner: novice, average, and elite. The inter-group analysis explored how many runners in each group stopped running over time and whether the composition of the overall set of runners affected the motivation to run.

Based on the sensitivities highlighted by the tornado charts, the relationship between the key parameters that most affected the physical and mental endurance of each group of runners were explored. Using "Netlogo" Behavior Search and MATLAB, the mean physical and mental endurance changes were evaluated for groups of 50 novice, average and elite runners as they interacted with only their type of runners. Figure 31 shows that for novice runners, many low mileage runs per week increase physical endurance and high mileage with more runs per week lowers physical endurance. One key takeaway from Figure 31 is that novice runners cannot handle simultaneous maximization of mileage and number of runs. The mental endurance of novice runners dropped with increasing number of runs per week and increasing initial mental fatigue. For average runners running only with their type of runners, mean physical endurance decreased with increasing mental fatigue and number of runners and maximum number of runs and mean mental endurance dropped with increasing mental fatigue for 1 to 8 runs per week. Elite runners showed a decrease in mean physical and mental endurance with increasing mental fatigue for each mileage, ranging from 10-50 miles per week. Plots were not included for brevity.

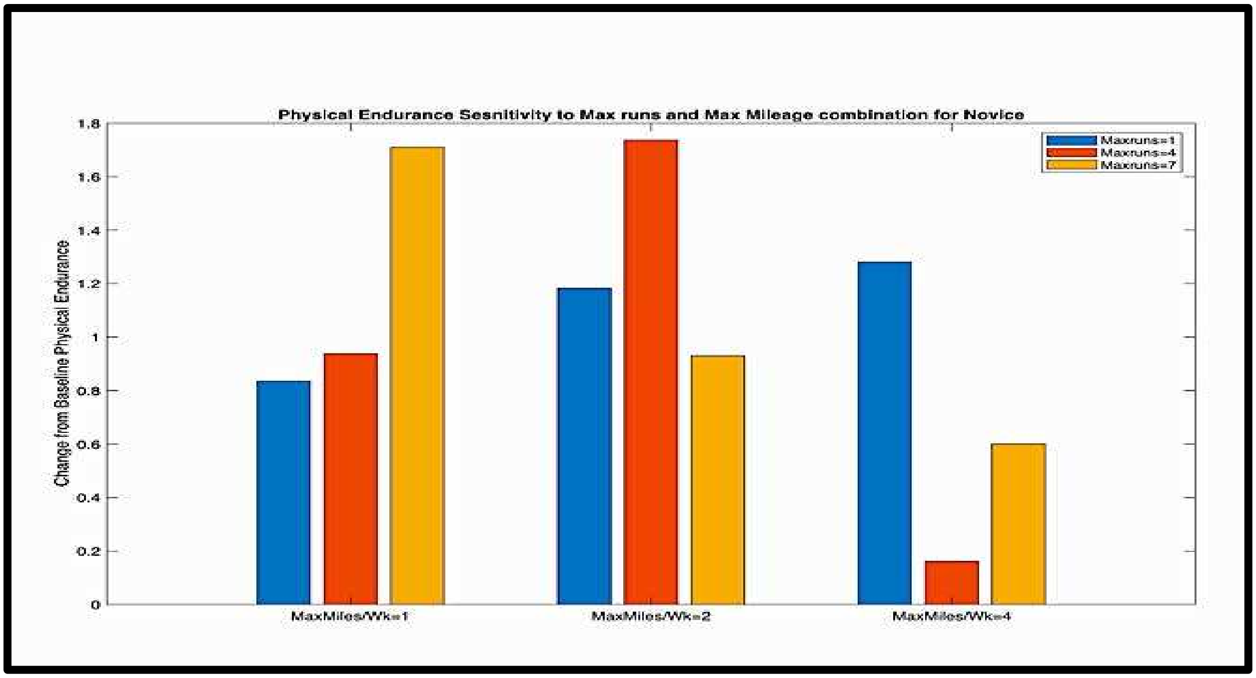
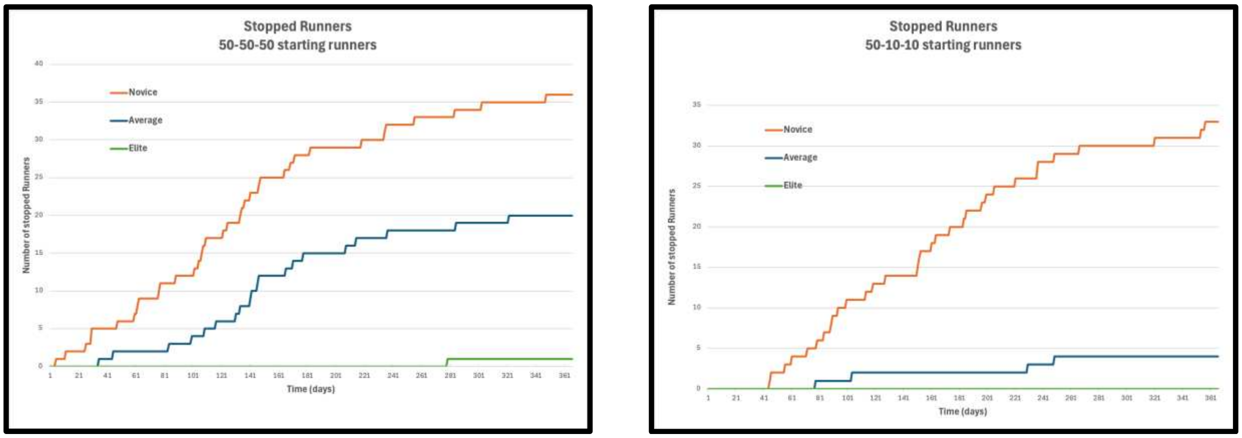


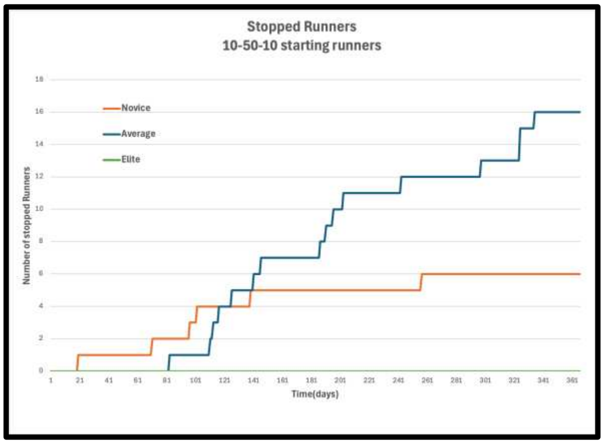
Figure 31: Novice runner physical endurance sensitivity to max runs and max mileage. Novice runners cannot handle simultaneous change in max runs and max mileage.

Another aspect explored was how many runners in each group stopped running over time and whether the composition of the overall set of runners affected the motivation to run. An initial detailed analysis of inter-group interactions showed that as the number of runners and corresponding interactions increased, the number of runners who stopped running increased. In the model, a runner stops if their motivation drops to zero and stays there. This motivation drop is a function of the number and type of interactions between runners, where the motivation levels of the runner decreased if they pushed too hard. For interactions between all three groups of runners, the novice or average group that had the highest number of runners showed a corresponding increase in stopped runners. This can be explained by the increased probability of interactions within their group and adjacent groups, resulting in decreased motivation over time. The elite group has very few stopped runners since they are typically highly motivated and do not get discouraged easily. Figure 32 a, b, and c show the number of stopped runners based on different numbers of each type of runner interacting with each other. This analysis provides insight to coaches and trainers on how to group runners to maximize their performance and adherence to running. The agent model could be used to evaluate the optimal mix of runners for a group based on their specific initial physical and mental fitness levels, that would maximize their performance.



a) 50Novice -50Average-50Elite

b) 50Novice-10Average-10Elite



c) 10Novice-50Average-10Elite

Figure 32: Number of stopped runners of each type of fitness group. a) 50Novice -50Average-50Elite pairing causes novice and average runners to stop. b) 50Novice -10Average-10Elite pairing causes mostly novice and some average runners to stop. c)) 10Novice -50Average-10Elite pairing causes mostly average and most novice runners to stop. Elite not affected by number of runners.

5.1.3 Individual Effects analyses:

The Monte Carlo sensitivity analysis and exploratory analysis showed that running with others affects endurance and that the fitness level of the person they train with affects endurance, from a group perspective. To highlight individual effects on a baseline, this research examined a group of ten low fitness runners who were assigned identical predetermined starting values of physical, mental, and behavioral parameters within the agent model to understand and capture the change in their baseline values. Using this baseline, four scenarios were explored to answer the experimental questions. The scenarios included a) ten runners running solo, b) ten runners interacting only with each other, c) ten runners interacting with others of same fitness type but not necessarily with same starting physical and mental parameters, d) ten runners interacting with runners of both their fitness level and a higher fitness level. Within scenarios c and d, the effect of number of runners of each type interacting with each other on their physical and mental endurance were investigated.

5.1.3.1 Result 1: Running with others affects endurance

When the ten runners ran solo, their physical endurance increases up to a point and then levels off/increases within some bounds. This historical plateau effect has been seen in shorter duration experiments and was documented by AV Hill as an indicator that maximal oxygen uptake had been reached by the body. The overall minimal increase in physical endurance comes from sustained running for a small number of runs and miles per week. Since the runners are not pushing themselves or varying their activity, their mental endurance continues to drop which causes their physical endurance to eventually plateau. This delayed effect has been documented in short-duration exercise. The actual points of change for physical and mental endurance will differ depending on initial values of all the parameters.

An interesting discovery from this research analysis was that the starting value of mental endurance affects the increase in physical endurance and the time taken to plateau. Higher values of mental endurance for the same physical endurance provide a greater increase in overall physical endurance and longer time to plateau.

When these ten runners interact solely with each other, both their physical and mental endurance are affected by random interactions. Some runners experience gains in physical endurance, while others see a decline. The net change in physical endurance is minimal, as all ten runners begin with nearly identical baseline values (with only minor floating-point differences). Consequently, variations in pace remain small which correspond to small changes in physical endurance. Every interaction influences mental endurance, which evolves continuously in response to these exchanges. This suggests that changes in mental endurance may trigger and facilitate corresponding changes in physical endurance over time. The specific nature of each interaction, whether a runner is faster or slower also plays a role in determining the gains or losses in both pace and endurance, physically and mentally. Future work will explore this aspect in greater depth to better understand how to tailor endurance improvements more effectively.

5.1.3.2 Result 2: Fitness level of running buddy affects endurance

In scenario three, the interaction of these 10 runners with 22 and 40 additional low fitness runners with different starting values within the low fitness range was explored. A key finding was that physical endurance improves when the corresponding mental endurance increases. This has implications that could possibly explain the plateau effect seen in short-duration exercise since the mental endurance does not increase enough to facilitate a major increase in physical endurance. Initial analysis of interaction data of runners that have large physical endurance increases, shows that they are more often the faster runner in the interactions. Future work will explore the effect of the type of interaction with the runner to enable optimization of interactions. When the same ten runners ran with average runners with higher physical and mental endurance, the change in physical endurance varied depending on the ratio of average to novice runners. Results indicate that it is beneficial for novice runners to run with more novice runners with a few interactions with average runners serving to instigate an increase in physical and mental endurance. However, too many interactions with average runners, can cause fewer runners to increase physical endurance since they were pushing themselves too much. Table 3 summarizes the scenarios, outcomes and key takeaways.

Table 3: Summary of scenarios and corresponding outcomes and key takeaways for individual effects

Scenario	Outcome	Key Takeaways/Emergent behavior
Solo	Physical endurance plateaus Mental endurance drops	Starting value of mental endurance affects the increase in physical endurance and the time taken to plateau with higher values of mental endurance for the same physical endurance providing a greater increase in overall physical endurance and longer time to plateau.
Interacting only with each other	Physical endurance shows small gains or declines Mental endurance changes continually due to interactions	Changes in mental endurance trigger and facilitate corresponding changes in physical endurance over time. The specific nature of each interaction, whether a runner is faster or slower also plays a role in determining the gains or losses in both pace and endurance, physically and mentally
Interactions with additional low fitness runners with different starting values	Physical endurance improves when the corresponding mental endurance increases. Runners that showed large physical endurance increases, were more often the faster runner in the interactions	Initial analysis of interaction data of runners that had large physical endurance increases, shows that they are more often the faster runner in the interactions. Future work will explore the effect of the type of interaction with the runner to enable optimization of interactions.

Interactions with average fitness runners	Change in physical endurance varied depending on the ratio of average to novice runners.	It is beneficial for novice runners to run with more novice runners with a few interactions with average runners serving to instigate an increase in physical and mental endurance. Too many interactions with average runners, can cause fewer runners to increase physical endurance since they were pushing themselves too much.

5.1.4 Group Effects Correlation Analysis

To examine the effects of the proposed behavioral parameters on endurance, a correlation analysis was conducted with 50 runners of each type randomly interacting only with their fitness type runners. The relationships between physical endurance, mental endurance, pace, motivation, confidence, perception of effort, mental fatigue, and perceived value were explored. The correlation heatmaps in Figures 33,34 and 35 visualize the Pearson Correlation coefficients ranging from –1 to 1, and depicts positive correlations as blue, negative correlations as red, with darker values indicating the strength of correlation. As seen from the heatmap in Figure 33, for lower fitness runners physical and mental endurance are strongly correlated with motivation and confidence. As perception of effort increases, pace, mental endurance, physical endurance, confidence and motivation decrease. For novice runners, confidence and physical endurance are highly correlated which means that novice runners sustainment of activity is dependent on how they feel they can complete the activity. This has implications in training so that novice runners may need to ramp up their training pace slowly and build up their confidence to gain physical endurance. This is consistent with real-life scenarios where novice runners give up running because they do not feel confident of their physical capability which makes them mentally fatigued, thus increasing their perception of effort. As confidence decreases, mental endurance decreases which eventually causes a corresponding decrease in physical endurance.

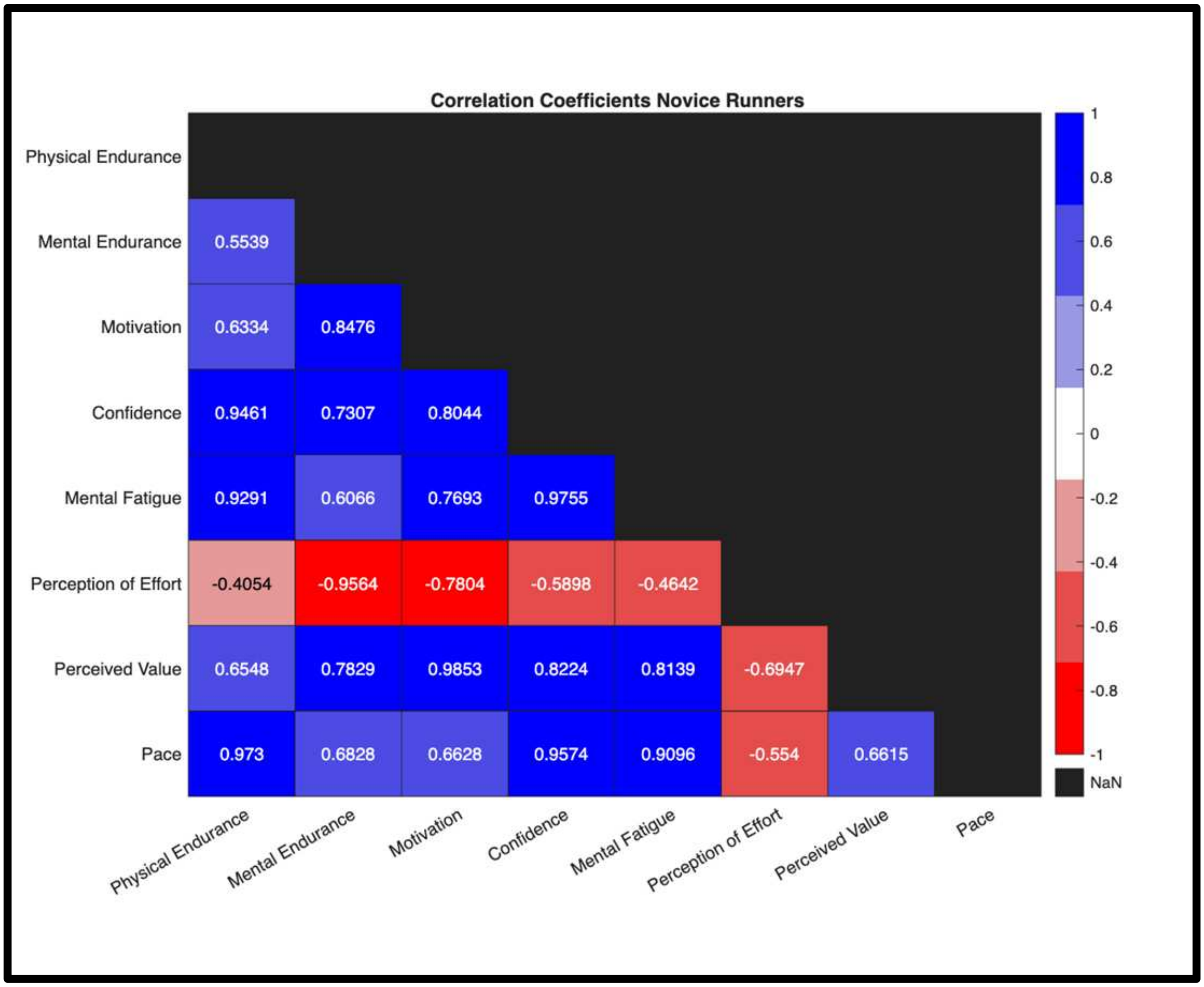


Figure 33: Heatmap of correlation coefficients of Novice group interacting within group. Confidence and Physical endurance are highly correlated: incremental training needed for novice runners

Figure 34 shows that for average fitness runners physical and mental endurance are correlated with pace and confidence. In this case, as the runner's motivation increases the perception of effort decreases. For average runners interacting together, pace and perceived value are highly negatively correlated which means that as the runner's pace increases, the perceived value of running decreases. Since perceived value and motivation are highly correlated, this has implications that average runners are likely to stop running if they are pushed too hard to increase their pace to match a running buddy.

