Part I

"Art of Coaching"

Periodization and Training Planning in Climbing

Introduction to the Historical Development and Evolution of Periodization

The concept of periodization, often misconstrued as a product solely of the Soviet Union and primarily attributed to L. Matveyev, is, in reality, the result of a long and rich developmental history involving numerous contributors. Although Matveyev is often hailed as the "Father" of Periodization, his systematic model, formalized around 1964, was built upon pre-existing foundations and insights from various scholars and practitioners. Matveyev's model, derived from observing Soviet athletes preparing for the 1952 and 1956 Olympic Games, emphasized structured training cycles to optimize performance at crucial competitions (Haff, 2024).

Periodization's roots can be traced back to ancient times. Claudius Aelius Galenus (Galen) in his treatise "On the Preservation of Health" and Philostratus in "Gymnasticus" discussed principles akin to modern periodization. Galen's work categorized and sequenced exercises, emphasizing recovery through proper nutrition and relaxation, while Philostratus detailed a structured preparation period for the Olympic Games (Fleck & Kraemer, 2004).

In the modern era, before Matveyev, notable contributions came from figures like Boris Kotov and Lauri Pihkala. Kotov delineated stages of preparation, transitioning from general to specific fitness training. Pihkala proposed dividing the annual training plan into phases, incorporating periods of active rest, and emphasized the balance between training intensity and recovery (Bompa & Buzzichelli, 2019).

Matveyev's model integrated the mechanistic ideas of stress and adaptation from H. Selye, N.N. Yakovlev, and I.P. Pavlov, applying the concept of "supercompensation" to explain the accumulative effects of training and the importance of load variations. Despite being labeled a "linear" model, Matveyev's approach actually highlighted the necessity of nonlinearity and rhythmicity in training, advocating for oscillating loads to optimize athlete performance (Issurin, 2016).

The widespread adoption of periodization, particularly within the Soviet Union, led to its application across Eastern Bloc countries, contributing to their dominance in international sports during the mid-20th century. This success prompted further development and formalization of periodization models, influencing training methodologies globally (Stone et al., 2021).

In the West, early works by J. Garhammer and Counsilman in the 1970s began to popularize periodization for strength training and swimming, respectively. Subsequent experimental studies and theoretical advancements by researchers like Stone and O'Bryant ensured the global dissemination and adaptation of periodization concepts (Buford et al., 2007).

Overall, the evolution of periodization reflects a collaborative and iterative process, enriched by contributions from various scholars and practitioners worldwide. Its development continues to be scrutinized and refined, demonstrating its enduring significance in the realm of sports science and athletic training (Issurin, 2008).

Models of Periodization

Beyond the foundational model proposed by Matveyev, several other periodization models have been developed, each offering unique approaches to structuring training for optimal performance.

1. **Block Periodization**:
   - Developed by Vladimir Issurin, block periodization focuses on highly concentrated training workloads within specialized mesocycles or "blocks". Each block targets specific fitness attributes, such as strength, endurance, or speed. This model is particularly useful for athletes who compete multiple times throughout a season, allowing for targeted improvements and peak performance during crucial competitions (Issurin, 2008).
2. **Undulating Periodization**:
   - This model, also known as nonlinear periodization, involves frequent changes in training intensity and volume within a cycle. Instead of following a linear progression, undulating periodization varies the load and repetitions on a weekly or even daily basis, helping to avoid plateaus and maintain high levels of neuromuscular adaptation (Haff, 2024).

3. **Conjugate Periodization**:
   - Popularized by Louie Simmons of Westside Barbell, the conjugate method incorporates multiple training stimuli concurrently rather than sequentially. This approach involves rotating exercises and training modalities to continually stimulate different physiological adaptations, effectively developing multiple attributes such as strength, power, and speed simultaneously (Fleck & Kraemer, 2004).
4. **Flexible Periodization**:
   - Introduced by Tudor Bompa, this model allows for adjustments based on the athlete's performance and readiness. Flexible periodization acknowledges that not all athletes respond identically to training stimuli, and it incorporates ongoing assessments to tailor the training plan dynamically (Bompa & Buzzichelli, 2019).
5. **Reverse Periodization**:
   - Contrary to traditional models that start with high volume and low intensity, reverse periodization begins with high-intensity, low-volume training. This approach is often used for endurance sports, where building a strong base of high-intensity work early can lead to greater endurance gains in later phases (Fleck & Kraemer, 2004).

Each of these models provides different methodologies for structuring training programs, allowing coaches and athletes to select or combine approaches that best meet their specific goals and contexts. The diversity in periodization models underscores the adaptability and complexity of training science, reflecting ongoing advancements in understanding human performance and adaptation.

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Differences Between Programming and Periodization

Periodization

Periodization is the macromanagement of the training process, involving the allocation of time toward various fitness phases that align strategically with a competition calendar. It provides a blueprint that allows coaches to forecast and assign periods of training to target the acquisition and attainment of specific fitness characteristics (Cunanan et al., 2018). Periodization can be broken down into different cycles:

- **Macrocycle:** Typically a year-long plan that outlines the overall training goals and timelines.
- **Mesocycle:** A block of training usually lasting several weeks to a few months, focusing on specific training objectives.
- **Microcycle:** A week-long plan that details the specific workouts and training sessions.

The goal of periodization is to optimize an athlete's performance by systematically varying the training load to prevent overtraining and ensure peak performance at the time of competition.

Programming

Programming is the micromanagement of the delineated stages of training. It involves the detailed organization of various components of training, such as the frequency of training load, training volume and intensity, exercise selection and order, number of sets and repetitions, and other factors DeWeese et al. (2014) Cunanan et al, (2018), Fig.1. Programming ensures appropriate variation in these training factors to modulate fatigue and optimize long-term adaptations.

When properly constructed, a training program should differentiate the time continuum into discernable patterns based on intended objectives. This differentiation allows for precise adjustments in training stimuli to meet specific goals, such as increasing strength, endurance, or power.

Fig 1.The relationship between programming and perodization according to DeWeese B 2014.

General Adaptation Syndrome (GAS)

The General Adaptation Syndrome (GAS), developed by Hans Selye, describes the body's short-term and long-term reactions to stress Fig.2. Haff et. al (2012) identified three stages of response to stress:

1. **Alarm Reaction Stage:** The initial response to a stressor, characterized by a decrease in performance due to shock and subsequent mobilization of resources.
2. **Resistance Stage:** The body adapts to the stressor, and performance improves as it builds resistance against the stress.
3. **Exhaustion Stage:** If the stress continues beyond the body's capacity to adapt, performance declines, leading to fatigue, burnout, and potential injury.

GAS has been widely applied in sports training to explain the relationship between stress and adaptation. It provides a framework for managing stress and fatigue to direct adaptation during training. By understanding and applying the principles of GAS, coaches can design training programs that optimize performance and prevent overtraining (Cunanan et al., 2018).

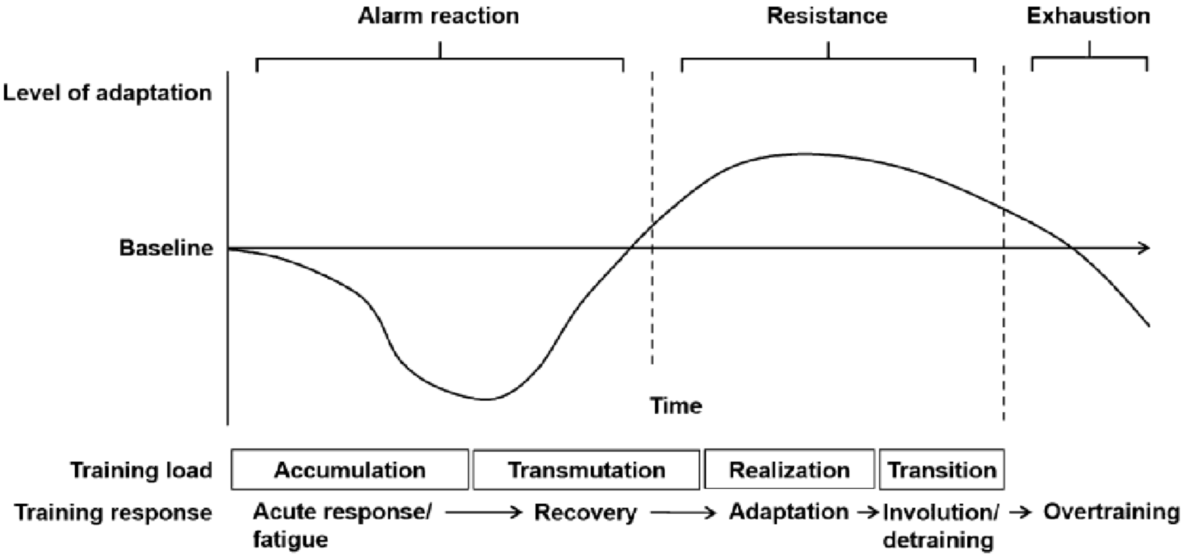


Fig 2. General Adaptation Syndrome (GAS) Selye, H. (1946).

The Fitness-Fatigue Paradigm in Sport

The **fitness-fatigue paradigm** is a model used in sports science to understand the complex relationship between training, performance, and recovery Zatsiorsky (2021).

This model divides the effects of training into two primary components: fitness and fatigue. It helps in planning training and optimizing performance by considering how these components interact over time.

Components of the Fitness-Fatigue Paradigm

1. **Fitness**:
   - **Description**: Represents the positive adaptations resulting from training, such as increases in strength, endurance, and speed. These improvements are gradual and have a lasting impact on physical capabilities.
   - **Characteristics**: Develops slowly but tends to be long-lasting. Effective training progressively enhances fitness levels.
2. **Fatigue**:

Fatigue plays a vital role in both physical activity and everyday tasks, making it a key factor to consider when structuring an athlete's training program. It can be understood from various perspectives: for instance, a biomechanist might interpret it as a decline in muscle force output Zarzisi (2020), while a physiologist might define it as the malfunctioning of a particular physiological system Green (1997). A psychologist, on the other hand, could describe it as the subjective experience of feeling tired. By merging these interpretations, fatigue can be broadly understood as a sensation of weariness coupled with decreased muscle functionality and performance Green (1997).

Fatigue can be categorized into two primary types: **Peripheral Fatigue** and **Central Fatigue**.

Peripheral Fatigue arises when disruptions occur within the motor unit, such as the motor neuron or the muscle fibers it controls Valli (2024). This form of fatigue results in a decrease in muscle strength and power due to disruptions in muscle contraction processes. Accumulation of metabolic byproducts such as inorganic phosphate (Pi), adenosine diphosphate, and hydrogen ions contribute to this fatigue Keyser (2010). Additionally, depleted glycogen stores, especially within muscle fibers, can reduce calcium release from the sarcoplasmic reticulum, further worsening fatigue Hultman (1986).

Example of Peripheral Fatigue: In endurance cycling, particularly during uphill stages, cyclists may experience peripheral fatigue. As they push against resistance for prolonged periods, their leg muscles may begin to feel weak or heavy due to the buildup of metabolites and reduced energy stores in the muscles. This leads to a gradual decline in their ability to produce the necessary force to maintain speed or power.

Central Fatigue

Central fatigue refers to the central nervous system's (CNS) diminished capacity to sustain effective muscle activation during prolonged physical activity. This condition is marked by a reduction in the neural signals transmitted from the brain to the muscles, resulting in lower voluntary muscle activation and decreased force production during exercise (Tornero-Aguilera, 2022). Unlike peripheral fatigue, which originates in the muscles themselves, central fatigue has both physiological and psychological components. Physiologically, it involves the weakening of neural drive from the brain to the muscles, impairing the body’s ability to continue functioning at a high level. Psychologically, factors such as motivation, stress, mental fatigue, and focus also significantly impact the onset and progression of central fatigue (Leavitt, 2010). Central fatigue is particularly prominent in prolonged or mentally exhausting tasks, where both physical exertion and cognitive effort are required over extended periods. The interplay of these physiological and psychological elements makes central fatigue a multifaceted challenge, especially in endurance sports or activities demanding sustained concentration and effort.

Example of Central Fatigue: Central fatigue is often seen in activities that require prolonged concentration and coordination, such as playing chess for several hours or completing a long, technical rock climb. For example, a rock climber on a multi-pitch climb may feel mentally fatigued after hours of focusing on each movement, making decisions, and battling fear, even though their muscles are still capable of physical exertion. The mental strain of sustained focus can reduce the ability to continue efficiently. In both cases, peripheral and central fatigue affect overall performance, with peripheral fatigue manifesting as a direct loss of muscle power, while central fatigue results from the interplay of physical and mental exhaustion.

Interaction Between Fitness and Fatigue

According to the fitness-fatigue paradigm, an athlete’s performance at any given time is the result of the interaction between fitness and fatigue:

Performance = Fitness - Fatigue

During a training cycle, both fitness and fatigue levels increase. While fatigue can temporarily obscure the gains in fitness, these gains become evident once fatigue dissipates through rest and recovery. This model underscores the importance of balancing training loads and recovery periods to optimize performance.

Supercompensation

Supercompensation refers to the body's natural adaptation process in response to intense physical stress. When a muscle is overloaded, some fibers are damaged, causing temporary fatigue and a drop in strength. Over the next 36 to 72 hours, the muscle repairs itself and returns to its initial performance level. Following this recovery, the muscle actually becomes stronger than before, preparing to handle future loads more effectively. This is the core of the supercompensation phenomenon (Folbrot, 1941; Selye, 1946), Yakovlev (1949) identified four stages in this supercompensation cycle. In the first stage, lasting 1 to 2 hours after training, the body experiences fatigue. The second stage, which takes 24 to 48 hours, is the recovery phase where the body restores its energy and strength. During the third stage, which occurs 36 to 72 hours post-training, performance improves beyond the baseline—a phase referred to as supercompensation. If no further training is applied, the fourth stage, lasting 3 to 7 days, sets in. This is called involution, where the benefits of supercompensation begin to fade due to the lack of new stimuli (Yakovlev, 1949). To maximize the benefits of supercompensation, it’s essential to properly time training and recovery. If another training load is applied at the peak of the supercompensation phase, further adaptation occurs. However, if no load is applied during this period, performance will gradually return to baseline (Zatsiorsky, 1995; Olbrecht, 2000).

Phases of Supercompensation Yakovlev (1949)

1. **Exertion Phase**:
   - **Description**: Right after training, the body experiences fatigue and a decrease in performance due to depleted energy reserves and muscle damage.
   - **Example**: After a rigorous strength training session, muscle glycogen stores are significantly reduced, and muscles may experience soreness and reduced strength.
2. **Recovery Phase**:
   - **Description**: The body starts to recover, repairing muscle damage and replenishing energy stores. Performance begins to return to baseline levels.
   - **Example**: Within 24-48 hours after training, glycogen stores are replenished, inflammation is reduced, and muscles start to recover.
3. **Supercompensation Phase**:
   - **Description**: The body's physical capacities exceed the initial baseline level, resulting in improved performance. This phase represents the optimal time to introduce further training stimuli.
   - **Example**: Post-recovery, muscle glycogen levels not only return to normal but are elevated, allowing enhanced performance in subsequent training sessions.
4. **Degradation Phase**:
   - **Description**: If no additional training occurs, physical capacities return to baseline or below, resulting in a loss of the gains achieved during supercompensation.
   - **Example**: Inadequate follow-up training after reaching the supercompensation phase leads to a decline in performance and loss of improvements.

Types of Supercompensation

1. **Energy Supercompensation**:
   - **Description**: Involves replenishing and exceeding baseline levels of energy reserves, such as glycogen and ATP, in muscles.
   - **Example**: After intensive training, muscle glycogen levels are replenished and increased above pre-training levels with proper recovery and nutrition.

2. **Structural Supercompensation**:
   - **Description**: Involves structural adaptations such as muscle hypertrophy and strengthening of connective tissues.
   - **Example**: Strength training causes micro-tears in muscles, which repair and grow stronger during recovery, leading to muscle hypertrophy.
3. **Functional Supercompensation**:
   - **Description**: Includes improvements in physiological functions such as cardiovascular endurance, muscle strength, coordination, and reaction speed.
   - **Example**: After a period of high-intensity interval training (HIIT), improvements in cardiovascular efficiency and metabolic rate enhance overall performance.

Types of Supercompensation Based on Performance Outcomes (Fig.3.).

1. **Positive Supercompensation**:
   - **Description**: After adequate recovery, an athlete's physical abilities surpass pre-training levels, indicating effective training and adaptation.
   - **Example**: An athlete who consistently trains and recovers properly shows improved performance in subsequent sessions or competitions.
2. **Zero Supercompensation**:
   - **Description**: Post-recovery, the athlete's performance returns to baseline, suggesting that the training did not produce significant gains or losses.
   - **Example**: An athlete who experiences no performance improvement may have insufficient training stimuli or inadequate recovery.
3. **Negative Supercompensation**:
   - **Description**: After recovery, the athlete's performance is lower than before training, indicating overtraining or insufficient recovery, leading to decreased performance.
   - **Example**: Excessive training without proper rest results in decreased performance and higher risk of injury.

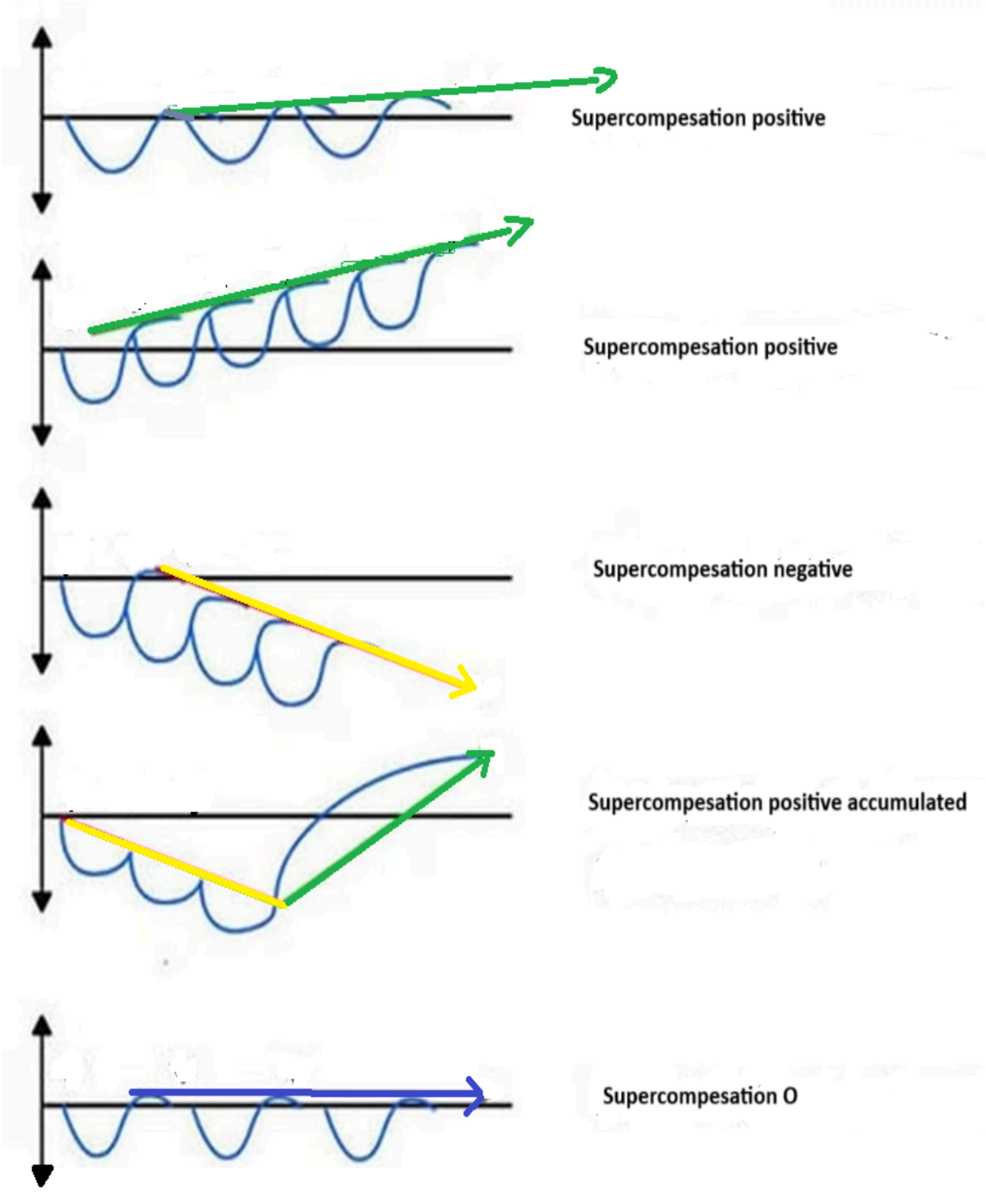


Fig.3 Types of super compensation according to the Zatsiorsky, V. M., & Kraemer, W. J. (2006).

Accumulated Supercompensation

Accumulated Supercompensation involves long-term adaptations to repeated training stimuli. It reflects the cumulative effects of multiple supercompensation cycles and leads to sustained improvements in physical performance.

Process of Accumulated Supercompensation

1. **Series of Training Stimuli**:
   - Repeated, well-planned training sessions create successive cycles of fatigue and recovery.
   - Each supercompensation cycle builds upon previous adaptations, leading to cumulative improvements.
2. **Cumulative Adaptations**:
   - Successive cycles of supercompensation result in gradual structural, functional, and energetic adaptations.
   - Example: Continuous strength training results in progressive muscle hypertrophy and increased strength over time.
3. **Long-Term Performance Improvement**:
   - Properly managed training and recovery lead to long-term performance enhancements.
   - Example: A long-term training regimen for endurance athletes leads to improvements in aerobic capacity and overall endurance.

Recovery Times for Specific Types of Effort Olbrecht et. al 2000

Recovery is an essential component of athletic performance, allowing the body to restore its energy reserves, repair muscle tissues, and prepare for subsequent training or competition. Effective recovery ensures that athletes can perform at optimal levels and avoid the risk of overtraining, injury, or performance stagnation. Different types of physical effort place varying demands on the body’s energy systems and musculature, which, in turn, dictate the length of time required for complete recovery. In this context, it is important to understand the specific recovery times associated with anaerobic, aerobic, and mixed types of physical effort. The following sections provide an in-depth examination of the recovery needs for each of these effort types, based on the foundational work by Olbrecht et al. (2000) Fig.4.

1. Anaerobic Effort (e.g., Strength Training, Sprints)

Anaerobic exercise is characterized by short bursts of high-intensity effort that primarily rely on the anaerobic energy systems, such as the ATP-PC (adenosine triphosphate-phosphocreatine) and glycolytic systems. Activities like sprinting, weightlifting, and maximal strength training fall under this category. These efforts lead to a high degree of muscle fiber recruitment, resulting in significant muscle damage (microtears) and depletion of stored energy reserves, particularly phosphocreatine.

Recovery Time: 48-72 hours

Reason: Anaerobic effort causes substantial mechanical stress on muscles, resulting in microtears that require time to repair. Additionally, anaerobic activities rapidly deplete energy stores, including phosphocreatine and muscle glycogen, both of which require adequate recovery time to be replenished. During the recovery process, muscle protein synthesis increases to repair damaged fibers, and energy stores are restored. This process typically takes between 48 to 72 hours, depending on the intensity and duration of the anaerobic effort. Furthermore, the severity of muscle soreness, commonly referred to as delayed onset muscle soreness (DOMS), often peaks within 24-48 hours post-exercise, further emphasizing the need for sufficient recovery in anaerobic activities.

2. Aerobic Effort (e.g., Long-Distance Running, Cycling)

Aerobic exercise involves prolonged, moderate-intensity activity that primarily relies on the aerobic energy system to produce ATP through the oxidative metabolism of carbohydrates and fats. Activities like long-distance running, cycling, and swimming fall into this category, where endurance and cardiovascular efficiency are the main determinants of performance.

Recovery Time: 24-48 hours

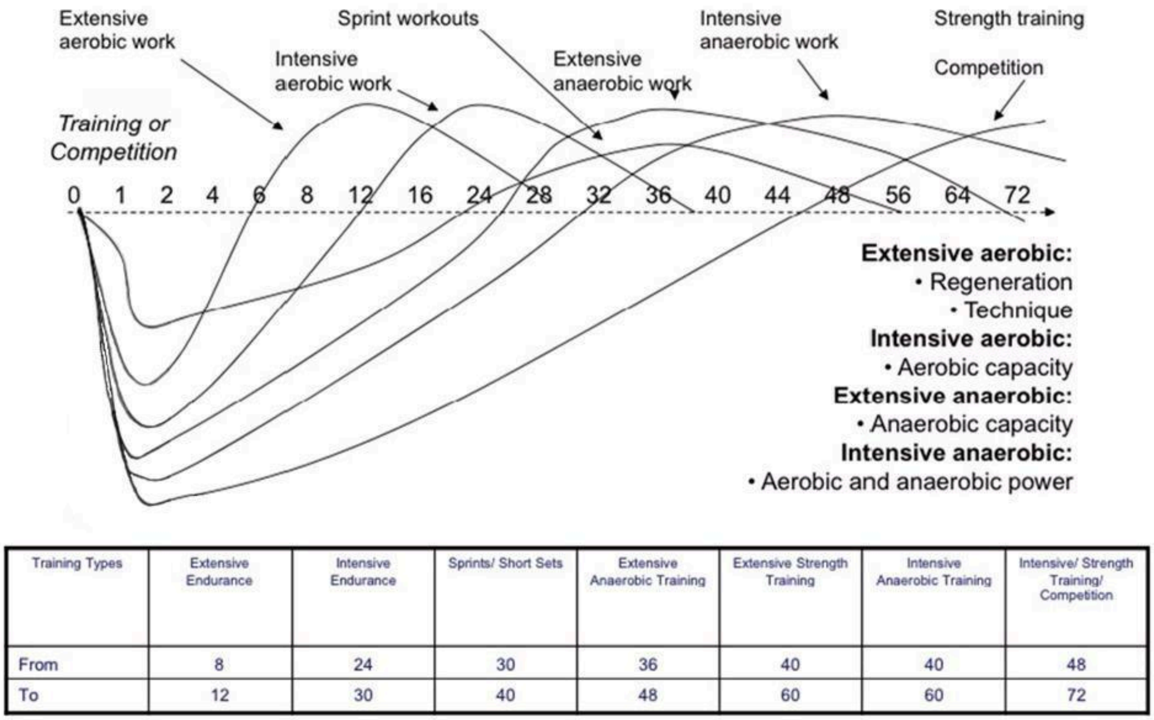
Reason: Although aerobic efforts can lead to muscle fatigue, they cause less mechanical damage to muscle fibers compared to anaerobic efforts. The primary issue during aerobic exercise is the depletion of muscle glycogen stores, which are essential for sustained energy production. Recovery from aerobic exercise primarily focuses on the replenishment of these glycogen stores, which can take 24-48 hours, depending on the duration and intensity of the activity. Additionally, aerobic training does not result in the same degree of muscle damage as anaerobic efforts, meaning the recovery process is quicker. However, if aerobic training sessions are particularly long or involve high-intensity intervals, the recovery time may extend beyond the 48-hour mark to allow for full restoration of energy reserves and optimal muscle function.

3. Mixed Effort (e.g., Interval Training, High-Intensity Interval Training)

Mixed effort activities combine both aerobic and anaerobic systems, as seen in interval training or high-intensity interval training (HIIT). These workouts typically involve alternating periods of high-intensity anaerobic effort, followed by lower-intensity aerobic recovery phases. Due to the combination of energy systems and the varying intensity of effort, mixed efforts place a significant strain on both muscle tissues and energy reserves.

Recovery Time: 48-72 hours

Reason: Mixed effort training is particularly demanding because it requires the body to simultaneously recover from both the high-intensity anaerobic bursts and the prolonged aerobic phases. The anaerobic phases result in muscle microtears and energy depletion, similar to traditional anaerobic exercises, while the aerobic phases deplete glycogen stores, increasing the need for recovery. Given the dual demands on the body's energy and muscular systems, recovery time for mixed efforts is typically in the 48-72 hour range. During this recovery period, the body works to repair muscle damage, replenish energy stores, and restore normal physiological function. The balance between anaerobic and aerobic recovery depends on the specific nature of the training session and the athlete's conditioning level.



Training Types	Extensive Endurance	Intensive Endurance	Sprints/ Short Sets	Extensive Anaerobic Training	Extensive Strength Training	Intensive Anaerobic Training	Intensive/ Strength Training/ Competition
From	8	24	30	36	40	40	48
To	12	30	40	48	60	60	72

Fig. 4. Recovery times for specific types of effort Olbrecht 2000.