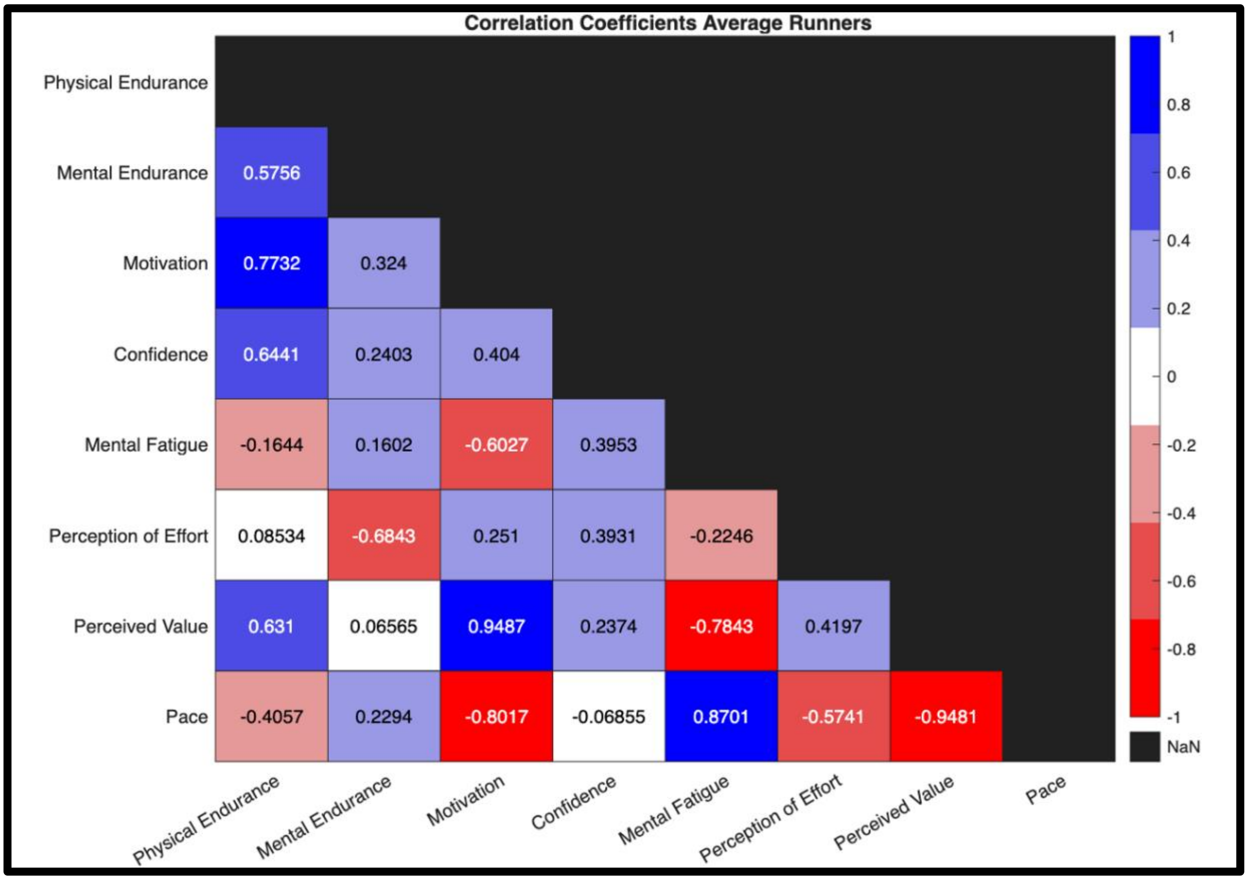


Figure 34: Heatmap of correlation coefficients of Average group interacting within group. Pace and perceived value are highly negatively correlated: average runners are likely to stop running if they are pushed too hard to increase their pace

As seen in figure 35, elite runners' physical and mental endurance show weak correlations. As they get more motivated, their perceived value for the run increases. The heatmap shows that perceived value and mental fatigue are inversely correlated which indicates that as the elite runners perceived value for the run increases, they overcome their mental fatigue. This is consistent with "cognitive dissonance phenomenon" seen in experimental results with elite runners who are able to push themselves to run at high intensities and durations despite mental fatigue.

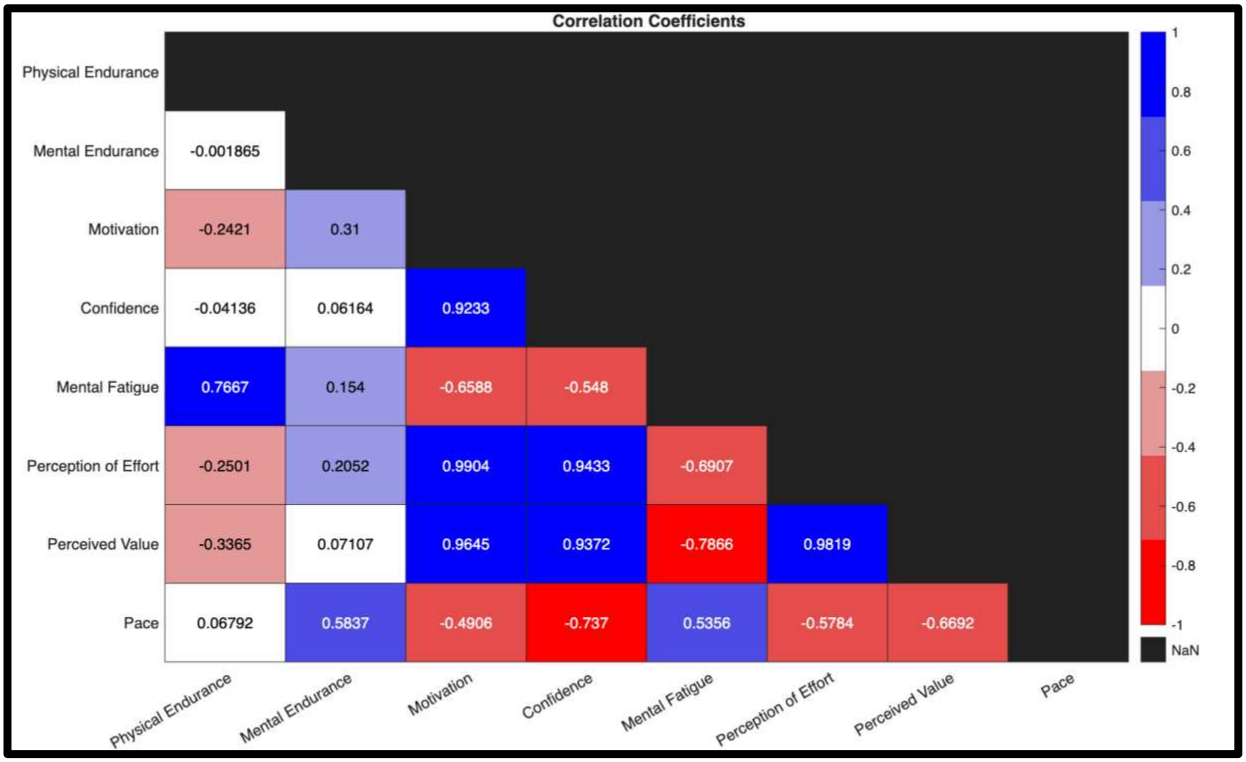


Figure 35: Heatmap of correlation coefficients of Elite group interacting within group Motivation and Perception of effort are positively correlated: Elite runners do better with greater challenges.

In elite runners, perception of effort, motivation, perceived value and confidence are highly positively correlated. This is an emergent behavior which could explain why elite runners push themselves to great extents. For elite runners, a harder run has greater value, so they are more motivated by the increased perception of effort unlike lower fitness runners. Since mental fatigue and physical endurance are correlated, an elite runner will have lower physical performance if they are stressed. Starting with increased initial mental fatigue will cause an even greater loss of physical endurance performance. This phenomenon has been seen in elite athletes who show reduced or complete loss of performance if they are too stressed. Another correlation that could have significant impact is the inverse correlation between pace and confidence which could cause elite runners to lose confidence if they have to slow down due to injury or have to run with slower runners.

Overall, the heatmaps indicate that initial physical fitness affects the behavioral path to sustained activity. For all types of runners, the perception of effort is inversely correlated with physical endurance and perceived value is strongly correlated with motivation. For novice runners, changes in physical endurance, confidence, and mental fatigue play a larger role in the intention to sustain activity. For average and elite runners, perceived value, confidence and motivation are correlated and affect their intention to sustain the activity. In average runners, their pace and physical endurance together determine their perceived value of running, which in turn affects their confidence and motivation to run. Elite runners are motivated by the improvement in pace and the increased perception of effort, which drives their perceived value and intention to keep running.

These insights can provide information on designing tailored training plans based on the initial physical and mental fitness of a specific runner to achieve a performance target. Current methods of one-size-fits-all training plans or even AI based predictive methods that use historical data for a specific runner, do not incorporate the psychological and behavioral factors (mental endurance, mental fatigue, perception of effort, motivation, performance, etc.) that affect a runner's performance. This research quantifies the psychological and behavioral factors and integrates them with physiological factors and adds a new leverage point which is the effect of running with others to improve performance. This achievement adds to the body of fitness knowledge using systems thinking. It provides a method for predicting endurance that captures changes in body and mind over a long duration. It encapsulates and builds upon previous separate bodies of research on physiological factors that affect physical endurance and psychobiological factors that affect mental fatigue for short-duration activities. It prescribes current methods for initial values such as using calculated or measured VO2max for initial values of physical endurance and metrics such as MTQ48, MeBTough, or MeTInd for initial mental endurance. Based on this research and a model-based systems thinking approach, coaches, trainers, and individuals can use paired or group running strategies to improve performance. For example, the models show novice runners will benefit from shorter runs over a week to build up both confidence and endurance whereas elite runners will benefit from progressively harder runs to build confidence and endurance. Stress and mental fatigue must be considered for all runners when planning on the intensity and duration of the runs.

5.2 Endurance System Dynamical Model Analyses & Results

The model was exercised using a framework that captures three types of runners of low, medium, and high physical fitness levels. The effects of age, gender, added weight, Body Mass Index(BMI), training intensity, initial mental fitness, added mental stress, combined effects and the effect of encouragement were explored for the three fitness types. Example plots are shown below for brevity to examine the effect of single and multiple attributes.

5.2.1 Effect of Inherent Factors on Endurance

This section examines the effects of inherent physiological and mental factors such as age, gender, and BMI on endurance enhancement.

Literature has shown that as a person gets older their physical endurance growth is slower. This effect can be lower if the person has originally higher physical endurance. Runners of the same physical attributes and initial physical fitness of age 25 and 55 were compared in figure 36. The model shows that younger runners have higher physical endurance growth but older runners have greater mental endurance growth and stay motivated longer.

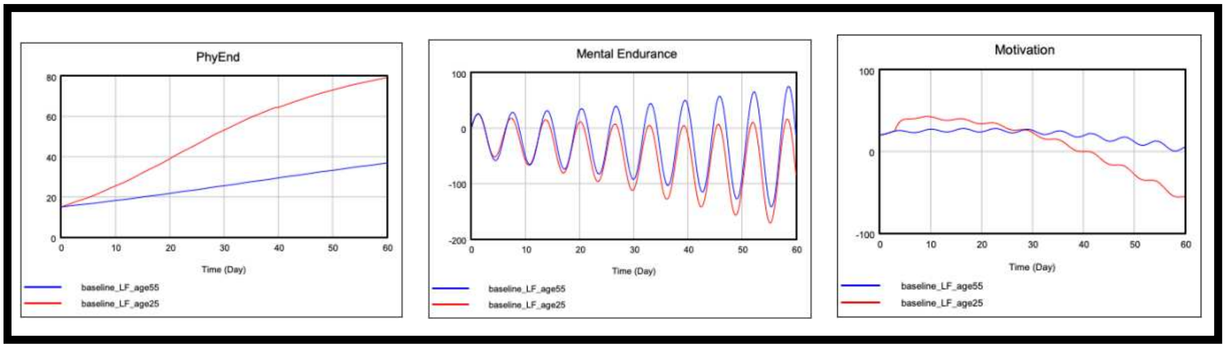


Figure 36: Age Effect on Physical and Mental Endurance and Motivation. Increase in age slows growth of physical endurance but increases growth of mental endurance and sustains motivation. Low fitness individuals shown. Red=Age 25 and Blue =Age 55

One of the factors that affects individual variability in physical and mental endurance is a person's gender. Empirical observational data has shown that physiological differences in cardiovascular systems, lower blood volume and higher body fat percentage cause women to have lower oxygen carrying capacity (Santisteban et al., 2022c) . Although females show higher proportional area of type I muscle fibers, use fatty acids and carbohydrates better during prolonged exercise than males, it typically is not enough to overcome the other physiological differences in competition settings (Besson et al., 2022). Improved biomechanics and mental toughness through self-talk and social dynamics can provide an improvement (Yarayan et al., 2024). As seen in figure 37, females have overall lower physical endurance growth even if they may be at the same initial physical fitness as a male. The model result shows that although the difference in mental endurance is minimal between the sexes, females tend to lose confidence faster but stay motivated longer due to their employment of strategies such as self-talk, social groups, etc. This model result came from the feedback loops between the different physical and mental attributes. Since this effect has been documented in observational literature, it provides confidence that the model structure represents the system adequately. This result has implications for the development of training strategies for females.

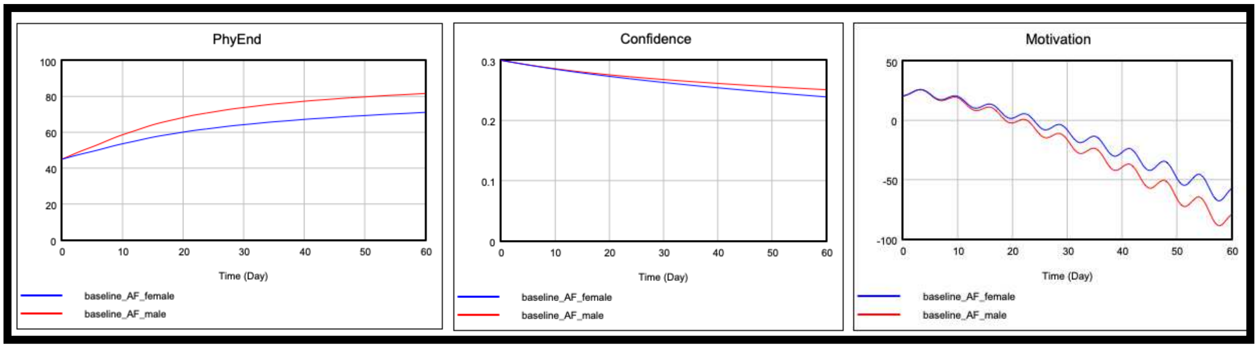


Figure 37: Gender Effect on Physical Endurance, Motivation and Confidence. Overall females show slower growth in physical endurance than males but sustain motivation and confidence longer. Average fitness individuals compared: Red=Male and Blue =Female

Body composition can make a difference in how much a person's endurance changes with training. Two individuals who have the same initial physical fitness and weight but different height will show differences in physical endurance enhancement due to changes to BMI and resulting body fat percentage. As seen in figure 38, the lower BMI person shows a greater increase in physical endurance since they have relatively more muscle and less fat. An emergent result is that the person with higher BMI stays motivated longer than the person with low BMI. This can be explained by the fact that a higher BMI person has to train harder to overcome the deficiencies related to muscle mass and body fat percentage.

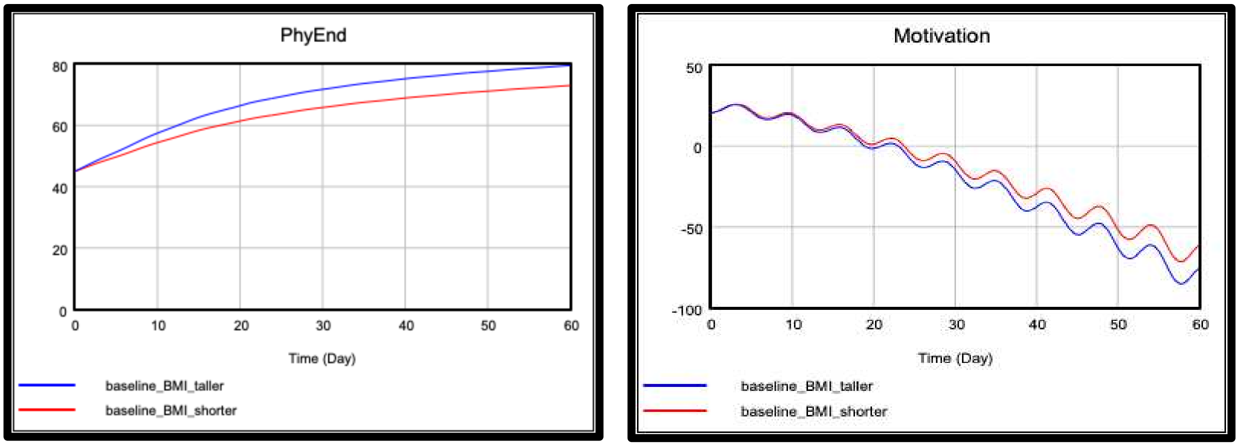


Figure 38: BMI Effect on Physical and Mental Endurance and Motivation. Lower BMI improves physical endurance growth. Low Fitness Individuals compared with different BMIs and same initial physical endurance. Red -baseline Blue-lower BMI

Observational studies and experiments have documented that initial physical fitness impacts how fast a person builds endurance. The percentage increase in physical endurance for a lower fitness individual will be higher than that of high fitness individual since the lower fitness person has more to change. To achieve a specific endurance level, a lower fitness person will take longer than a higher fitness individual as shown in figure 39.

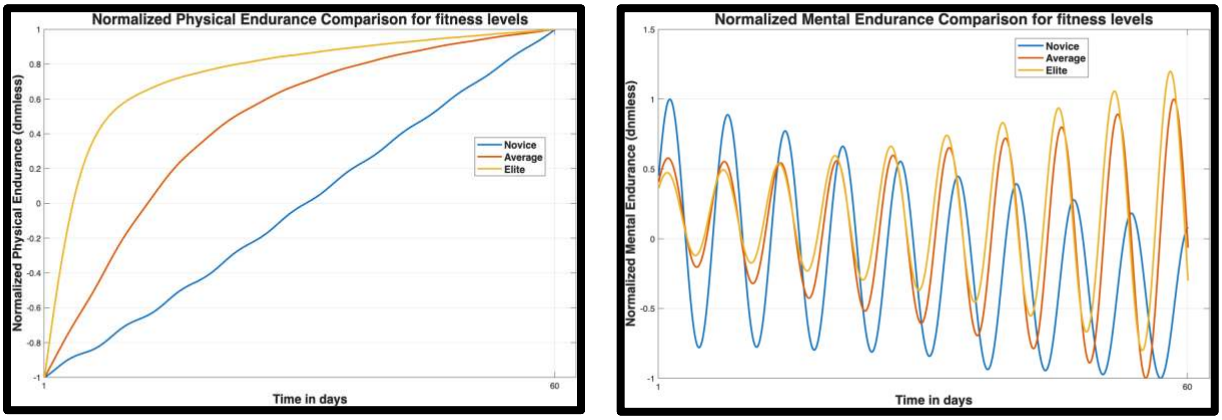


Figure 39: Rate of increase of Physical and Mental Endurance for various fitness levels. Lower fitness levels require longer to increase physical endurance. Blue=low fitness,Orange=med fitness and Yellow=high fitness

5.2.2 Effect of External Factors on Endurance

This section examines the effects of exogenous factors such as added weight, training intensity, mental stress, combined effects and encouragement. Warfighters in training or combat situations have to carry heavy equipment and gear ranging from 40 to 120 pounds. The additional weight causes physical and mental fatigue and can impact the sustainment of training and combat readiness. This effect was examined for an average fitness, female warfighter carrying no additional weight, 50 lbs. and 100 lb. added weight. Figure 40 shows that as the amount of weight carried increases, the person's physical and mental endurance and motivation drop. This effect was seen for all fitness types and genders.

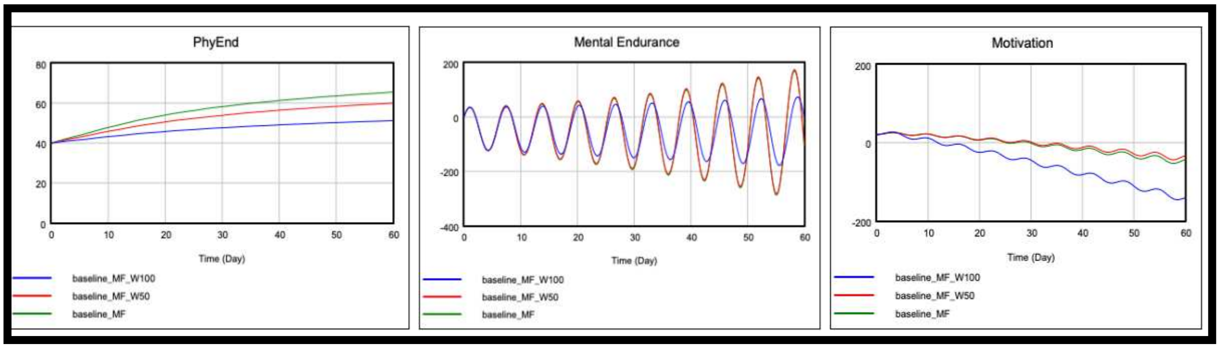


Figure 40: Added Weight Impact on Physical and Mental Endurance and Motivation. Negative effect on physical and mental endurance and motivation. Medium Fitness Individual shown. Green=no added weight; Red=carrying 50lb weight; Blue=carrying 100lb weight.

Training intensity has a direct impact on an individual's physical and mental endurance. In the model, change in pace is the attribute that reflects training intensity and duration. A slow progression in pace over time will improve a person's physical endurance slowly. For a low fitness person, this may be necessary to avoid too much exertion. However, for higher fitness individuals, a higher progression will provide a faster increase since they can typically handle the exertion. The agent model correlation analysis showed that the higher pace motivated elite runners and increased their confidence. This is reflected in figure 41 which shows how high fitness individuals' physical endurance increases as training intensity increases to higher levels compared to the baseline of low intensity. Their mental endurance overall has an increasing trend but stabilizes at a lower amount.

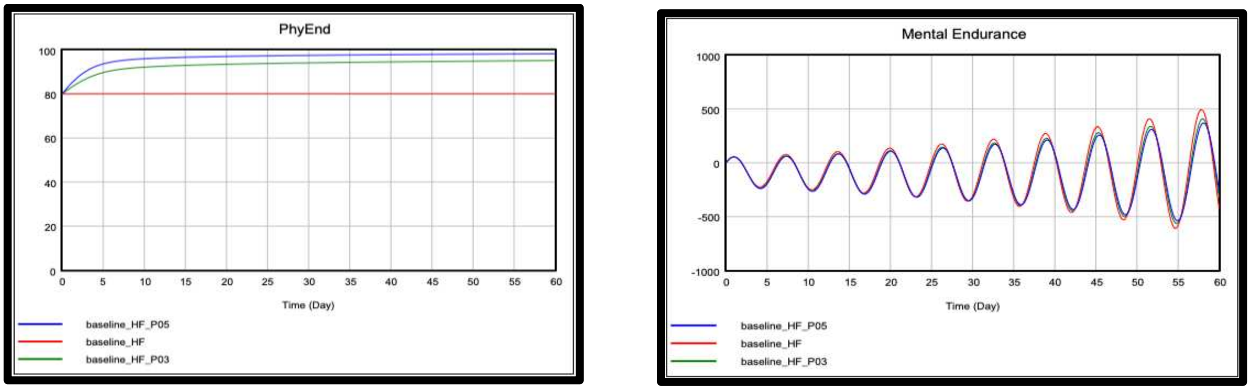


Figure 41: Training Intensity Impact on Physical and Mental Endurance. Increasing training intensity improves physical and mental endurance for high fitness runner shown. Red=very low intensity; Green= medium intensity and Blue=high intensity

Mental stress is a key contributor to decreases in physical and mental endurance through a corresponding increase in mental fatigue. Mental fatigue impacts perception of effort, perceived value as well as motivation and confidence which in turn impact physical and mental endurance. The model shows the impact of added mental stress on physical and mental endurance as well as motivation and confidence. Figure 42 shows how increased mental stress causes a reduction in physical and mental endurance as well as motivation and confidence for a low fitness individual. Mental fatigue increases which results in higher perception of effort and lower perceived value to sustain the activity. These results were seen for all fitness levels.

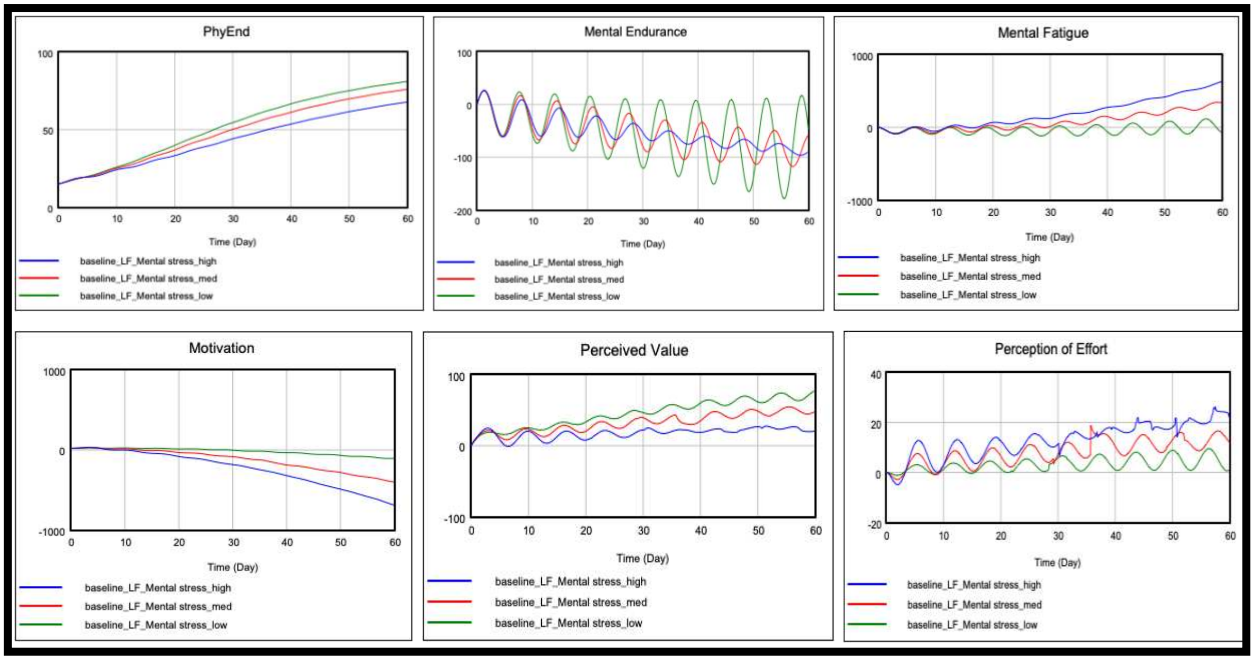


Figure 42: Effect of Mental Stress on Physical and Mental Attributes. Increased mental stress has a negative effect on low fitness runner. Green=low mental stress; Red=some mental stress; Blue=high mental stress

During intense training maneuvers or combat scenarios, warfighters have to run while carrying heavy equipment and deal with incoming fire or stressful situations. This scenario was simulated with the dynamic model by subsequently adding weight, increasing training intensity, and mental stress which compounds the problem. In figure 43, a low fitness person starts by just jogging with no carried gear(green), followed by jogging and carrying 50 pounds of equipment while jogging(red) and finally is jogging while carrying 50-pound weight and being mentally stressed(blue). This negative compounding effect on physical and mental endurance of low fitness warfighter increases further for every day the scenario continues. This result is seen across all fitness levels.

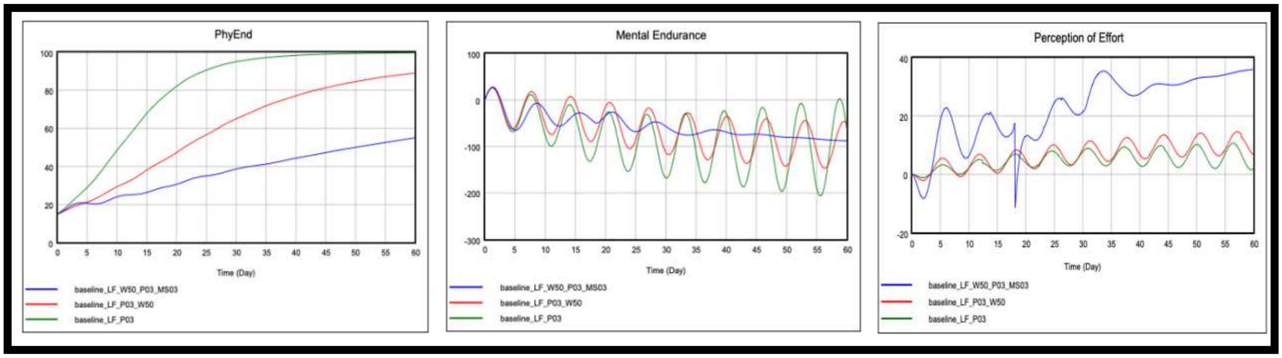


Figure 43: Effect of Combined Weight, Training Intensity and Mental Stress on Physical and Mental Endurance. Negative compounding effect on physical and mental endurance of low fitness warfighter. Green=jogging(no gear) ; Red=jogging and carrying 50 lb. gear; Blue=jogging, carrying 50 lb. gear and mentally stressed

Research has shown that encouragement or criticism by trainers or coaches during training of an individual has an impact on performance in physical fitness tests. This is particularly relevant in warfighter training in bootcamp for marines and special operations forces. This corresponds to the subjective norms and initial motivation behavioral attribute in the model. Subjective norms are an individual's perception of social pressure from people whose opinion they value such as coaches, family, friends, or peers to perform or not perform a specific behavior. Encouragement increases these values and motivates an individual to work harder to sustain an activity whereas criticism can reduce confidence and demotivate a person. Figure 44 shows how encouragement can increase a low fitness person’s physical and mental endurance while criticism has a detrimental effect on their physical and mental endurance.

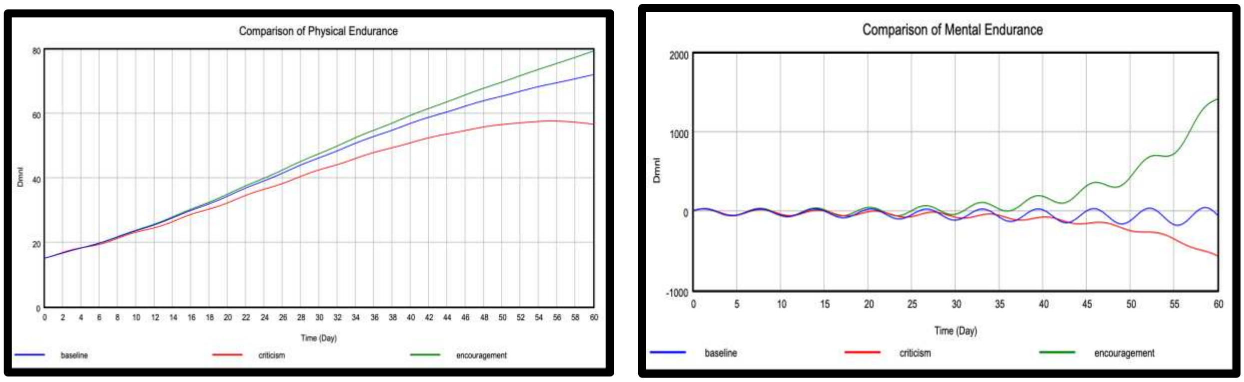


Figure 44: Effect of Encouragement & Criticism on Physical and Mental Endurance. Encouragement improves and criticism degrades mental and physical endurance of low fitness person. Blue=baseline-no coach; Red=criticism; Green=encouragement)

5.2.3 Reference Mode Analysis

The agent model was exercised to generate a reference mode that is the average of the physical endurance for a group of low fitness runners interacting with each other with randomly generated different physical and mental attributes. This was compared to the system dynamical model output of physical endurance which matched it to a low fitness individual running at slow pace who is not mentally stressed as shown in figure 45.

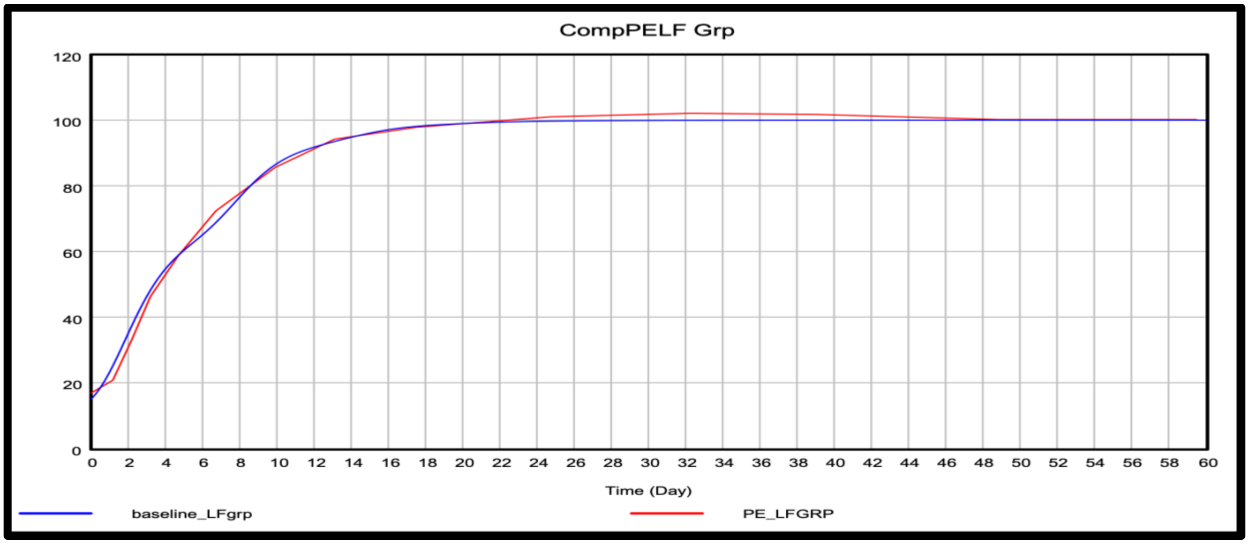


Figure 45: Reference mode Comparison of Physical Endurance of Low fitness individuals. Endurance SD model matches reference mean physical endurance from ABM to low fitness individual running at slow pace who is not mentally stressed.

The agent model was exercised to generate a reference mode that is the average of the physical endurance for a group of medium fitness runners interacting with each other with randomly generated different physical and mental attributes. The system dynamical model matched this to a medium fitness individual running at medium pace and is slightly mentally stressed is shown in figure 46.

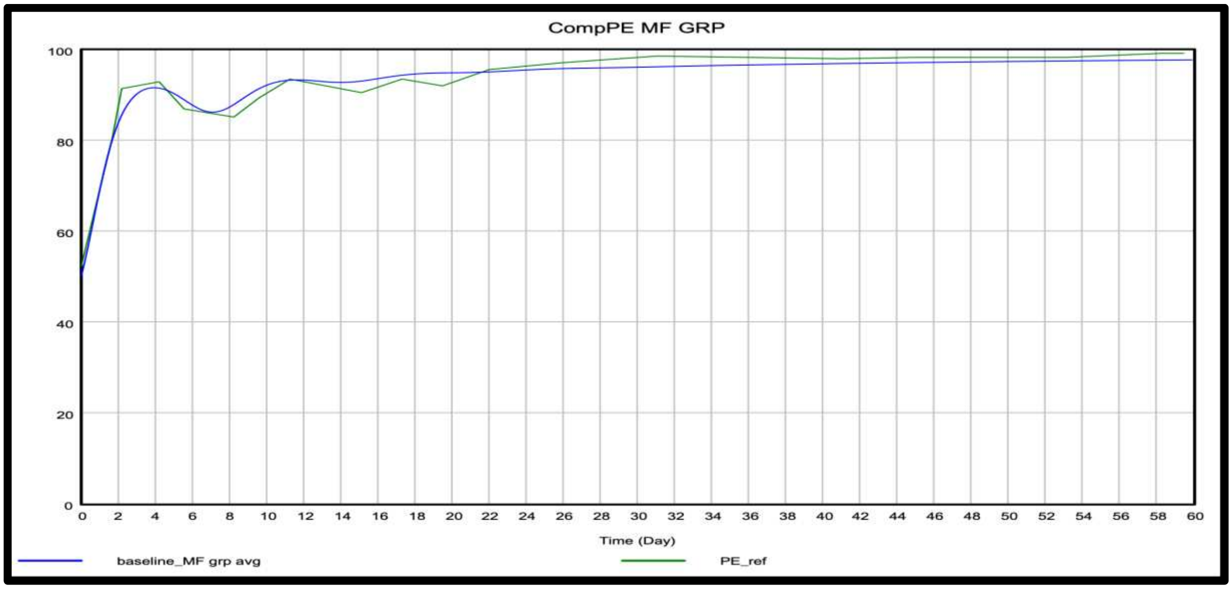


Figure 46: Reference mode Comparison of Physical Endurance of Medium fitness individuals. Endurance SD model matches reference mean physical endurance from ABM to medium fitness individual running at medium pace who is slightly mentally stressed.