Loading in Sport: Types and Applications

In sports science, the concept of "loading" refers to the systematic application of physical stress during training to induce specific physiological adaptations, improve performance, and manage recovery. The management of training loads is central to periodization, the process of organizing training into phases to optimize athletic performance over time. Proper load management ensures that athletes experience adequate stress to elicit adaptations while avoiding the risks of overtraining or undertraining. "The manipulation of training loads is a fluid construct that is modifiable based on the athlete's response to the training load" Haff (2025). This makes the understanding of different loading methods crucial for coaches and athletes alike.

Training loads are typically classified into several categories, each serving a different purpose in an athlete’s overall program: stimulating, retaining, and detraining loads. More advanced strategies include linear loading, standard loading, and other progressive or non-linear methods.

Each of these approaches plays a specific role in facilitating an athlete's growth, maintaining their performance, or allowing for recovery.

Types of Training Loads according to Zatiorsky et al (2021)

1. **Stimulating Load:** Stimulating loads are designed to push the athlete beyond their current levels of preparedness, triggering positive adaptations in strength, endurance, and other performance markers. "A stimulating load provides overload and results in positive adaptations that elevate preparedness" .This type of load is typically applied during preparatory phases of training when the goal is to improve an athlete's capacity. As athletes improve, stimulating loads must be increased to continue eliciting adaptations.
2. **Retaining Load:** Retaining loads are used to maintain an athlete's current level of preparedness without overburdening them. These loads are commonly applied during competition periods or when recovery is a priority. "A retaining load maintains the athlete's current level of preparedness but does not provide enough overload to stimulate positive adaptations". This method is essential when an athlete must perform consistently over a season but does not need to increase their physical fitness significantly.
3. **Detraining Load:** Detraining refers to a reduction in training intensity and volume, which leads to a decrease in fitness levels. Athletes may be exposed to detraining loads during off-season periods or when rest and recovery are the priority. However, too much detraining can lead to significant performance losses. "If the training load is reduced too much, the athlete will be exposed to what is often referred to as a detraining load and will experience a reduction in overall preparedness and performance capacity".

Loading Models:

Linear Loading

Linear loading follows a progressive increase in training load over time, ensuring consistent and gradual improvements in performance Tab. 1. This method is effective for beginners or athletes who need to focus on steady, uninterrupted gains. "Linear loading is typically accomplished through the use of progressive loading strategies, which allow the athlete to be exposed to increasing training loads that align with their current capacities" Haff (2025). The model works well in early phases of training but can lead to plateaus as athletes become more advanced.

Although linear loading is beneficial for short-term gains, evidence suggests that this method may not optimize long-term performance development. "It has been suggested that individual performance cannot be developed in a 'linear manner' Matveyev (1977) and that changes between one training period and the next are not linear but saltatory in nature" Nádori (1989). As a result, other loading strategies may be more effective for athletes who need continuous performance improvements over extended periods.

Standard Loading

Standard loading employs similar training loads consistently over time Tab. 2. This model is useful for maintaining fitness but may not be as effective for driving performance gains Haff et al., (2025). "Standard loading involves applying similar training loads across several mesocycles, which allows the athlete to maintain fitness levels without pushing the body toward new adaptations". It can be a good strategy during competition periods when maintaining performance is more important than improving it.

However, standard loading can lead to a performance plateau if used over too long a period. "If standard loading is undertaken for too long during the competitive period, it is very likely that there will be an involution of performance capacity that occurs in the later stages" .Therefore, it is crucial to monitor the athlete’s response to this type of loading and make adjustments as needed.

Step Loading

Step loading alternates between periods of high-intensity training and recovery, allowing for progressive overload while minimizing the risk of overtraining Tab. 3. "In step loading, the training load increases over several microcycles, followed by a reduced load to manage fatigue" Haff et al., (2025). This strategy allows athletes to accumulate the necessary stress for adaptation while providing sufficient time for recovery.

A typical step loading structure involves increasing the load over three weeks, followed by one recovery week, creating a 3:1 ratio. "This method helps balance the need for progressive overload with the management of fatigue, ensuring long-term performance gains without excessive risk". Step loading is especially useful for more advanced athletes who require more variation in their training to stimulate continuous improvements.

Week	**Training Load %**
1	70
2	75
3	80
4	85
5	90

Tab.1. Linear Loading Pattern

Week	**Training Load %**
1	80
2	80
3	80
4	80

Tab. 2. Standard Loading Pattern

Week	Training Load %
1	85
2	90
3	95
4	70 (Recovery)

Tab. 3. Step Loading Pattern

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General Training Variables

Frequency

Training Frequency refers to the number of training sessions or the number of times a specific muscle group or physical activity is performed within a set period, typically a week. It is a key variable in many forms of physical training, including resistance training, endurance sports, and skill-based disciplines (Schoenfeld et al., 2016c). When training volume is kept constant, research suggests that frequency does not significantly affect outcomes such as muscle hypertrophy. However, when volume is not controlled, higher training frequencies tend to favor better results, potentially due to the ability to maintain intensity while optimizing recovery between sessions (Schoenfeld et al., 2019a).

In resistance training specifically, higher frequencies, when paired with appropriate volume and intensity, can enhance muscle growth by distributing workload more evenly throughout the week. Nonetheless, excessive frequency combined with high intensity may lead to overtraining and performance declines, highlighting the importance of incorporating recovery periods or tapering phases (Fry et al., 1994). This applies to other forms of training, such as endurance sports, where frequency impacts performance and adaptation. Individual responses to frequency can vary significantly, meaning that personalizing training frequency is essential to optimize adaptation and performance for each individual (Haff & Nimphius, 2012). Moreover, frequency may influence the overall training volume, a variable that shows a dose-response relationship with adaptation and hypertrophy (Schoenfeld et al., 2017a).

Intensity in Sports and Climbing

Intensity in sports refers to the qualitative measure of effort exerted by an athlete and plays a significant role in physiological adaptations and performance outcomes. It can be defined in various ways depending on the discipline, type of exercise, and the tools used to measure it. Intensity is a crucial factor influencing muscle hypertrophy, endurance, and strength development (Fry, 2004). Komi (43, 44) defines intensity in terms of power output (i.e., energy expenditure per unit of time), opposing force, or speed of movement. According to this definition, the more work an athlete performs in a given period, the higher the intensity. Intensity is also a function of neuromuscular activation, with higher intensities requiring greater neuromuscular involvement.

Types of Intensity

Intensity in training can be classified in various ways, including:

- Power or workload output Komi (2003), where the more work an athlete performs over a given time, the higher the intensity.
- Energy system involvement, which considers the primary energy system used during physical exertion.

Intensity Zones Based on Energy Systems Bompa & Haff (2009)

Intensity can be divided into four main zones depending on the duration of the effort and the dominant energy system providing energy. These zones are important in both endurance training and strength-based disciplines, such as climbing:

1. **Zone 1** – Maximal Intensity:
    - Duration: Less than 6 seconds.
    - Energy system: Exclusively anaerobic, dominated by the phosphagen system (ATP-PC).
    - Characteristics: Activities like shot put, very short sprints, or typical plays in American football. These efforts are brief but demand maximum power output. The intensity of work in this zone is substantially higher than the athlete's VO2 max, relying primarily on stored ATP and phosphocreatine (PCr) (79). After these

efforts, excess post-exercise oxygen consumption (EPOC) is required to replenish energy stores.

2. **Zone 2** – High Intensity:
    - Duration: 6-30 seconds.
    - Energy system: A combination of the phosphagen system (ATP-PC) and fast glycolysis (anaerobic).
    - Characteristics: Efforts such as 100m or 200m sprints. Energy must be supplied quickly, and intensity remains high, but slightly lower than Zone 1. The rate of energy supply is rapid, but the reliance on anaerobic metabolism creates a significant oxygen deficit (79).
3. **Zone 3** – Moderate Intensity:
    - Duration: 30 seconds to 2 minutes.
    - Energy system: Predominantly fast glycolysis, with increasing reliance on slow glycolysis and aerobic metabolism.
    - Characteristics: Efforts like 400m or 800m runs, or short track cycling events. High-intensity exercise endurance (HIEE) is critical in this zone, with significant lactic acid production. Performance is limited by decreasing ATP, PCr, and glycogen stores, along with the accumulation of lactic acid .
4. **Zone 4** – Low Intensity:
    - Duration: More than 2 minutes.
    - Energy system: Mixed, with increasing reliance on aerobic metabolism. As the duration increases, the oxidative system becomes the primary energy provider.
    - Characteristics: Long-distance activities like marathons or triathlons. The effort is less intense but sustained over a long period, requiring a strong aerobic system and efficient energy management, including glycogen and fat stores. Pacing strategies are often crucial for maintaining performance over long durations.

Measuring Intensity in Resistance Training

In resistance training, intensity is commonly measured as a percentage of a person's one-repetition maximum (1RM) for a specific exercise. For example, if an athlete's 1RM for a lift is 100 kg, lifting 80 kg means working at 80% intensity. Another way to measure intensity is through the Rate of Perceived Exertion (RPE) scale, which subjectively assesses effort (Schoenfeld, 2010).

Resistance training programs aimed at optimizing muscle hypertrophy typically use moderate to high loads (around 70-85% of 1RM), which recruit high-threshold motor units necessary for muscle adaptation (Schoenfeld, 2010). Research also shows that even lower loads (below 60% 1RM) can induce similar hypertrophic effects when training is performed to failure, though high-load training often results in slightly better hypertrophic outcomes (Schoenfeld et al., 2016a).

Measuring Intensity in Climbing

In climbing, traditional methods of measuring intensity, such as heart rate or weight lifted, are less applicable due to the complexity of the sport. Instead, the intensity of a climb is often expressed as a percentage of the climber's maximum difficulty—defined as the hardest route or boulder problem the climber can complete in a specific style (e.g., on-sight, redpoint). However, quantifying intensity in climbing is inherently more complex because it depends on several additional factors beyond just the difficulty grade (Schoenfeld et al., 2016c).

These factors include:

- The style of climbing (e.g., lead, top-rope, bouldering),
- The length of the route, as longer routes may require greater endurance,
- The overhang or angle of the route, which affects the level of exertion,
- The number of cruxes (difficult sections) on the route,
- The homogeneity of effort, meaning whether the difficulty is evenly distributed or concentrated in specific areas.

These variables make it difficult to assign a precise numerical value to climbing intensity, as the physical and technical demands vary significantly depending on the route. Therefore, while intensity in climbing can be roughly estimated as a percentage of the climber's maximum difficulty, the true intensity is context-dependent and influenced by the unique characteristics of each route. Additionally, psychological strain can play a significant role, as mentally demanding climbs may feel more intense even with lower physical strain.

Volume

Training Volume and Measurement

Training volume represents the total amount of work or activity performed during a training session or phase. It plays a crucial role in athletic programs as it directly influences technical, tactical, and physical development. The way training volume is measured varies depending on the sport, but it generally involves tracking the workload an athlete undertakes (Komi, 2003).

Components of Training Volume

1. Training duration or time: This refers to the total length of time spent in a training session or phase. It is a common method for measuring volume across many sports, especially when assessing overall workload within a session or training block.
2. Distance covered: Particularly relevant in endurance sports like running, swimming, cycling, and rowing, total distance is often used as a primary indicator of volume (26, 61). For instance, a long-distance runner may aim to cover a specific distance over the course of a week to progressively increase their volume.
3. Volume load in strength training: In resistance training, volume is measured as the product of sets, repetitions, and the resistance used (volume load = sets × repetitions × weight in kilograms). This method is more accurate than simply counting repetitions, as it considers the intensity of the load as well as the quantity of work performed (65, 69, 72, 79).
4. Repetitions: In activities that involve technical skills or plyometrics, such as throwing in baseball or track and field, repetitions are counted to assess the training volume (50, 51,

49). This method is useful for tracking specific movements or skills that are being practiced.

In its simplest form, training volume is defined as the total amount of work performed during a workout or over a specific period. Tracking and measuring volume is essential to ensure that athletes are progressing as expected and to prevent overtraining or undertraining (Bompa & Haff, 2009). In endurance sports, volume is typically measured by the total distance covered, whereas in strength training, the volume load (measured in kilograms) provides a more precise indicator of the work completed (10, 52).

Methods to Measure Training Volume

1. Relative volume: This refers to the overall amount of training time or work completed by a group of athletes, such as a team. While useful for tracking collective workload, it does not offer detailed insights into the individual workload of each athlete.
2. Absolute volume: This method quantifies the amount of work or effort an individual athlete performs within a given time, providing a more personalized and accurate measure of volume. Absolute volume is particularly useful when designing individualized training programs based on an athlete's capacity and recovery ability.

As athletes progress in their careers, their capacity to manage and adapt to higher training volumes increases (62, 82, 83). For instance, experienced athletes can handle more demanding training loads because they recover more quickly between sessions (65). Elite athletes, such as competitive swimmers or marathon runners, may perform multiple sessions per day, reaching 6-12 sessions per week (35, 37, 82). Their ability to recover efficiently allows them to tolerate larger volumes of work (65).

Strategies to Increase Training Volume

1. Increasing training frequency: This involves adding more training sessions to the schedule, allowing for a gradual increase in overall volume.

2. Increasing the volume within each session: Extending the duration of the session, adding more sets or repetitions, or increasing the weight used can all contribute to higher training volume within a single session.
3. Combining both approaches: This strategy involves increasing both the frequency of sessions and the volume within each session, progressively raising the overall workload.

Measuring Volume in Climbing Using Hand Movements

In climbing, traditional methods like distance or volume load are less applicable due to the unique nature of the sport. Instead, volume can be effectively measured using the number of hand movements made during climbs. Here’s how this can be done:

1. Number of hand movements per route: Count the total number of hand movements or hand holds used to complete a route. For example, a route may require 30 hand movements.
2. Total number of routes climbed: Keep track of the total number of routes completed in a session. For instance, if the climber completes 5 routes, this forms the basic volume for that session.
3. Calculating total hand movements: Multiply the number of hand movements per route by the total number of routes completed. For example, if each route has 30 hand movements and the climber completes 5 routes, the total hand movements equal $30 \times 5 = 150$.

Training Load

Definition: A measure that combines intensity and volume to represent the overall stress or demand placed on the athlete during training.

How to Measure: Training load can be calculated using various methods depending on the sport and available data. Two common methods are the Rate of Perceived Exertion (RPE) and Training Impulse (TRIMPS).

Rate of Perceived Exertion (RPE)

Rating of Perceived Exertion Foster (2001) is a subjective scale that allows athletes to monitor the physiological stress their bodies experience during exercise based on their personal perceptions of effort. Athletes can adjust their training intensity by gauging how hard they feel they are working. RPE has been shown to correlate well with physiological measures such as heart rate during steady-state exercise and high-intensity interval cycling. However, research has found weaker correlations between RPE and heart rate during short-duration, high-intensity activities like soccer drills and step dance sessions. A meta-analysis concluded that while the Borg (1985) 6–20 RPE scale is a valid measure of exercise intensity, the validity coefficients between RPE and physiological criteria (such as heart rate, blood lactate, and VO2 max) are moderate. Further research is needed to better understand the physiological mechanisms behind the cognitive perception of effort, which may clarify what RPE truly represents.

Example: If an athlete rates a climbing session as an RPE of 7 and the session lasts 60 minutes, the training load is 7 × 60 = 420.

Training Impulse (TRIMP) is a method used to quantify the overall physical effort or "dose" of a training session based on the athlete’s heart rate response to exercise and the duration of the session. Developed by Banister et al. (1991), TRIMP calculates how much the exercise raises the athlete's heart rate relative to resting and maximal heart rate levels. This method is represented mathematically, incorporating factors like the duration of the session and heart rate data, to provide a single measure of training load.

TRIMP is designed to emphasize high-intensity exercise by applying a weighting factor based on lactate profiles, which ensures that short, intense activities are not undervalued compared to longer, lower-intensity sessions. The equation considers variables such as resting heart rate, maximal heart rate, and the average heart rate during the session.

Despite its practicality for quantifying endurance activities, TRIMP has limitations, particularly with exercises that do not rely on aerobic energy systems, such as resistance training. In such cases, heart rate does not reliably reflect exercise intensity, so alternative methods, like using RPE (Rating of Perceived Exertion), have been developed to complement TRIMP for non-aerobic exercise modes.

Applying Training Load to Non-Measurable Sports (e.g., Sport Climbing)

For sports where direct measurements like distance or weight are not applicable, subjective and objective measures are crucial.

1. **RPE-Based Approach:** Athletes can rate the difficulty of each climbing session using the RPE scale. This subjective measure can be multiplied by the duration to estimate the training load.

Example: A climbing session with an RPE of 8 lasting 90 minutes results in a training load of 8 × 90 = 720.

2. **Session-RPE Method:** Similar to the RPE-based approach, but applied to the entire session rather than individual activities within it.

Example: After a climbing workout, an athlete rates the entire session as RPE 7. If the session lasted 2 hours, the training load is 7 × 120 = 840.

Monitoring Training Load: The Role of Monotony and Strain

Monotony and **strain** are two key indices used to monitor training load (TL) and manage the risk of overtraining. These indices are calculated from session-RPE data collected during a training microcycle and are especially useful in evaluating day-to-day training variability.

- **Monotony** measures the consistency or variability in training load across a week. It is calculated using the formula:

Monotony = Weekly mean TL / SD,

where the weekly mean TL is the average daily training load during the week, and SD is the standard deviation of the daily training loads. High monotony indicates low variability in training load, which, when combined with high TL, can increase the risk of overtraining and related issues (Foster, 1998).

- **Strain** represents the cumulative effect of training load and monotony. It is calculated by multiplying the weekly TL by the monotony score:

Training strain = Weekly TL × Monotony.

High training strain often occurs when athletes experience high TLs with little variation (high monotony), which can lead to poor performance and increased risk of illness (Putlur et al., 2004). Low strain, on the other hand, is achieved when there is regular variation in load (low monotony), even with high or low TLs. High training strain is typically seen during the preparation phases when athletes are not engaged in regular competition. These scores are useful for optimizing periodization and ensuring recovery is prioritized when necessary.

Calculating Training Monotony and Strain in Climbing

Calculation:

1. Daily Training Load: Calculate the training load for each day. This can be done using a combination of volume (e.g., hand movements, distance climbed) and intensity (e.g., route difficulty).

- Example: Use RPE (Rate of Perceived Exertion) × Volume for each day.

2. Average Daily Training Load: Calculate the average training load over a week.

$$Average\ Daily\ Load\ = \frac{\sum Daily\ Loads}{Number\ of\ Days}$$

3. Standard Deviation of Daily Loads: Calculate the standard deviation of the daily training loads over the same period.

$$Standard\ Deviation\ = \sqrt{\frac{\sum(Daily\ Load - Average\ Daily\ Load)^2}{Number\ of\ Days}}$$

4. Training Monotony: Divide the average daily training load by the standard deviation of the daily loads.

$$Training\ Monotony\ = \frac{Average\ Daily\ Load}{Standard\ Deviation}$$

Example Calculation:

- Daily Loads:

$$[300, 320, 280, 310, 290, 330, 300]$$

- Average Daily Load:

$$\frac{300+320+280+310+290+330+300}{7} = 304$$

- Standard Deviation:

$$\sqrt{\frac{(300-304)^2+(320-304)^2+(280-304)^2+(310-304)^2+(290-304)^2+(330-304)^2+(300-304)^2}{7}} \approx 17.08$$

- Training Monotony:

$$\frac{304}{17.08} \approx 17.8$$

Training Strain

Calculation:

1. Weekly Training Load: Sum the daily training loads for the week.

$$Weekly\ Load = \sum Daily\ Loads$$

2. Training Strain: Multiply the weekly training load by the training monotony.

$$Training\ Strain = Weekly\ Load \times Training\ Monotony$$

Example Calculation:

- $Weekly\ Load = 300 + 320 + 280 + 310 + 290 + 330 + 300 = 2130$
- $Training\ Strain = 2130 \times 17.8 \approx 37914$

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Fundamentals of Periodization

Annual Training Plan Structure

The following subsection presents a detailed structure of an annual training plan, outlining the various periods and phases that constitute the yearly cycle of athlete preparation. This breakdown is essential for understanding how athletes are systematically trained to achieve peak performance at the right times Tab. 4. The plan encompasses all critical phases, ensuring a comprehensive approach to athlete development and performance enhancement. Table 5. further elaborates on this structure by illustrating the division of the training year into macrocycles, mesocycles, microcycles, and individual training units, based on Bompa's methodology. This methodical approach is a cornerstone of sports science and is universally adopted across all sports disciplines. It provides a systematic framework that helps in optimizing training loads, preventing overtraining, and ensuring progressive adaptation and improvement. Macrocycles represent the largest timeframe within the annual plan, typically spanning several months to a year. They encompass multiple mesocycles, each designed to achieve specific training objectives. Mesocycles usually last several weeks to a few months and are tailored to focus on different training aspects such as endurance, strength, or technique. Within each mesocycle, there are microcycles, which are shorter training periods usually lasting one week. Microcycles are focused on specific training components and allow for precise adjustments to training intensity and volume. Each microcycle is made up of individual training units or sessions, which are the building blocks of the overall training plan. These sessions are carefully planned to target various aspects of athletic performance, such as cardiovascular fitness, muscular strength, technical skills, and recovery. The principles laid out in these tables are designed to create a balanced and effective training regimen that aligns with the natural physiological and psychological cycles of the athlete. By adhering to these guidelines, coaches and athletes can systematically build and maintain peak performance levels throughout the competitive season.

In the subsequent sections of this chapter, we will provide detailed annual training plans specifically tailored for sport climbing athletes. These plans will demonstrate how the general principles of periodization and structured training are adapted to meet the unique demands of sport climbing. This includes considerations for the sport’s specific physical and technical requirements, competition schedules, and the need for both high-intensity training and adequate recovery periods.

Annual Plan

The annual training plan is a structured approach to managing the training process, organizing and dividing the calendar year into distinct phases, each with clearly defined goals and objectives. Its primary purpose is to maximize physiological adaptations and optimize the athlete's performance capacity, allowing for peak performance at selected points during the competition season. This plan, as a fundamental component of periodization, ensures a logical and sequential progression of training loads, the control of fatigue, and the management of both physiological and psychological stress.

The most important task of the annual plan is to ensure the athlete reaches peak performance during the most important competitions of the season. To achieve this, it is crucial to manage the training process carefully, which includes gradually increasing competition readiness, minimizing fatigue, and shaping physiological adaptations to ensure the athlete is fully prepared for key moments in the season.

Preparatory Phase:

The preparatory phase in an annual training plan is a crucial period that establishes the physical, technical, and mental foundation for further athletic development. It is the longest phase, aimed at preparing the body to handle increased loads in subsequent stages. The physiological adaptations developed during this time enable the athlete to better cope with the higher intensity of training during the competition phase.

The goals of the preparatory phase include:

1. Building and enhancing general training capacity.
2. Developing the biological motor abilities necessary for the specific sport.
3. Strengthening psychological resilience.
4. Improving and refining technical skills specific to the sport.
5. Introducing athletes to basic strategic elements, which will be further developed in later phases.

This phase typically lasts between 3 to 6 months, depending on the sport, climate, and the structure of the annual training plan. In climbing, the preparatory phase usually lasts from 12 to 16 weeks.

The preparatory phase, as an essential component of the annual training plan, is divided into two distinct subphases: General Preparation and Specific Preparation. These subphases help progressively build the athlete’s physical and mental capabilities, preparing them for the demands of their sport. Each subphase targets specific aspects of training, allowing the athlete to gradually adapt to increasing workloads and more specialized exercises.

Subphases:

1. General Preparation I (GP I)
   This is the starting phase of the training program, where the primary focus is on laying the groundwork for future physical and technical progress. In this stage, athletes begin by building general fitness and improving basic physical capacities. It's a time for focusing on overall development to ensure the body is prepared for more intense work in later stages.
   - Macrocycle: Anatomical adaptation
   - Microcycle: 3 weeks
   - During this phase, the aim is to develop general strength and endurance, as well as prevent injuries through pre-habilitation. Activities include low to moderate intensity aerobic exercises, basic strength training, flexibility routines, and mastering fundamental skills to establish a solid base.
2. General Preparation II (GP II)
   In the second phase, the focus shifts from general fitness to more specific strength-building, preparing the body for higher intensity and specialized work. This stage builds on the foundation laid in the previous phase, targeting muscle growth if necessary, depending on the athlete’s requirements for their sport.
   - Macrocycle: Hypertrophy (if needed)
   - Microcycle: 4 weeks
   - This phase emphasizes increasing muscle mass and developing more robust physical capabilities. Training incorporates moderate-intensity aerobic and anaerobic conditioning, strength work focused on hypertrophy, refinement of skills, and the introduction of tactical elements relevant to the sport.

3. Specific Preparation

   As the athlete moves closer to the competition phase, the focus narrows towards sport-specific skills and maximum strength. The training becomes more specialized to match the exact demands of the athlete's sport. This phase is critical for converting the general strength and fitness built earlier into performance-specific abilities.

   - Macrocycle: Maximum strength
   - Microcycle: 4 weeks
   - The emphasis during this phase is on high-intensity strength development, focusing on the specific needs of the sport, such as climbing. Athletes work on refining their techniques, performing sport-specific drills, engaging in more tactical training, and simulating competitive conditions to ensure readiness for the upcoming events.

Competitive Phase

The **competition phase** in the annual training plan is a vital stage, where the main goal is to maintain and refine essential skills to achieve top results during the most important competitions. During this period, athletes focus on specialized training aimed at improving not only technique but also mental and tactical readiness, crucial for success in competition.

In climbing, the World Cup cycle typically begins in April, with the first part of the season focused on bouldering competitions. Later, the season transitions to lead climbing. The combination of both disciplines—bouldering and lead—takes place only during major events such as the European Championships, World Championships, and the Olympic Games. The only discipline that runs throughout the entire competitive season is speed climbing, though athletes competing in this event generally do not participate in other climbing disciplines.

The competition phase requires careful management of training intensity to ensure peak performance while avoiding fatigue. Most training during this phase is centered around sport-specific exercises, allowing athletes to prepare fully for the most critical moments of the season.

This phase is further divided into two subphases: **pre-competitive** and **competitive**

Pre-Competitive:

The pre-competitive phase is a part of the preparatory period that includes unofficial and smaller competitions, aimed at obtaining feedback on the athlete's level of readiness and preparedness for upcoming main events. This phase typically follows a macrocycle focused on converting general strength into specific sport requirements, such as power, power endurance, or muscular endurance, with a microcycle duration of about 4 weeks. The objective during this time is to prepare the athlete for the competitive season by adapting their general fitness to the specific demands of the sport.

Key activities during the pre-competitive phase include high-intensity interval training, sport-specific drills, competition simulations, tactical and strategic training, and recovery practices. Competition simulations are a critical aspect of this phase, allowing athletes to test their skills in conditions that closely resemble real competitions. These simulations help athletes refine their technique, tactics, and mental readiness while providing feedback for necessary adjustments in the training plan.

Although the results during the pre-competitive phase do not directly impact the final outcome in major competitions, this phase serves as a valuable tool for evaluating performance, making corrections, and optimizing preparation for the main events.

Competitive

The competition phase, particularly the main subphase, is designed to help athletes achieve and sustain their best performance during the most important competitions of the season. The emphasis is on maintaining maximum strength and specific conditioning for the sport throughout the competition period. The macrocycle in this phase focuses on sustaining peak strength, while the microcycle, usually lasting between 8 to 10 weeks, ensures the athlete stays in prime condition for events.

This stage combines both real competitions and competition simulations, which allow athletes to sharpen their skills in realistic settings. Training during this time is highly specialized, involving intense workouts aimed at maintaining strength, power, and technical proficiency. Importantly, although the overall training volume should be reduced, high intensity must be maintained throughout the phase to ensure peak performance.

Additionally, to preserve endurance capacity, it is more effective to use the repetition method rather than interval training. Endurance-focused interval training should be avoided during this period, as it can compromise recovery and negatively affect competition readiness.

To balance this intensity, regular recovery sessions are included to manage fatigue and prevent overtraining. Tactical and strategic components are continuously refined based on the outcomes of competitions and simulations, allowing athletes to respond effectively to the demands of upcoming events. Special methods are used to keep athletes mentally and physically prepared, ensuring they perform optimally when it matters most.

Transition

The **transition phase** is a crucial period in the annual training cycle, during which athletes, including climbers, focus on physical and mental recovery after intense competitions and demanding training cycles. The primary goal of this phase is to allow the body and mind to fully recover and restore balance following extended periods of effort. One of the most common practices among climbers during this phase is to **change their training environment** by shifting from indoor climbing gyms to **outdoor rock climbing**. Instead of focusing on high-intensity gym sessions or artificial walls, climbers take to natural rock formations, which provides both physical activity and mental relaxation. However, it is essential to remember that, during the transition phase, additional stress should be avoided. This means **not pressuring athletes to push themselves by sending hard climbing routes**. The focus should be on recovery, not on achieving high-performance outcomes. During this period, the overall training intensity is significantly reduced, and activities are more recreational in nature, allowing for recovery and preventing burnout. Athletes are encouraged to engage in less demanding physical activities that help them maintain fitness without risking overtraining or exhaustion.