The agent model was exercised to generate a reference mode that is the average of the physical endurance for a group of high fitness runners interacting with each other with randomly generated different physical and mental attributes. Figure 47 shows the system dynamical model match to a high fitness individual running at a high pace and is slightly mentally stressed.

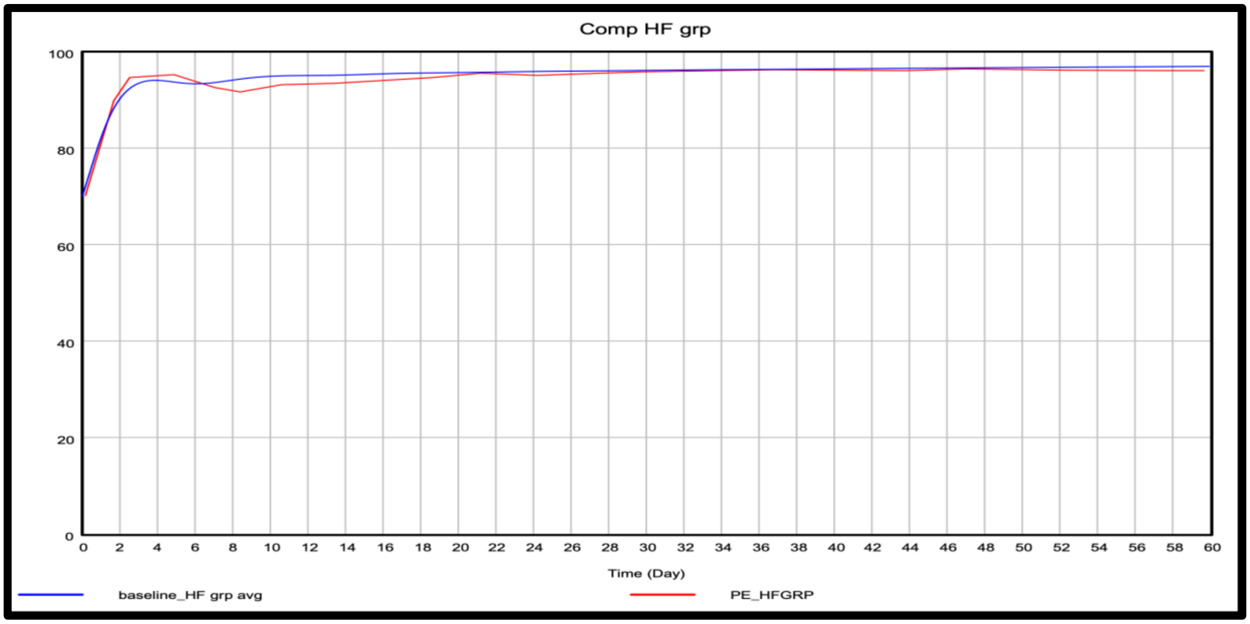


Figure 47: Reference mode Comparison of Physical Endurance of High fitness individuals. Endurance SD model matches reference mean physical endurance from ABM to high fitness individual running at fast pace who is slightly mentally stressed.

The reference mode comparison shows that the patterns of behavior produced by the system dynamical model are representative of runners of various fitness levels with different physical and mental attributes.

5.2.4 Sensitivity Analysis

A sensitivity analysis determines how a model outputs change when uncertain input parameters (constants) are varied to assess model robustness and build confidence by identifying critical assumptions, revealing output uncertainty and behavioral boundaries. Its function is to explore uncertainty, find critical variables, validate model assumptions, and understand the range of possible outcomes for better decision-making.

A sensitivity analysis was conducted that identified which parameters most significantly affect model outcomes to determine if the real system exhibits similar sensitivities. Vensim statistically varies the variables by +/- 10 percent to create the sensitivity graphs. The first analysis was to understand the sensitivity of physical endurance to added weight. The sensitivity plot shown in figure 48 highlighted that added weight has an immediate effect on physical endurance so that as weight is increased the variability in physical endurance increases. An operational validation was conducted that compared the results obtained from the model to real world scenarios observational data and found that to be consistent.

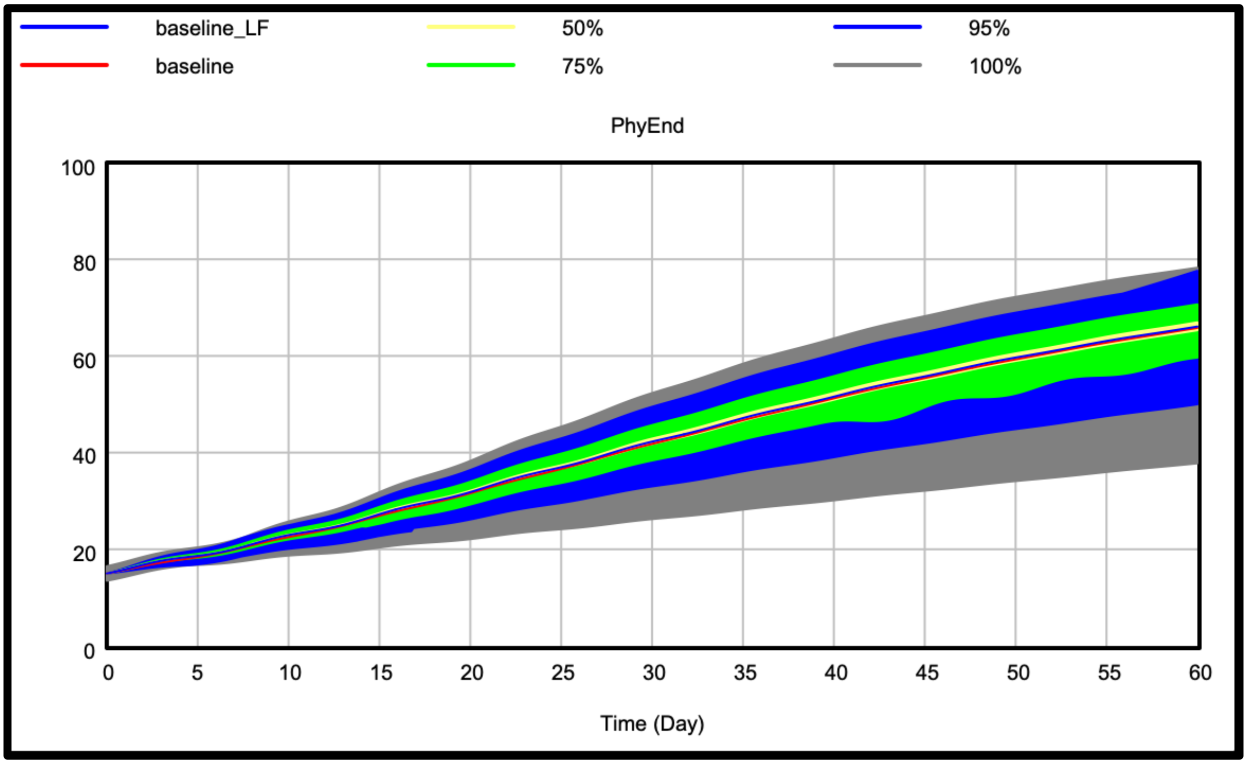


Figure 48: Sensitivity Analysis of Added Weight on Physical Endurance. Vensim statistically varies the variables by +/- 10 percent to create the graph shown above. 95% of the outcomes are shown as blue in the graph. As weight is increased for low fitness person, the variability in their physical endurance increases.

The second sensitivity analysis was the joint effect of initial mental fitness and mental fatigue. The sensitivity plot shown in figure 49 indicates that as initial mental fitness and mental fatigue change they affect physical endurance over time. The wide range of yellow below the baseline is indicative of the negative causal relationship of mental fatigue with physical endurance.

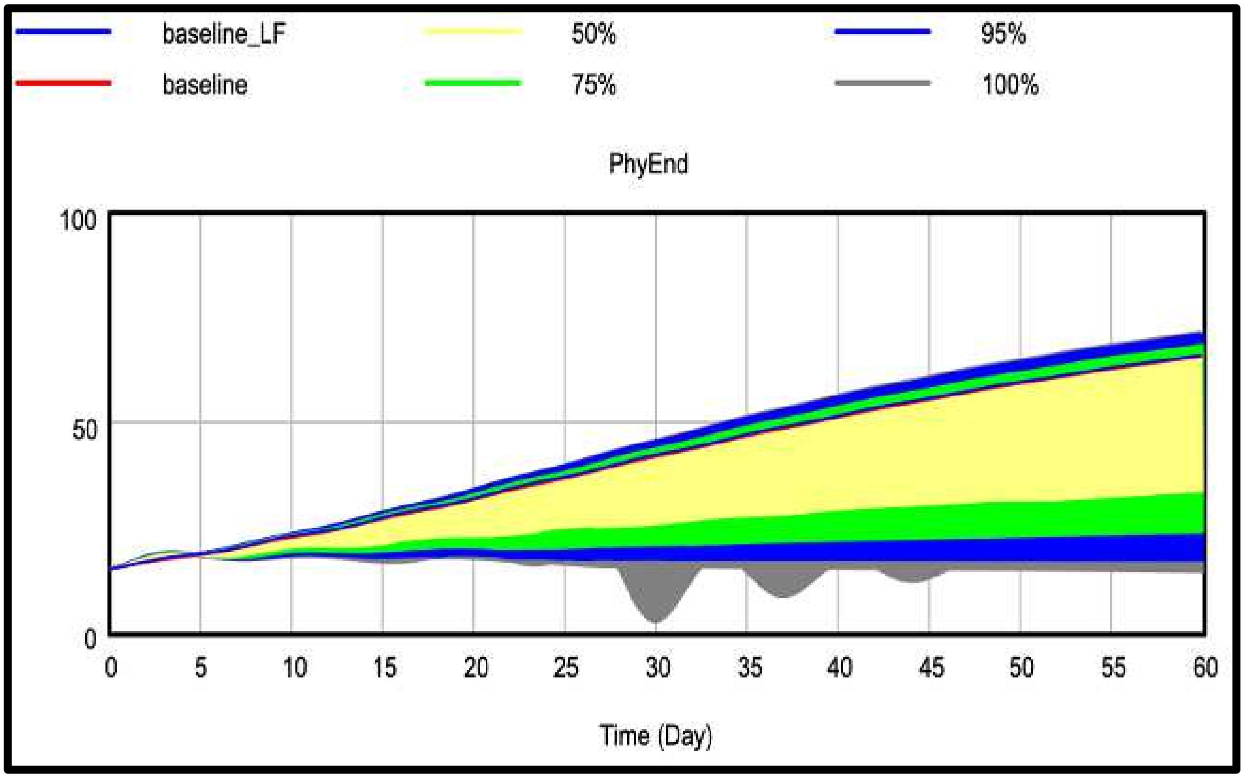


Figure 49: Sensitivity Analysis of Initial Mental Fitness and Mental Fatigue on Physical Endurance. Vensim statistically varies the variables by +/- 10 percent to create the graph shown above. As mental fatigue increases, variability in physical endurance increases. Yellow areas below the baseline are indicative of the negative causal relationship of mental fatigue with physical endurance.

5.3 Recovery for Endurance System Dynamical Model

The model was exercised using a framework that captures how various recovery strategies affect the physical and mental endurance of different fitness level individuals.

5.3.1. Effect of recovery strategies

The recovery sub model incorporates proactive, passive and active recovery strategies. It simulates the cumulative effect of proactive strategies such as tapering, rest, diet, hydration as the initial recovery value of the Recover stock in the model. A higher value signifies a greater amount of proactive recovery. This improves the baseline of recovery of an individual. Passive recovery techniques modelled are diet, hydration and sleep which can start and end at specific times and have different magnitudes. Active recovery strategies modelled are stretching, walking, jogging and running which correspond to the increasing magnitude of this attribute. This attribute can start and end at different times to represent an individual's choice to perform this activity.

The cumulative effect of utilizing increasing recovery strategies for the same training load is shown in figure 50. As the amount of recovery increases, a person's fatigue drops and physical and mental endurance improve.

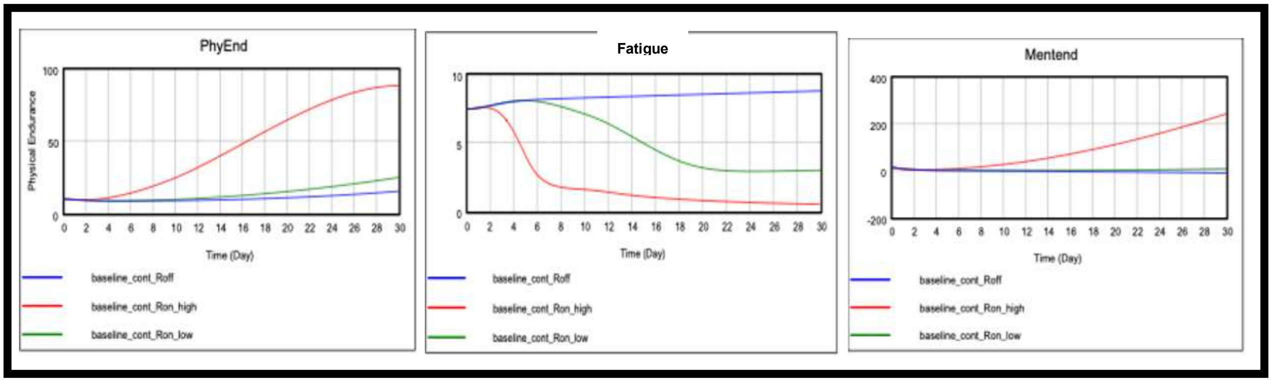


Figure 50: Effect of Increasing Recovery Strategies on Fatigue, Physical and Mental Endurance. Increasing recovery strategies for low fitness person improves physical and mental endurance. Blue=no recovery; Green=some recovery and Red=most recovery

As seen in figure 51, a higher training load requires more recovery and improves physical and mental endurance.

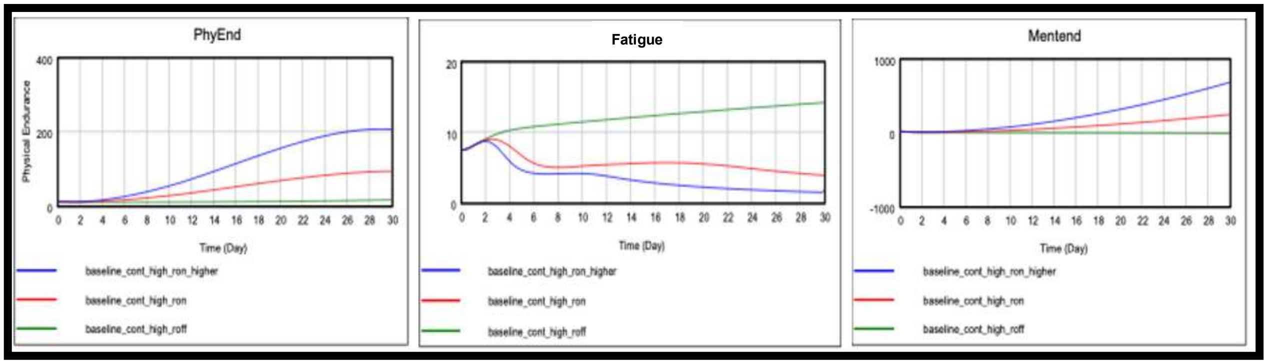


Figure 51: Effect of Increasing Training Intensity on Recovery for Fatigue, Physical & Mental Endurance. Higher training intensity for low fitness person requires more recovery but also improves physical and mental endurance. Green=no recovery; Red=some recovery and Blue=most recovery

A comparison of recovery for low and high training intensity for low, medium and high physical fitness was conducted. As shown in figure 52, for the same training intensity the model shows that higher fitness individuals need less recovery. This is consistent with real world observations. This highlights the variability seen between individuals on how much recovery is needed to overcome physical and mental stress of training and how they can continue to train.

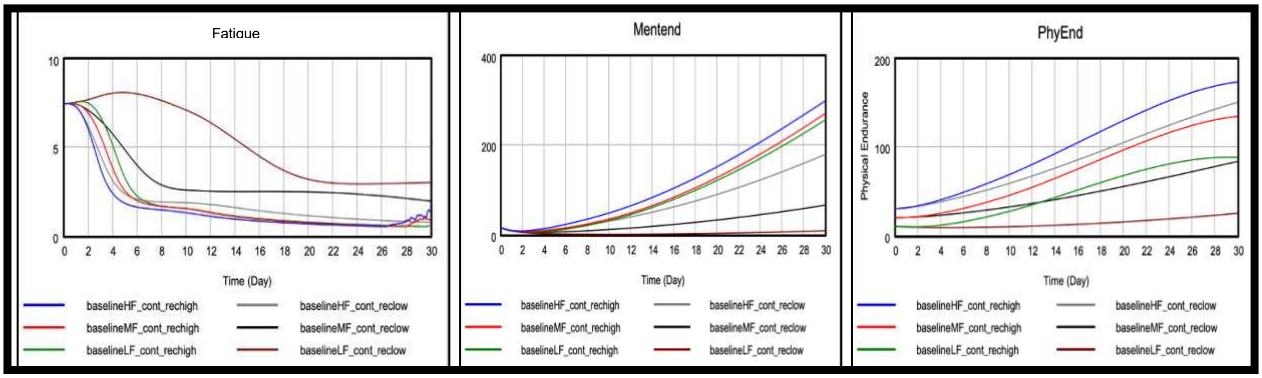


Figure 52: Comparison of Recovery Effect for different fitness levels on Fatigue, Physical and Mental Endurance. For the same training intensity, higher fitness individuals need less recovery. Low fitness: Brown=low recovery; Green=high recovery; Medium fitness: Black=low recovery; Red=high receovery; High fitness: Grey=low recovery; Blue=high recovery

To explore the effect of timing of recovery strategies on recovery, recovery methods were started on day one, day two and day three after training for a lower fitness individual. Figure 53 shows that with each day delay in applying recovery, the individual's recovery is delayed, which results in reductions in physical and mental endurance over time. The figure shows effects for low level recovery.