Phase of training	**Preparatory**				**Competitive**		**Transition**
Subphases	General preparation I	General preparation II	Specific preparation		Pre-competitive	Competitive	Transition
Mesocycles	Anatomical adaptation	Hypertrophy if necessary	Maximum strenght	Conversation to specific (power, power endurance or muscular endurance)	Maintenance of maximum strenght and specific strenght	Cessation of strenght	Compesation training
Microcycles	3 weeks	4 weeks	4 weeks	4 weeks	4 weeks	8-10 weeks	3-4 weeks

Tab. 4. Annual Plan.

1 YEAR
MACROCYCLES
MESOCYCLES
MICROCYCLES
1TRAINING

Tab. 5. Diagram showing breakdown of training cycles Bompa (2019).

	Months	**November**				**December**				**January**				**February**					**March**				**April**			
	Weeks	7	14	21	28	4	11	18	25	2	11	18	25	2	9	16	23	30	6	13	20	27	3	10	17	24
Competition plan	National																**CS**									
	International																		WCB		WCB			WCB	WCBB	
	City																Innsbruck		Moscow		Meringen			Wujaing	Keqiao	
Periodization	Phase	Preparatory												Competitive												
	Subphase	General Preparation I and II								Specific Preparation				Pre-Competitive bouldering					Competitive							
	Strength	Hypertrophy and max strength/ power								Conversation to specific (power, power)				Maintenance of maximum strength and specific strength					Cessation of strength							
	Endurance	Strength endurance								Power endurance developing, strength endurance maintenance.									Strength & power endurance maintenance							
	Speed																									

Tab 5.1. Periodization pattern for bouldering and lead climbers based on a modified model proposed by W.H Freeman (2001).

Annual Periodization Plan for Bouldering and Lead Climbing: Preparation Phase Overview

An example of the annual periodization is presented in Tab 5.1 and 5.2. In November, the preparation phase began for an athlete competing in both bouldering and lead climbing, encompassing several key stages aimed at building a solid foundation for high performance in these disciplines. A detailed overview of this period is provided in Tab. 5.1.

Initial Preparation Phase (November Onwards)

The athlete's preparation began with an emphasis on hypertrophy, targeting muscle groups essential for optimal performance in bouldering and lead climbing. This initial phase concentrated on increasing muscle mass and strength. To address any movement deficiencies that might have developed in the previous season, prehabilitation work was integrated into the regimen. This proactive approach aimed to prevent injuries and improve overall movement efficiency.

During this phase, the athlete also incorporated a significant volume of plyometric exercises. These exercises were crucial for enhancing explosiveness, an area identified as a weakness in the athlete's previous performance. Plyometric training included exercises such as jump squats and box jumps to develop rapid force production and dynamic strength.

Second Sub-Phase (GP2): Climbing-Specific Training

As the preparation period advanced, the focus shifted to more climbing-specific training. In this second sub-phase (GP2), the athlete engaged in specialized strength training designed to develop the strength needed for bouldering. This included working on 8-move boulder problems that closely mimicked competition scenarios.

Additionally, climbing-specific hypertrophic training was introduced. This training involved circuits consisting of 12 moves per set, with each set containing 4 circuits and 90-second rest intervals between sets. Each circuit was focused on a single type of hold, such as crimps or slopers, to develop specific grip strength and endurance.

Transition to World Cup Preparation

As the preparation period progressed, the focus transitioned to tasks aimed at preparing the athlete for the World Cup in bouldering. This phase was centered on developing maximum strength and power, as well as refining climbing tactics and techniques. To gauge progress and readiness, the athlete participated in a simulated competition in February, which served as a qualifier for the World Cup circuit in bouldering.

Competitive Phase and Maintenance

In the subsequent two months, the athlete engaged in regular competitive events. The primary goals during this time were to perform well in competitions and to maintain a high level of specific fitness. To manage pre-competition fatigue and optimize performance, the athlete underwent several tapering phases. These tapering periods helped reduce fatigue but also temporarily decreased training capacity, necessitating a careful balance between competition and recovery.

	Months	**May**					**June**				**July**				**August**					**September**				**October**			
	Weeks	3	10	17	24	31	7	14	21	28	6	12	19	26	2	9	16	23	30	7	14	21	29	4	11	18	24
Competition plan	National																										
	International					ECL	ECL				WCL	WCL				EChL								WCL	WCL		
	City					Imst	Kiev			Gaflenz	Villars	Chamonix				Edenburg								Xiamen	Seul		
Periodization	Phase	Pre-Competitive Lead					Competitive										Maintence					Competitive					
	Subphase	Specific Preparation					Competitive										Maintence					Competitive					
	Strenght	Max strenght/ power					Power maintence												Max strenght	Power				Maintance			
	Endurance	Strenght endurance					Strenght edurance maintence																				

Speed

Tab 5. 2. Periodization pattern for bouldering and lead climbers based on a modified model proposed by W.H Freeman (2001).

Transition Period from Bouldering Season to Lead Season

Tab 5.2 outlines the transition period from the bouldering competition season to the lead climbing season. This crucial phase began immediately after the final event of the Bouldering World Cup series and extended until mid-May, ensuring the athlete had sufficient time to adapt and prepare for the new challenges of lead climbing.

Early Transition Phase (Post-Bouldering World Cup)

Immediately following the last Bouldering World Cup event, the athlete entered a recovery and transition period. This phase was critical for physical and mental recuperation after the intense bouldering season. The focus was on active rest, light training, and addressing any lingering injuries or imbalances. This period also involved preliminary preparation for the lead climbing season, gradually introducing lead-specific training elements.

Mid-May: First Competitive Lead Event

In mid-May, the athlete participated in a preliminary competition at the European Cup in IMST. This event was designed to test the athlete's readiness and served as a qualifying event for the Lead World Cup. The competition provided valuable feedback on the athlete's current performance level and highlighted areas needing further improvement.

Regular Lead World Cup Participation

Following the IMST event, the athlete commenced regular participation in the Lead World Cup series. These competitions occurred once or twice a month, each providing opportunities to refine techniques, improve endurance, and gain valuable competitive experience. Training during this period was tailored to maintain peak performance while allowing adequate recovery between events.

Mid-July to Early August: Focused Preparation

From mid-July to early August, the athlete took a strategic break from competitions to concentrate on intensive preparation for the European Championships in Edinburgh. This phase emphasized developing maximum strength and power, essential for the demands of lead climbing. The training regimen included specialized exercises to enhance specific climbing skills and prevent a decline in strength endurance.

The European Championships in Edinburgh were a significant milestone in the athlete's lead climbing season. The competition assessed the athlete's progress and readiness for the latter part of the season. The performance at this event provided insights into the effectiveness of the training program and areas that required further focus.

Extended Preparation for Final World Cup Events

After the European Championships, the athlete entered an extended preparation period for the final World Cup events in Xiamen, China, and Seoul. This phase allowed for a more comprehensive and focused training approach, addressing any weaknesses identified during earlier competitions. The extended timeframe provided the opportunity to peak at the right moment for these crucial events.

Transition and Recovery Phase

Following the final competitions in Xiamen and Seoul, the athlete transitioned into a recovery phase. This period included a personal trip with rock climbing activities, allowing for mental relaxation and physical recovery in a less structured environment. Subsequently, the athlete moved into a phase of reduced training intensity, focusing on active recovery and maintaining a base level of fitness.

Next Preparatory Cycle

After the recovery phase, the athlete began the next preparatory cycle, marking the start of a new annual training plan. This cycle built upon the experiences and lessons learned from the previous season, incorporating adjustments to optimize performance and address any identified deficiencies.

Conclusion

This comprehensive overview provides a logical and detailed account of the annual training plan for athletes competing in the World Cup series in sport climbing. The structured approach ensures that athletes are well-prepared for the unique demands of both bouldering andlead climbing, enabling them to achieve peak performance throughout the competitive season.

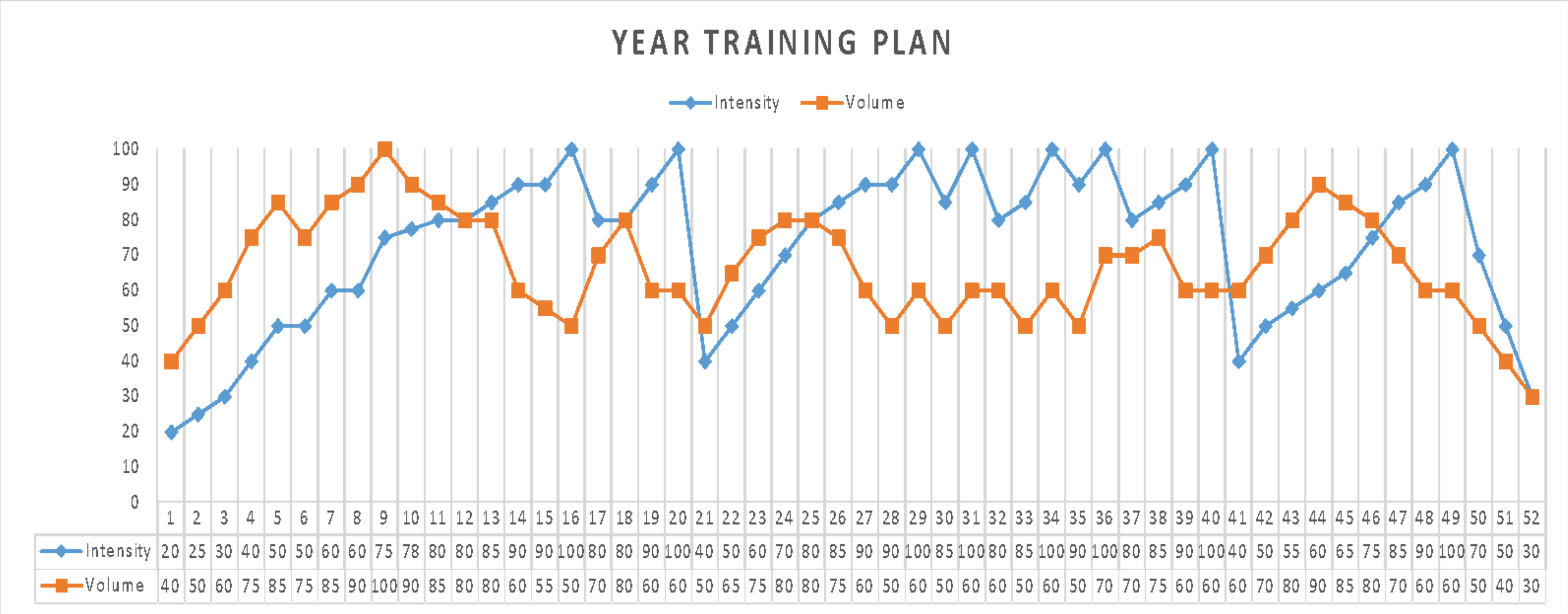

Fig 5. Annual training plan including training volume and intensity for speed climbing discipline.

Example of an Annual Training Plan for Speed Climbing Athletes

The annual breakdown of training volume and intensity for speed climbing athletes is illustrated in Fig 5. This breakdown takes into account the competition calendar and aligns with the annual training plan detailed in Tab. 6.1 and 6.2.

The first preparation period covered the dates from 1 November to 30 March (Tab.6 .1), during which time the athlete competed in the first edition of the World Cup (held on 20 March in Moscow), this competition was preceded by a qualification event held 4 weeks earlier. The first preparation period was longer than the second preparation period, the training volume was also higher. The aim of this period was to build a solid base of physical preparation and to improve climbing technique. After the first World Cup competition in Moscow the training volume and intensity was lowered during the transition period in order to regenerate the athlete mentally and physically. The amount of specialist training was also reduced. Then the training volume increased until the 24th and 25th week of the preparation period. In the 25th week the trend changed and the training volume was lowered and the intensity increased in order to relieve the athlete for the second start in a control competition of a lower rank (European Cup in Mezzolombardo Tab 6.2). Subsequently, further competitions were held in a short period of time, which made it impossible to increase the training volume, but only to maintain the high intensity. Only the break between the World Cup in Chamonix and the European Cup in Belgrade made it possible to increase the volume and lower the training intensity. After the European Cup in Belgrade, during which the intensity was high and the volume medium, there was a significant decrease in intensity and an increase in volume until the 44th training week, after which there was a linear decrease in volume and an increase in intensity. In week 48 the athlete made his last World Cup start after which the volume and intensity decreased to 30% in order to reach the transition phase and later the post-season break and rest.

Months	**November**	**December**	**January**	**February**	**March**	**April**

	Weeks	7	14	21	28	4	11	18	25	2	11	18	25	2	9	16	23	30	6	13	20	27	3	10	17	24
Competition plan	National																**CS**									
	International																				WC					
	City																Innsbruck				Moscow					
Periodization	Phase	Preparatory 1												Competitive									Transition 1		Preparatory 2	
	Subphase	General Preparation								Specific Preparation				Pre-Competitive					Competitive				Transition		General Preparation	
	Strenght	Hypertrophy and max strenght/ power								Conversation to specific (power, power)				Maintenance of maximum strenght and specific strenght					Cessation of strenght				Compesation training		Max strenght / power	
	Endurance	Power endurance								Speed edurance developing									Speed edurance maintence				Global Endurance		Power endurance	
	Speed	Max speed developing																	Max speed maintence				Compesation training		Max speed developing	

Tab 6.1. Periodization pattern for speed climbers based on a modified model proposed for sprinters by W.H Freeman (2001).

	Months	**May**					**June**				**July**				**August**					**September**				**October**			
	Weeks	3	10	17	24	31	7	14	21	28	6	12	19	26	2	9	16	23	30	7	14	21	29	4	11	18	24
Competition plan	National																										
	International				ECS		ECS			ECS	WCS	WCS				ECS								WCS			
	City				Mezolombardo		Kiev			Ibk Gaflenz	Villars	Chamonix				Belgrad								Xiamen			
Periodization	Phase	Prepatory 2		Pre-Competitive								Competitive							Maintence					Competitive			

Subphase	General Preparation	Specific Preparation	Competitive	Maintence		Competitive
Strenght	Max strenght/ power		Power maintence	Max strenght	Power	Maintance
Endurance	Power endurance		Speed edurance maintence			
Speed	Max speed developing		Max speed maintence	Max speed developing		Max speed maintence

Tab. 6.2. Periodization pattern for speed climbers based on a modified model proposed for sprinters by W.H Freeman (2001).

Framework and Function of Macrocycles, Mesocycles, and Microcycles in Athletic Training

Macrocycles:

The **monocycle macrocycle** is designed to achieve one primary peak of form within a year, but it is not limited to preparing athletes for a single major event like the Olympics or World Championships. In many sports, including **climbing**, the monocycle is used to maintain peak performance across a defined competitive season. This cycle includes a large preparatory phase, followed by a competitive phase and a transition phase. The intensity gradually increases until the athlete reaches their peak, which is then maintained through careful management of training loads. In climbing, this approach helps athletes remain in top form throughout a series of competitions, ensuring consistency across the season rather than a singular peak for one event.

The **bicycle macrocycle** aims to create two peaks of form within a year. It consists of two preparatory phases, two competitive phases, and two transition phases. The intensity is divided into two periods of intensification, with recovery breaks between them. This macrocycle is typical in sports that have both summer and winter seasons, such as running or swimming, where athletes need to be in top form twice during the year. In **climbing**, bicycle macrocycles are less common but may be used when there are distinct events in different disciplines (e.g., bouldering and lead) that require peak performance at different times of the year.

For sports requiring multiple peaks throughout the year, the **tricycle macrocycle** is designed to accommodate three peaks of form. It includes three preparatory, competitive, and transition phases. With three periods of intensification and shorter recovery breaks, this cycle is suitable for sports like tennis or combat sports, which have more frequent competitions throughout the year.

Mesocycles:

Within these macrocycles are **mesocycles**, shorter cycles that target specific training objectives. The **building mesocycle** focuses on increasing training volume and developing basic physical conditioning. Typically lasting 4 to 6 weeks, this phase involves moderate intensity with a significant focus on aerobic and strength training. It serves to establish a foundation for future athletic progress.

As athletes progress, they enter the **specialized mesocycle**, which emphasizes the development of sport-specific skills and abilities. Intensity increases to moderate or high levels, and training becomes more tailored to the athlete's discipline. For example, sprinters might spend 4 to 6 weeks working on explosiveness during this phase. The **pre-competitive mesocycle** is designed to help athletes reach their peak just before a competition. This phase involves high-intensity training that closely simulates competition conditions. Typically lasting 2 to 4 weeks, it prepares athletes to perform at their best in upcoming events.

During the competitive season, athletes follow the **competitive mesocycle**, where the goal is to maintain peak performance while balancing recovery between competitions. This phase involves high-intensity training but includes a greater focus on recovery to avoid fatigue. It usually lasts between 4 to 8 weeks, depending on the length of the competitive season. After the competitive phase, athletes move into the **transition mesocycle**, which is focused on rest and recovery. Training intensity decreases significantly, with an emphasis on active recovery and lighter activities. Lasting 2 to 4 weeks, this phase helps athletes recover fully before they begin another training cycle.

Microcycles:

Lastly, **microcycles** are short-term cycles, often lasting a week, with specific goals. The **adaptive microcycle** helps the body adjust to new training loads, with low to moderate intensity at the beginning of a new program. The **building microcycle** aims to increase both the volume and intensity of training, pushing athletes to adapt to more demanding workouts.

In contrast, the **recovery microcycle** reduces intensity to allow the body to rest and recover after a challenging mesocycle. This period of light training helps athletes recover both physically and mentally. The **competitive microcycle** prepares athletes for competition, with high-intensity training balanced by recovery periods. This phase, occurring in the week leading up to an event, ensures the athlete is fully prepared for competition.

Traing demand	Intesity	Intensity RPE	% of maximum

Very High	Maximum	9-10	90-100
High	Heavy	8-9	80-90
Moderate	Medium	7-8	70-80
Low	Low	6-7	60-70
Very Low	Very lw	5-6	50-60
None	Recovery	0	

Tab. 7. Training Demand, Intensity, and Intensity zone adapted from Haff 2024.

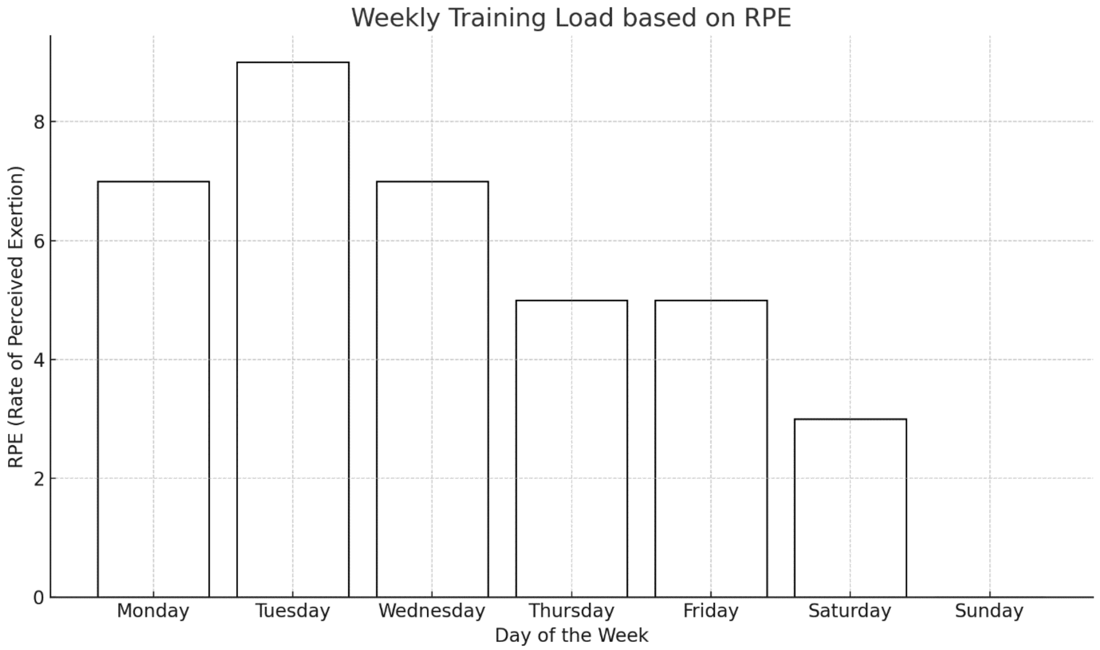

Fig 6. Example of a one-peak microcycle with high demand at the beginning of the week

The figure 6 represents a typical one-peak microcycle, where the training load starts high on Monday (RPE 7) and peaks on Tuesday (RPE 9). Monday and Wednesday involve moderate load (RPE 7), Tuesday features a very high load (RPE 9), while Thursday and

Friday have lower loads (RPE 5). Saturday is marked by a very low load (RPE 3), and Sunday serves as a recovery day with no load (RPE 0). This breakdown of training demand, intensity, and corresponding intensity zones is further detailed in Tab. 7, adapted from Haff 2024.

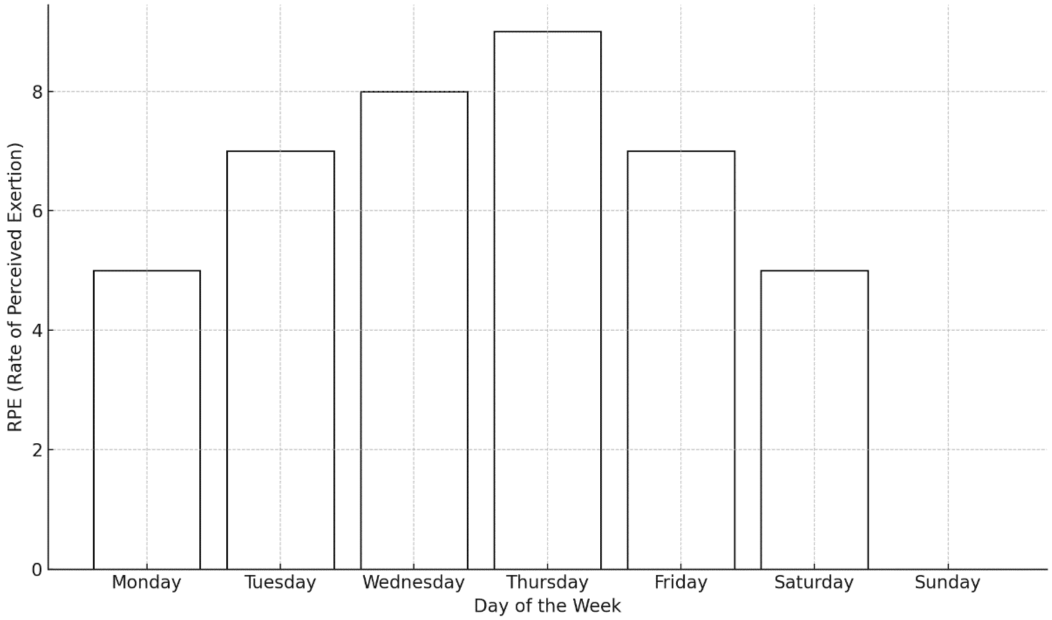

Fig.7**.** Example of a one-peak microcycle with increasing load and peak in the middle: **Monday**: RPE 5 - Moderate load, **Tuesday**: RPE 7 - High load, **Wednesday**:RPE 8 - High load, **Thursday**: RPE 9 - Very high load (peak), **Friday**: RPE 7 - High load, **Saturday**: RPE 5 - Moderate load, **Sunday**: RPE 0 - Recovery,

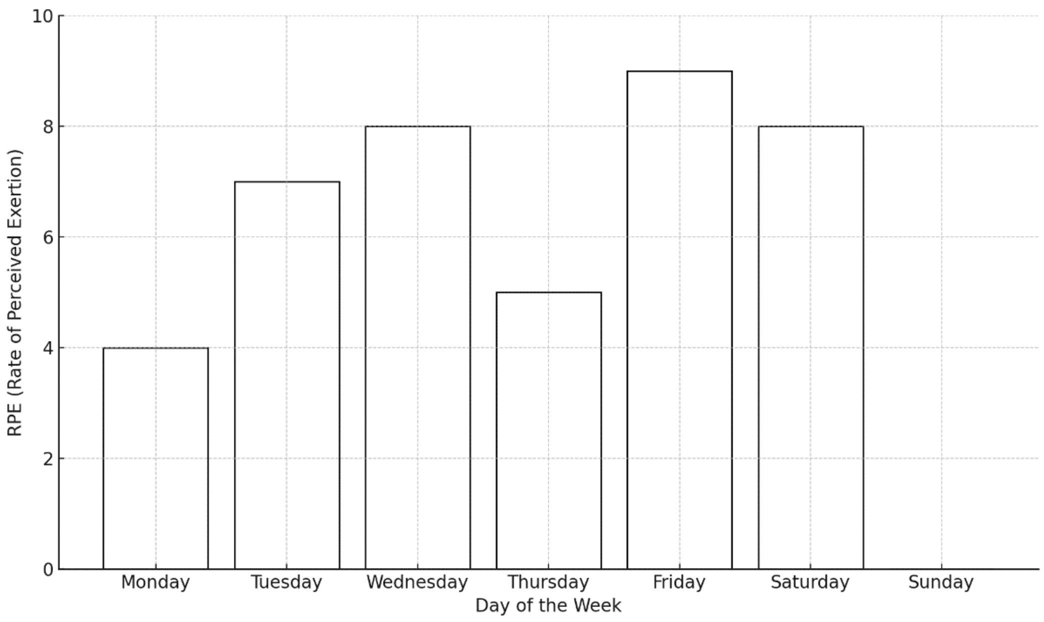

Fig. 8. Example one-peak macrocycles: **Two high-demand training days in the cycle: Monday**: RPE 4 - Low load ,**Tuesday**: RPE 7 - High load, **Wednesday**: RPE 8 - Very high load, **Thursday**: RPE 5 - Moderate load, **Friday**: RPE 9 - Very high load, **Saturday**: RPE 8 - High load, **Sunday**: RPE 0 - Recovery.

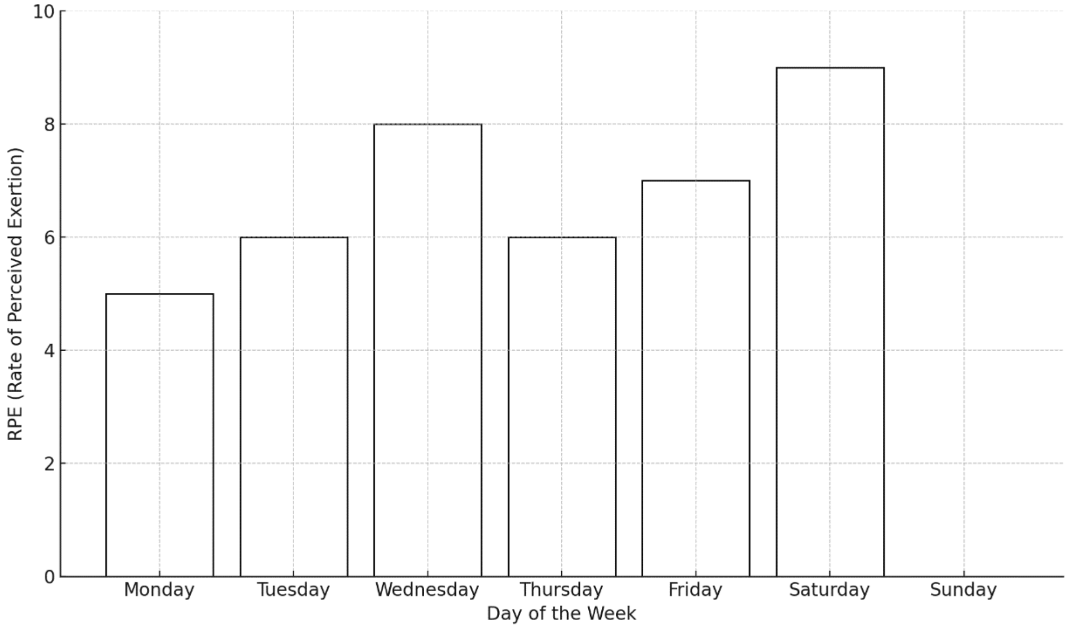

Fig. 9**.** Example one-peak macrocycles: **Macrocycle with two ascending-demand training days:Monday**: RPE 5 - Moderate load, **Tuesday**: RPE 6 - High load, **Wednesday**: RPE 8 - Very high load, **Thursday**: RPE 6 - High load, **Friday**: RPE 7 - High load, **Saturday**: RPE 9 - Very high load, **Sunday**: RPE 0 - Recovery.