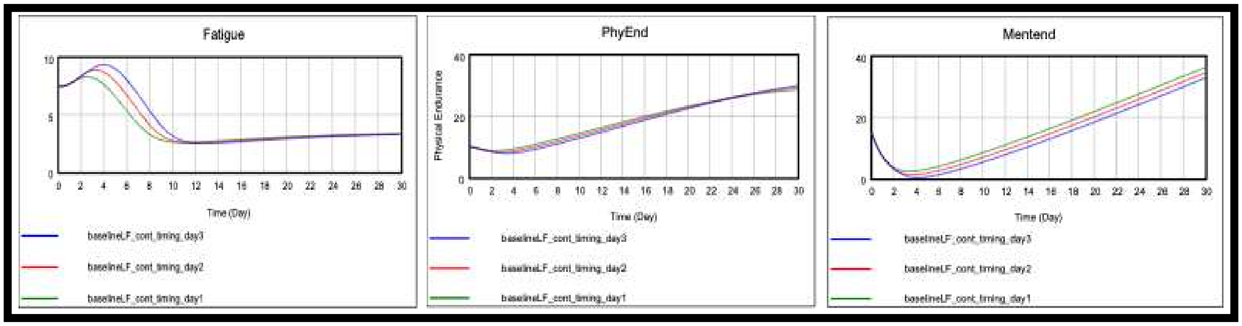


Figure 53: Impact of Timing of Recovery on Fatigue, Physical and Mental Endurance. Each day delay in applying recovery, reduces physical and mental endurance. Low fitness person shown Day1=green Day2=red and Day3=blue

A common practice for high fitness level athletes is reducing training intensity and duration(tapering) and increasing rest and nutrient intake a few weeks before a higher intensity training or a race. A comparison of the effects of higher amounts of proactive recovery vs. small amounts on overall recovery (with minimal other recovery strategies) is shown in figure 54. Higher amounts of proactive recovery have a greater effect on reducing fatigue quickly which results in higher physical and mental endurance. An interesting result is the effect of proactive recovery for low fitness individuals as seen in figure 55. This can be used by trainers to enable better endurance enhancements for low fitness individuals. Future work will explore how the timing and the individual strategies of proactive recovery affect recovery after a training load.

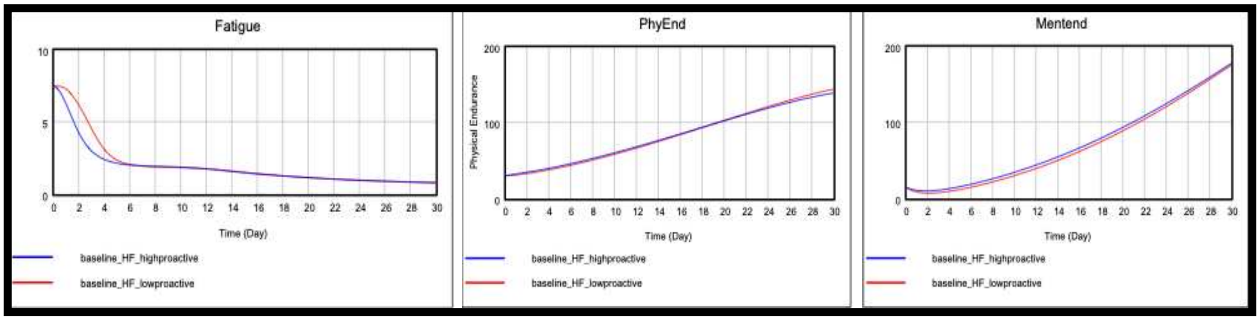


Figure 54: Effect of Proactive Recovery for High fitness individual on Fatigue, Physical and Mental Endurance. Higher amounts of proactive recovery strategies have a greater effect on reducing fatigue quickly which results in higher physical and mental endurance. Red=low recovery; Blue=high recovery strategies employed

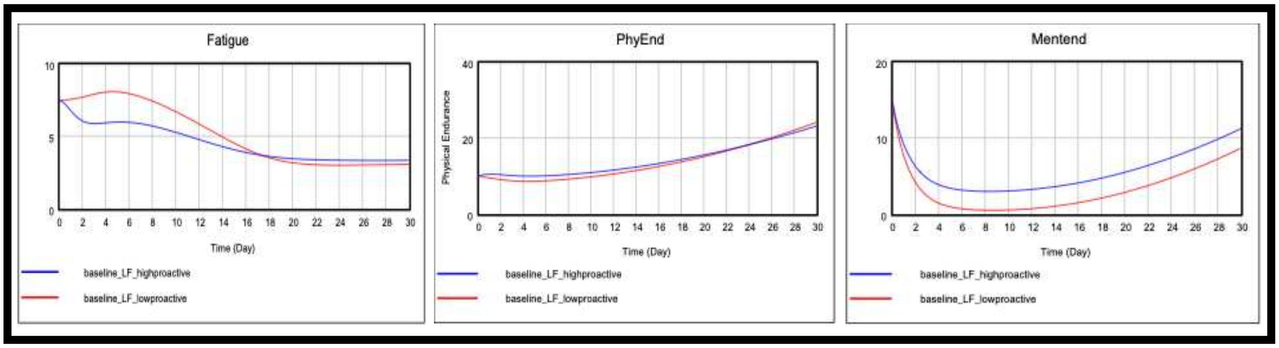


Figure 55: Effect of Proactive Recovery on Low fitness individual for Fatigue, Physical and Mental Endurance. Higher amounts of proactive recovery strategies have a greater effect on reducing fatigue quickly which results in higher physical and mental endurance. Red=low recovery; Blue=high recovery strategies employed

Nutrient intake is key to passive recovery and affects how quickly the body repairs muscle tissue and replenishes nutrients. Figure 56 shows the positive effect of low-level diet and hydration compared to high level diet and hydration strategies for a medium fitness individual.

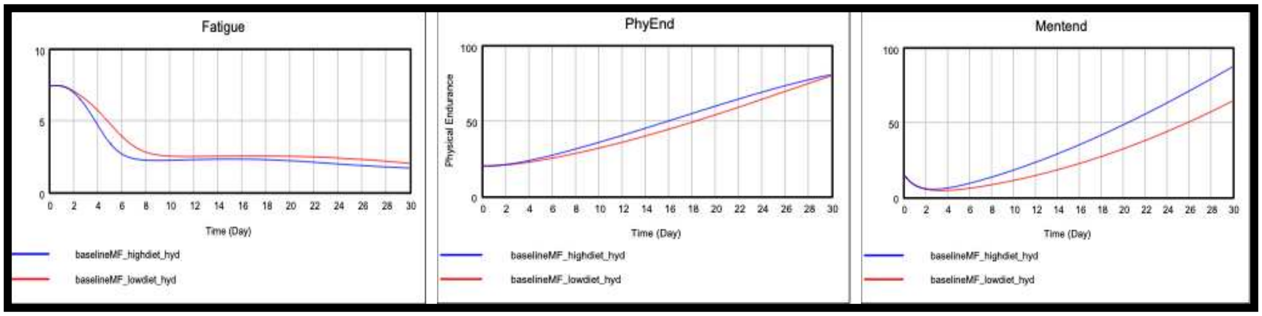


Figure 56: Effect of Increased Diet and Hydration Recovery on Fatigue, Physical and Mental Endurance. Increasing nutrient intake has positive effect on physical and mental endurance. Medium fitness person shown: Red=low diet and hydration; blue=high diet and hydration

Active recovery has been shown to enhance recovery when added to other recovery techniques. The model shows that the intensity of the active recovery activity for a particular fitness level has a direct effect on fatigue and physical and mental endurance. For example, if a low fitness individual starts to jog instead of stretching, their fatigue levels could increase instead of decrease and reduce their physical and mental endurance. Figure 57 shows how too intense of active recovery can lead to a drop in physical and mental endurance for a low fitness individual.

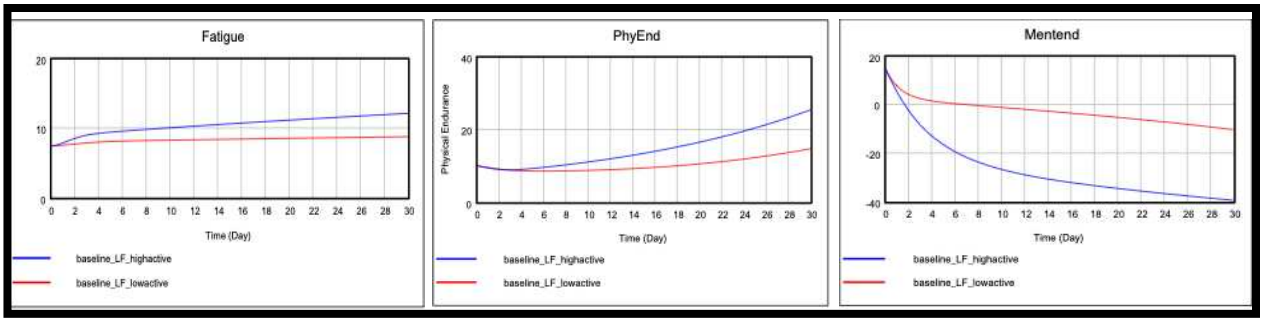


Figure 57: Effect of Increased Active Recovery on Fatigue, Physical and Mental Endurance. Higher levels of active recovery for low fitness person can be detrimental to physical and mental endurance for them. Red=low active recovery. Blue=High active recovery

A common real-world problem seen in higher fitness level individuals is to start running at too high an intensity right after a high intensity training session. This action limits their recovery and if continued can lead to overtraining injuries or illness.

The effect of mental stress on recovery was simulated. Figure 58 shows how added mental stress can delay recovery from physical fatigue and reduce performance, physical and mental endurance for a low fitness individual. The red lines correspond to responses to no additional mental stress and the blue lines corresponds to responses to added mental stress. The stress can be due to pressure from combat or just everyday scenarios. The responses show a cumulative effect over time. This effect was seen for all three fitness levels.

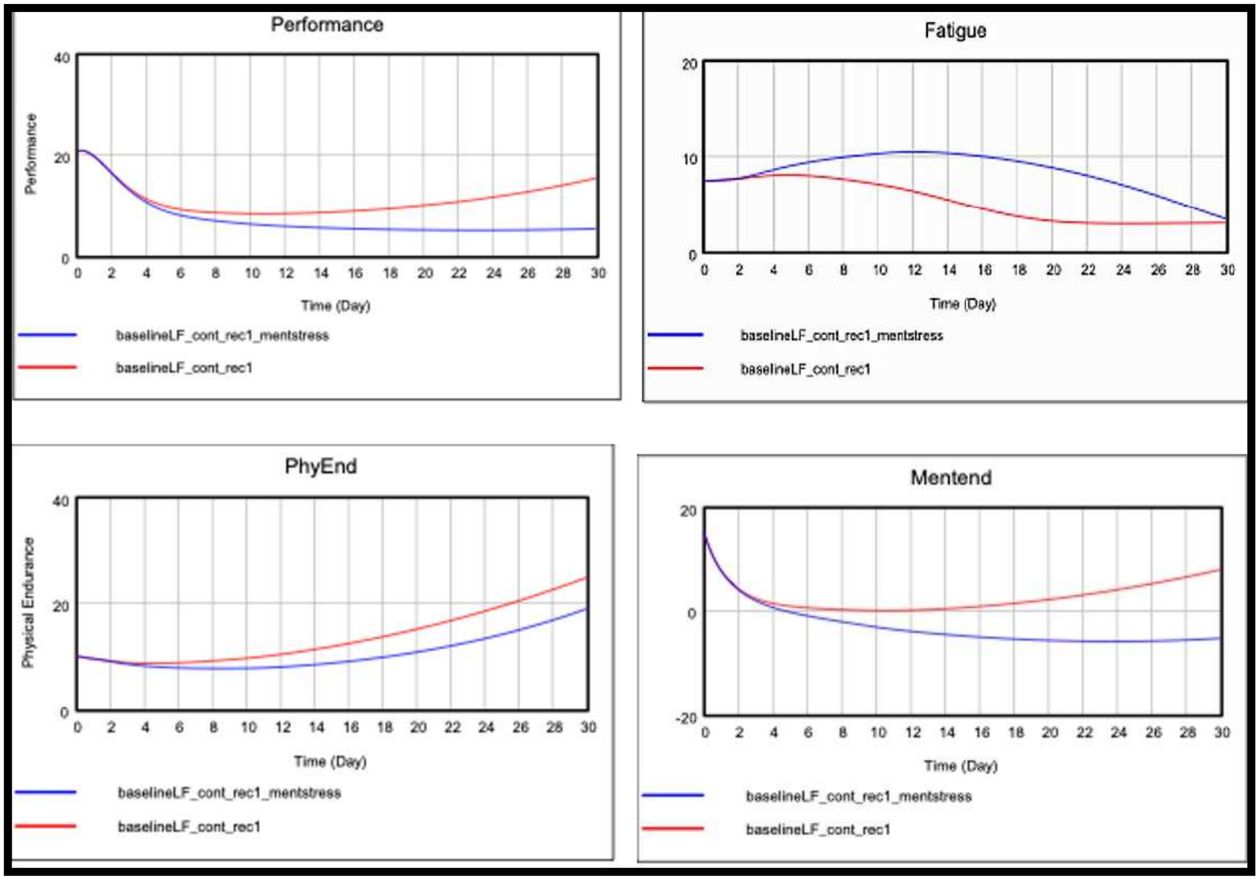


Figure 58: Effect of Mental Stress on Recovery. Added mental stress delays recovery from physical fatigue and reduce performance, physical and mental endurance. Low Fitness person:Red=no mental stress; Blue=some mental stress

5.3.2 Sensitivity analysis

A sensitivity analysis of the effect of recovery strategies on recovery was conducted. Since recovery was modelled as an on-off effect, the range of variability and uncertainty increased as shown by the extensive grey in figure 59.

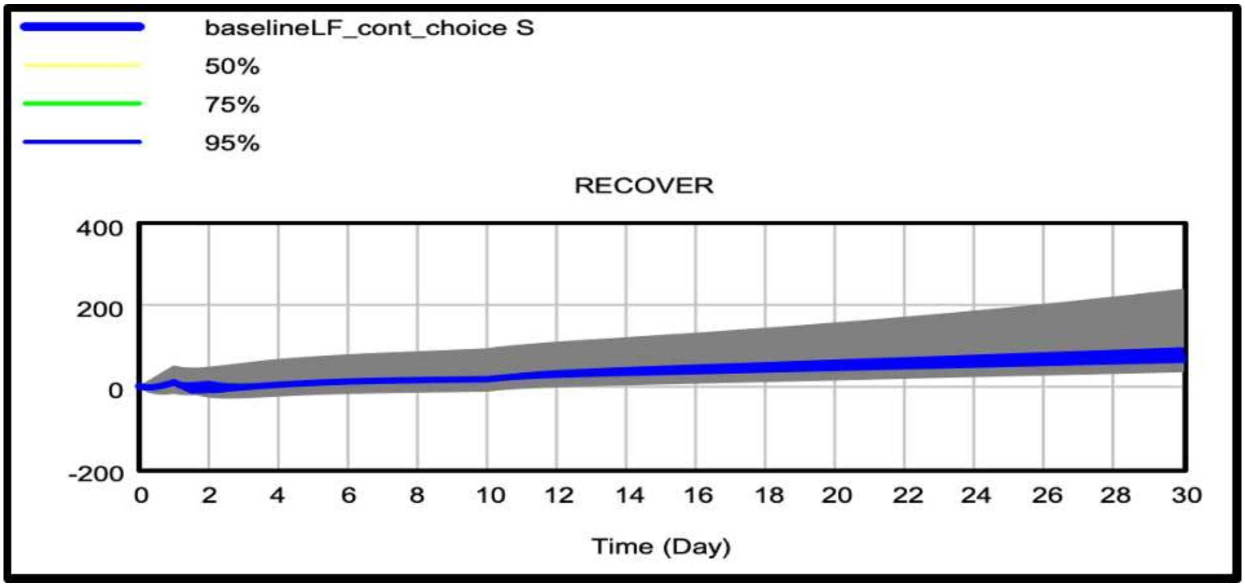


Figure 59: Sensitivity plot of effect of recovery strategies on recovery. Vensim statistically varies the variables by +/- 10 percent to create the graph shown above. Recovery was modelled as an on-off effect which causes the range of variability and uncertainty to be increased as shown by the extensive grey.

A tornado plot shown in figure 60 shows the specific sensitivities of recovery to initial physical fitness and mental stress followed by active recovery and overtraining and sleep. The timing of when diet and hydration strategies are started and end directly affect physical endurance growth. This is consistent with empirical data and SME observations.

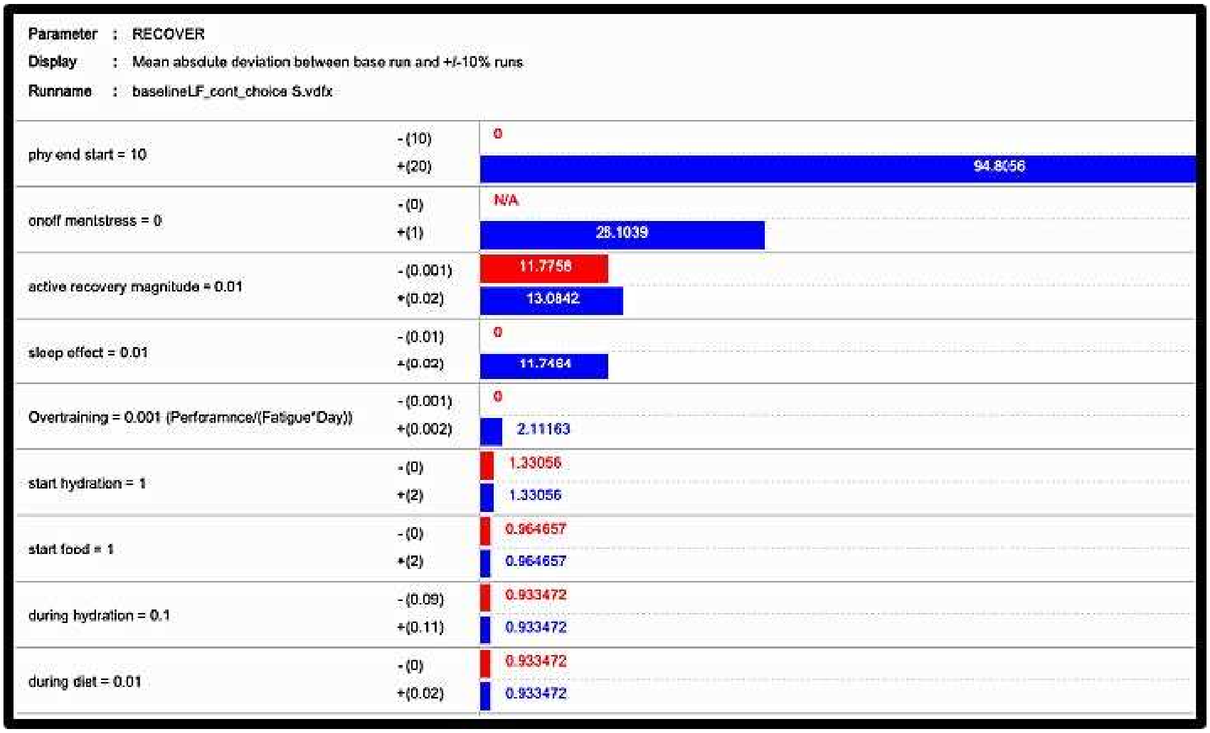

Parameter : RECOVER
Display : Mean absolute deviation between base run and +/-10% runs
Runname : baselineLF_cont_choice 5.vdfx

Figure 60: Tornado plot of attributes that affect recovery. Initial physical fitness and mental stress have highest impact on recovery.

CHAPTER 6: APPLICATION OF FRAMEWORK AND METRICS

This research developed a framework that combined physical, mental and behavioral dynamic attributes into three dynamic models to explain the interplay and contribution of physical and mental endurance on sustaining, strenuous activity for periods of time. The Agent Based Model(ABM) provides a testbed for examining long-term training scenarios. The ABM can simulate how different intensity patterns (steady pacing, interval training, or progressive overload) affect endurance across populations of recreational runners, competitive athletes, or military warfighters. In one scenario, the ABM could test how an injured runner with low mental confidence recovers differently when training alone versus within a supportive team environment. The correlation analysis for the various groups of runners can be used by coaches/trainers to develop confidence-building training plans for novice runners and progressively challenging running plans for elite runners. Insights from these agent-based patterns of endurance were used to construct the system dynamics causal model of endurance, allowing broader exploration of reinforcing and balancing loops at the population level and identification of leverage points for building endurance at the individual level. The Endurance System Dynamical Model enables individuals with different physical and mental attributes to gauge their specific response to different intensity training and environments. Using specific physical values, VO2max and mental questionnaires to calibrate the model provides the ability to tailor a training regimen suited for a person's capabilities at that time. The Recovery for Endurance model can be used to optimize recovery for individuals. Beyond athletic training, such applications could help military organizations design group conditioning programs that optimize both the physical and psychological endurance of warfighters in high-stress environments. The framework includes two metrics to aid in planning effective training that incorporates mental effects on physical fitness. First is an instantaneous metric developed for quick planning of single runs and the second provides estimate of endurance and performance over time for "what-if" analysis for various training and recovery strategies.

6.1 EPower metric:

This research developed a simple metric called Endurance Power that evaluates the joint effects of the physiological and psychological variables at a given time on a runner's expected performance. The metric combines a physics-based equation for power with perception of effort at the start of a run, to calculate expected performance and plan strategies for training runs. To calculate the power output for long durations and distances, calculations are made using the System Dynamical model which incorporates perception of effort that is dynamically changing with physical and mental endurance. This allows development of a long-term pacing strategy to optimize performance and endurance and enable tailoring parameters for individual endurance enhancement.

Extensive literature investigation shows runners commonly use quantifiable and subjective calculations and metrics, such as pace, heart rate, power, Ratings of Perceived Exertion (RPE), Training Impulse (TRIMP), and Training Stress Score (TSS) to measure their training intensity and effort level. Duration, distance, pace, and heart rate/Heart Rate variability (HRV) and power calculations are used to provide real-time pacing management individually or combined in various TRIMP calculations to quantify the cardiovascular load of a workout. Session RPE TRIMP scaling combines a post exercise rating of intensity felt by the athlete with the duration of the workout, for a subjective measure of stress and fatigue. Power calculations provide an instantaneous, objective measure of the energy being expended based on individual runners' weight, efficiency, terrain, wind, etc., via running watches and sensors but calculations vary. TSS is a commercial metric that enables monitoring fitness and cumulative training load over time. None of these methods evaluate the joint effects of the physiological and psychological effects at a given time or over time.

For instantaneous calculations, a new simple metric known as Endurance Power (EP) has been developed that adds a parameter to the physics-based formula for power or force required to propel a person forward. This parameter, the rate of perceived exertion (RPE), accounts for mental fatigue and stress and is can be calculated by the BORG RPE scale. Modifying the physiological effects with a variable for psychological effect, we have equation 18:

$$\text{Endurance\_Power} = \text{Running\_Power x } \left(1 - \frac{1}{\text{RPE}}\right) \tag{17}$$

where:

$$\text{Running\_Power(Watts)} = (m * g * v * G) + (m * \text{ECOR} * v)$$

where (m * g * v * G) is the power to overcome gravity on the incline, and (m * ECOR * v) is the power to overcome flat ground running resistance.

RPE =Rate of Perceived Exertion rating on Borg RPE scale

m=Body mass (kg)

g=acceleration due to gravity=9.81 m/s^2

v=running speed based on pace(m/s)

G=gradient or incline of terrain(percent)

ECOR=Energy Cost of running = ~1.04 kJ/kg/km(average), 0.9 kJ/kg/km(elite), and 1.09 kJ/kg/km(novice).

Data from literature searches of the effect of RPE on power output was used in development of this new metric called Endurance Power (Brownsberger et al., 2013; Hill, 2023; McMahon &

Jenkins, 2002). A key difference from the session RPE TRIMP method is that this metric evaluates RPE prior to the run to evaluate initial mental stress instead of after the run. This allows the metric to be used to evaluate what pacing strategy to use for training runs. For example, if a coach asks a novice runner who weighs 82 kg and is currently running a 13 min/mile(1.3m/s) to run at a 12 minute per mile (2.24 m/s) for 3 miles on flat ground and the runner perceives the run to be hard (BorgRPE15), the runners Endurance Power is 186.86 watts/m. This corresponds to 12.8 min per mile run. The coach can adjust the strategy for the runner to either accept the smaller improvement in pace due to the perceived exertion or reduce the mileage to account for the lowered perceived exertion for shorter distance.

The key takeaway from figures 61 and 62 is that perception of exertion is a big factor in physical performance. Figure 61 shows that the endurance power required to achieve a certain pace increases with rate of perceived exertion. The orange curves in Figure 62 highlight the point that one can achieve higher speeds with a lower perceived exertion at a specific power level. The orange dashed line shows the speed achieved for high perceived effort (RPE =15) to accomplish the desired power output while the orange solid line shows the speed achieved for low perceived effort (RPE =6) to accomplish the same power output. These plots provide a qualitative framework that can be used by coaches to gives confidence and reassurance of achievability feedback into physical performance. A randomized controlled trial (RCT) experiment would be necessary to quantify these findings in the future.

The Endurance System dynamics model uses perception of effort which is dynamically changing with physical and mental endurance to calculate the power output for long durations and distances. This allows calculation of a long-term pacing strategy to optimize performance and endurance.

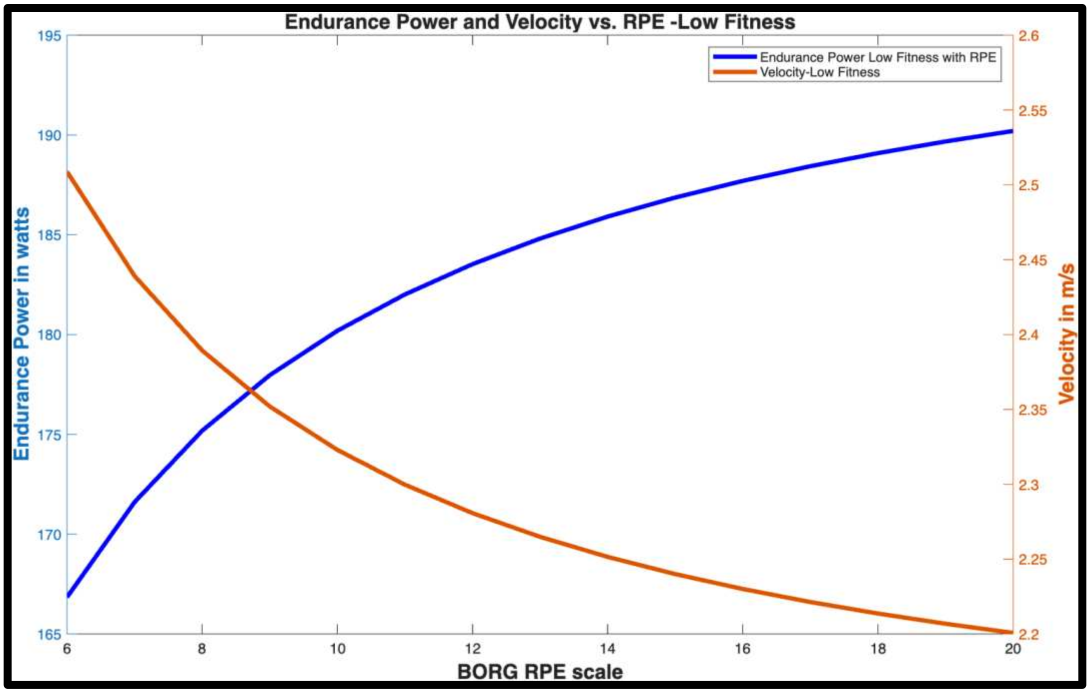


Figure 61: Higher Endurance Power needed as perceived effort(RPE) increases. Blue line =Endurance Power needed for a given perceived effort. Orange line=Speed achieved for different perceived effort to accomplish the same power output.

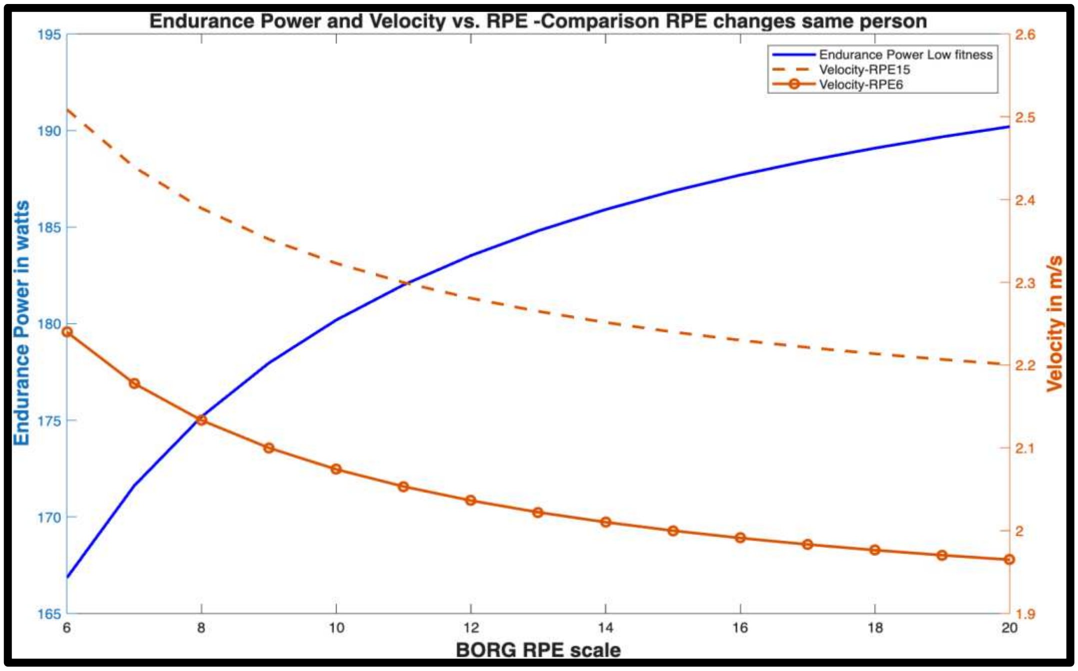


Figure 62: The perception of exertion affects speed attained. Blue line=EPower needed for a given perceived effort. Orange dashed line=Speed achieved for high perceived effort (RPE =15) to accomplish the desired power output. Orange solid line=Speed achieved for low perceived effort (RPE =6) to accomplish the desired power output.

6.2 Endurance enhancement for Individuals and Coaches

The endurance enhancement framework shown in figure 63 was developed as a notional process for implementation. This implementation assumes an initial randomized control trial has calibrated the models.

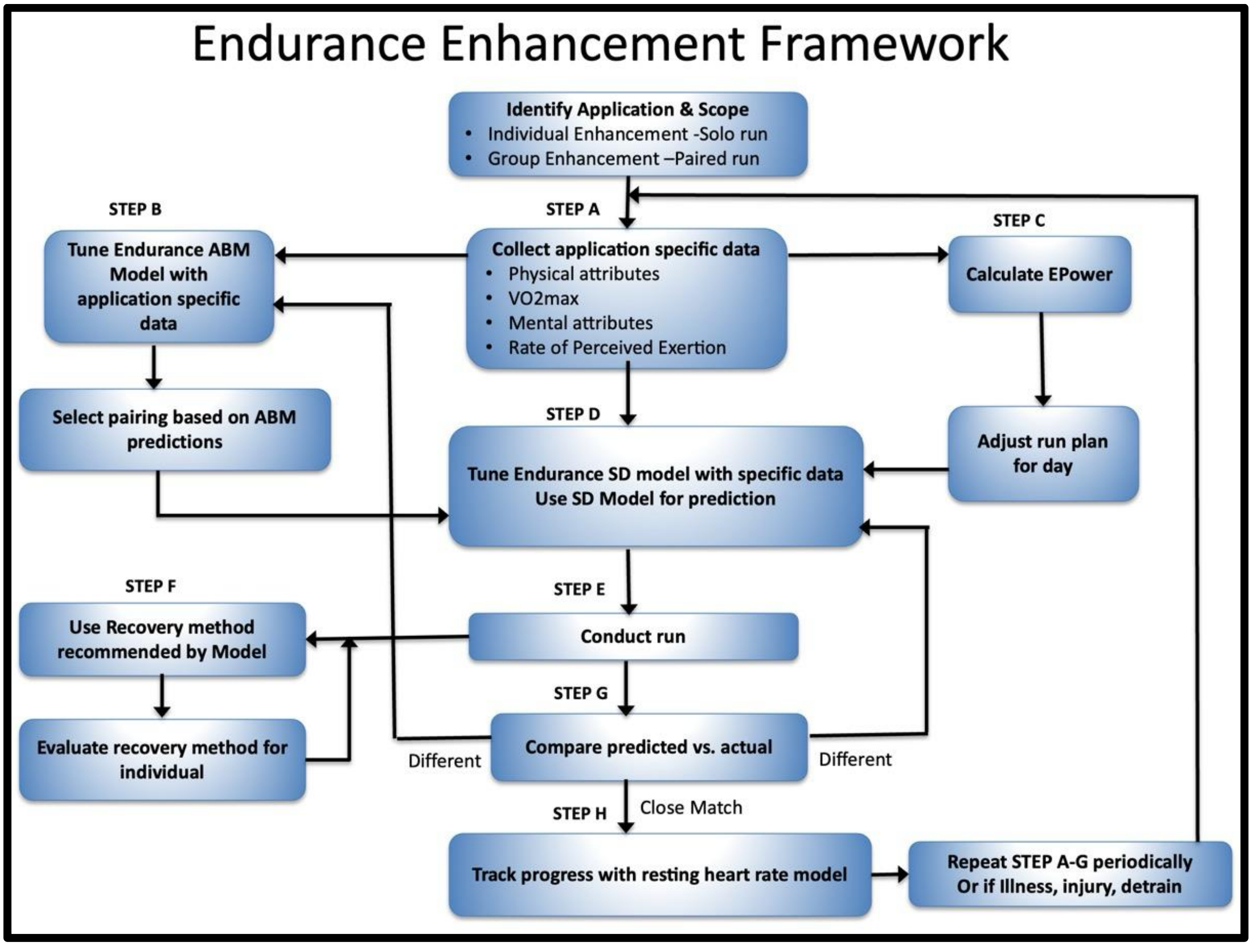


Figure 63: Endurance Enhancement Framework for Potential Implementation. Outlines steps to utilize framework by individuals and coaches. These steps are necessary to tune the method to specific new types of sport, groups and athlete types.

To practically use this framework, an individual or trainer must first identify if they are applying it to a team/group or only to an individual and determine the notional desired scope and duration of training and recovery. For either case, they will need to first gather the initial values for physical and mental attributes for each individual. For example, VO2max can be used as the initial physical endurance value by directly measuring it or calculating it through an indirect method outlined in section 2.3.1. Mental attributes such as initial mental endurance, mental fatigue, confidence, motivation, etc. can be estimated using the MTQ 48 or other questionnaires as described in section 2.3.2. Biometrics such as resting and maximum heartrate can be derived from wearables or measurements. For team training, the initial values can be input into the agent model and exercised to determine which pairings or groupings can be mutually beneficial during the timeframe of the desired activity and beyond. For each of the individuals, the initial values can be input into the Endurance System Dynamical model and predictions of endurance gathered. An assessment of rate of perceived exertion for the immediate desired training using the BORG RPE scale described in section 2.3.3 must be taken and applied to calculate the EPower for that training activity. At this point, adjustments can be made to the training plan based on the outputs of the models and EPower metric results. The run can be conducted at this point and the recovery model can be utilized to determine the recovery strategy that provides the most recovery. The results of the run can be compared to predictions. The difference can be used to fine tune the models and the process can be used for subsequent runs till the differences between estimated and predicted are within ten percent. Since the models have been set up for various fitness level individuals, this should be affine tuning effort not a full recalibration. Once the model predictions are acceptable, it can be used for several months. Steps A through G in the model must be repeated every few months assuming no major changes in a person’s physical and mental fitness or earlier if a person is injured, ill, has to stop training over two weeks or has a major life event that affects them mentally.