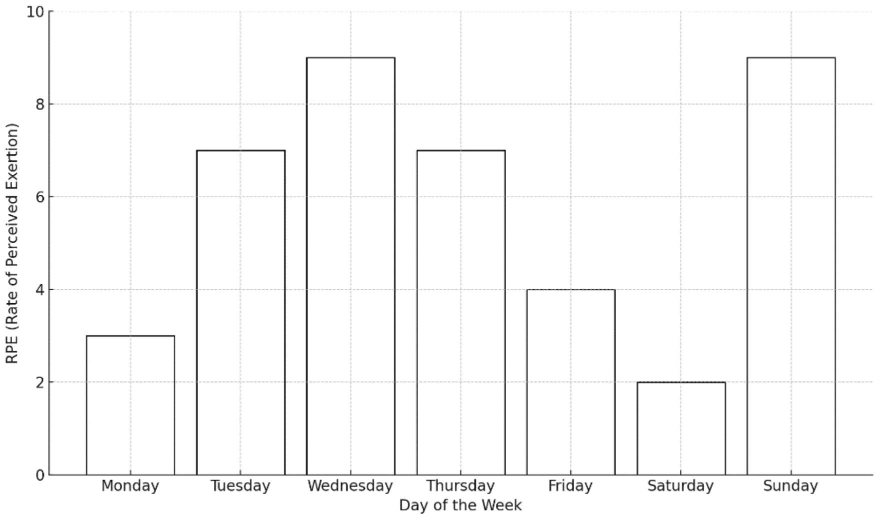

Fig. 10. Example two-peak microcycle leading in competitions. Microcycle with two high-demand training days:**Monday**: RPE 3 - Low load**, Tuesday**: RPE 7 - High load**, Wednesday**: RPE 9 - Very high load**, Thursday**: RPE 7 - High load**, Friday**: RPE 4 - Moderate load**, Saturday**: RPE 2 - Very low load**, Sunday**: RPE 9 - Competition day.

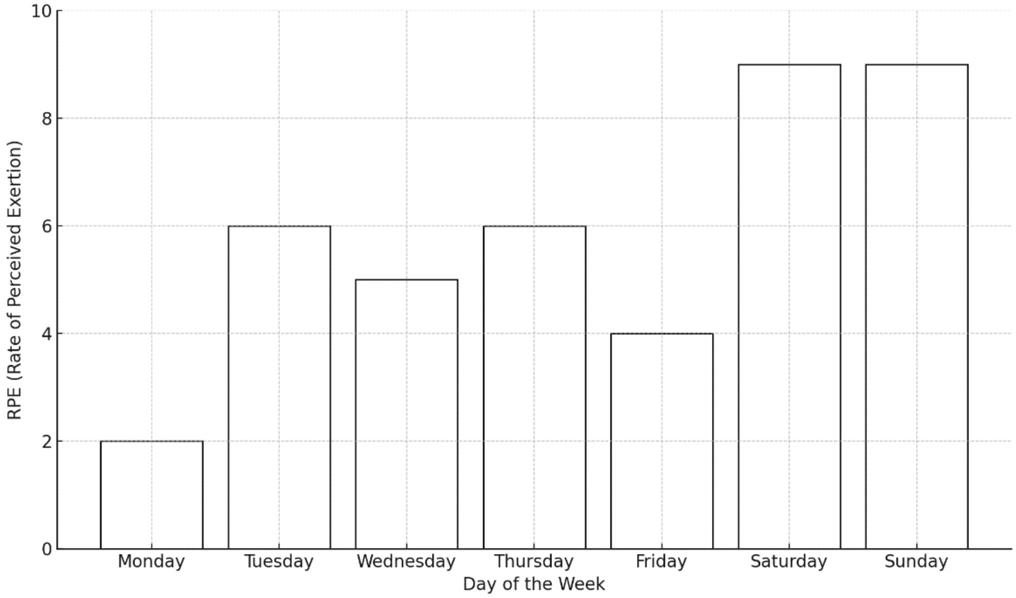

Fig. 11. Example two-peak microcycle leading in competitions. Microcycle with two adjacent high-demand competition days**: Monday**: RPE 2 - Very low load**, Tuesday**: RPE 6 - High load**, Wednesday**: RPE 5 - Moderate load**, Thursday**: RPE 6 - High load**, Friday**: RPE 4 - Moderate load**, Saturday**: RPE 9 - Competition day**, Sunday**: RPE 9 - Competition day.

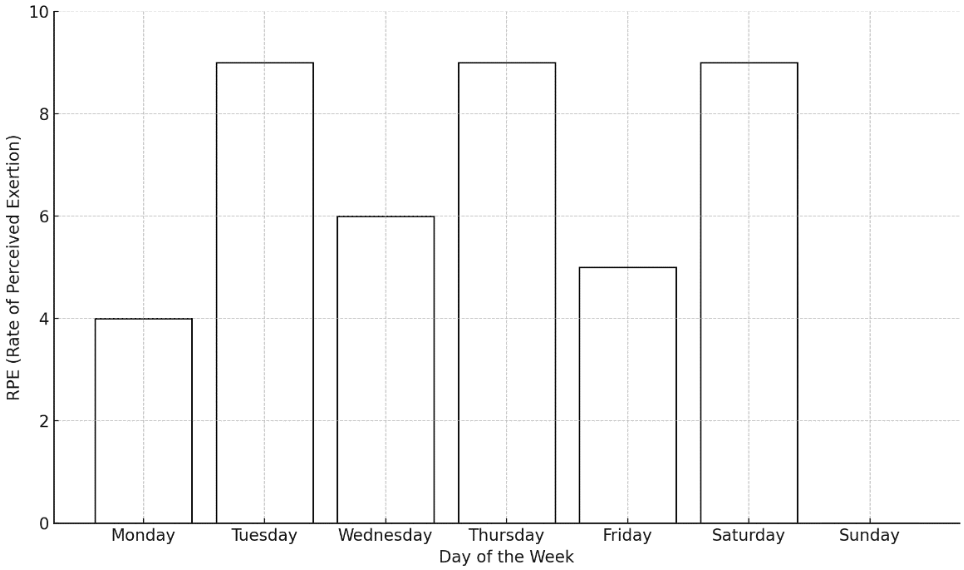

Fig . 12. Example three-peak microcycle. **Monday**: RPE 4 - Low load, **Tuesday**: RPE 9 - Very high load, **Wednesday**: RPE 6 - Moderate load, **Thursday**: RPE 9 - Very high load, **Friday**: RPE 5 - Low load, **Saturday**: RPE 9 - Very high load, **Sunday**: RPE 0 - Recovery.

In the following subsection, four training units with different goals are presented, each applied at various stages of an athlete's form preparation. The next element discussed is a larger component of the training process, namely a microcycle, which includes work on different energy systems over the course of one week. This is highly important because climbing efforts often involve the interplay of various energy systems, each contributing differently. This significantly influences the training structure and methods of periodization.

Next, we delve into the mesocycle, with a detailed description of the training variables. Additionally, the section includes material that describes strength training during this period, presented in separate tables.

Training Units

1. **Hypertrophy**: Focused on increasing muscle size, this unit includes moderate to high-volume exercises with controlled rest periods. It is essential during the early phases to build muscle mass that can later be converted into strength and power. This training consists of a warm-up phase that includes pre-habilitation exercises primarily targeting the shoulder girdle, followed by the main phase. During the main phase, muscle hypertrophy work is conducted in a manner specific to climbing. The athlete is required to complete a training routine consisting of 4 boulder problems, each containing 12 moves, to be repeated 4 times. The rest interval between repetitions is 90 seconds, and the break between sets is 8 minutes Tab. 8. To enhance the effectiveness of this training, it is often performed on holds that activate similar muscle structures, specifically the finger flexors. It is recommended to start this training with medium holds, such as edges, progressing to small edges, pinches, and slopers. Starting with holds that cause deep fatigue by activating larger muscle groups, such as slopers, is not advised. This training can also be conducted on varied holds, which might reduce the hypertrophic effect but provides greater opportunities for developing technique and tactics. After the climbing portion, the athlete undergoes a classic hypertrophy training session as detailed in Table 9. This can be done immediately after the climbing portion or after a minimum break of 4 hours.

This type of training induces significant fatigue, so it is not recommended to force highly complex technical movements at high speed.

Date	Spec.exe.	B.Project	B.Repetion	Power Edurance	S&C	Playo	Competion
3.10				Long Boulder 12 moves x 4 Rep x 4 Set. BR"90S BS' 8min.	Hyp.1		

Tab. 8. Hypertrophy Training - Specific and General, see Table 9., **B**-Bouldering.

2. Strength and Power: This type of training includes a warm-up phase that heavily engages the shoulder girdle and fingers due to plyometric exercises on the campus board. The goal of this training is to develop upper body power, rapid power generation, and maximum strength under climbing-specific conditions. Therefore, the main phase focuses on project bouldering, involving attempts to climb the most challenging boulders possible from a physical standpoint to maximize the athlete's performance. Recommended boulder problems should consist of 4 to 6 moves Tab. 9.

After the climbing portion, the athlete may also undergo a general strength training session consisting of 2 to 4 main exercises, depending on the preparation period. This can even be reduced to one exercise if the goal is to maintain the strength of large muscle groups. These exercises should be performed using a classic strength training regimen of 4 repetitions and 4 sets with full rest intervals.

Date	Spec.exe.	B.Project	B.Repetion	Power Edurance	S&C	Playo	Competion
3.10	1,2 (Tab. 11)	2h 4projects				1,2,3	

Tab. 9. Training for power and specific strength in climbing, **B**-Bouldering.

3.Endurance: Designed to improve the athlete's anerobic capacity and muscular endurance.

The goal of this training regimen is twofold: to enhance local muscular endurance and to maintain overall strength levels. To achieve this, the training starts with a warm-up phase that incorporates post-activation potentiation (PAP) exercises. These exercises, such as one-arm hangs on a hangboard or weighted pull-ups, are designed to maximize muscle recruitment with minimal fatigue. The aim is to prime the muscles for the subsequent workout while ensuring they are not overly fatigued.

The main phase of the training consists of 8 circuits performed on the climbing wall. Each circuit involves 30 moves of uniform intensity. The objective is to complete each circuit using a repetition method, with full rest intervals between circuits. These rest periods should range from 6 to 8 minutes to allow for adequate recovery. For less advanced climbers, the intensity can be modified by incorporating larger rest holds after the 15th or 20th move within each circuit. This approach helps train the ability to rest effectively during climbing, which is crucial for performance Tab.10.

After completing this type of training, it is not advisable to engage in additional strength training, as the two types of training can be antagonistic. Instead, it is beneficial to focus on relaxation exercises or core workouts. These activities help in recovery and maintaining core stability, which is essential for overall climbing performance and injury prevention.

Date	**Spec.exe.**	**B.Project**	**B.Repetion**	**Power Edurance**	**S&C**	**Playo**	**Competion**
3.10	PAP 7			8x30 BR’6min			

Tab. 10. Training for Local Muscular Endurance with Pre-Training Emphasis on Post-Activation Potentiation (PAP). **PAP (Post-Activation Potentiation)**: A training strategy that involves performing a high-intensity exercise to enhance subsequent performance in related activities, **B**-Bouldering

4.Technical and tactical skills: The objective of this training session is to develop the climber's technique and tactics through a simulation of a bouldering qualification round, such as those in a World Cup event. After the qualification round, the coach reviews the climber's performance, discusses errors, and suggests correct solutions. This feedback should be supported by video analysis and, if possible, the expertise of the route setter Tab. 11.

Following this review, the second part of the training focuses on improving technical and tactical skills on simulated boulder problems. In addition to the primary goals of refining technique and tactics, this session also aims to develop the climber's energy systems. The qualification round simulation is designed to address strength endurance, ensuring that climbers are well-prepared for the demands of actual competition scenarios.

Date	**Spec.exe.**	**B.Project**	**B.Repetion**	**Power Edurance**	**S&C**	**Playo**	**Competion**
3.10	10 (Tab.10)			**x**			1.Simulation of bouldering qualification 2.Technical training 1h

Tab. 11. Technical and tactical training, **B**-Bouldering.

WARM UP

	Reps/Sets/Time		Reps/Sets/time/distance

1.Tiss ue Quality (key points)

1	Back fascial rolling	
2		
3		
4		

2. Activation

1	Face Pull Press T-Band	3x10
2		

3. Correcive Exrecise

1		
2		

4. Dynamic Stretching/ Theromogenesis

1		
2	Prone Rocking y Fot.1	2x30s
3	Shoulders mobilisation	2x10 side
5	Quadruped TS Rotation Fot 2.	2x10 side
5	The World's Greatest Stretch Fot. 4	2x10 side
6	Sumo Roatio Fot.5	
7		

5. Neural Preparation

1		
2		

MAIN PART

Exercises		**Tempo**	**REPS/Sets/kg**				
			Week 1	**Week 2**	**Week 3**	**Week 4**	**Week 5**
1	Pull-ups	4	10/4/	10/3/	10/4/	8/4/	
2	Goblet squat	4	10/4/	10/3/	10/4/	8/4/	
3	Barbell Rowing	4	10/4/	10/3/	10/4/	8/4/	
4	Dumbell press	4	10/4/	10/3/	10/4/	8/4/	
CORE							
Anti Extension	Pike TRX		3x30s				

Anti Rotation	Mountain climber		3x30s				
Scapulothoracic	Dead Bug T-Band		4x30s				
Rest interval between exercises 90s							
Rest interval between exercises 5min							
Intensity (% 1RM) **80%**							
COOLDOWN							
Static Stretching 5-10 min			indyvidually				
Workout duration							
	RPE		9	8	9	8	
	Session Load		540	400	540	480	

Tab. 12. Example of general hypertrophic training.

Special Exercises		
Name	Set	Rep
1.Campus 1-3-5-7	3	6
2.Campus 1-4-7	3	4
4.Campus 1-5-8	3	4
5.Campus Double Jumps 1-3-5	3	3
6.Fast pull-ups	3	6
7.Catch and hold bar	8	1
8.Catch and pull bar	8	1
9.Catch and hold hold	8	1
10. Run Start	6	1

Tab. 13 . Examples of special exercises used in sport climbing.

Plyometrics Exercises		
Name	Set	Rep
1.Pogo Jump	4	15m
2.Linear Bound	4	10m
3.March A	4	20m
4.CMJ 2l	4	4
5.SJ 2l	4	4
6.Wall Drill	4	6
7.CMJ 1l	3	3
8.SJ 1l	3	3

9.Droop jump	6	1

Tab. 14. Examples of plyometric exercises used in sport climbing.

Microcycle

The microcycle presented in Tab. 15 logically demonstrates how specific climbing training can be organized throughout a week, utilizing different energy systems to ensure that one training session does not interfere with the effectiveness of another. This approach aims to optimize performance by carefully balancing various training modalities.

An overview of these energy systems for easier understanding is provided in Tab. 16 (Haff 2024). This table breaks down how different types of training sessions target specific energy systems, allowing for a more comprehensive understanding of how to structure a training week effectively.

The proposed microcycle is particularly useful during advanced phases of the season, such as specific preparation. It includes an RPE (Rate of Perceived Exertion) scale, which is a valuable tool for gauging the intensity of each training session. RPE helps athletes and coaches monitor how hard the athlete feels they are working, providing subjective feedback that complements objective measures.

Training load, calculated based on gross training time (which includes rest periods), provides insight into the overall demand placed on the athlete. This includes both active and recovery periods, ensuring a complete picture of the training stress. In addition, some solutions use calculations based solely on actual working time, excluding rest periods. This approach can offer a more precise measure of the effective training effort, particularly in high-intensity sessions where rest intervals are strategically used.

By incorporating both RPE and training load calculations, coaches can tailor training programs more effectively to the needs of the athlete, ensuring that each session contributes positively to overall performance goals. The detailed discussion of these methods and their implications for training will be explored further in the next chapter.

Day	**Training Focus**	**Details**	**RPE**	**Load**
Monday	Anaerobic Alactic	1) Technical skills (1-10s): Technical Bouldering 2) Max Strength: Bouldering 4-6 movements	7	500
Tuesday	Anaerobic Lactic	1) Glycolytic Technical Training 2) Power Endurance: Bouldering with long time under tension (12-15 moves) or medium length circuit (up to 20 moves)	9	800
Wednesday	Aerobic	1) Oxidative-compressive training: Running at 120-130 HR, pre-hab exercises	2	100
Thursday	Anaerobic Alactic	1) Technical skills (1-10s): Technical Bouldering 2) Max Power: Dynamic bouldering, Campus board 3) Max Strength: Bouldering 4-6 movements	7	500
Friday	Anaerobic Lactic	1) Glycolytic Technical Training 2) Power and Strength Endurance: Repetition Bouldering 4x4 BR (Break Repetition) 1min BS (Break Set) 5min	8	700
Saturday	Aerobic	1) Oxidative-compressive training: Climbing-specific recovery workout 4x50 BR (Break Repetition) 8min easy moves on a slight overhanging wall, pre-hab exercises	5	300
Sunday	Day Off	Rest	0	0

Tab. 15. Microcycle Involving Various Energy Systems.

Phosphagen Training (Anaerobic Alactic)	**Glycolytic Training (Anaerobic Lactic)**	**Oxidative Training (Aerobic)**
1) Technical skills (1-10s)	1) Technical skills (10-60s),	1) Technical skills (>60s),
2) Tactical skills (5-10s)	2) Tactical skills (10-60s)	2) Tactical skills (>60s)
3) Acceleration and maximum speed	3) Speed endurance (10-60s)	3) Aerobic endurance
4) Strength and maximum power	4) Power endurance, short-term muscular endurance	4) Intermediate and long-term muscular endurance

Tab. 16 . Division of Energy Systems in Sports According to Haff (2024).

Mesocycle

The presented mesocycle (Tab. 17) is an example of a competition-specific mesocycle, which includes two competition events within a month at both international and national levels. This mesocycle incorporates phases of overload and tapering, strategically designed to enhance the climber's performance during the competitive phase.

Tapering involves reducing training volume and intensity to facilitate peak performance. The variability in training loads is monitored through the RPE (Rate of Perceived Exertion) scale and calculated training load. These tools help track how training intensity and fatigue levels are managed, ensuring that the climber can perform optimally during competitions.

During this phase, special emphasis is placed on managing fatigue and the quality of training sessions. Therefore, the selection and quantity of climbing routes should be under strict supervision by the coach. This careful monitoring ensures that the training remains effective and aligns with the goals of enhancing performance for the upcoming events.

Additionally, non-specific strength training should be minimized to avoid diminishing the athlete's competitive readiness. The focus should be on maintaining the climber's peak condition and avoiding any activities that could negatively impact their performance.

Implementing tapering requires particular coaching skills and a deep understanding of the athlete's adaptive and maladaptive responses. Effective tapering can bring significant performance benefits if executed correctly, but it also has the potential to cause maladaptation if not managed properly. Coaches must be well-versed in the principles of tapering and closely monitor the athlete’s response to ensure that the approach yields the desired performance enhancements.

In summary, the success of a competition-specific mesocycle depends on a balanced approach to training intensity, fatigue management, and careful application of tapering strategies. Proper execution can lead to peak performance in competitions, while mismanagement can result in decreased performance or maladaptation.

Date	spec exe.	B.Project	B. Rep.	S&C	Power Endurance	Competition	Plyo	Rope	RPE	Load
20.04		Parkour							5	300
21.04	6		5x4 BR'1BS'3	Max2					8	700
22.04	**Day Off**								0	0
23.04	10,9	1h coordination , 1 h power					1,2,3		6	450
24.04	7 after				Cluster 4x20x2BR3 BS8		6		9	1000
25.04	10.9	Technical easy					1,2,3		2	200
26.04	7				4x50 easy		1,2,3		3	300
27.04	**Day Off**								0	0

28.04	10, 9	2h 5x5B Full		Core					7	500
29.04	**Day Off**								0	0
30.04		70min power		Core					6	480
1.05	9	90 min power strenght							8	600
2.05	**Day Off**								0	0
3.05	9	90 min power easy					7		4	360
4.05	**Day Off**								0	0
5.05	Spec activation								1	100
6.05	EC IMST								10	300
7.05	EC IMST								10	250
8.05	**Day Off**								0	0
9.05		2h		Max2					8	460

10.05					Cluster 4x20x2B R3 BS8		1,2,3		9	900
11.05									0	0
12.05	7		5x5 full break 1x4 no feet						7	420
13.05								6 Route 7c-8b	8	800
14.05									0	0
15.05		2h							7	600
16.05					2x20, 4x30 Full B				8	700
17.05								5x2 7c	6	540
18.05									0	0
19.05		hard 90min		Max2					8	800
20.05									0	0
21.05								3x8B	10	350

22.05					5x30 Full B		1,2,3		7	600
23.05									0	0
24.05	10	1h power							4	200
25.05		Spec activation					7		1	100
26.05									0	0
27.05	National Competition								10	350
28.05									10	200

Tab. 17. Comp-Spec Mesocycle: Competition-Specific Mesocycle, 2 Starts: Two Competition Events, **Spec Exe.:** Specific Exercises, **B. Project:** Bouldering Project, **B. Rep.:** Bouldering Repetition, **S&C:** Strength and Conditioning, **Power Endurance:** Power Endurance Training, **Competition:** Competition, **Plyo:** Plyometric Exercises, **Rope:** Rope Lead Climbing**, RPE:** Rate of Perceived Exertion, **Load:** Training Taperin.

Peaking in Sport

Peaking in sport refers to the process of planning and optimizing an athlete's training and recovery to achieve their highest level of performance at a specific time, typically for major competitions or events. The objective is to reach peak physical and mental condition, ensuring that all physiological, psychological, and technical elements are maximized. A crucial aspect of peaking involves two sequential phases—overreaching followed by tapering. This sequence is essential to elicit the supercompensation effect, wherein the athlete's performance temporarily declines due to overreaching but then significantly improves during the tapering phase as recovery allows the body to adapt and enhance its capabilities. Scientific evidence supports this approach, emphasizing that the correct implementation of these phases leads to optimal performance gains (Mujika & Padilla, 2003).

Strategies for Peaking

Overreaching in Athletic Training

Overreaching is a strategic method used in athletic training, involving a temporary increase in training intensity and volume designed to overload the body. This phase induces short-term fatigue and a temporary decline in performance, but when followed by proper recovery, it triggers a process called supercompensation. This leads to enhanced performance and long-term adaptations. Overreaching is a fine balance between pushing the limits of physical capacity and ensuring sufficient recovery to avoid negative consequences.

Types of Overreaching

Functional Overreaching (FOR) Bell et al. (2020), is defined as a short-term decrease in performance lasting from days to weeks, which is followed by performance supercompensation after a period of adequate recovery.

Non-functional Overreaching (NFOR) Bell et al. (2020), , on the other hand, is described as a performance decrement lasting over weeks to months. Although full recovery is typically achieved, no supercompensation effects are realized during this process.

Planned Overreaching

Planned overreaching is an intentional period of intensified training designed to overload the athlete. It usually occurs in two main phases: the **training phase** and the **recovery phase**.

In the **training phase**, which typically lasts 1-3 weeks, athletes undergo a period of high volume and high intensity. This phase pushes them beyond their usual limits, targeting both the muscular and cardiovascular systems. For example, in endurance sports, this could mean increasing mileage and incorporating high-intensity interval training, while in strength sports, athletes might lift heavier weights or increase the number of repetitions and sets. In team sports, this phase might involve more frequent and intense skill and tactical drills. The goal during this phase is to place the athlete in a state of fatigue, priming the body for the adaptation that will follow Fig. 13.

Following the training phase is the **recovery phase**, where the athlete's training volume and intensity are significantly reduced. This phase can last anywhere from a few days to two weeks, depending on the severity of the overreaching. The focus during this period is on regeneration, incorporating techniques such as active recovery, optimizing sleep, and supporting recovery through proper nutrition. Examples of this include reducing the number of training sessions, lowering intensity, incorporating more rest days, and utilizing recovery modalities like massage, stretching, and hydrotherapy. The recovery phase is critical for allowing the body to repair itself and adapt to the increased training load, which ultimately leads to performance improvements.

Aim of Overreaching

The primary goal of overreaching is to provide a **strong adaptation stimulus** to the body. By pushing the athlete's physical limits during the overreaching phase and then allowing sufficient recovery, the body adapts to the new demands placed on it. This results in enhanced strength, endurance, and overall performance capacity.

In addition to the physical benefits, overreaching also builds **psychological resilience**. Training under fatigue conditions challenges the athlete mentally, helping them develop mental toughness and focus, which are essential during competition. Overreaching teaches athletes how to push through fatigue, manage stress, and maintain performance under pressure, all of which are valuable assets in competitive sports.

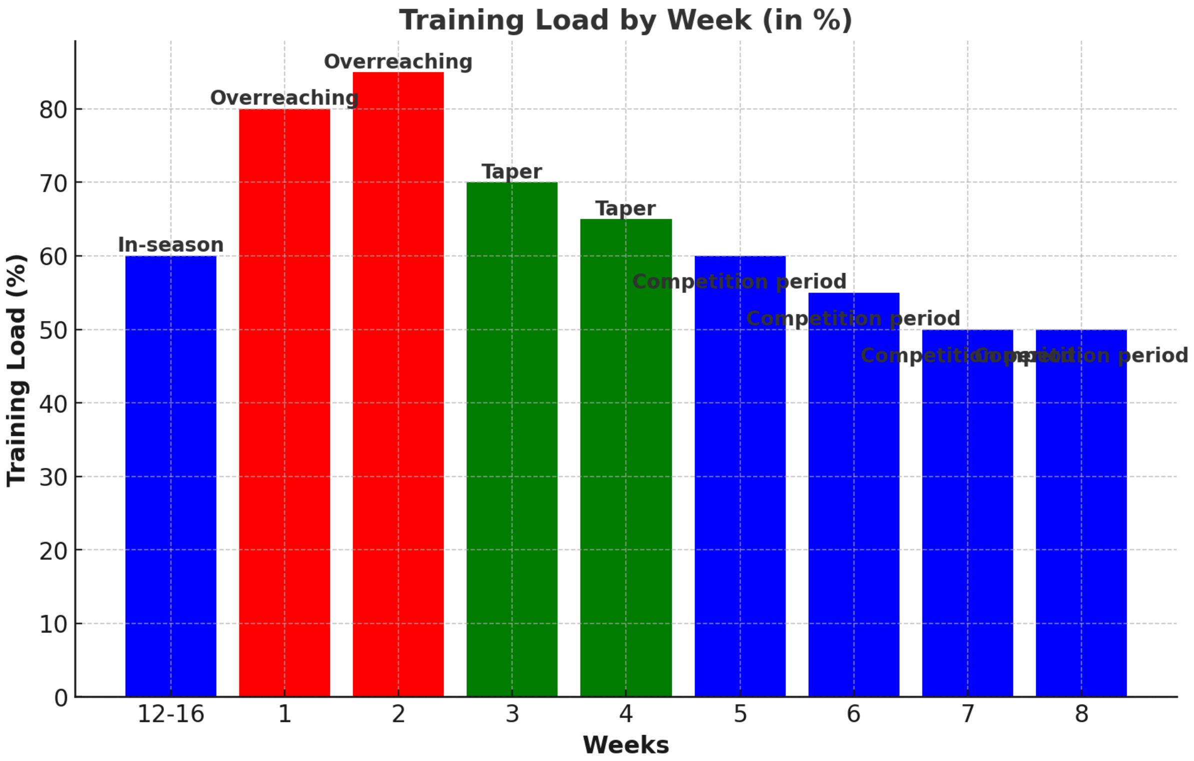

Fig. 13. **Progression of Training Load Across Mesocycles**

The chart illustrates the variation in training load percentage over the course of multiple mesocycles, beginning with a steady in-season phase, followed by a period of overreaching to induce performance gains, a tapering phase for recovery and adaptation, and concluding with the competition period. The training load is strategically reduced during the taper and competition phases to ensure peak performance during critical events.

Tapering in Sports Training

Tapering is a widely used strategy in sports training, particularly before competitions, designed to reduce accumulated fatigue while allowing athletes to peak their performance at the right time. It involves the progressive reduction of training volume and intensity, allowing the body to recover and optimize physiological and psychological readiness for competition. As defined by Mujika and Padilla, tapering is “a progressive nonlinear reduction of the training load during a variable period of time, in an attempt to reduce the physiological and psychological stress of daily training and optimize sports performance” Mujika & Padilla, (2003) Fig. 14.