The framework allows individuals, coaches, firefighters, etc. to evaluate and develop training regimens based on current physical and mental factors and enhance endurance. The Endurance Agent-Based Model identified key behavioral factors for each fitness level that help them sustain an activity. It can be used as a tool to provide insight into how groups and individuals with different physical and mental attributes should be paired to train together to enhance endurance. The Endurance System Dynamical model provided insight into how coaches and trainers can have a direct impact on physical and mental endurance through confidence and motivation

The model can be used to tailor individual training to enhance physical and mental endurance. Resting Heart rate and perception of effort models provide objective measures to measure change in endurance. The Recovery for Endurance System Dynamical model showed how both physical and mental endurance are affected by recovery strategies integrated with a person's fitness level. The model can be used to tailor individual recovery to enhance physical and mental endurance.

The endurance enhancement framework transforms complex data into a practical roadmap for both everyday athletes and high-stakes professionals, such as firefighters or tactical teams. By utilizing an Agent-Based Model, the framework identifies how specific behavioral factors and fitness levels influence an individual's ability to sustain activity. This allows coaches and team leads to move beyond "one-size-fits-all" drills and instead strategically pair individuals with complementary physical and mental attributes. In a professional setting, this means creating squads where high fitness individuals can bolster the group's collective resilience, ensuring that the team as a whole remains effective under pressure.

Beyond social dynamics, the System Dynamical models offer a sophisticated look at how the mind and body interact over time. The research emphasizes that a coach's influence is not merely physical; it is a direct driver of endurance through the management of confidence and motivation. By monitoring objective metrics like Resting Heart Rate alongside subjective measures like the Perception of Effort, trainers can precisely tailor regimens to the individual. This ensures that as a person's physical engine grows stronger, their mental "governor" is recalibrated to match, preventing burnout and maximizing performance gains.

Crucially, the framework treats recovery as an active, integrated component of the training cycle rather than an afterthought. The Recovery for Endurance System Dynamical model demonstrates that recovery strategies must be synchronized with an individual's specific fitness level to be effective. For the average person or professional, this means that rest is no longer just "time off," but a tailored intervention designed to restore both physical stamina and mental clarity. By integrating these recovery insights, individuals can maintain a higher baseline of readiness, ensuring they are physically capable and mentally sharp when it matters most.

6.3 Warfighter Endurance Enhancement

The framework developed in this research allows Department of War (DoW) trainers to evaluate and enhance warfighter endurance to optimize performance and missions. The Endurance and Recovery for Endurance System Dynamical Models and Agent Based Model can be used by bootcamp and pre bootcamp trainees and coaches to find optimal individual training strategy to prevent injuries, overtraining and drop out. Active-duty personnel can use the models to tailor training to qualify and pass fitness tests based on their specific physical and mental attributes. Military training leadership can use them to understand the impact of Mindfulness Based Training(MBAT) programs on physical and mental endurance. Coaches can use the models to develop training scenarios for peacetime and wartime and understanding their impact on warfighter combat readiness, to design integrated training programs designed for warfighter fitness evaluations and to gauge endurance enhancement or depletion trends for an individual. The EPower metric enables adjustment of training sessions based on mental stress. The Resting heart rate and perception of effort sub models gauge warfighter mental stress and endurance change.

This framework shifts the paradigm from "brute-force" training to a high-precision, data-driven approach to combat readiness. By treating physical stamina and mental resilience as a single, integrated system, the Department of War (DoW) can move beyond traditional fitness standards to a model that predicts and prevents the point of failure before it occurs on the battlefield.

At the recruitment and initial entry training level, the Endurance and Recovery System Dynamical Models serve as a critical screening and retention tool. Instead of a sink or swim mentality that often leads to stress fractures and high attrition, trainers can use these models to identify the specific physiological and psychological threshold of each recruit. By tailoring the ramp-up of physical stress based on the individual's current fitness tier, the military can significantly reduce "wash-out" rates and medical discharges, ensuring that the investment in every trainee is protected.

The framework provides a tactical advantage by aligning training with specific mission requirements for active-duty personnel. The EPower metric is particularly vital because it allows leadership to adjust training intensity based on the real-world mental stress a unit is facing. If Sailors or Marines are experiencing high cognitive load from complex tactical environments, the EPower metric signals a need to cut back physical demands to prevent overtraining. By using Resting Heart Rate and Perception of Effort as daily biomarkers, commanders can objectively gauge the endurance depletion patterns. This allows for are you ready-to-fight indicators that tells a leader exactly which soldiers are at peak performance, and which require immediate recovery to maintain unit lethality.

Military leadership can use these models to quantify the investment in Mindfulness-Based MBAT and other cognitive performance programs. By integrating MBAT data into the Agent-Based Model, leaders can see how mental training directly impacts physical endurance and strength of mind during high-stress simulations. This allows for the design of integrated training programs that aren't just about running faster or lifting more but about expanding the warfighter's mental capabilities to perform under the chaotic stressors of both peacetime drills and active combat scenarios.

CHAPTER 7: DISCUSSION, FUTURE WORK AND CONCLUSIONS

7.1 Discussion

This research demonstrates that enhancing endurance performance requires an integrated balance between physiological capacity and psychological resilience. Endurance is not solely determined by physical fitness; rather, it emerges from the continuous interaction between the body and the mind. Individuals with varying levels of physical and mental fitness, novice, average, and elite, exhibit different adaptation trajectories based on their baseline capabilities, motivation, and behavioral patterns. The results show that physical endurance and mental endurance are not independent: a decline in physical endurance after prolonged exertion can lower confidence and motivation, while mental resilience can buffer fatigue and enable further physical gains. Over multiple training cycles, this mutual reinforcement or decay creates divergent fitness trajectories that highlight the importance of coupling both domains. As a result, endurance development must be approached as a personalized, dynamic process rather than a one-size-fits-all solution. Behavioral factors serve as critical enablers in achieving endurance goals. Training consistency, goal commitment, self-regulation, and adherence to structured programs significantly influence long-term performance outcomes. Even when individuals possess strong physiological potential, suboptimal psychological states and behavioral habits, such as mental fatigue, irregular training, poor recovery practices, or inadequate nutrition, can severely limit performance gains. Conversely, mental resilience and disciplined behavioral strategies can compensate for lower initial fitness levels by fostering progressive adaptation over time. The E-Power metric developed in this dissertation can be utilized for single training run adjustments as well as for forecasting long-term endurance gains or losses. The proposed models provide a quantitative and systems-based framework for designing tailored training interventions. By incorporating physical, mental, behavioral, and exogenous variables, these models enable the customization of training plans based on an individual's initial state and targeted performance outcomes. Novice individuals benefit from gradual workload progression, confidence-building strategies, and habit formation. Average performers require optimized intensity modulation, recovery scheduling, and motivation reinforcement. Elite athletes benefit from fine-tuned workload management, challenging goals, marginal performance gains, and mental resilience training.

These adaptive models allow practitioners to forecast performance trajectories, identify bottlenecks, and adjust training variables dynamically to maximize endurance gains while minimizing injury and burnout risks. Individuals can customize training to avoid overtraining, injuries, illness (e.g. Exertional rhabdomyolysis, depression) and drop out.

Beyond civilian athletic applications, the research has direct relevance to warfighter fitness optimization. The modeling framework can be used to develop data-driven physical training programs tailored to military operational requirements. By integrating mission-specific physical demands, cognitive stressors, environmental conditions, and recovery constraints, these models support:

- Objective fitness readiness assessments
- Personalized conditioning programs
- Injury risk reduction
- Performance sustainment under operational stress

The framework enables military leadership to move beyond static fitness standards toward adaptive performance evaluation systems that account for individual variability and mission context. This capability is critical for maintaining combat readiness, reducing attrition, and enhancing operational effectiveness.

In summary, this research establishes endurance enhancement as a complex adaptive system governed by physical capacity, psychological resilience, behavioral discipline, and environmental context. The proposed modeling framework offers a scalable, evidence-based tool for optimizing endurance performance across civilian and military populations.

7.1.1 Limitations

This dissertation utilized existing empirical observational data and studies from multiple disciplines to identify key attributes and causal connections and develop the system dynamical models. The limitations of the experiments and studies will be carried forward in the base assumptions. The behavioral model leverages the Theory of Planned Behavior and Prospect theory which assume rational decision making. Both theories use self-reported data and can fail to account for emotional, environmental, or unconscious influences. Agent-based modelling incorporates simple rules to describe complex interactions, can be difficult to calibrate and could be sensitive to small changes. The research attempts to overcome these limitations by using existing standards and values for the initial conditions of key attributes, developing coupled differential equations that encapsulate the feedback loops between attributes as rules to update the key dynamical attributes and explored sensitivities by developing a method to conduct Monte Carlo simulations for agent-based models. System dynamical modelling can be limited by the need to simplify complex structures which can result in missed details, inaccurate parameter estimation and high sensitivity to initial conditions. The research utilized extensive literature search, multi method analysis to capture sensitivities, pattern of behavior and face validation methods to compensate for the limitations. The framework provides foundational models for endurance with a primary focus on long distance running. The framework generally scales to other endurance activities like long distance cycling and swimming but the range of values for initial conditions may be slightly different and additional factors may have to be considered. For example, the initial VO2max ranges for runners have been shown to be slightly higher than that of cyclists and other metrics and attributes such as critical power, cycling equipment and efficiencies may need to be added . The models do not directly factor in cross training and strengthening exercises but instead just look at the cumulative effect of intensity and duration change on physical and mental attributes. To apply the framework to strength training applications which can have higher peak values with shorter time constants, the models would have to be calibrated to account for this difference.

7.1.2 Verification and Validation

The framework used to develop the models combined multiple approaches that were systematically aimed to provide empirical validation of the model outcomes with real-world data for both individual and group behaviors. The approach to validation combined Forrester and Senge tests for structural and outcome-based validation with newer approaches that utilize case studies for structure validation (Barlas, 1996; Forrester J, 1979; Hasanabadi Bob. et al., 2026; Oreskes, 1998). Structural tests included were Parameter Verification tests which assessed whether the model parameters corresponded to real-life descriptions, Boundary Adequacy tests which ensured that the model includes all relevant low-level structures necessary to address the problem and Case Studies for various fitness levels. Structural confirmation indicates that the framework is mathematically correct and fundamentally valid. To gain confidence in the results produced by the models, Empirical Validation/Behavioral Reproduction tests were performed to match model outcomes to real world and representative patterns of behavior. Multiple sensitivity analyses were employed to explore how sensitive the model's outputs were to changes in its input parameters and assumption. Detailed sensitivity and individual analysis were utilized to test for robustness. Face validation of the results was conducted by subject matter and domain experts to determine if the model and its outputs appear plausible and reasonable. Other tests conducted were a Family Member test to see if the models scale to other members within the same class of systems such as long-distance cycling and Behavior Anomaly test which modified the structure to evaluate if anomalous results were produced. To the best of my knowledge, this is the first agent-based model that integrates physical, mental, and behavioral parameters to explore the feedback loops between them as they relate to dynamics of endurance. The model utilizes and builds on knowledge gained from actual experimental and survey results for short duration exercise on athletes of varying fitness levels. The connections in the causal loop diagrams and proposed equations which characterize the relationships between parameters were developed from insights gained from actual data. Data from literature reviews reflect the ranges used for initial values for physical, mental, and behavioral parameters, and the rules used to update the agent attributes at every time step. The proposed behavioral model is anchored in two separate classic behavioral theories, Theory of Planned Behavior, and Prospect Theory, which have not typically been used together but make sense in the context of endurance to incorporate real life influences. The ABM was set up to be intentionally non-prescriptive so that interactions happen randomly based on availability to run with someone and changes in pace occur only if they are within a realistic predetermined bound. The pace updates are solely made based on slower versus faster runner and do not examine any other attribute of the runners to adopt a pace. This methodology gave validity to the model results that showed physical endurance reaching a plateau after some time for solo runners and some interacting runners as well as the delayed/lag effect of mental to physical endurance -all of which have been documented in real life experiments(Coyle et al., 1999; Van Cutsem et al,2017; VanHaitsma et al.,2023). The reasons for the plateau that is sometimes seen in runners can vary from reaching a physiological limit, achieving the point of diminishing returns, and perception of effort (Midgley et al.,2007). The analysis of the model results showed that the reasons for the plateau were encapsulated organically by including parameters such as maximum number of runs, maximum mileage, and perception of effort. This effect was delayed and is less evident when runners were interacting with other runners due to variability in intensity and duration. The model correlation results highlighted the effects of behavioral aspects that were mentioned generally in literature but showed up as key influencers of the intention to sustain running. Domain experts were consulted in the areas of exercise physiology, behavioral science system dynamics, as well as novice, average, and elite runners to gain their assessment of realism and reasonableness of the model and results.

7.2 Future Work

This research developed foundational models and simulations that integrate physical, mental and behavioral attributes that interact and evolve and affect physical and mental endurance. The limitations of the ABM simulations are that once the initial conditions of random variable are assigned; these conditions do not change for the initial number of miles. However, the runners always run the same number of initial miles that is assigned using a random number, within their present fitness range for the entire duration. Future work will incorporate changes to the number of runs every week and number of miles per training session based on changes to physical and mental endurance. The ABM model does not currently factor in the physical and mental effects of diet, injury, detraining, terrain, heat, or humidity on the runner. The effect of timing and type of runner interactions on all affected runners to optimize endurance, the effect of added mental stress and how frequency and volume of running affects runners of varying physical and mental endurance as they run with others, can be explored further. All these areas can be analyzed in future work. The limitations of the Endurance System Dynamical model are that nutrients, injury, detraining, rest, recovery, terrain, and weather effects were not explored. These can be research topics for future students building upon this research. Detailed psychological and behavioral age or gender specific effects extensions of the model can be developed in the future. The limitations of the Recovery for Endurance System Dynamical model are that it starts at the point of training so the impact of specific recovery activities prior to training were not explored. An in-depth focused analysis and modelling of the interaction and impact of specific recovery strategies can be a research topic for future students building upon this research. Other future topics of research include specific expansions of the framework for other activities such as cycling, swimming, strength training as well as a combined framework that incorporate multiple activities. A randomized controlled trial (RCT) experiment should be performed to quantify these findings in the future.

Future work can develop management flight simulator that does not require knowledge of endurance factors. Other extensions of this model include long-term training scenarios with varying behavioral, environmental, physical, and mental parameters, incorporation of real-time biometric feedback, machine learning optimization, and mission-specific performance simulations of endurance to further advance human performance science. This research could help overcome the current limitations of the “state-of-the-art” fitness apps that despite using artificial intelligence and biometrics, are causing overtraining and injuries for users. Follow on work includes conducting randomized control trials to calibrate and characterize attributes for various fitness levels. Models can be set up on a website for anyone to use by calibrating with individual data uploaded from fitness trackers, by using calculated or measured VO2max and MBTQ questionnaire. Large language models can provide forecasts of physical and mental endurance as well as other health metrics. For warfighters, models can be incorporated into fitness apps and Official Navy PFA app to use biometric data to track physical and mental endurance changes. With the increased trend of using wearables to track fitness, future models could be directly incorporated into fitness trackers and watches to utilize the biometric data and watches for real- time physical and mental health assessments. Current wearable technology trends include using devices such as smart rings, smart jewelry and even smart clothing which utilize special biosensors to monitor heart rate, Electrodermal activity (EDA) for sweat response, and sleep to detect stress levels and emotional states and using generative AI for mental health coaching. This could eliminate the need to take questionnaires or surveys for gauging mental exertion and stress. The trend towards lower power and faster compute neuromorphic AI edge hardware can result in AI integrated models embedded in wearables or clothing to track fitness. This will be especially useful to warfighters in stressful combat situations to help assess their fitness to fight. Integrating these models with AI based methods will strengthen the predictive capability of the framework and enable any person of any mental and fitness level to take advantage of this research effortlessly.

7.3 Conclusions

The research conducted in this dissertation has contributed to the body of knowledge in multiple fields and provides a practical implementation framework for future use. The following sections describe the many contributions and possible future uses of this research.

7.3.1 Major Contributions

This dissertation documents research that fills the gap of providing an understanding of the complex interactions between mind and body and their contribution to enhancing endurance. The main research question of whether endurance performance could be characterized as a function of mental and physical attributes was answered using a holistic Model Based Systems Thinking approach. The first research question answered was whether relevant physical and mental attributes that affect endurance could be identified. The causal connections between the attributes were captured by extensive literature searches of empirical data from the separate disciplines of physiological, psychological, psychobiological, behavioral and systems science. This was used to develop new causal loop diagrams of dynamic endurance. The second research question of whether the combined dynamics and interaction of physical and mental aspects could be modelled, was answered by developing the Endurance System Dynamical Causal Model. This model combines all the key “psychosociophysical” attributes related to endurance. A novel Endurance Agent Based model which captures peer group effects and a new behavioral model for endurance were developed to answer the third research question, whether performing an activity with others changes physical and mental endurance. A new recovery system dynamical model was developed that shows the inter influence of recovery methods on fatigue, physical and mental endurance. This answered the fourth question on whether changes in mental models that affect behavior and recovery choices could be modeled. To answer the fifth question on how to gain confidence in the modeling, multiple analysis methods including Monte Carlo, sensitivity, exploratory, individual and group analyses, and expert validation were used. The analyses provided empirical validation of the model outcomes with real-world data for individuals and groups. To answer the sixth question on how to practically use the dynamic models to implement strategies for different types of individuals and groups, a notional endurance enhancement framework with metrics was developed. This unique framework utilizes the three different system dynamical models along with metrics to enable individuals as well as groups to achieve tailored endurance enhancements. The dynamic models are tunable and tailorable to individual characteristics and apply to a layperson, athlete, as well as professional such as warfighters and firefighters. The models provide insight into how to set up pairings for group training so that all trainees gain a personalized benefit from the training.

The multiple system dynamical models used to explore endurance enhancement provided new insights into how individuals and groups can enhance endurance. An agent-based model was implemented using a new endurance behavior model that explored how dynamic social interactions among runners influence individual physical and mental fitness trajectories during endurance training. The ABM showed insights never modeled before, that running with others can contribute to improvements in physical endurance. An emergent result of this work was that the initial physical and mental fitness of interacting runners affects the physical and mental endurance of runners. This has implications in training so that novice runners may need to ramp up their training pace slowly and build up their confidence to gain physical endurance. For average runners interacting together, pace and perceived value are highly negatively correlated which means that as the runner’s pace increases, the perceived value of running decreases. Since perceived value and motivation are highly correlated, this has implications that average runners are likely to stop running if they are pushed too hard to increase their pace to match a running buddy. Positive and reinforcing peer interactions improve training consistency and fitness gains, while negative or disruptive interactions can hinder fitness improvements. Results showed that behavioral constructs such as motivation and confidence change dynamically over time, and both affect and are affected by mental and physical endurance. As confidence decreases, mental endurance decreases which eventually causes a corresponding decrease in physical endurance. Sensitivity analysis showed that initial mental fatigue and maximum mileage also play a large role in accomplishing endurance outcomes. The model demonstrated the delayed feedback effects of physical and mental endurance on each other over time. An Endurance System Dynamical Model was developed that explored individual variability in physical, mental and behavioral attributes among runners. The model showed that confidence and motivation act as a bridge between mental and physical endurance. They are affected by praise or criticism behaviors of leaders/trainers and impact physical and mental endurance. Results show that physical attributes such as weight, body fat percentage and BMI and training intensity have an impact on physical and mental endurance and carrying added weight increases physical and mental stress. The model highlights the fact that initial physical and mental endurance interact with physiology to affect outcomes. The model showed that mental stress affects endurance and the motivation to sustain activity. Increasing training intensity will increase physical and mental endurance to a point depending on initial physical fitness. Low fitness individuals have higher injury and drop-out risk and lose motivation to continue running if intensity is too high. A Recovery for Endurance System dynamical model was developed that shows how specific recovery methods evolve with feedback to produce better endurance performance depending on the initial physical and mental fitness of the individual. This model can be used to reduce the effects of overtraining and failure to achieve endurance goals. The model explains the real-world individual variability of response to recovery methods. It showed that both physical and mental recovery are affected by recovery strategies and that timing of recovery methods affects how quickly and how much a person recovers. Combining recovery strategies is critical to reduce fatigue since time constants for recovery strategies are different. Results show that a person's physical & mental endurance and training intensity affect overall recovery and mental stress reduces the recovery effect on physical and mental endurance. Other results are that sleep has a cumulative effect on recovery, diet and hydration affect the magnitude of recovery, and that active recovery (stretch, walk, run) must match the fitness level of runner otherwise it can cause overtraining A new simple metric called Endurance Power was introduced to measure performance and plan strategies for training runs. In the endurance system dynamics models, perception of effort which is dynamically changing with physical and mental endurance was used to calculate the power output for long durations and distances. This allows calculation of a long-term pacing strategy to optimize performance and endurance and enable tailoring parameters for individual endurance enhancement. A randomized control trial experiment is recommended using the brand-new metric of Endurance Power to quantify and validate the effect of rate of perceived exertion from changes in endurance capabilities. In the trial, the control would be people or a group that does not received positive feedback and perceives a run to be hard versus people who do receive positive reinforcement. These models can provide information on designing tailored training plans based on the initial physical and mental fitness of novice, elite, and average people who engage in endurance activities to achieve a performance target. This could also be useful in the physical training programs designed for warfighter fitness evaluations.

7.3.1.1 Understanding human behavior as a complex machine

This research establishes high-fidelity dynamic models that redefine endurance as a complex adaptive system, moving beyond traditional physiological metrics to capture non-linear interplay between physical capacity and cognitive governance. By implementing Agent-Based Modeling, the study quantifies how dynamic social interactions serve as a driver of individual fitness trajectories. For average runners, the research identified a significant negative correlation between pace and perceived value, suggesting that when intensity exceeds a specific psychological threshold, motivation collapses, leading to an increased probability of dropout. These findings also demonstrate that positive mentally reinforcing peer interactions act as a force multiplier for training consistency, while disruptive social dynamics can accelerate the onset of exhaustion.

Central to the research is the development of the Endurance System Dynamical Model, which formalizes the latent behavioral constructs of confidence and motivation. This acts as the functional bridge between mental toughness and physical execution. Through extensive sensitivity analysis, the model demonstrates that initial mental fatigue is often a more potent predictor of performance failure than physical weight or BMI. By treating coaching behaviors, such as praise or criticism, as model inputs, the research proves that external psychological stressors directly alter internal physiological thresholds. The model further reveals the delayed feedback effects inherent in human performance. As confidence erodes, mental endurance degrades, eventually triggering a systemic collapse in physical output. This underscores the necessity of managing the "Motivation-Confidence" feedback loop to sustain high-intensity activity, particularly in high-stakes environments like military operations or tactical training.

To address the limitations of current recovery protocols, a Recovery for Endurance System Dynamical Model was developed to optimize the timing and composition of recovery. This research highlights that various recovery interventions, ranging from sleep to active recovery, possess distinct time constants, meaning that their integration must be synchronized to prevent overtraining. Crucially, the model shows that "active recovery" is not universally beneficial; for low-fitness individuals, improperly scaled activity can increase injury risk and fatigue due to the same factors as over training. To unify these findings into an actionable framework, this research introduced "Endurance Power," a metric that integrates the Rate of Perceived Exertion, RPE, with dynamic physiological changes. The Endurance Power metric is a composite indicator developed to quantify the instantaneous and cumulative work capacity of an individual by integrating objective physical output with subjective cognitive load. Unlike traditional power metrics that focus solely on mechanical wattage or metabolic equivalents, “EPower“ accounts for the "psychological tax" that accelerates fatigue that can be a factor before embarking on an endurance enhancement activity. This allows for the calculation of long-term pacing strategies that optimize performance by accounting for the mental aspects of exertion.

The models and metrics are applicable to individuals of any gender, age, physiology or fitness level in both civilian and military contexts. The framework can be applied at a group level to synergistically enhance endurance for multiple people with different physical and mental aspects simultaneously. Section 6.2 outlined the tuning needed to apply the framework to individuals and groups initially and in the long-term as their physical and mental baselines change due to life events, injury, illness, etc. The framework can be extended to other activities such as long-distance cycling and swimming as well as strength training. These extensions may need to add additional attributes specific to the activity and adjust the causal relationships between some of the parameters. Collectively, these models provide a predictive architecture for designing tailored training plans that ensure individuals, from novice athletes to elite warfighters, reach their performance targets with maximum efficiency and minimal risk.

7.3.1.2 Advancement of Systems Thinking and Systems Engineering Methods

This research provided novel insights in the area of Systems Dynamics and endurance enhancement that have not been fully explored in current research. It contributed to the field of Systems Engineering by demonstrating that the thought processes and tools can be applied to other disciplines. The research expanded the application of model-based systems thinking to health, sport and military science which spans both civilian and warfighter domains. The models can be scaled to other endurance sports such as long-distance cycling and swimming and extended to include other areas such as strength conditioning and weightlifting. The research contributed the systems engineering field both methodologically as well as technically. It advanced the area of uncertainty quantification analysis in agent-based modelling by developing a new method to conduct a Monte Carlo simulation of an agent-based model. The method enables exploration of sensitivity to multiple variables with random initial values that change simultaneously, which has not been done before. It applied Prospect Theory and Theory of Planned Behavior to a completely new area. The research integrated agent-based models with system dynamical causal models which provided synergistic cross validation and expanded the scope of modelling dynamic complex systems at different time scales. The endurance implementation framework demonstrates the "slow" and "fast" learning loops in the Model

Based Systems Thinking(MBST) process where the slow learning loop develops the foundational model and the fast-learning loop can be used to tune the model to individuals and groups. It developed a new EPower metric that accounts for the contribution of perception of effort in planning to perform an activity. It incorporates metrics in the form of models such as resting heart rate, perceived value and the perception of effort that can gauge the effectiveness of a training regimen continually over time. The research used correlation, sensitivity, and exploratory analysis to both provide an understanding of the interactions between physical and mental attributes and gain an understanding of drivers that affect physical and mental endurance for difference fitness levels. This enables tailoring training regimens at both the individual and group levels so that both simultaneously enhance enhancement.

A key contribution is a systemic understanding of endurance as a multifaceted dynamic adaptive system of systems. This is akin to revealing the entire picture of the “elephant” in the Sufi story of the “Blind men and the elephant”. In this parable, multiple men who encounter an elephant by each touching only one part, come to different conclusions based on their limited perceptions. A wise leader intervenes, explaining that they are all partially right and partially wrong, and that they must combine their experiences to understand the whole picture. Similarly, individual disciplines including physiology, psychology, psychobiology, behavioral science, systems, etc. have explored endurance from their frame of reference which provide part of the answer and cannot explain the individual variability of outcomes. This research integrates and combines all these insights and research to develop a holistic model that captures the key attributes and interactions between these systems and provides a whole picture of endurance and its dynamics. The research in essence supports the “mind-body dualism” theory by Renee Descartes who in 1637 postulated that mind and body while separate operated as a unified whole in living humans.

This research gives the general population a positive path forward to sustaining activity by gaining an understanding of the impacts of training with others. Enhanced endurance could provide the asymmetrical advantage required by warfighters to win future conflicts.

7.3.2 Reflections on integration of research with future technologies

This research studied the complex interactions of mental and physical endurance and developed foundational models and metrics. This section explores how this research can possibly be expanded and integrated with other technologies in the future. An expansion of this research would be the development of a single holistic framework that incorporates multiple endurance and short duration activities to provide real-time evaluations of physical and mental aspects for any individual. One possible future use of the research performed for this dissertation is the construction of a digital twin of a person wishing to improve their fitness. Current wearables track heart rate and steps, but they fail to account for the mental aspects that effect endurance mentioned in this dissertation. Technology trends of using biometric data such as heart rate, sweat, skin temperature, sleep patterns and eye tracking can provide both physical and mental stress estimates in real-time. A futuristic application would be a bio-integrated sensor suite with a hybrid quantum-generative (reasoning and context aware) AI, that calculates Endurance Power in real-time along with physical and mental aspects to gauge true fatigue and subject capabilities. The endurance digital twin could be put through hundreds of possible scenarios for the subject to choose a few that fits their lifestyle and capabilities. It is imagined that a subject would reject the scenarios in which injury occurred. The hybrid quantum-AI would self-calibrate by using all available data from activities performed by the individual. This assumes the evolution of quantum and AI encryption and decryption methods to protect personal data.

Given the current trends towards shifting AI processing from the cloud to the device itself (Edge AI) which allows for real-time analytics without needing constant internet connectivity, the digital twin could reside on a smart ring, pin, glasses or clothing. Instead of just providing alerts or data, it could provide personalized, actionable advice on fitness, sleep, and stress. For athletes it can engage as a coach who immediately starts administering stress relieving methods or alerts medical personnel if the situation is acute in training or competition settings. For individuals who are older or have health conditions such as diabetes, heart disease, mental conditions, etc. it can be tied to devices that administer lifesaving medication and can alert emergency services.

The Endurance Digital Twin could be applied to military applications. This dissertation includes tailoring strategies for the warfighter. Digital Twins of warfighters could be used for future training and combat scenarios to predict when a soldier is reaching a breaking point that physical sensors alone might miss. A Digital Twin teammate could monitor a warfighters individual variability for physical and mental parameters. Each individual digital twin can utilize camera information from teammates in the vicinity to analyze gaze, facial expressions and body language and integrate with individual digital twin data to assess their combat readiness. Using the Systems Dynamical models in this dissertation, it would predict when a soldier's decision-making will degrade due to the interaction of physical exhaustion and mental stress. A future warfighter bio suit that includes an artificial exoskeleton, cooling , noise suppression, and other technologies can be used to compensate for physical fatigue and stressors.

Expanding on the Digital Twin concept, one could envision creating a “Symbiotic Digital Twin”, a virtual organism whose health, evolution, and survival are directly tethered to the subject’s physical and mental endurance metrics. This synthesis would transform the Endurance Power metric from a number on a screen into a living responsibility similar to the Bandai’s Tamagotchi toys of the 90s. This Symbiotic Digital twin would bridge the gap between the "one-size-fits-all" fitness approach by creating the emotional bond of electronic companions. This could be done for subjects of all ages by creating a system with feedback where caring for the self is indistinguishable from caring for the companion. An example would be instead of a chart showing the percentage change in resting heart rate or variability, the user sees their Symbiont hungry, sleepy, shivering or needing a walk. This could trigger the nurturing instinct, making the labor of training feel like the joy of caretaking. This could help alleviate the childhood obesity problem in the U.S. by providing non-attributional ways of making sleep and diet choices, physical exercise and mental training a fun activity for children. Helping their digital symbiont would in effect help them without realizing it. To address the negative feedback effect of not achieving goals, the symbiont would suggest ways to accomplish the goals given their current physical and mental endurance or provide the ability to scale effects on the symbiont. This could be particularly useful for children and elderly who may not be aware of their stress and needs or be able to express them to an adult. This digital symbiont can also be used in avatars and other digital representations in gaming and warfighting trainers to “kick up” the intensity of the experience, since it now requires physical and mental agility.

This can be taken one step further by providing access to digital twin data to an AI based synthetic being with Artificial General Intelligence (AGI) who would possess the ability to reason, learn, and apply knowledge across any intellectual task at a human-equivalent or superior level. This being can autonomously fuse and analyze all relevant, available data from multiple sources to provide timely interventions as needed to a person to improve their quality of life. All these possibilities are enabled by this research to provide a future where every person is able to achieve optimal endurance to live a long, active healthy life.

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APPENDIX A: AGENT MODEL RULES

Global variables:

1. Agent color is based on the value of fitness/endurance:

   Low/Novice color =Blue; Med/Average color =Yellow ; High/Very fit color =Green; Stopped color=Red

2. Week start[level: 0,1]
3. Assign variables for parameters for each type of runner for display on interface
4. Assign agent breeds as Novice =unfit, Average=average and Elite =superfit

Environmental Behavior on its Own:

Rule: Count ticks to keep track of time to enable the reset of agents.

Rule: Reset week on every eighth tick and change week start to 1

Rule: Every tick reset Run completed for the day to No (this allows one run per day)

Agent with Environment:

Rule: Initialize agent parameters randomly with values between ranges shown in Appendix C corresponding to agent breed (novice, average, or elite)

Rule: If the agent encounters the eighth tick, reset the number of runs per week for agents, reset the mileage per week, and increment the total number of runs,

Rule: Start run count when agent encounters another agent

Rule: Start run count for an agent with running buddy preference = 0

Rule: Update parameters at every tick

Rule: If motivation of agent is below zero, stop agent from running

Rule: Monitor state of running- if state of running is 0, change agent color to red

Rule: Change color of agent if homeostatic endurance improves

Rule: If current physical endurance is greater than the physical endurance of that week by 0.1, increase maximum mileage of the runner by 0.5 miles else decrease maximum mileage of the runner by 0.5 miles.

Rule: Move randomly on the grid

Rule: Change position if running state changes

Rule: Do not change position if the running state changes to not running

Rule: If agent exceeds number of runs or maxmileage for that week, make them rest till eighth tick.

Rule: If agent is running solo, change pace to a random value between +/- (3 - 6) miles and update perceived value, perceived effort, motivation, confidence, mental fatigue, physical endurance, mental endurance, and homeostatic endurance after each tick

Rule: If agent is in resting status, change pace by 0.001 % and update perceived value, perceived effort, motivation, confidence, mental fatigue, physical endurance, mental endurance, and homeostatic endurance after each tick

Agent with Agent :

Rule: If agent encounters another agent and they start run, increment the Total number of runs for each agent by 1

Rule: If agent encounters another agent and preference is run with others, link and compare pace.

Rule: If both agents are already running, continue to move randomly

Rule: If difference in pace between linked agents is <=1 min/mile, then change pace of slower agent to pace of faster agent, increase confidence and perception of effort by 0.05%, and reduce motivation by 0.1

Rule: If difference in pace between linked agents is between 1 and 2 min/mile, then change pace of slower agent by 0.5 min/mile, increase confidence 0.5%, and reduce motivation by 0.2

Rule: If difference in pace between agents is between 2 and 4 min/mile, slower agent increases pace by 2 min/miles to pace for that run, reduces confidence by 0.5%, changes perceived effort to difference in pace - (0.01 * physical endurance) - (0.01 * mental endurance) - (motivation) + (1.5 * mental fatigue) and reduce motivation by 0.3

Faster agent loses 1 min/mile overall for that run, increases confidence by 0.5%, reduces motivation by 10% and perception of effort by 0.5%

Rule: Compute perceived value, perceived effort, motivation, confidence, physical endurance, mental endurance, and homeostatic endurance after each tick depending on if agent is slower or faster runner and whether the agent has reached maximum mileage for the week. See Appendix B for equations.

APPENDIX B: RANGES OF INITIAL VALUES

Baseline:

Parameter	Value
Number of Low fitness runners	50
Number of medium fitness runners	50
Number of high fitness runners	50
Value Exercise low fitness runners	0.1
Value Exercise medium fitness runners	0.1
Value Exercise high fitness runners	0.1

Parameter	Value Per week
Maximum runs of Low fitness runners	2
Maximum runs of medium fitness runners	4
Maximum runs of high fitness runners	6
Maximum Mileage low fitness runners	2.5
Maximum Mileage med fitness runners	9
Maximum Mileage high fitness runners	55

Parameter	Value Per week
Mental stress/fatigue of Low fitness runners	(0-4), 21 , 30
Mental stress/fatigue of medium fitness runners	(0-3), 21 , 30
Mental stress/fatigue of high fitness runners	(0-2), 21 , 30
Buddy Preference low fitness runners	1 = wants to run with other runners
Buddy Preference med fitness runners	1
Buddy Preference high fitness runners	1

Initial Value Ranges of Key Parameters:

All initial parameters (except number of runners) were assigned randomly to runners in a fitness group with the chosen value as an upper limit.

Parameter	Novice Range	Average Range	Elite Range
Number of runners	1-100	1-100	1-100
Buddy Preference **0=Run solo** **1= Run with others** **2=solo/buddy some of the time**	0-2	0-2	0-2
Maximum Runs per week	1-7	2-8	4-9
Maximum Mileage per week	0.1-10	4-20	10-50
Mental fatigue	0-5	0-4	0-3
Pace (minutes/mile)	13-20	7.1-12.9	5-7
Physical Endurance (mL/kg/min)	1-10 (=25-40 VO2max)	11-30 (=40-55 VO2max)	31-50 (=55-70 VO2max)
Mental Endurance	0.1-2	1-2	1-3
Confidence	1-10	1-10	1-10
Miles	3	5	8
Motivation	0.1-3	1-3	6-9

Belief	0.01-0.3	0.01-0.6	0.01-0.9
Coupling	0.01-0.3	0.01-0.2	0.01-0.1
Perception of Effort	0.01-0.5	0.01-0.4	0.01-0.3
Perceived Value	0.01-0.4	0.01-0.6	0.01-0.8