Different tapering models can be employed, including linear, exponential, and step tapers. In a linear taper, the training load is reduced systematically, such as a 15% reduction in training load each week over several weeks. In contrast, exponential tapers involve a more rapid reduction in training load, either slow or fast, where the reductions are exponentially decreased (e.g., a 60% load reduction followed by a 40% reduction). The step taper, on the other hand, involves a sudden and constant reduction in training load, typically around 50%, maintaining a steady level of reduced load throughout the taper period.

1.Linear Tapering

In **linear tapering**, training volume is systematically reduced in a steady, linear fashion leading up to the competition. The reduction in volume is gradual, and intensity may either remain constant or decrease slightly as the event approaches. This approach is beneficial for athletes who need to maintain a certain level of intensity while still giving their bodies time to recover Fig. 14.

2.Exponential Tapering

Exponential tapering involves reducing training volume at a rate that decreases exponentially as the competition nears. There are two variations of this method Fig. 14:

Fast Exponential Tapering: This approach involves a significant reduction in training volume at the beginning of the taper. Once the volume has been reduced, it stabilizes at a much lower level until the competition. This method is effective for athletes who need to recover quickly from a high training load.

Slow Exponential Tapering: In this variation, the reduction in training volume is more gradual and steady over time. The slower pace allows for a more controlled decrease, ensuring the athlete stays sharp while progressively easing into recovery.

3.Step Tapering

In **step tapering**, the training volume is abruptly reduced by a set percentage and then maintained at that lower level until the competition. This method gives the athlete immediate relief from intense training, allowing their body to recover without further reductions in volume. Step tapering can be particularly effective for athletes who benefit from maintaining a stable routine with a focus on recovery Fig. 14.

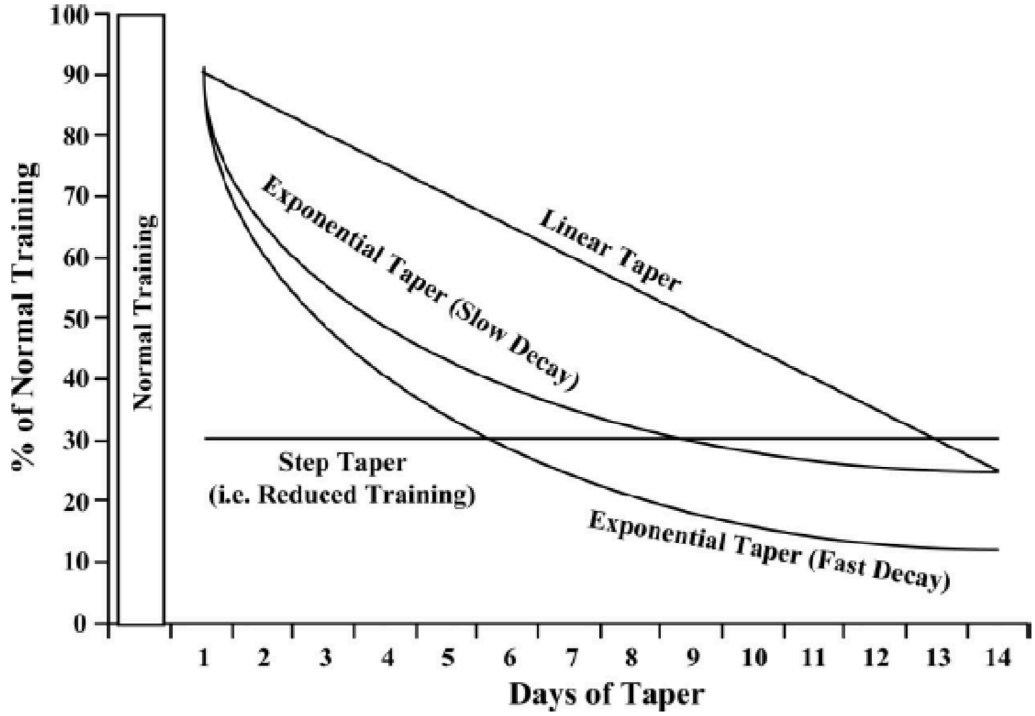

Fig. 14. Types of tapers: linear taper, exponential taper with slow or fast time constants of decay of the training load, and step taper. Mujika and Padilla (2003).

Tapering: A Strategy for Peak Performance

Tapering is a crucial strategy in athletic preparation, involving a deliberate reduction in training volume and intensity leading up to a major competition. The primary goal of tapering is to reduce accumulated fatigue, allowing the athlete's body to recover fully and perform at its best during the most important events. By managing fatigue effectively while maintaining fitness, tapering helps enhance performance, whether in speed, strength, or endurance.

Variables Reduced During Tapering

Several key training variables are adjusted during the tapering period, with the goal of balancing recovery and performance readiness:

1. **Training Volume**: The most significant reduction during tapering is in training volume, typically cut by 40-60% relative to regular training. In some cases, the reduction may be even greater, depending on the athlete's needs and the demands of the sport.
2. **Training Intensity**: While volume decreases, intensity may either be maintained at a steady level or reduced slightly, usually by 10-20%. Maintaining intensity ensures that the nervous and muscular systems remain stimulated without excessive load.
3. **Training Frequency**: Training frequency might also be reduced by around 20-30%, although it often remains constant to preserve the athlete's rhythm and routine. A steady training frequency helps maintain the mental and physical flow of preparation while allowing the body to recover.

Physiological Changes During Tapering

Tapering not only reduces fatigue but also triggers several physiological adaptations that contribute to enhanced performance. These improvements include:

1. **Increased Muscle Strength**: With better recovery during tapering, muscle strength improves, allowing athletes to perform more powerfully.

2. **Higher Muscle Glycogen Levels**: Tapering enables the body to store more glycogen in the muscles, which is essential for endurance and high-intensity efforts.
3. **Enhanced Plasma Volume**: The body's plasma volume increases, leading to improved circulation and oxygen delivery to the muscles.
4. **Improved Aerobic Capacity**: As the cardiovascular and respiratory systems recover, athletes experience enhanced aerobic capacity, increasing stamina.
5. **Faster Recovery Speed**: Athletes find that they recover more quickly between training sessions or competitions due to reduced fatigue and better-managed recovery strategies.

Physiological Variables That Decrease During Tapering

At the same time, tapering reduces several physiological stresses that could otherwise hamper performance:

1. **Lower Stress Hormone Levels**: Cortisol and other stress hormones decrease, which reduces the risk of overtraining and improves overall recovery.
2. **Reduced Nervous System Load**: The reduced workload lightens the load on the nervous system, resulting in better focus, concentration, and overall well-being.
3. **Decreased Metabolite Accumulation**: Harmful byproducts of intense exercise, like lactic acid, are reduced, helping athletes feel less fatigued and more energized.

Biomechanical Benefits of Tapering

Biomechanical improvements also occur during tapering, which can have a significant impact on performance:

1. **Improved Movement Economy**: With better recovery and reduced fatigue, athletes become more efficient in their movement patterns, expending less energy to perform the same tasks.

2. **Enhanced Coordination and Technique**: Tapering sharpens coordination and technique, as athletes can focus more on precision and skill refinement due to reduced fatigue.

Tapering in Sports with Mixed Energy Systems

In sports like **sport climbing**, which rely on a combination of endurance and strength, tapering requires careful adjustments to optimize both areas without sacrificing key skills. The following strategies are often employed:

1. **Reduction in Training Volume**: Training volume is reduced by 40-60%, with the focus shifting to core aspects of the sport, such as technique and specific strength.
2. **Maintenance of Intensity**: While training volume decreases, intensity remains high to preserve the sport-specific skills required in climbing. Sessions are shortened, but intensity is reduced by only 10-20% to maintain stimulation without overloading the athlete.
3. **Focus on Technical Exercises**: During tapering, technical exercises that improve coordination, technique, and movement efficiency are emphasized. These exercises are performed in a controlled manner to prevent excessive fatigue.
4. **Recovery Techniques**: Tapering includes the addition of recovery days and the use of recovery techniques like massage, stretching, and relaxation to ensure full physical and mental regeneration.
5. **Timing of Tapering**: Tapering typically begins 7-14 days before a key event, with adjustments made based on the athlete's individual needs and the nature of the competition.

Risks of Deadaptation from Prolonged Tapering

While tapering is essential for optimal performance, a prolonged or overly aggressive taper can lead to **deadaptation**, where fitness and performance levels decline due to insufficient stimulation. Deadaptation risks include:

1. **Loss of Aerobic Capacity**: A prolonged reduction in training volume can lead to a decrease in aerobic fitness, reducing endurance capabilities.
2. **Decrease in Muscle Strength and Power**: If tapering extends too long or training loads are cut too drastically, muscle strength and power, critical for explosive movements, may decline.
3. **Diminished Technical Skills**: A significant drop in training intensity and volume can result in a loss of technical proficiency and coordination, which are key in sports like climbing.
4. **Psychological Impact**: Reduced training loads can lead to decreased confidence and motivation, as athletes might feel they are losing fitness or sharpness.

Two-Phase Tapering

A more advanced approach is **two-phase tapering**, which involves two distinct tapering periods within a single training cycle. This method helps maintain a higher overall fitness level while still providing adequate recovery before important competitions. It allows athletes to stay sharp over an extended competitive season without losing the benefits of tapering Fig. 18.

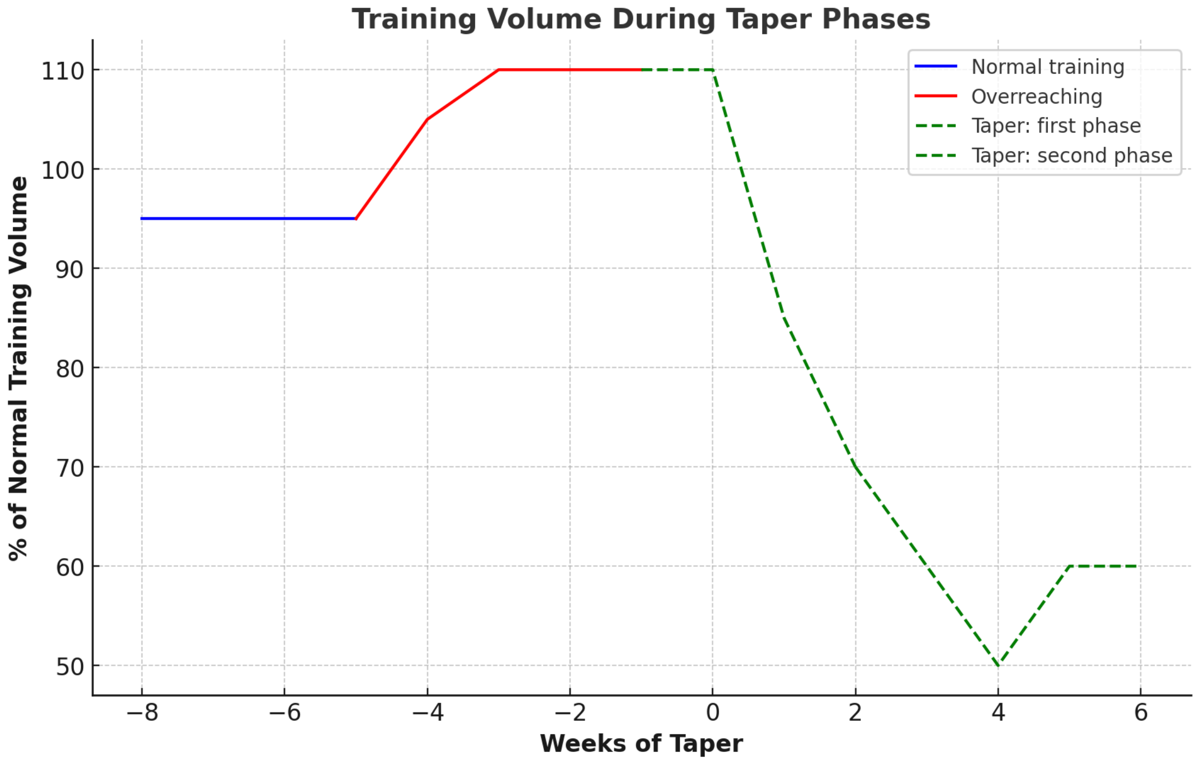

Fig. 15. Training Volume Progression During Taper Phases

This chart illustrates the changes in training volume as a percentage of normal training across different phases: normal training, overreaching, and taper. The overreaching phase sees an increase in volume above 100%, followed by a two-phase taper. The first phase of taper involves a sharp reduction in volume to allow for recovery, while the second phase shows a slight increase to stabilize performance leading up to competition. *Figure: Two-phase taper adapted from Thomas, Mujika, and Busso (2009).*

First Phase: The initial stage of tapering involves a significant reduction in training volume to allow the body to partially recover and begin the adaptation process. This phase is essential to reducing fatigue without losing the benefits of prior high-intensity training.

Second Phase: In the second phase, some training intensity and volume are reintroduced to sharpen performance before the final taper. This phase helps stabilize performance, ensuring the athlete enters competition in peak condition without the risk of deadaptation.

This two-phase tapering strategy strikes a balance between maintaining fitness and optimizing performance, preventing the decline that comes from a prolonged reduction in training load.

Example Peaking Strategy

This example demonstrates a comprehensive peaking strategy for athletes, spanning a 12-16 week preparation period. It includes an overreaching phase, tapering, and a final competition phase, all carefully designed to optimize performance.

1. Preparation Phase (12-16 Weeks): The preparation phase focuses on building endurance, strength, and sport-specific skills. Training volume and intensity are gradually increased over time to develop the athlete's base fitness and technical proficiency. The structure of this phase ensures that the athlete's performance capabilities are enhanced as they progress toward their peak.

2. Overreaching Phase (2 Weeks): Overreaching involves a temporary, controlled increase in training volume and intensity, pushing the athlete beyond their usual limits. This phase typically lasts for 2 weeks and induces a state of fatigue, stimulating physiological adaptations. It is followed by a short recovery period to allow initial fatigue to dissipate, setting the stage for peak performance.

3. Tapering Phase (10-14 Days): Tapering begins after the overreaching phase, lasting 10 to 14 days. It consists of two parts:

    - Initial Taper (5-7 Days): The first part involves a gradual reduction in training volume while maintaining intensity to retain fitness. This ensures the athlete is still engaged in training without overexertion.

    - Final Taper (5-7 Days): The second part further reduces training volume, focusing on full recovery and technical refinement. This phase prepares the body and mind for peak performance while eliminating any lingering fatigue.

4. Competition Phase (4 Weeks): The competition phase is where all the preparation and tapering culminate. It spans 4 weeks and is designed to maintain peak

performance throughout a series of competitions. During this phase, the focus shifts to mental preparation, technique refinement, and event-specific strategies. The goal is to ensure that the athlete is fully prepared and confident, performing at their best in every competition.

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Overtraining and Overreaching in Sports

In the literature on overtraining, the terminology used is often inconsistent, which leads to confusion in definitions. For this review, overtraining is understood as an increase in the volume and/or intensity of training that results in long-term declines in performance, lasting from several weeks to months (Fry et al., 1994). Overtraining is linked to chronic fatigue, largely due to inadequate rest and recovery (O'Connor et al., 1989). This concept aligns with the General Adaptation Syndrome (GAS), introduced by Hans Selye, which applies not only to physiological systems but to many other areas as well (Selye, 1956). GAS involves a disruption of homeostasis, followed by an adaptation phase. If the adaptation is insufficient, an exhaustion phase occurs, potentially leading to failure of the system.

When training stress triggers overtraining syndrome, the body attempts to restore homeostasis as part of its adaptive strategy. A marker of overtraining syndrome can be defined as any physical, physiological, or psychological characteristic that changes in response to the training load leading to this syndrome (Lehmann et al., 1992). Overtraining is typically characterized by increased training intensity and a corresponding decrease in performance (Fry et al., 1994).

Various alternative terms have been proposed to describe overtraining, such as "chronic overwork," "physical overstrain," "overtraining syndrome," and "burnout" (Budgett, 1990). These terms differ from "muscular overstrain," which refers to the short-term, acute fatigue that occurs immediately after exercise (Stone et al., 1991).

It is important to differentiate overtraining from overreaching, which is a short-term decrease in performance that lasts for several days, after which recovery typically occurs quickly (Kuipers & Keizer, 1988). Overreaching is often intentionally used in training programs because it can lead to improved performance after a recovery period (Fry et al., 1991). It is thought that overreaching represents an early stage of overtraining, and if left unchecked, it can progress into full overtraining syndrome (Lehmann et al., 1993).

Two main types of overtraining have been identified: sympathetic overtraining (characterized by increased sympathetic nervous system activity) and parasympathetic overtraining (where parasympathetic nervous system activity predominates). These have been described in numerous reviews (Kindermann, 1986). Sympathetic overtraining is more common in younger athletes who focus on speed and power, while parasympathetic overtraining is associated with a more advanced stage, where neuroendocrine function is compromised, leading to lower resting heart rates and other symptoms (Fry et al., 1994).

Fatigue and Overtraining

Fatigue is generally classified into two main types: acute fatigue and chronic fatigue.

Acute Fatigue:

Acute fatigue is specific to the activity being performed and relates primarily to the type of effort involved. It can be caused by disturbances in neuromuscular coupling, which is the process where signals from the nervous system cause muscle contraction. Fluctuations in calcium ion (Ca2+) levels inside and outside the cells can also affect muscle performance. Moreover, elevated levels of inorganic phosphates can disrupt muscle function, and low glycogen stores (the body's energy reserves) can reduce the efficiency of muscle contractions. The rate at which an athlete recovers from acute fatigue depends on the type of training performed and the athlete's muscle fiber composition.

Chronic Fatigue

Chronic fatigue results from the accumulation of both physical and psychological stress, making it difficult for the body to recover between training sessions. It manifests as a reduction in performance, such as decreased muscle strength and the speed at which force is generated. Chronic fatigue is often associated with depleted energy reserves, hormonal imbalances, issues with calcium regulation in the muscles, and nervous system fatigue. As chronic fatigue progresses, the body's ability to adapt to training stimuli decreases, leading to further performance declines.

Overreaching and Overtraining

Overreaching refers to a temporary drop in performance due to the accumulation of training and other stressors. It is typically part of a planned training program, where a period of intense training is followed by recovery, resulting in supercompensation and performance improvement. Overreaching can be divided into two types: functional and non-functional. Functional overreaching leads to positive physiological adaptations, with recovery taking a few days to weeks. Non-functional overreaching occurs when intense training continues for too long, leading to stagnation or a decline in performance, requiring a longer recovery period. Prolonged non-functional overreaching can evolve into full overtraining Fig. 16.

Overtraining is a long-term reduction in performance caused by excessive training loads and external stress. It presents with physiological and psychological symptoms of poor adaptation, such as changes in nervous and hormonal system functioning, sleep disturbances, mood swings, and immune system issues. Full recovery from overtraining can take weeks or even months. Overtraining can be caused by excessively monotonous training or an overload from too much volume or intensity. Monotonous training leads to central nervous system fatigue, which results in stagnation or performance decline. Excessive volume or intensity in training leads to overwork, overwhelming the body's ability to adapt to the stimuli.

Both training volume and intensity can contribute to overtraining if not properly managed. The symptoms of overtraining are more severe than those of overreaching, and recovery time significantly increases as the intensity and duration of training stressors rise.

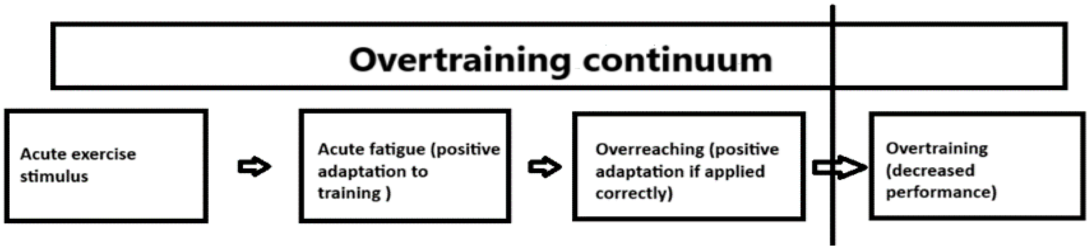

Fig. 16. Overtraining continuum adapted from Fry et al. (1991)

Markers of Overtraining

Markers of overtraining can be divided into several categories: **physiological**, **biomechanical**, **psychological**, and **performance-related**. These markers provide insight into how the body and mind respond to chronic overloading and inadequate recovery.

Physiological Markers:

- **Decreased muscle and liver glycogen stores**: Glycogen is essential for fueling muscles during physical activity. Depleted stores indicate insufficient recovery and the body's inability to restore energy reserves.
- **Increased heart rate and blood pressure**: Overtraining can cause a chronic elevation in resting heart rate and blood pressure due to prolonged stress on the cardiovascular system.
- **Decreased overall body mass and lean muscle mass**: Over time, prolonged overtraining may lead to a reduction in muscle mass as the body breaks down tissue for energy.
- **Increased creatine kinase and lactate dehydrogenase levels**: These enzymes are markers of muscle damage, indicating that the body is struggling to repair itself after intense exertion.
- **Hormonal imbalances**: Decreased testosterone in men, reduced estradiol and progesterone in women, and elevated cortisol levels reflect the body's impaired ability to regulate stress and recovery processes.

- **Immune system dysfunction**: Increased susceptibility to upper respiratory infections, swollen lymph nodes, and delayed wound healing are all signs of compromised immune function.

Biomechanical Markers:

- **Delayed Onset Muscle Soreness (DOMS)**: This soreness, typically occurring 24-72 hours after intense activity, may become more persistent and severe during overtraining.
- **Tendon strains and inflammation**: Overuse injuries are common in athletes who do not allow their bodies adequate time to recover.
- **Stress fractures and muscle strains**: The increased mechanical load on the body without proper recovery increases the risk of fractures and strains, as bones and muscles are unable to repair and strengthen.
- **Decreased movement economy and coordination**: Overtrained athletes often experience a loss of movement efficiency and fluidity, which can negatively impact performance in skill-based sports.

Psychological Markers:

- **Decreased well-being and emotional stability**: Overtrained athletes often report feeling low, with reduced self-esteem and a general sense of irritability or frustration.
- **Increased anxiety and depression**: The pressure to perform, combined with fatigue and burnout, can lead to heightened levels of anxiety or even clinical depression.
- **Reduced concentration and focus**: Cognitive performance is often impaired during overtraining, making it difficult for athletes to concentrate on tasks or perform complex movements.

- **Fear of competition and workload**: Overtrained athletes may become more anxious about their ability to compete and handle the demands of their sport, leading to avoidance behaviors.
- **Insomnia and disturbed sleep patterns**: Overtraining can disrupt sleep, which exacerbates fatigue and hinders recovery.

Performance-Related Markers:

- **Inability to reach supercompensation**: Supercompensation is the phase where the body adapts to training stimuli and improves performance. Overtrained athletes fail to reach this stage, seeing no improvement despite ongoing effort.
- **Decreased anaerobic capacity**: High-intensity, short-duration efforts suffer, with athletes struggling to maintain power and speed.
- **Muscle stiffness and chronic pain**: Athletes may experience persistent discomfort, making it difficult to perform at their usual levels.
- **Slower movement speed and poor reaction times**: Reduced physical and mental sharpness is common, with athletes unable to maintain their normal pace or agility during competition.

Preventing Overtraining in Athletes

Preventing overtraining is an essential part of athletic training to ensure that athletes maintain a healthy balance between exercise and recovery. Overtraining happens when physical and mental stress accumulate without enough recovery time, leading to chronic fatigue, performance decline, and potential injury. Recognizing early signs and applying effective strategies can help avoid these negative outcomes Meeusen et al. (2013).

Structured Training Periodization

Periodization involves structuring training into cycles that vary in intensity, volume, and recovery. This approach helps balance high-intensity workouts with periods of lower intensity, reducing the risk of accumulated fatigue. Including regular deload weeks-where the training load is decreased-supports recovery and adaptation.

Monitoring Recovery and Fatigue Levels

Athletes and coaches should track signs of both physical and mental fatigue. Using tools like heart rate variability (HRV), perceived exertion scales, and regular performance assessments can identify early signs of overreaching. Monitoring sleep quality, mood changes, and muscle soreness also provides valuable insight into recovery levels.

Nutrition and Hydration Support

Adequate nutrition plays an important role in supporting recovery and maintaining performance. A balanced diet with sufficient carbohydrates, proteins, and fats, along with proper hydration, helps replenish energy stores and repair muscles. Nutritional deficiencies can exacerbate fatigue, increasing the likelihood of overtraining.

Prioritizing Rest and Recovery

Recovery should be prioritized as much as training itself. This includes both passive recovery, such as sleep and relaxation, and active recovery, like light exercises that promote circulation and muscle healing. Getting 7-9 hours of quality sleep each night is necessary for both physical and mental well-being.

Introducing Variety in Training

Adding variety to workouts, including cross-training with different activities, can help prevent monotony and mental burnout. Alternating between various forms of exercise, such as swimming, cycling, or stretching routines, allows different muscle groups to recover while improving overall fitness.

Gradual Progression of Training Load

Increasing the training load gradually is a key way to avoid overtraining. Athletes should follow the principle of progressive overload, increasing intensity and volume step by step, allowing the body to adapt without overwhelming it. Avoiding sudden increases in workload reduces the risk of excessive fatigue.

Listening to Body Signals

It is important for athletes to pay attention to their body's signals and take breaks when necessary. Ignoring fatigue, soreness, or mental exhaustion can quickly lead to overtraining. Taking a rest day or reducing training intensity when feeling fatigued is a much better option than pushing through and risking longer-term problems.

Recognizing Early Signs of Overreaching and Overtraining

Identifying early signs of overreaching can prevent it from developing into full overtraining syndrome. Common signs include:

- Persistent fatigue
- Reduced performance despite training efforts
- Mood swings or irritability
- Increased resting heart rate
- Difficulty sleeping or poor sleep quality

When such signs manifest, it is essential to modify the training regimen to incorporate additional recovery strategies, thereby preventing the escalation of overreaching into overtraining, a condition that may require several weeks or even months for complete recovery.

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Part II

Testing and monitoring in climbing

The Importance of Performance Evaluation and Monitoring in Athletes

Performance evaluation and monitoring are critical components of effective athletic training. They ensure that training is not only scientifically based but also tailored to the individual needs of athletes, enabling them to reach their full potential. The primary purpose of performance evaluation and monitoring is to objectively assess and optimize an athlete's physical and mental capacities, ensuring that training is as efficient and effective as possible.

One of the key reasons athletes should undergo regular testing is to accurately identify strengths and weaknesses in their performance. While athletes and coaches can often make educated guesses about which abilities may be underdeveloped, these assumptions are not always accurate. Scientific tests provide objective data that can reveal specific areas where an athlete may need to focus more attention. This is particularly important in complex sports like climbing, where numerous factors—such as strength, endurance, technique, and mental toughness—contribute to overall performance.

Moreover, regular performance assessments help track progress over time. By comparing test results at different stages of training, coaches and athletes can determine whether the current training regimen is effective or if adjustments are needed. This continuous feedback loop is essential for ensuring that training remains aligned with the athlete's goals and is responsive to their evolving needs. This approach not only maximizes performance gains but also minimizes the risk of overtraining or injury by ensuring that the intensity and volume of training are appropriately managed.

In addition to optimizing physical capabilities, performance testing also plays a crucial role in psychological preparation. Knowing the specific areas of strength and weakness helps build an athlete's confidence and allows for more targeted mental training. This is particularly relevant in high-pressure sports, where mental resilience can be as important as physical prowess.

Furthermore, performance evaluations provide essential information for individualized training programs. Each athlete has unique physical and mental attributes, and standardized training programs may not address these individual differences effectively. By identifying an athlete’s specific needs through testing, coaches can design personalized training plans that target the areas most in need of development, leading to more efficient and effective training.

It is also important that performance tests provide the maximum amount of relevant information while minimizing disruptions to training and the risk of injury. Effective testing should be as non-invasive as possible, allowing athletes to continue their training with minimal interruption. Additionally, the financial accessibility of these tests is crucial; they should be affordable and widely available to as many practitioners as possible. This broad accessibility not only helps more athletes benefit from testing but also aids in the establishment of comparative norms, which are valuable for evaluating individual performance relative to a wider athletic population.

In summary, performance evaluation and monitoring are indispensable for athletes who aim to maximize their potential. These processes provide objective, detailed insights into an athlete's physical and mental state, allowing for the identification of strengths and weaknesses, the tracking of progress, and the customization of training programs. Without regular testing, athletes risk plateauing in their development or, worse, regressing due to inadequate or misdirected training efforts. By integrating regular performance evaluations into their training routines, athletes and coaches can ensure that they are making the most of their time and energy, leading to peak performance when it matters most.

Monitoring and Diagnostics in Sport Climbing

In the 1980s, research on climbing effort was limited, with a modest increase in studies during the 1990s. Early works, such as those by Viviani et al. [1991] and Watts et al. [1993], provided some of the first insights into the somatic profile of competitive climbers. The latter study not only described the basic body composition but also detailed the strength characteristics of sport climbers. Billat et al. [1995] and Watts and Drobish

[1996] presented key physiological indicators of climbing effort. Grand et al. [1996] explored the anthropometric and motor conditions affecting climbing performance. A pivotal contribution to understanding the factors influencing climbing effectiveness was made by Mermier et al. [2000].

One limitation of these early studies was the small sample sizes, with only a few involving elite climbers. Often, comparisons were made between higher-ranked climbers and non-climbers or recreational climbers, making it difficult to isolate the specific factors that determine peak climbing performance.

Significant interest in rock climbing research emerged at the turn of the millennium. Watts [2004] published a review on the morpho-functional profile of competitive climbers, while Sheela [2004] summarized knowledge on the physiological potential of sport climbers. Giles et al. [2006] provided an updated review of research on body composition, strength, endurance, and physiological indicators in climbers.

New research tools began to emerge during this period, shedding light on the role of strength and endurance in sport climbing and the nature of the climbing effort itself. Notably, the use of specialized dynamometers and spectroscopy methods advanced the understanding of climbing dynamics. Studies by Rokowski [2006] and Balasi et al. [2012] significantly enhanced the knowledge of climbers' motor potential. Ozimek, Sztaszkiewicz, and Rokowski's publication [2016] on the validity of associative tests used in climbing added valuable insights.

In 2022, an interdisciplinary team of sport scientists and engineers utilized machine learning to quantify climbing techniques in speed climbing. This marked the first attempt to apply advanced technologies, including neural networks and artificial intelligence, in the biomechanical diagnostics of climbers. The tool developed by the research group is now being further refined for broader application, with the goal of supporting coaches and athletes Pandurevic [2022].

Since 2010, key research directions have included physiological, biochemical, biomechanical, motor, and body composition aspects of sport climbing. Globally, the field is advancing in several important directions:

1) **Advanced Biomechanical Analysis**: Researchers are employing motion capture systems and wearable sensors to analyze climbing techniques and movements in greater detail, helping to optimize performance and reduce injury risk Pandurevic [2022] .

2) **Psychophysiological Studies**: There is increasing interest in the mental aspects of climbing, including stress, focus, and decision-making under pressure. Studies are exploring how these psychological factors affect climbing performance and training Sheela [2004], Rokowski [2020, 2021].

3) **Nutritional Strategies**: Research is focusing on the role of diet and nutrition in climbing, aiming to enhance endurance, strength, and recovery through tailored dietary interventions Gibson-Smith [2024], Mora-Fernandez [2024].

4) **Genetic and Epigenetic Factors**: Emerging studies are investigating the genetic and epigenetic factors that may influence climbing ability and susceptibility to injuries, providing insights into personalized training approaches Saito [2021].

5) **Innovative Training Technologies**: The development and use of advanced training tools, such as virtual reality and augmented reality systems, are being explored to create more effective and engaging training environments Pandurevic [2020], Pieprzycki [2023, 2024].

6) **Recovery and Rehabilitation**: Enhanced methods for recovery and injury prevention are being studied, including the use of cryotherapy, electrostimulation, and advanced physiotherapy techniques Kovářová[2024], Saeterbakken [2024].

This monograph will not only address climbing-specific tests but also include information on other assessments related to functional fitness. By integrating a broad range of diagnostic tools, it aims to provide a comprehensive view of the physiological and functional aspects crucial for optimizing climbing performance. This approach will support coaches and athletes in developing more effective training regimens and enhancing overall athletic capabilities.

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Monitoring Training Load in Sport Climbing: A Comprehensive Overview

Introduction

Sport climbing, with its demanding combination of strength, endurance, technique, and mental acuity, requires precise monitoring of training loads to optimize performance and prevent overtraining. Effective monitoring systems help in adapting training programs, minimizing injury risks, and ensuring peak performance during competitions. This chapter explores various tools and methodologies for monitoring training load in sport climbing, with a focus on internal and external load measures, and includes detailed information on psychological, hormonal, biochemical, and biomechanical indicators.

Internal and External Load Monitoring in Sport Climbing

External Load Indicators

1) Climbing Volume and Intensity

Volume: Measured by total hand movements or routes climbed. Multiply hand movements per route by the number of routes. Difficulty-weighted volume combines difficulty with hand movements.

Intensity: Calculated as a percentage of the climber's maximum difficulty. For details, see PART I.

2) Power Output and Velocity

Power output in climbing can be measured using devices that track movements and forces applied during climbs. While less common in climbing, technologies similar to those used in cycling (like power meters) are emerging Krawczyk et .al (2021). For climbing competitions such as speed climbing, speed is a direct measure of performance and can be monitored to assess improvements or declines in performance over time.

For non-speed disciplines, metrics like power output and high velocity during dynamic movements or on boulder problems are also relevant Levernier (2021).

Internal Load Indicators

1) **Perception of Effort (RPE)** The Rating of Perceived Exertion (RPE) is a widely used method to gauge internal load Haddad [2017] Wallace [2009]. Climbers rate their perceived exertion during or after climbing sessions, which can be correlated with physiological measures.

2) **Session-RPE** The session-RPE method involves multiplying the climber’s RPE score by the duration of the climbing session. This provides a single value that represents the overall training load. This method is simple and effective for tracking internal load across different training sessions.

3) Heart Rate (HR) Monitoring

Heart rate (HR) measurements in climbing are an important parameter for assessing climbers' physiological responses, but their significance in relation to climbing performance is not straightforward. Studies, including those by Mermier et al. [1997], Watts and Drobish [1998], and others, indicate that HR increases with the difficulty and inclination of the climb. However, HR does not necessarily follow the traditional linear relationship with oxygen consumption (V˙O2) seen in other forms of exercise like treadmill running or cycling. This is due to the upper body stress and static contractions required during climbing, which can elevate HR without a corresponding increase in V˙O2. While HR is useful for understanding general exertion levels, it may not be the most reliable indicator of climbing performance alone. Other factors, such as climbing economy, oxygen uptake, and ventilation efficiency, might provide more meaningful insights into a climber's ability and endurance.

4) Heart Rate Variability (HRV)

Assessing heart rate variability (HRV) both in resting conditions and following exercise is regarded as one of the key methods for evaluating an athlete's adaptation to training Buchheit et al. [2007], Plews et al. [2012] . A decline in HRV indices related to vagal activity is typically a sign of negative training responses or non-functional overreaching Bosque [2008]. In contrast, an increase in these same indices is often linked to enhanced fitness levels Lee [2003] and better athletic performance Buchheit [2007] .

While HRV analysis is widely considered beneficial for monitoring endurance training adaptations, the findings from studies involving elite endurance athletes or those with long training histories have been mixed Buchheit et al. [2011].

HRV, which measures the variation in time intervals between successive heartbeats, offers crucial insights into the functioning of the autonomic nervous system and overall recovery (Dong, 2016). For climbers, consistent HRV tracking helps monitor recovery, identify potential overtraining or fatigue, and evaluate how the body is adapting to sustained training efforts.

Hormonal and Biochemical Indicators

1) Hormonal Measures

Hormonal measures such as cortisol and testosterone levels provide insights into the climber's stress response and recovery status. Elevated cortisol levels may indicate increased stress or overtraining, while testosterone levels can reflect muscle recovery and adaptation. Regular monitoring of hormones can help assess the athletes physiological response to training loads Conte [2020].

2) Biochemical Markers Serum Creatine Kinase (CK)

Serum CK levels are commonly used to assess muscle damage and recovery Mougios [2007]. Elevated CK levels can indicate muscle damage from intense training, providing valuable feedback on the intensity and recovery needs of sports training .

3) Lactate Concentrations

Blood lactate levels are a critical marker of metabolic stress and performance in climbing. Several studies have investigated the changes in blood lactate post-climbing, revealing that lactate levels rise significantly during and after climbing. For example, Billat et al. [1995] reported a blood lactate level of 5.8 ± 1.0 mmol/L three minutes after a climbing route, while Watts and Drobish [1998] found levels of 5.9 ± 1.2 mmol/L one minute after a four-minute bout on a 102° angle. Booth et al. [1999] documented an increase from 1.43 mmol/L at rest to 6.5 mmol/L following five minutes of climbing, reaching up to

10.2 mmol/L at exhaustion. These increases in lactate suggest that climbing, particularly on more overhanging walls, involves significant anaerobic energy production.

The increase in blood lactate during climbing is influenced by the intensity and duration of the climb. More overhanging walls typically result in higher lactate levels, indicating greater metabolic stress Watts and Drobish [1998]. The recovery process also impacts lactate levels, with active recovery methods like light cycling proving more effective in lowering lactate than passive recovery. For instance, during active recovery, lactate levels may return to baseline faster compared to passive recovery, where elevated levels can persist for up to 30 minutes Watts and Daggett [2000].

These findings emphasize the importance of lactate management in climbing. Efficient clearance and tolerance of lactate can significantly impact performance. Thus, incorporating effective recovery strategies and understanding lactate responses can aid climbers in optimizing their performance.

Biomechanical Indicators

1) Rate of Force Development (RFD)

RFD measures how quickly force can be developed, which is crucial for explosive movements in climbing. High RFD is essential for dynamic climbing and powerful moves. Measuring RFD through tests can help assess and monitor strength and power development in climbers Stein [2021], Vereide [2022].

2) **Jump Tests and Force Platforms**

Jump tests, such as countermovement jumps (CMJ), can be used to assess lower body power and explosive strength. These tests provide data on variables like peak power, jump height, and rate of force development, which are relevant for speed climbing performance Krawczyk [2019, 2020].

3) **Finger flexor strength and endurance**

Are considered the most thoroughly studied factors in the diagnostics of sport climbers. These two parameters are crucial in determining climbing performance, and their importance has been consistently emphasized by researchers. Although dynamometric tests provide valuable data on maximal grip strength, specific climbing-related tests, such as hang tests on holds of varying depths, are used more frequently in practice Rokowski [2017].

4) **Shoulder girdle muscle strength and endurance**

   An essential aspect of monitoring climbers' performance is the assessment of shoulder girdle muscle strength and endurance. This is often evaluated through general strength tests, such as the one-repetition maximum (1RM) pull-up test with additional weight, or endurance tests like the maximum number of consecutive pull-ups. Additionally, climbing-specific assessments, such as the Edlinger test, are employed to gauge endurance under more realistic conditions. The significance of upper body strength and endurance, beyond just finger flexor muscles, has been emphasized in studies by Draga et al. [2023, 2024], which highlight the important role of these parameters in enhancing climbing performance.

Psychological Indicators

1) Profile of Mood States (POMS)

The Profile of Mood States (POMS) is a well-established psychological assessment tool that evaluates mood states across several dimensions, including tension, depression, anger, vigor, fatigue, and confusion. This tool has proven to be a reliable predictor of sport performance in competitive athletes across a wide range of sports and athletic outcomes. In particular, when measured before performance, most POMS scales and the Total Mood Disturbance (TMD) have been found to effectively predict athletic performance Beedie [2000], Terry [2000].

In the context of sport climbing, POMS can be especially useful for understanding the psychological impact of training loads and fatigue. This is consistent with Morgan’s [1980, 1985] mental health model, also known as the iceberg profile, which remains a viable method for analyzing and improving athletic performance. Although the traditional iceberg profile includes various mood states, focusing on POMS scales excluding anger can still provide valuable insights into an athlete's mental state and its influence on performance

Implementation in Sport Climbing

1) **Mood Assessment**: Administering the POMS questionnaire periodically (e.g., weekly or bi-weekly) can help in tracking mood changes in relation to training intensity and recovery. For example, increased tension and fatigue scores might indicate that a climber is experiencing excessive training loads or inadequate recovery.
2) **Integration with Training Data**: Combining POMS scores with external and internal training data provides a comprehensive view of a climber's overall state. This integrated approach allows coaches and climbers to make more informed decisions regarding training adjustments and recovery strategies.

Example Questionnaire for Monitoring

Profile of Mood States (POMS) Questionnaire

- **Instructions**: For each of the following items, please circle the number that best describes how you have felt over the past week.

1) **Tension**: 1 (Not at all) 2 (A little) 3 (Moderately) 4 (Very much)
2) **Depression**: 1 (Not at all) 2 (A little) 3 (Moderately) 4 (Very much)
3) **Anger**: 1 (Not at all) 2 (A little) 3 (Moderately) 4 (Very much)
4) **Vigor**: 1 (Not at all) 2 (A little) 3 (Moderately) 4 (Very much)
5) **Fatigue**: 1 (Not at all) 2 (A little) 3 (Moderately) 4 (Very much)
6) **Confusion**: 1 (Not at all) 2 (A little) 3 (Moderately) 4 (Very much)

Scoring: Higher scores in Tension, Depression, Anger, Fatigue, and Confusion indicate greater negative mood states, while higher scores in Vigor suggest positive mood and energy Kellmann [2002].

Conclusion:

Monitoring training load in sport climbing involves a combination of external and internal measures, including psychological, hormonal, biochemical, and biomechanical indicators. Each measure provides unique insights into different aspects of training stress and recovery, enabling climbers and coaches to tailor training programs effectively. By integrating these various monitoring tools, climbers can enhance their performance, prevent injuries, and ensure optimal adaptation to training loads.

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The Importance of Body Composition, Proportions, and Measurement Methods

Body Composition in Sport Climbing

Body composition, as assessed through somatotype, plays a crucial role in sports, including sport climbing Krawczyk [2014, 2018] Gibson-Smith et. al [2020]. Somatotype is comprised of three components: ectomorphy, endomorphy, and mesomorphy, evaluated according to the Heath-Carter methodology. Ectomorphy refers to the leanness of the body, endomorphy to the amount of body fat, and mesomorphy to muscle development. Sport climbers often exhibit an ectomorphic-mesomorphic body type, indicating a dominance of ectomorphy and/or mesomorphy in their physique . Cárdenas-Fernández [2017] In sport climbing, body height and weight are key factors. Athletes typically have average height but low body mass, which is associated with the necessity to maintain a high relative strength. Climbers are also characterized by low body fat levels, which helps improve their relative strength index. Furthermore, climbers often have longer upper limbs, which facilitates reaching distant holds and reduces strain on the arms. Differences in body composition can also be observed among climbers specializing in different disciplines, with each group exhibiting unique physical characteristics tailored to the demands of their specific climbing style.

Somatic Characteristics and Indicators	**Climbing Discipline**	**Mean**	**SD**	**Min-Max**	**V (%)**
Body Height (cm)	Lead	173,5	7,47	158-185	4,3
	Bouldering	174,5	7,2	167-188	4,1
	Speed	177,5	8,7	166-190	4,9
Body Mass (kg)	Lead	60,4	5,8	48-67	9,6
	Bouldering	62	7,5	51-77	12,1

	Speed	70,7	9,5	64-81	9,5
BMI	Lead	20,02	0,76	18,8-21	3,8
	Bouldering	20,22	1,4	17,8-21,8	6,9
	Speed	22,4		22,4-21,3	3,7
Rohrer Index	Lead	1,17	0,07	1,06-1,17	6,4
	Bouldering	1,16	0,07	1,06-1,28	6,7
	Speed	1,26		1,14-1,4	7,1
Slenderness Index	Lead	44,25	0,77	43,7-45,5	1,7
	Bouldering	44,22	2,3	42,7-45,5	2,3
	Speed	42,93	2,3	41,5-44,4	2,3

Table18. Statistical Characteristics of Body Composition in the Studied Male Climbers Considering the Sport Discipline According to Rokowski et al. (2019).

This table presents the somatic characteristics and indicators for each climbing discipline, including Lead, Bouldering, and Speed, as reported by Rokowski et al. [2019] Tab. 18,19 The data specifically pertains to male climbers. For each discipline, the mean, standard deviation (SD), minimum and maximum values (Min-Max), and the coefficient of variation (V) are provided. The comparison highlights significant differences in body mass, body mass index (BMI), Rohrer Index, and Slenderness Index among the disciplines, emphasizing the distinct physical demands and body composition requirements specific to each type of climbing. Notably, significant differences are marked: between Lead and Speed, and between Bouldering and Speed.

Somatic Characteristics and Indicators	**Climbing Discipline**	**Mean**	**SD**	**Min-Max**	**V (%)**
Body Height (cm)	Lead	159,4	4,4	153-164	2,8
	Bouldering	163,1	2,1	160-166	1,3
	Speed	167	5,7	162-178	3,4
Body Mass (kg)	Lead	47,2	3,7	42-52	7,8
	Bouldering	53	3,4	49-59	6,4
	Speed	55,8	6,8	49-67	12,2
BMI	Lead	18,5	2,08	17,1-19,6	5,8
	Bouldering	20,02	1,73	18-22,2	8,6
	Speed	20,01	1,13	18,59-21,15	5,7
Rohrer Index	Lead	1,16	0,06	1,07-1,24	5,5

	Bouldering	1,22	0,1	1,09-1,36	8,4
	Speed	1,2	0,03	1,13-1,24	3,27
Slenderness Index	Lead	44,13	0,85	43,18-45,44	1,9
	Bouldering	43,43	1,2	41,87-45	2,8
	Speed	43,7	0,47	43,17-44,5	1,07

Table 19 . Statistical Characteristics of Body Composition in the Studied Female Climbers Considering the Sport Discipline According to Rokowski et al. [2019].

This table presents the somatic characteristics and indicators for each climbing discipline, including Difficulty, Bouldering, and Speed, as reported by Rokowski et al. [2019]. The data specifically pertains to female climbers. For each discipline, the mean, standard deviation (SD), minimum and maximum values (Min-Max), and the coefficient of variation (V) are provided. The comparison highlights significant differences in body mass, body mass index (BMI), Rohrer Index, and Slenderness Index among the disciplines, emphasizing the distinct physical demands and body composition requirements specific to each type of climbing. Notably, significant differences are marked: between Difficulty and Speed, and between Bouldering and Difficulty.

1) Body Fat Measurement

In sports climbing, body fat plays a significant role in achieving high performance. Elite climbers are characterized by low body fat, a factor frequently highlighted in scientific literature. Rokowski (2020) found that sport climbers in the lead competition have a low body mass (64.0 ±4.42 kg), low fat percentage (8.41 ±1.96%), and average height (174.16 ±4.40 cm). Other studies confirm that lower body fat and mass are crucial for performance in climbing, as they influence relative muscle strength (Rokowski & Tokarz, 2007).

Somatic analyses of climbers have shown that international-level athletes possess significantly lower skinfold sums—by 40.5%—compared to national-level athletes. This was reflected in their lower fat mass, with international climbers showing a fat mass of 14.4 ±2.0%, compared to the higher value of 15.66 ±2.74% for national climbers (Ozimek et al., 2016). Compared to the general population, elite climbers exhibit lower fat percentages, suggesting a positive correlation between lower body fat and athletic performance (Ozimek et al., 2016).

In speed climbing, athletes tend to have slightly higher body fat levels compared to other climbing disciplines. Research reported a mean body fat percentage of 9.42 ±1.82% for speed climbers, in contrast to 7.43 ±1.89% for bouldering climbers (Levernier et al., 2020).

Although some researchers argue that the Body Mass Index (BMI) does not have a direct link with climbing performance, lower body fat and, consequently, lower body weight can contribute significantly to better results in climbing disciplines.

Methods:

- Skinfold Thickness Measurements:
    - Method: Skinfold calipers are used to measure fat thickness at various body sites, using protocols such as the ISAK and Heath-Carter methods.
    - Key Sites: Triceps, biceps, subscapular, suprailiac, abdomen, thigh, and calf.
    - Calculation: These measurements estimate body fat percentage through specific formulas or charts.
- Bioelectrical Impedance Analysis (BIA):
    - Method: BIA uses a small electrical current to estimate fat percentage by measuring tissue resistance.
    - Limitations: Results can vary due to hydration levels, making it less precise.
- Dual-Energy X-ray Absorptiometry (DEXA):
    - Method: DEXA scans use X-rays to differentiate between bone mass, fat mass, and lean tissue, providing high accuracy.
    - Application: Despite its accuracy, DEXA is mostly used in research due to its cost and complexity.

Research Insights:

Studies such as those by Vanesa et al. (2009) emphasize the comparison of skinfold measurements with DEXA in elite climbers, underscoring the importance of precise body fat assessment for performance optimization.

2) Lean Body Mass (LBM)

Definition and Importance:

LBM encompasses the total mass of muscles, bones, organs, and fluids, excluding fat. In climbing, higher LBM correlates with greater strength and power output, critical for dynamic movements and maintaining holds.

Calculation:

- Formula: LBM = Body Weight - (Body Weight × Body Fat Percentage) Heymsfield et. al [2005].

3) Body Mass Index (BMI)

Definition and Limitations:

BMI categorizes individuals based on their weight relative to their height. However, in climbers, BMI can be misleading as it does not differentiate between muscle and fat mass. Climbers often have higher muscle mass, which may result in a higher BMI without excess body fat.

Formula:

- BMI = Weight (kg) / Height^2 (m^2) Heymsfield et. al [2005].

Practical Application:

While BMI is a standard health metric, its limitations in athletic populations, particularly in sport climbers, mean it should be interpreted with caution.

4) Rohrer Index (Ponderal Index)

Definition and Application:

The Rohrer Index, or Ponderal Index, measures body slenderness, which is particularly relevant in climbers, where a leaner physique aids maneuverability and endurance.

Formula:

- Rohrer Index = Weight (kg) / Height^3 (m^3) Roher et. al [1921]

Interpretation:

- Lower values indicate a more slender build, advantageous in climbing.
- Higher values suggest a more robust build, potentially hindering performance.

5) Anthropometric Landmarks: Locations and Proper Nomenclature

Accurate body measurements require identifying specific anatomical landmarks, serving as reference points to ensure consistency and precision in assessing body composition and proportions. Key landmarks include Fig .17:

- Vertex (V): Highest point on the head, used in height measurement.
- Acromion (A): Outermost point on the shoulder, used for shoulder width and arm length.
- Radiale (R): Uppermost point of the radius bone at the elbow, essential for arm length.
- Stylion (Sty): Distal point on the radial styloid process at the wrist, crucial for forearm length.
- Iliocristale (IC): Most lateral point on the iliac crest, used for hip width and skinfolds.
- Trochanterion (TRO): Superior point on the greater trochanter of the femur, relevant for leg length.
- Malleolus Medialis (MM) and Malleolus Lateralis (ML): Prominent points on the ankle, used for lower leg length and ankle circumference.

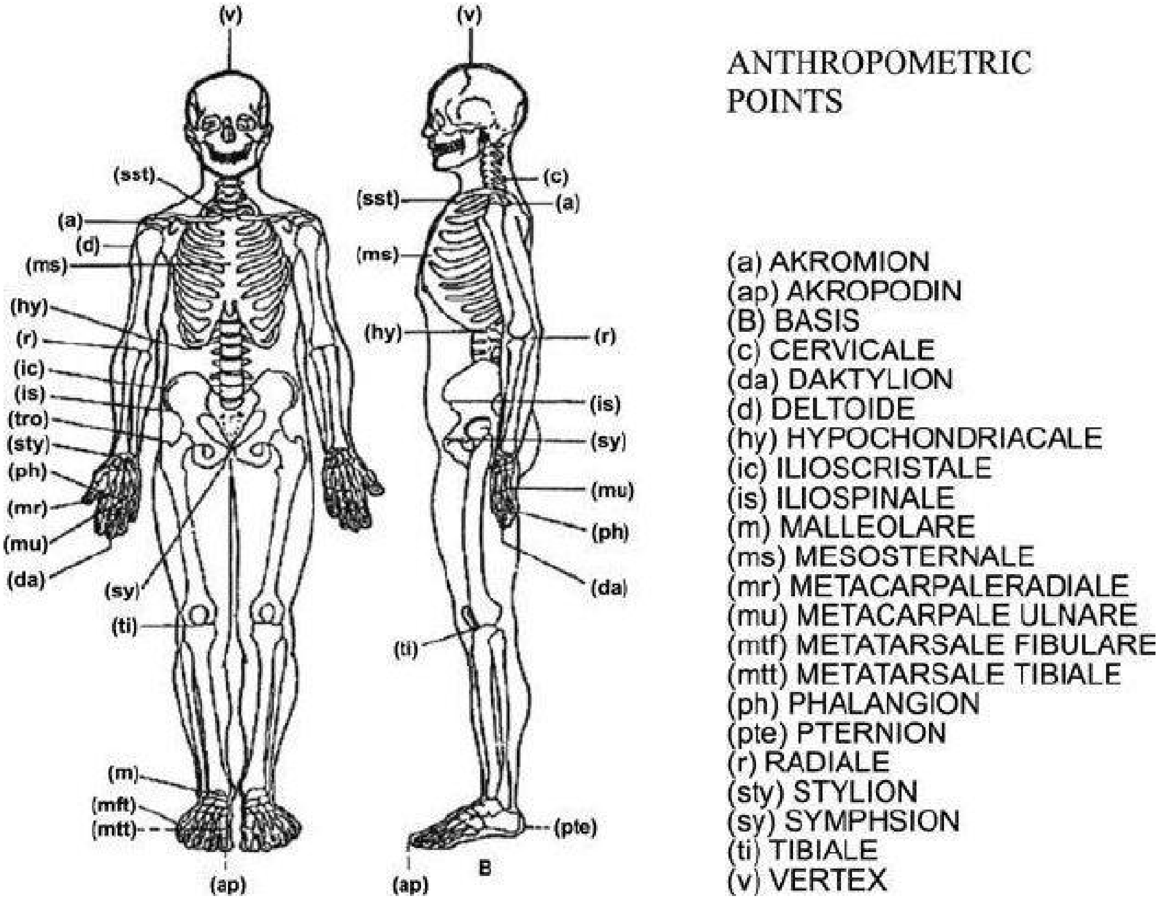

Figure 17. Antropometric landmarks Ujević, D et.al (2006).

6) Ape Index

Definition and Relevance:

The Ape Index, or the ratio of arm span to height, is a significant metric in climbing. A higher Ape Index (where arm span exceeds height) provides an advantage in reaching holds and maintaining balance on the wall.

Calculation:

- Ape Index = Arm Span / Height Lavoie et al. [1986]

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Testing in climbing

Testing in climbing is a complex and multifaceted discipline that involves evaluating a range of motor skills under various energetic conditions. This complexity arises from the need to assess different body structures, such as the fingers (Ozimek, 2016; López-Rivera, 2019), upper limbs (Draga, 2023, 2024), lower limbs (Krawczyk, 2020; Kozina, 2020), and core muscles (Saeterbakken, 2018).

Climbing performance is influenced by multiple factors, including strength (Michailov, 2018), endurance (Michailov, 2018; Balas, 2021), power (Draper, 2011; Krawczyk, 2020), and flexibility (Draga, 2020). To gain a comprehensive understanding of climbing ability, effective testing must address these diverse aspects, ensuring a well-rounded assessment of each contributing factor to overall climbing performance.

Core Criteria for Evaluating Climbing Performance: Reliability, Standardization, Validity, and Specificity.

For exercise tests to be useful in assessing the physical fitness of climbers, they must meet several key criteria that ensure accurate McGuigan (2019). Comfort (2023), reliable, and sport-specific information about a climber's abilities. These criteria include reliability, standardization, validity, and specificity.

Specificity is closely related to validity. A test must be designed to assess the particular physical attributes relevant to climbing. For example, maximal strength tests should involve overcoming significant external resistance, while endurance tests should vary in length depending on whether they assess aerobic or anaerobic capacity. The use of climbing-specific dynamometers, which can measure various mechanical parameters, enhances the specificity, reliability, validity, and objectivity of the tests.

Reliability refers to the consistency of test results across repeated trials. A test is considered reliable if a group of climbers can perform it multiple times under the same conditions, and the results remain consistent. Reliable tests are crucial because they accurately reflect the actual state of the measured abilities, allowing for meaningful comparisons between different climbers and for tracking progress over time

Standardization is another essential aspect. For a test to be standardized, all conditions of the test should be identical for every climber. This includes factors such as climbing hold size, body, arm, and finger positions, as well as the settings for workload parameters. Standardization ensures that any variation in results is due to the athlete's performance rather than external factors, which enhances the test's reliability Atkinson & Nevill, (1988), McGuigan (2019) Fig 18.

Validity concerns whether the test accurately measures what it is intended to measure. In the context of climbing, this means that the workload of the test should be specific to the demands of the sport. For example, using standard hand dynamometers or cycle ergometers might not accurately assess the strength or work capacity required in climbing. A valid test for climbers should involve climbing-specific tasks that mimic the physical and technical demands of the sport. However, it is important to note that the test should not exactly replicate the efforts required in actual climbing (e.g., lead or bouldering) but should focus on the specific ability it aims to assess, such as maximal strength or aerobic endurance .

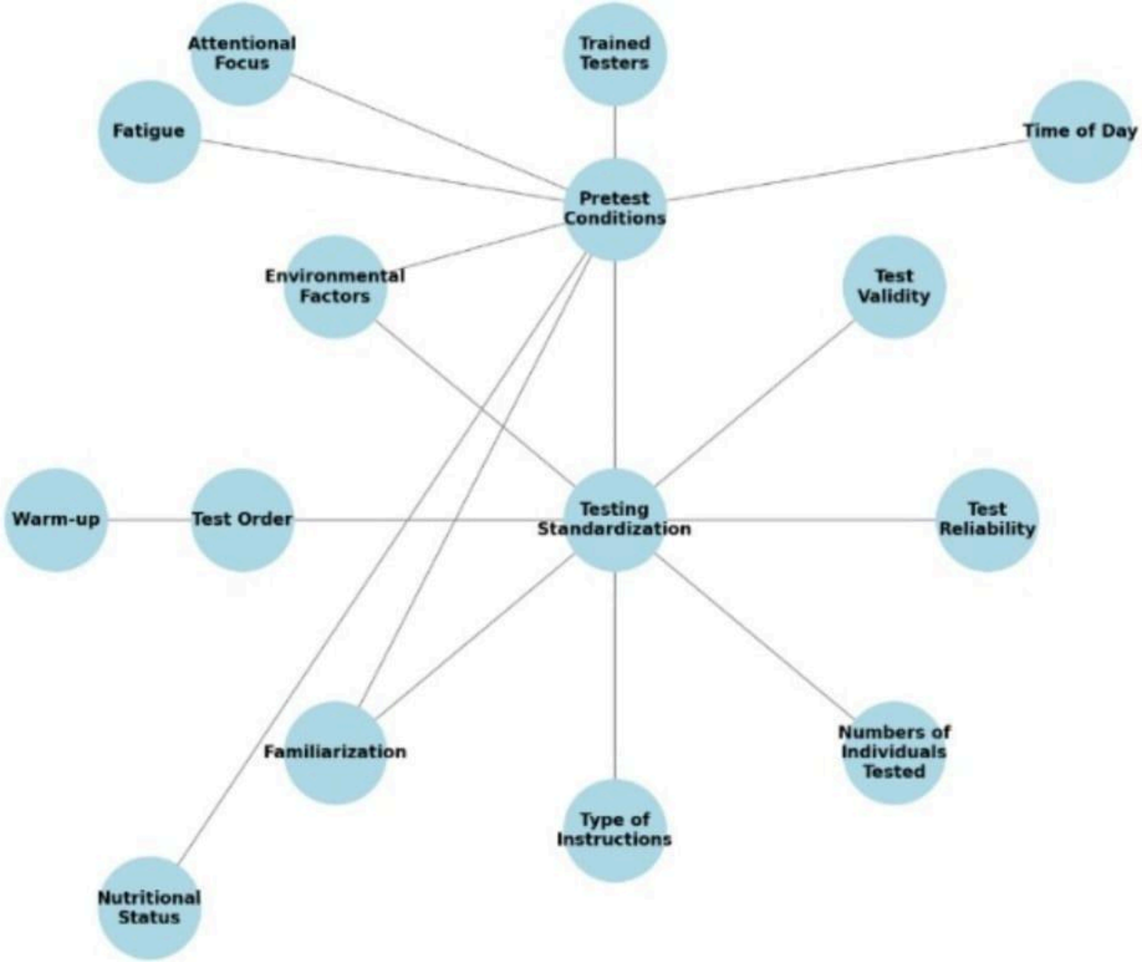

Figure 18. The diagram illustrates the various factors that contribute to the standardization of testing protocols.

Practical Tips for Fitness Testing in Climbing

Test Specificity:

- Relate Tests to Climbing: Design tests that reflect the specific demands of climbing. For example, focus on finger strength tests, endurance assessments on a climbing wall, or explosive power exercises such as pull-ups. The closer the tests mimic climbing movements, the more relevant and accurate the results.

Testing Order:

- Sequence of Testing: Begin with body composition assessments first. Follow this with power tests while the athlete is fresh. After that, move on to maximal strength tests. Endurance tests should be performed last due to the fatigue they induce.
- Separate Power and Endurance Tests: Ideally, schedule power and endurance tests on separate days to avoid the effects of fatigue. This ensures that the results from each type of test are accurate and not compromised by fatigue from the other.

Warm-Up:

- **General Warm-Up:** Start with a general warm-up to elevate body temperature and enhance joint mobility. Include dynamic stretching and light aerobic exercises.
- **Test-Specific Warm-Up:** Follow the general warm-up with exercises specific to the upcoming test.

Climbing-Specific Warm-Up: Climbers should particularly focus on properly warming up their fingers in different grip positions—open grip, half crimp, and full crimp. Special attention should be given to the ring finger, as it is most prone to injury. Additionally, ensure thorough activation of all muscles responsible for upper limb flexion and shoulder girdle stability, such as:

Finger Flexors: Flexor Digitorum Profundus, Flexor Digitorum Superficialis

Forearm Muscles: Brachioradialis, Pronator Teres

Biceps Brachii: For elbow flexion

Triceps Brachii: For elbow extension

Deltoid: For shoulder abduction

Rotator Cuff Muscles: Supraspinatus, Infraspinatus, Teres Minor, Subscapularis

Testing Standardization:

- **Pretest Conditions:** Keep conditions like time of day, nutrition, hydration, and rest consistent across all testing sessions.

- **Trained Testers:** Use experienced testers to administer the tests, ensuring consistency in test administration and results.
- **Test Validity and Reliability:** Choose tests that are validated for climbing performance and are reliable over repeated measures.
- **Environmental Factors:** Control variables such as temperature, humidity, and surface to reduce external influences on performance.
- **Test Order:** In the assessment of strength and power in climbing, the sequence of tests is a pivotal factor that can influence the results. It is essential to consider how one test might impact the performance in subsequent tests. One significant factor is post-activation potentiation (PAP), which refers to the phenomenon where performing a maximal strength test can enhance performance in subsequent power tests (Suchomel et al., 2016; Crewther et al., 2011).Ideally, to minimize potential confounding effects, strength and power tests should be scheduled on separate days. However, practical considerations often necessitate conducting tests within the same training session. In such cases, the sequence of testing becomes fundamental, as the order in which tests are administered can create order effects that may impact the accuracy of the results. Moreover, individual variability in response to PAP or preconditioning must be taken into account. Climbers may exhibit different levels of potentiation, which can influence their performance. Therefore, it is important to standardize the order and timing of tests as much as possible to ensure reliable and valid outcomes. Recognizing and addressing these factors can enhance the precision of the testing process and improve the overall assessment of climbing performance.
- **Familiarization:** Allow athletes to practice the tests beforehand to reduce the learning effect and ensure more accurate measurements.
- **Type of Instructions:** Give clear and consistent instructions to all participants to ensure uniformity in how the tests are performed.
- **Number of Individuals Tested:** Maintain a consistent number of individuals in each testing group to allow for reliable statistical comparisons.

Motivation and Feedback:

- **Use Feedback to Motivate:** Provide feedback to the athlete after tests to help set training goals and motivate improvement. This is crucial for addressing specific weaknesses and enhancing strengths.

Recording and Reporting:

- **Track Body Mass and Metrics:** Record body mass and other relevant metrics before testing to ensure consistency. This data should be reported to the athlete and coaching team for training adjustments.

Repeat Testing for Monitoring:

- **Frequency:** Conduct major tests every 4 to 6 weeks to evaluate training effectiveness. This allows enough time to observe training adaptations.
- **Non-Invasive Tests:** Tests like Rate of Force Development (RFD) or Countermovement Jump (CMJ) can be repeated more frequently as they induce minimal fatigue and are quick to perform.
- **Training Impact Consideration:** When interpreting the results of frequent tests like RFD or CMJ, the coach must consider the impact of ongoing training on these outcomes. The results might reflect not only the athlete's current capacity but also the accumulated fatigue from recent training sessions.
- **Endurance Tests:** Perform endurance tests less frequently due to the higher levels of fatigue they generate.
- **Body Mass Monitoring:** Body mass can be monitored without restrictions, as it doesn't interfere with training. Similarly, psychological assessments like the Profile of Mood States (POMS) questionnaire can be conducted regularly without impacting physical performance.

Interpretation of Results:

- **What:** Analyze the results to determine the athlete's strengths and weaknesses. For example, a consistent increase in RFD might indicate improved power output, while stable CMJ results might show maintained or improved explosive strength.
- **Why:** Understanding why these results are important helps guide training focus. If RFD scores decrease, it might signal fatigue or overtraining, which needs to be addressed in the training plan.
- **How:** Use the data to adjust the training program. If power tests show a decline, the athlete might need more recovery time or a focus on power training. Conversely, if endurance tests improve, it might indicate that the current training regimen is effective for building endurance.

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Strength Capacities and Terminology

Strength Terminology

Muscular strength, which is the capacity to resist external resistance or handle one's body weight during static or slow, high-intensity movements [Szopa et al., 1996], is a key factor in various sports, including sport climbing. This type of strength relies heavily on the anaerobic and phosphagenic energy systems, involving actions like pulling, lifting, and pushing. Assessing muscular strength can be done through both laboratory and associative tests. Laboratory tests, often performed in biomechanics labs [Osiński, 2003], focus on measuring maximum strength in controlled settings, while associative tests, such as pull-ups or bench presses, evaluate strength in more functional, movement-based scenarios. Below, we explore key strength terminologies relevant to athletic performance, highlighting the specific parameters and aspects measured in each Tab. 20.

1) Dynamic Strength

Dynamic strength is the capacity to apply force while the muscles undergo changes in length, usually moving through a full range of motion. This type of strength is crucial for actions like lifting, pushing, or pulling objects. A commonly used approach to measure muscular strength is through maximal dynamic testing, where the goal is to identify the heaviest load that can be lifted. Such testing is frequently performed using a one-repetition maximum (1-RM) or three-repetition maximum (3-RM) protocol (McGuigan et al., 2022). When evaluating strength endurance, tests involving 8-12 repetitions at the maximum possible weight are commonly employed (Haff and Dumke, 2012).

Aspects Measured:

Parameter Units	Definition	Calculation Method
Repetition Count	A single cycle of movement, typically used in exercises where multiple cycles (repetitions)	Count the number of complete movements performed.
Power (W)	The rate at which work is performed, calculated as the product of force and velocity.	Power = Force × Velocity ($P = F \times v$)
Average Power (W)	The mean power output over a specified duration or number of repetitions.	Average Power = Total Work / Total Time
Velocity (m/s)	The speed of movement, especially critical in explosive activities like sprinting or jumping.	Velocity = Distance / Time ($v = d / t$)
Rate of Force Development (RFD) (N/s)	The speed at which force is developed during the initial phase of muscle contraction, measured over various time intervals (e.g., 0-50ms, 0-100ms, 0-200ms).	RFD = Change in Force / Change in Time ($RFD = \Delta F / \Delta t$) for each specific time interval

Impulse (N·s)	The total force exerted over time during dynamic movements, reflecting the overall effectiveness of force application.	Impulse = Force × Time (Integral of the force-time curve)

Table 20. Key variables assessed during dynamic movements, including definitions and calculation methods.

2) Absolute Strength

Definition:

Absolute strength is the total amount of force an individual can produce, regardless of body weight.

Aspects Measured:

- Maximal Force Output: The highest level of force an athlete can produce in a single effort, commonly measured during one-repetition maximum (1RM) tests.

3) Relative Strength

Definition:

Relative strength is the amount of force an individual can produce relative to their body weight. This measure is crucial for athletes in sports where body weight impacts performance, such as gymnastics or climbing.

Aspects Measured:

- Force-to-Weight Ratio: The ratio of maximal force output to body weight, providing insight into how efficiently an athlete can move their own body or external loads relative to their size.

4) Isometric Strength

Definition:

Isometric strength refers to the ability to produce force without any change in muscle length or joint movement. This strength type is often assessed in static positions, where the muscle is engaged but does not visibly shorten or lengthen McGuigan (2019) Tab. 21.

Parameter Units	**Definition**	**Calculation Method**
Peak Force (N)	Measures the absolute (N), relative (N/kg)	PF (Absolute peak force), PF/body mass (kg)
Average Force (N)	Measures the average force produced over a specific time period during the isometric test.	Average force over a selected time period (e.g., 0–100 ms)
Rate of Force Development (RFD) (N/s)	Measured in several ways from the relationship between force and time, including overall, average, peak RFD, and within specific time periods (e.g., 0–100 ms).	RFD0-50 ms, RFD0-100 ms, RFD0-150 ms, RFD0-200 ms, RFD0-250 ms, RFD50-100 ms, RFD100-150 ms, RFD150-200 ms, RFD200-250 ms (calculated as F/time for each interval)
Impulse (N·s)	Integral of force–time.	Integral of the force-time curve, computed as the area under the curve (Force x Time)
Starting Strength (N)	Force at 50 ms.	F at 30 ms
Index of Explosiveness	The ability to produce force in the minimal amount of time.	F at 50 ms/F at 100 ms
Reactivity Coefficient	Ratio of the index of explosiveness to body mass.	Index of explosiveness/body mass (kg)
S-Gradient	The RFD at the start of the movement (often calculated over the first half of the movement).	RFD calculated over the initial part of the movement (e.g., RFD0-50 ms, RFD0-100 ms)
A-Gradient	The RFD during the latter stage of the movement.	RFD calculated during the latter part of the movement (e.g., RFD100-150 ms, RFD150-200 ms, RFD200-250 ms)

Table 21. Key variables assessed during isometric tests, including definitions and calculation methods adapted from McGuigan 2019.

5) Reactive Strength

Definition:

Reactive strength is the ability to rapidly switch from an eccentric (muscle lengthening) to a concentric (muscle shortening) contraction. It is particularly relevant in plyometric exercises that involve quick, explosive movements McGuigan (2019) Tab. 22.

Aspects Measured:

Parameter Units	Definition	Calculation Method
Reactive Strength Index (RSI)	A measure of reactive strength calculated by dividing jump height by ground contact time.	RSI = Jump Height / Ground Contact Time
Rate of Force Development (RFD) (N/s)	The speed at which force can be produced during the transition from eccentric to concentric phases.	RFD = Change in Force / Change in Time (RFD = $\Delta F / \Delta t$)
Impulse (N·s)	The total force generated during the rapid stretch-shortening cycle.	Impulse = Force × Time (Integral of the force-time curve)
Flight Time (s)	The time spent airborne during a jump, indicating explosive capability.	Measure the time from take-off to landing during a jump.
Contact Time (s)	The duration of ground contact during a plyometric movement, essential for assessing efficiency in transitioning from eccentric to concentric actions.	Measure the time the foot is in contact with the ground during the movement.

Table 22. Key variables assessed during isometric tests, including definitions and calculation methods.

6) Strength Endurance

Definition:

Strength endurance is the ability to sustain force production over an extended period. It is critical for activities that require prolonged muscular effort, such as long-distance running, cycling, or high-repetition weight training McGuigan (2019).

Aspects Measured:

- Endurance Capacity: The ability to maintain a certain percentage of maximal force over time, typically tested through high-repetition exercises.
- Time to Fatigue: The duration an athlete can maintain a specific force output before fatigue sets in.

7) Starting Strength

Definition:

Starting strength refers to the ability to generate force at the very beginning of a movement, particularly from a static position. It is critical in activities requiring a quick start, such as sprinting, powerlifting, or jumping McGuigan (2019).

Aspects Measured:

- Initial Rate of Force Development (RFD): The rate at which force is generated at the onset of movement, measured within the first 50-100ms of a contraction.
- Impulse: The total force generated during the initial phase of movement, indicating how effectively an athlete can overcome inertia.

8) Power and strnengt endurance

Definition:

Power endurance is the ability to sustain high-intensity, powerful movements over an extended period. Unlike strength endurance, which focuses on maintaining force output, power endurance emphasizes maintaining high power output during repeated explosive efforts.

Difference from Strength Endurance:

- Power Endurance: Involves maintaining the ability to produce high power repeatedly over time, such as in repeated sprints or plyometric exercises. It is crucial for sports requiring continuous bursts of explosive effort.
- In contrast, strength endurance refers to the ability to sustain lower, but consistent, levels of force production over longer periods. Traditionally, muscular endurance has been defined as *"a measure of the capacity to perform repeated contractions with a given load or exerting force for an extended period"* (Lawton et al., 2013). It is commonly emphasized in activities such as distance running, high-repetition resistance training, or prolonged physical labor, where muscle endurance is more important than explosive power.

Key Mechanical Concepts in Strength and Performance

In the context of strength, several mechanical definitions are essential for understanding how these concepts apply to athletic performance:

- **Power**: Defined as the work performed per unit of time, power is crucial in climbing, particularly when quick, forceful movements are necessary. Mathematically, power can be expressed as: $P = force \times velocity$ or $P = \frac{W}{t}$

  where $\boldsymbol{W}$ is work and $\boldsymbol{t}$ is time Turner (2020).
- **Explosive Strength**: This refers to the ability to "push or pull hard and fast," particularly over a short period. It is closely related to the rate of force development (RFD), which is the change in force over a given period, expressed as RFD= $\frac{\Delta F}{\Delta t}$.
- **Force**: In mechanical terms, force is the ability to accelerate a mass, following Newton's First Law of Motion, and is expressed as $F = m \times a$
- , where $\boldsymbol{m}$ is mass and $\boldsymbol{a}$ is acceleration Turner (2020).
- **Impulse-Momentum Theorem**: This concept explains the momentum, which is the product of force and the time over which it is applied, and its effect on the velocity change of an athlete. It is represented as $p = F \cdot t = m \cdot \Delta v$ where $\boldsymbol{p}$ is momentum Turner (2020).

Understanding these mechanical principles is crucial in climbing, where the balance of power, force, and the ability to generate explosive strength significantly impacts performance.

The Importance of Muscular Strength in Sport Climbing

Relative and Absolute Strength – Dynamometric Tests

Research by Watts et al. [1993] utilized the "grip strength" dynamometric test to assess the strength capabilities of elite World Cup climbers. The study found that while male climbers' absolute strength was around the 50th percentile compared to the general population, their relative strength was in the 80th percentile. Female climbers exhibited high relative strength, surpassing the 90th percentile, even though their absolute strength was around the 75th percentile. These findings suggest that in climbing, relative strength—strength relative to body weight—might be more critical than absolute strength.

Further research by Rokowski [2006] reinforced this, showing that elite climbers performed better in grip strength tests, especially when strength was normalized to body weight, underlining the importance of relative strength in climbing. However, this study also questioned the significance of absolute strength, noting that it might not be the sole determining factor for climbing performance, or that the tools used to measure strength may not fully capture the specific demands of climbing.

Testing 1RM (One Repetition Maximum)

Overview of 1RM Estimation Equations

1RM testing is a crucial component in assessing an individual's maximal dynamic strength. However, directly testing 1RM can be challenging, particularly in practical settings where time constraints, safety concerns, and resource availability may prevent frequent testing. As a result, various estimation equations have been developed to predict 1RM without the need for direct testing.

These estimation methods are grounded in the relationship between the maximum load that can be lifted and the number of repetitions performed. The primary advantage of these methods is that they allow for regular adjustments to training programs without the constant need for 1RM testing. They are particularly useful for practitioners and researchers who require a quick and efficient way to gauge an individual's strength levels.

Several commonly used formulas assume different types of relationships between load and repetitions. For example:

- Linear Relationships: Formulas such as Brzycki (1993) suggest a straightforward linear relationship between the load and the number of repetitions.
- Exponential Relationships: The Epley formula (1985) assumes an exponential relationship, which can provide a quick estimate of 1RM.

Below in Tab. 23 is a summary table of common equations used for estimating 1RM.

Authors	**Prediction Equation for 1RM**	**Example (80 kg × 5 repetitions)**
Brzycki, (1993)	load / (1.0278 − 0.0278 × number of repetitions)	80 / (1.0278 − 0.0278 × 5) = 87.4 kg
Epley (1985)	(weight lifted × number of repetitions × 0.0333) + load	(80 × 5 × 0.0333) + 80 = 93.32 kg
Lander (1984)	load / (1.013 − 0.0267123 × number of repetitions)	80 / (1.013 − 0.0267123 × 5) = 88.1 kg
Lombardi (1989)	load × (number of repetitions^0.1)	80 × (5^0.1) = 86.2 kg
Mayhew (1992)	load / (0.522 + 0.419 × e^−0.055 × repetition)	80 / (0.522 + 0.419 × e^−0.055 × 5) = 95.3 kg
O'Conner (1989)	load × (1 + (0.025 × reps))	80 × (1 + (0.025 × 5)) = 90 kg
Tucker (2006)	1.139 × load + (0.352 × reps) + 0.243	1.139 × 80 + (0.352 × 5) + 0.243 = 90.1 kg

Table 23. Estimation of One-Rep Max (1RM) Based on Predictive Formulas Using a Load of 80 kg for 5 Repetitions.

Determining 1-RM Using Velocity Measurement: Implications for Climbing Disciplines

To optimize resistance training, monitoring training load is crucial, with training intensity being the most critical factor for achieving desired neuromuscular adaptations. Traditionally, intensity in resistance exercises has been determined using the 1-Repetition Maximum (1-RM) test, which measures the maximum load that can be lifted only once. However, in recent years, less demanding methodologies, such as velocity measurement, have emerged as effective alternatives to the traditional 1-RM test. Velocity measurement technology is based on the relationship between load and movement speed, allowing for an accurate estimation of 1-RM and its corresponding percentages without the need for a maximal lift test.

Understanding the Velocity-Strength Profile

The velocity-strength profile describes the relationship between the load lifted (as a percentage of 1-RM) and the speed at which that load is moved. This relationship is highly individualized, meaning each athlete has a unique profile that reflects their specific neuromuscular capabilities. By analyzing the velocity at different loads, strength and conditioning coaches can determine an athlete's strength capabilities and make informed decisions about training loads and intensities. This approach provides a more precise and less fatiguing method of assessing strength than traditional 1-RM testing.

A study by Muñoz-Lopez et al. (2017) on the prone pull-up exercise demonstrated a very strong relationship between load (expressed as %1-RM) and mean propulsive velocity ($R^2 = 0.975$). This finding allows for accurate estimation of the velocity at which each percentage of 1-RM is performed. The study emphasizes the importance of using individualized regression equations to estimate %1-RM accurately, as the relationship between load and velocity can vary depending on the athlete's strength level and other factors. This method offers significant practical benefits, such as reducing fatigue and the potential risk of injury, which are often associated with traditional maximal tests.

Differences in Force-Velocity Profiles Among Climbing Disciplines

The force-velocity (F-V) profiles among elite climbers across different disciplines - bouldering, lead climbing, and speed climbing—exhibit significant differences, as highlighted in a study by Levernier and Samozino (2020). Boulderers demonstrated a higher power output (Pmax) compared to lead and speed climbers, primarily due to their ability to produce greater force at high velocities. This ability is crucial given the dynamic and high-intensity nature of bouldering, where maximal power output was significantly higher (11.03 W·kg−1) than that of lead climbers (8.57 W·kg−1) and speed climbers (8.13 W·kg−1).

Several factors contribute to the superior power production by boulderers. First, bouldering is characterized by dynamic and explosive movements that require athletes to produce rapid and powerful upper body actions. Boulderers have developed a higher capacity to generate force quickly, as evidenced by their significantly higher initial velocity (V0) values compared to lead and speed climbers. Specifically, boulderers recorded a V0 of 2.09 m·s−1, compared to 1.59 m·s−1 for lead climbers and 1.64 m·s−1 for speed climbers.

In contrast, speed climbing emphasizes lower limb velocity, with climbers relying on quick, efficient leg movements to ascend the wall as fast as possible. The test focused solely on upper body performance, which may have underestimated the full velocity potential of speed climbers. Additionally, in speed climbing, climbers typically avoid starting from a fully extended arm position, which minimizes the range of motion and maintains velocity. On the other hand, both boulderers and lead climbers often initiate movements from a fully extended arm position to maximize range of motion, requiring fast force production across a broader amplitude. This difference in movement patterns helps explain why boulderers excel in producing rapid upper body power, which is less critical in speed climbing.

No significant differences were observed in the maximal force (F0) generated among the disciplines, with all groups showing high values (between 19.81 and 21.23 N·kg−1). These high F0 values reflect the elite status of the climbers in the study, who have undergone years of rigorous training to develop substantial upper body strength. The study highlights that while high force production is necessary across all climbing disciplines, the ability to convert this force into rapid movement is particularly crucial for boulderers.

Implications for Training and Performance

These differences suggest that training regimens for climbers should be tailored to the specific demands of their discipline. Boulderers benefit from focusing on exercises that enhance their ability to produce force rapidly and maintain power output at high velocities. On the other hand, lead climbers might require a balance of strength and endurance training, with an emphasis on sustaining force production over longer durations and under varying loads.

The research underscores the importance of a specialized approach to training in competitive climbing, particularly as the sport evolves with events like the combined Olympic format, where climbers must compete across all three disciplines. The ability to optimize the force-velocity-power profile according to the specific demands of bouldering, lead climbing, or speed climbing could provide a competitive edge, particularly in multi-discipline competitions.

Overview of Velocity Measurement Technologies in Velocity-Based Training

Velocity-Based Training (VBT) has gained significant attention in the strength and conditioning community for its ability to optimize performance through precise monitoring of movement velocity during resistance exercises. Central to the effectiveness of VBT is the accurate measurement of velocity, which allows coaches and athletes to tailor training loads, monitor fatigue, and adjust exercises in real-time to maximize outcomes. Various technologies have been developed to measure velocity with differing levels of accuracy, portability, and ease of use. Below is an overview of the primary velocity measurement technologies used in VBT, including how they work, their advantages, and their limitations.

1) Linear Position Transducers (LPTs)

How They Work:

Linear position transducers measure the vertical displacement of a barbell or other equipment by attaching a cable to it. As the athlete lifts the weight, the cable extends or retracts, and the transducer records the velocity based on the rate of this movement.

Advantages:

- High accuracy in measuring barbell velocity and displacement.
- Provides real-time feedback, allowing immediate adjustments.
- Suitable for a wide range of exercises.

Disadvantages:

- Requires attachment to equipment, which can be cumbersome.
- Cables can interfere with movement if not positioned correctly.
- Generally more expensive than other options.

2) Inertial Measurement Units (IMUs)

How They Work:

IMUs use accelerometers and gyroscopes to track the movement of the barbell or the athlete's body. These sensors measure the velocity by calculating the rate of acceleration and angular velocity, which are then processed to provide velocity data.

Advantages:

- Portable and can be used in various training environments.
- Does not require direct attachment to a barbell; can be worn on the body.
- Suitable for tracking complex movements, not limited to linear motion.

Disadvantages:

- Requires sophisticated algorithms to interpret data accurately.
- Potential for errors due to sensor drift or improper calibration.
- Generally less accurate than LPTs, especially for very high-speed movements.

3) Laser-Based Systems

How They Work:

Laser-based systems use laser beams to track the movement of the barbell or athlete in space. The system measures the time it takes for the laser to reflect back from the moving object, which is then used to calculate velocity.

Advantages:

- No physical attachment required, reducing interference with the athlete's movement.
- High precision in measuring velocity over a distance.
- Suitable for a wide range of exercises and movements.

Disadvantages:

- Expensive and often requires a controlled environment.
- Can be affected by external factors such as lighting or other reflective surfaces.
- Requires careful alignment to ensure accurate measurements.

4) Optical Tracking Systems

How They Work:

Optical tracking systems use cameras and software to track the movement of markers placed on the athlete or equipment. By analyzing the position changes of these markers frame by frame, the system calculates the velocity.

Advantages:

- Provides detailed data on movement patterns, not just velocity.

- Non-intrusive, as markers are small and lightweight.
- Can capture a wide range of movement types, making it versatile.

Disadvantages:

- Requires complex setup and calibration.
- High cost, particularly for systems with multiple cameras.
- Data processing can be time-consuming and may not provide real-time feedback.

5) Wearable Devices

How They Work:

Wearable devices typically combine IMUs with additional sensors, such as accelerometers and gyroscopes, to measure velocity and other performance metrics directly from the athlete's body.

Advantages:

- Extremely portable and easy to use.
- Provides real-time feedback, beneficial for both athletes and coaches.
- Can be used for a variety of exercises, including those not involving barbells.

Disadvantages:

- May provide less accuracy compared to systems specifically designed for barbell tracking.
- Data can be influenced by extraneous body movements unrelated to the exercise.
- Requires regular calibration to maintain accuracy.

Summary:

- Each VBT technology comes with its own set of strengths and weaknesses. Linear position transducers and laser-based systems are generally more accurate but less portable and more expensive. In contrast, IMUs and wearable devices offer greater flexibility and ease of use but may sacrifice some precision. The choice of technology often depends on the specific needs of the athlete or coach, the type of exercises being performed, and the training environment.

- Research supports the effectiveness of VBT in practical applications. The study by Muñoz-López et al. (2017) confirms that velocity measurement is a reliable method for determining training intensity (in terms of %1-RM) and assessing maximal force, velocity, and power capabilities in the prone pull-up exercise. This technology enables more precise monitoring and optimization of resistance training programs, benefiting both coaches and athletes.
- Additionally, Levernier and Samozino's (2020) research on elite climbers highlights significant differences in the force-velocity-power profiles of boulderers, lead climbers, and speed climbers, with boulderers demonstrating superior power and velocity attributes. These findings suggest that bouldering, with its emphasis on explosive movements, might be the most favorable discipline in combined climbing events. Future research could explore how targeted training can further optimize these profiles to enhance performance across different climbing disciplines.

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Associative Tests

Associative tests, such as fingerboard hangs or weight relief tests, are also used to measure climbers' strength. Studies by Rokowski et. al [2007,2013], and later by Ozimek [2016], found that advanced climbers scored higher on these tests, particularly in fingerboard hang tests with maximum load. The correlation between climbing level and fingerboard test performance was significant, with coefficients of R=0.61R = 0.61R=0.61 for advanced climbers and R=0.52R = 0.52R=0.52 in another study. These findings suggest that finger strength, particularly in specific grip positions, is crucial for climbing success.

The validity of these associative tests, particularly the fingerboard hang test, has been supported by studies like Bergua et al. [2018], which found a strong correlation (r = 0.84) between fingerboard test results and climbing performance among elite climbers. This correlation emphasizes the importance of specific strength assessments that reflect the unique demands of sport climbing.

Selected Tests for Finger and Arm Strength

In climbing, assessing finger and arm strength is critical for performance evaluation and training. Several specialized tests have been developed to measure these attributes, focusing on maximum strength in various grip positions. Below is a detailed description of these tests, as well as a discussion on the evolution of strength assessment tools used in the sport.

1) Finger Strength Tests

"Edge Hang 1" Test Rokowski (2006),Draga (2014, 2023)

This test measures the finger strength of both hands. The participant grips a 15 mm wide edge using eight fingers (four on each hand) in an open-hand position. The test begins when the participant lifts their feet off the ground, hanging with fully extended arms. The goal is to hang for 3 seconds with the maximum weight possible Photo. 1. The test continues until the participant can no longer sustain the hang with a given weight for 3 seconds. Rest intervals between attempts last 2-3 minutes, and the load is progressively increased with each trial.

Photo. 1. "Edge Hang 1".

2) "Edge Pull-Up" Rokowski (2006), Draga (2014, 2023)

This test assesses both finger strength and arm strength. The participant grips the same 15 mm edge with eight fingers, with their arms positioned shoulder-width apart. The task is to perform a pull-up with the heaviest weight possible. The test begins when the participant lifts their feet off the ground and continues until they are unable to perform the pull-up with additional weight Photo. 2. Rest intervals of 2-3 minutes are observed between attempts, with the load being incrementally increased in subsequent trials.

Photo 2. "Edge Pull-Up" Test (Rokowski 2006).

3) "Edge Scale" Test Köstermeyer (1999), Draga (2014, 2023)

In this test, which measures finger strength, the participant stands on an analog scale and grips a 15 mm edge using five fingers of one hand. The test starts when the participant begins to gradually offload their body weight, and the goal is to achieve the maximum weight reduction on the scale for at least 3 seconds Photo. 3. Rest intervals of 2-3 minutes are maintained between attempts. If the participant manages to fully offload their weight, additional weight is added in the next trial. This test, traditionally used to quantify finger strength in kilograms, can now be performed using modern tools such as a gauge sensor or the Climbro system. These tools allow for more precise and comprehensive measurements.

Photo. 3. "Edge Scale" Test.

Arm Strength Test

"Bar Pull-Up" Test

This test evaluates arm strength. The participant grips a bar with their hands shoulder-width apart. The task is to perform a pull-up with the maximum additional weight. The test starts when the participant lifts their feet off the ground and continues until they can no longer perform the pull-up with increased weight Photo 4. Rest intervals between trials last 2-3 minutes, and the load is increased incrementally in subsequent attempts.

Photo 4. Arm Strength Test.

Advancements in Strength Measurement Tools

The traditional method of measuring finger strength using weight reduction on a scale has been gradually replaced by more sophisticated research tools that allow for a more comprehensive analysis of strength qualities. Modern tools not only measure force in kilograms but also provide data on other important metrics such as force impulse, rate of force development (RFD), mean force, and peak force. These metrics offer a more detailed understanding of an athlete's strength profile and are particularly useful in training and performance diagnostics.

Advanced Measurement Technologies in Climbing

In recent years, the development of innovative measurement technologies has significantly enhanced the precision with which climbing-specific strength parameters can be analyzed. Two prominent tools widely adopted in the climbing community are the **Intelligent Hangboard (Climbro) and Force Sensors (e.g., Tindeq, Chronojump).**

1) Intelligent Hangboard (Climbro):

This advanced system has established itself as the gold standard for strength measurement in sport climbing Photo. 5. Unlike traditional hangboards, Climbro offers real-time data on strength metrics such as peak force Fig. 19 , Rate of Force Development (RFD) Fig. 20. Additionally, Climbro goes beyond just measuring these parameters by providing complete, structured training protocols tailored specifically to the user's strength profile. These protocols guide athletes through customized sessions, helping them target and improve specific areas of strength over time. By combining precise measurements with integrated training plans, Climbro enables climbers and coaches to optimize both performance and strength training strategies.

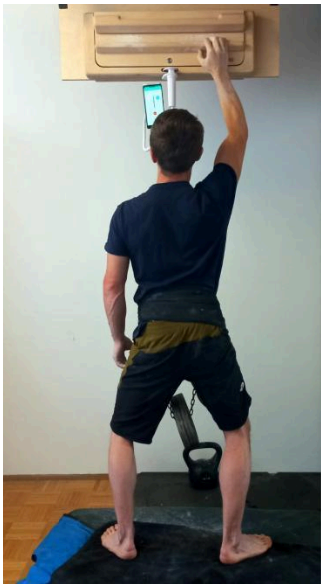
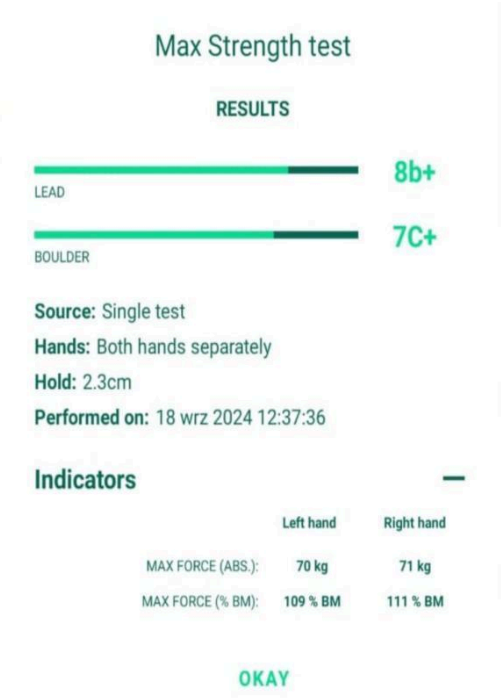


Photo. 5. The photograph shows a one-arm finger strength test using the Climbro device, with additional weight added for counterbalance. Since the individual's finger strength exceeded their body weight, they were able to perform a pull-up on the edge. Therefore, maximum strength capabilities could only be measured after adding extra weight.



Max Strength test

RESULTS

8b+

LEAD

7C+

BOULDER

Source: Single test

Hands: Both hands separately

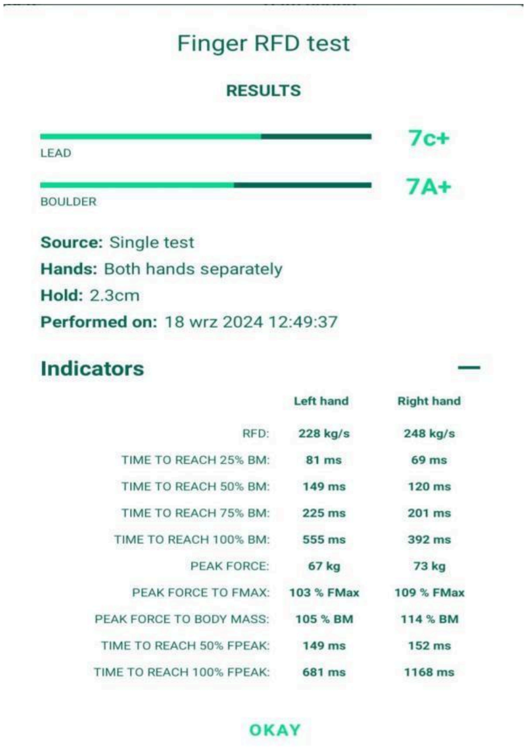
Hold: 2.3cm

Performed on: 18 wrz 2024 12:37:36

Indicators

	Left hand	Right hand
MAX FORCE (ABS.):	70 kg	71 kg
MAX FORCE (% BM):	109 % BM	111 % BM

Figure 19. Figure illustrates the results of a bilateral strength test, displaying both absolute values and values relative to body weight. The test was performed using the Climbro device.



Finger RFD test

RESULTS

7c+

LEAD

7A+

BOULDER

Source: Single test

Hands: Both hands separately

Hold: 2.3cm

Performed on: 18 wrz 2024 12:49:37

Indicators

	Left hand	Right hand
RFD:	228 kg/s	248 kg/s
TIME TO REACH 25% BM:	81 ms	69 ms
TIME TO REACH 50% BM:	149 ms	120 ms
TIME TO REACH 75% BM:	225 ms	201 ms
TIME TO REACH 100% BM:	555 ms	392 ms
PEAK FORCE:	67 kg	73 kg
PEAK FORCE TO FMAX:	103 % FMax	109 % FMax
PEAK FORCE TO BODY MASS:	105 % BM	114 % BM
TIME TO REACH 50% FPEAK:	149 ms	152 ms
TIME TO REACH 100% FPEAK:	681 ms	1168 ms

Figure 20 . Figure shows the results of the RFD test, including the time taken to reach 25%, 50%, 75%, and 100% of the maximum RFD, as well as the peak force and force relative to body weight.

2) Force Sensors (Tindeq, Chronojump Fig. 22, Photo 6, 7): Tindeq, a widely used commercial sensor, offers reliable and valid measurements of essential strength parameters, including RFD, peak force, and mean force Fig. 23. Its ease of use and cost-effectiveness make it an appealing option for both researchers and coaches. Studies such as Labott (2022) have confirmed the reliability and validity of Tindeq in various settings, making it a valuable tool for tracking performance and progress in climbing, even if it does not reach the precision level of Climbro.

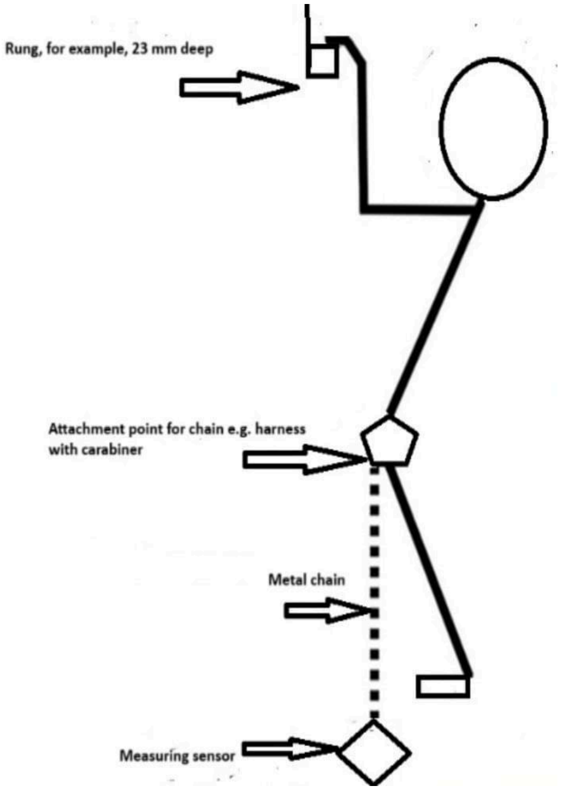


Figure 22. Figure shows the method for testing finger strength in both hands simultaneously, as proposed by Stein et al. (2021).

Photo 6. The photo shows a method for measuring finger strength. The subject stands on a platform connected by a metal chain to a 23 mm edge hold and a measurement sensor. The task is to assume the correct starting position, similar to the IMTP test, and extend the legs. To accurately isolate finger strength, the subject must not pull on the hold with their arms—movement should come solely from the legs, testing the weakest link in the chain, which is the fingers' strength.

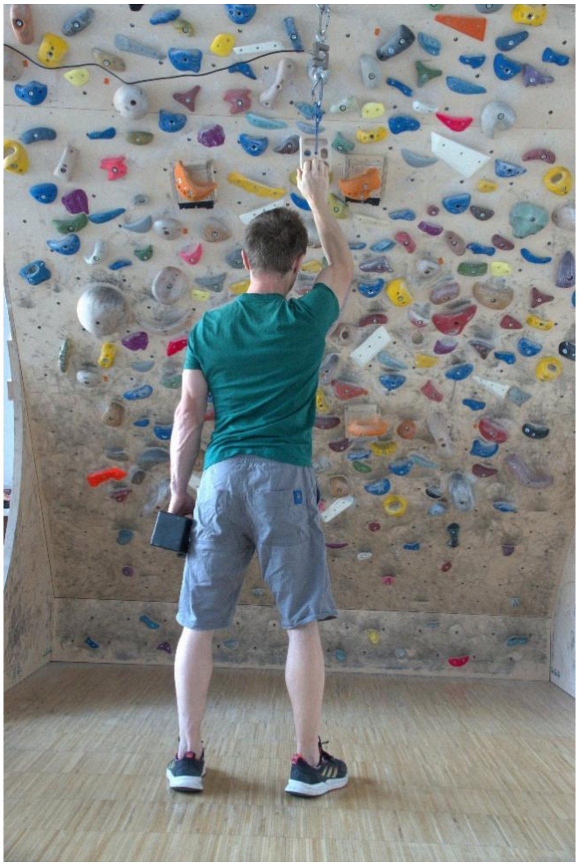
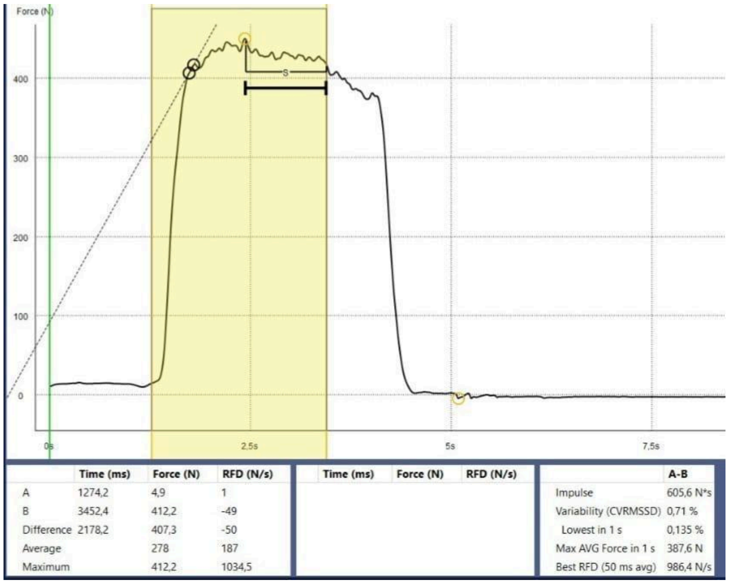


Photo 7 . The photograph shows a test of strength using a sensor placed above. The subject's task is to pull down on a 23 mm edge hold. In the image, the subject has been additionally weighted with an extra load equal to 15% of their body weight, as their relative strength exceeded their body mass. To measure the total force, this additional weight was necessary.



	Time (ms)	Force (N)	RFD (N/s)
A	1274,2	4,9	1
B	3452,4	412,2	-49
Difference	2178,2	407,3	-50
Average		278	187
Maximum		412,2	1034,5

	Time (ms)	Force (N)	RFD (N/s)

	A-B
Impulse	605,6 N*s
Variability (CVRMSSD)	0,71 %
Lowest in 1 s	0,135 %
Max AVG Force in 1 s	387,6 N
Best RFD (50 ms avg)	986,4 N/s

Figure 23. The figure presents the results of a finger strength test performed using the Chronojump force sensor. The analysis includes the maximum force value, rate of force development (RFD), force impulse, and the differences between measurements taken in sample A and sample B.

The Significance of Shoulder Girdle Power in Climbing and the Power Slap Test

Understanding Power vs. Strength in Climbing:

Strength in sports science is defined as the maximum force a muscle or group of muscles can produce against resistance. This can be measured by the maximum weight lifted in a single repetition or the peak force exerted during a contraction. Strength is vital for tasks that involve sustained force application, such as maintaining a hold or overcoming resistance, which is critical in many sports, including climbing.

Power, as defined in sports science, is the ability to exert force rapidly, combining strength with speed to produce explosive movements. Power is typically expressed as the rate at which work is performed or energy is transferred, and is crucial for activities requiring quick, forceful actions (Komi, 2003). In the context of climbing, power is essential for dynamic movements, such as reaching for distant holds or making explosive transitions between positions.

In climbing, it's crucial to differentiate between power and strength, particularly concerning the shoulder girdle muscles. While strength refers to the ability of the muscles to exert force over time, power is the ability to exert force quickly and explosively. In the context of climbing, power is essential for dynamic movements like reaching for holds, dynamic pulls, and explosive transitions, where the climber needs to move swiftly and with precision.

Diagnostic Test: The Power Slap

The Power Slap test Draper (2011) is designed to evaluate the power of the shoulder girdle muscles, which play a key role in such explosive climbing movements. The "power slap" test measures upper limb power generation in climbers. It requires a dynamic pull-up followed by touching the highest possible point on a measurement board, typically a campus board Photo 8. This test can be conceptually compared to the "jump and reach" version of the countermovement jump (CMJ), as both rely on the elastic energy of muscles and tendons and utilize the stretch-shortening cycle (SSC). This observation is based on practical analysis of climbing-specific movement patterns.

Test Instructions:

Normalization:

The test begins by normalizing the participant's reach. The climber's dominant arm should be fully extended at the shoulder and elbow, while the non-dominant arm is fully flexed at shoulder height, holding onto a rung. This helps standardize the starting conditions for all participants. The legs should be supported during this step to ensure consistent positioning.

Starting Position:

The climber starts by hanging from a wooden rung with straight arms, hands placed shoulder-width apart. The grip should be the climber's preferred type, whether an open hand, full crimp, or any variation in between.

The climber should be in a straight-arm hang position, with knees bent and feet positioned behind the body, ensuring no assistance from the legs during the movement.

Procedure:

The test begins with the climber initiating an explosive pull-up, focusing on generating power through the shoulder girdle muscles without using the legs to create momentum.

As they reach the peak of the pull-up, the climber attempts to slap as high as possible with one arm. The height of the slap is a direct measurement of the climber's shoulder girdle power.

Completion:

After each attempt, the climber returns to the ground before the next test begins.

Measurement:

The height of the slap is measured in centimeters, and the test is conducted with one arm at a time.

Equipment Specifications:

- Rung: The test requires a wooden rung that is 45 mm deep with a 12 mm radius, positioned perpendicular to the floor.

- Board: The rung should be mounted on a board with a 20-degree overhang and a minimum height of 140 cm.

This test is a valuable tool for assessing the explosive power of a climber's shoulder girdle muscles, providing insights into their dynamic performance capabilities on the wall.

Photo 8. Campus board (copy from www.climbro.com with permission).

Rate of Force Development (RFD)

The Rate of Force Development (RFD) refers to the speed at which muscles can generate force, making it a key measure of explosive strength. This metric is crucial in evaluating how quickly an athlete can develop force during movements, enhancing performance in activities such as jumping, sprinting, and weightlifting. A higher RFD indicates the ability to produce greater force in less time, contributing to more dynamic and effective athletic performance, even in sports like golf.

According to Maffiuletti et al. (2016), RFD is primarily determined by the capacity to produce maximal voluntary activation in the early phase of an explosive contraction (within the first 50-75 milliseconds). This rapid activation is linked to increased motor unit discharge rates. Both explosive-type and heavy-resistance strength training can improve RFD in various populations, from athletes to elderly individuals. However, accurately and reliably evaluating RFD poses significant challenges, and practical recommendations are necessary for valid measurements in both laboratory and clinical settings.

How to Measure RFD?

RFD can be measured in several ways, each providing different insights into an athlete's ability to generate force:

1) **Average RFD:** This is calculated by dividing the peak force by the time taken to reach it. While it gives a general measure of explosiveness, it might be less accurate due to individual differences in the time taken to achieve peak force.
2) **Time-Interval RFD:** This is measured over specific time intervals (e.g., 0-30 ms, 0-100 ms), allowing an assessment of how quickly an athlete generates force at different stages of the movement.
3) **Instantaneous RFD:** This measures the rate of force development at every millisecond, providing a very precise assessment of RFD.
4) **Peak RFD:** The maximum RFD achieved during a movement, often measured in short time windows (e.g., 5 ms).
5) **Time to Peak RFD:** The time required to reach the maximum RFD. Reducing this time can lead to improvements in explosiveness.

Types of RFD and Their Training Implications

Depending on the nature of the movement, different types of RFD can be identified, which have various implications for training:

1) **Fast-SSC Movements:** These are characterized by short ground contact times (less than 250 ms), such as sprinting. These movements generate lower peak forces but have a higher RFD, crucial for speed.
2) **Slow-SSC Movements:** These involve longer contact times (over 250 ms), like in countermovement jumps (CMJ). These movements allow for higher peak forces but with a lower RFD.

Training Factors Influencing RFD

Different training methods can impact the development of RFD in various ways:

- **Resistance Training:** Increases muscle strength, which can improve both maximum force and RFD.
- **Ballistic Training:** Focuses on fast, explosive movements with low resistance, benefiting RFD improvement.
- **Plyometric Training:** Engages fast, explosive actions, enhancing both RFD and maximum force.
- **Olympic Weightlifting:** Combines high forces and fast movements, potentially improving both RFD and peak force.

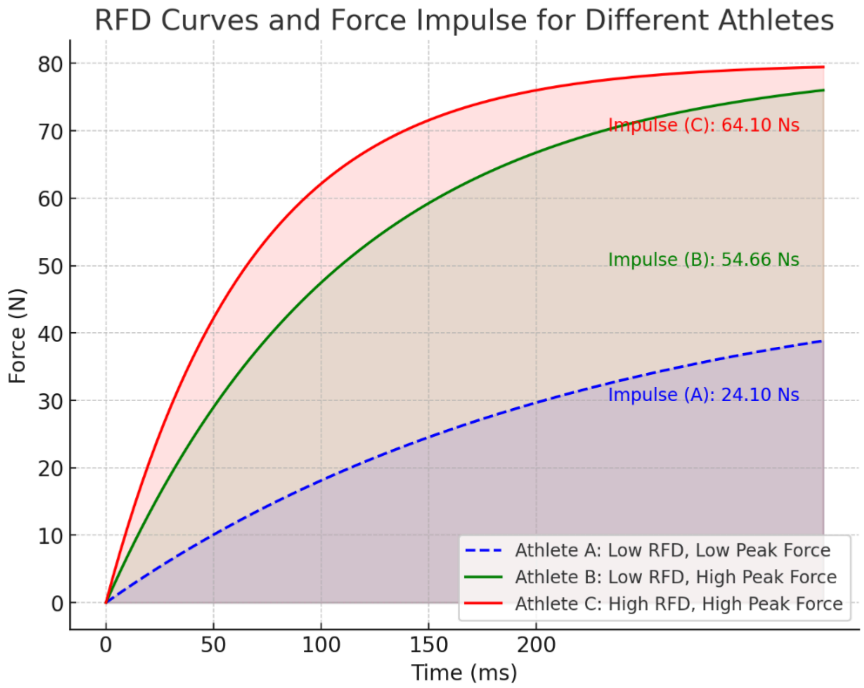


Figure 24. Graphical Representation of Hypothetical RFD and Force Impulse Curves for Three Athletes:

Athlete A: Low RFD, Low Peak Force.The curve rises quickly but reaches a lower peak.

Athlete B: Low RFD, High Peak Force.The curve rises more slowly but reaches a higher peak.

Athlete C: High RFD, High Peak Force. The curve rises quickly and reaches a high peak.

RFD and Force Impulse: Their Significance in Athletic Performance (Fig. 24.)

Impulse is a key concept in understanding force development. It represents the product of force and the time over which that force is applied. Mathematically, impulse is calculated as the area under the force-time curve (as shown by the shaded areas in the graph). Impulse is measured in Newton-seconds (Ns) and reflects the total amount of force generated over time.

- Athlete A: Low RFD, Low Peak Force results in a relatively small impulse since the force peaks early but does not reach a high level. This is typical for athletes focusing on quick, explosive movements.
- Athlete B: Moderate RFD, Moderate Peak Force produces a larger impulse despite the slower force development because the athlete reaches a much higher peak force, sustaining force production over time.
- Athlete C: High RFD, High Peak Force yields the largest impulse, as the athlete quickly generates a significant amount of force and sustains it at a high level. This combination of speed and force maximizes impulse.

Causes of Different RFD and Impulse Profiles Related to Training:

The Rate of Force Development (RFD) and the impulse of force observed in different athletes can be influenced by their specific training regimens. Below is a breakdown of how various types of training can lead to distinct RFD and impulse profiles seen in athletes A, B and C:

1) Athlete A: High RFD, Low Peak Force (Low Impulse)

- Ballistic Training: Athlete A's focus on ballistic training—such as plyometrics, sprint drills, and light-weight explosive exercises—emphasizes speed and the rapid production of force. This type of training enhances the neuromuscular system's ability to quickly recruit motor units, resulting in high RFD. However, since the training does not prioritize heavy loads, the peak force developed remains lower, which limits the overall impulse generated.

2) Athlete B: Moderate RFD, Moderate Peak Force (Moderate Impulse)

- Maximal Strength Training: Athlete B likely emphasizes maximal strength training, such as heavy resistance exercises (e.g., squats, deadlifts, and bench presses). This type of training increases the ability to produce a high peak force due to muscle hypertrophy and the development of Type IIx muscle fibers, which can generate significant force. However, since maximal strength training often involves slower, controlled movements, the RFD is lower. Despite this, the large force output results in a significant impulse.

3) ***At hlete C: High RFD, High Peak Force (High Impulse)***

- Combination of Maximal Strength and Ballistic Training: Athlete C engages in a balanced training program that includes both maximal strength exercises and ballistic or explosive training. This combination improves both the magnitude of force (high peak force) and the speed at which it is generated (high RFD). The inclusion of Olympic lifts, which involve both heavy loads and explosive movements, further enhances both aspects. As a result, Athlete C generates a high overall impulse by producing force quickly and at high levels.

Conclusion:

The training methods an athlete employs can significantly influence their RFD and force impulse profiles. Ballistic training tends to improve RFD but may not maximize peak force or impulse, while maximal strength training enhances peak force and impulse but may not optimize RFD. A combination of both training approaches—maximal strength and ballistic exercises—provides the best of both worlds, enabling athletes to excel in quick force generation and sustained, high overall force production, maximizing their impulse.

The Role of Rate of Force Development (RFD) in Sport Climbing

In sport climbing, particularly in disciplines like bouldering and lead climbing, the ability to generate force rapidly is crucial for success. This attribute, known as the Rate of Force

Development (RFD), plays a significant role in the sport, although its impact has been debated in the climbing community and scientific literature.

Understanding RFD in Climbing

RFD is a measure of how quickly an athlete can generate force, which is particularly important in explosive movements required for dynamic reaches and gripping difficult holds, often referred to as "contact strength." According to Guyon and Broussouloux (2004), maintaining a grip on challenging holds involves both isometric and contact strength, indicating a need for rapid force generation.

Early Research and Findings

Initial studies did not conclusively confirm the importance of RFD in climbing. For instance, research by Ozimek, Rokowski, and colleagues (2016) on 16 elite climbers, which employed classical grip strength tests, found no significant relationship between RFD and climbing performance. The study measured the maximum derivative of force over time (F'max) but observed no substantial differences in RFD across different performance levels.

Recent Insights and Advances

Contrary to these earlier findings, more recent and unpublished studies, which used different hand positions on the grip (where climbers applied force with their fingertips on a dynamometer), have shown that elite climbers exhibit significantly higher RFD levels than non-climbers. However, there were no notable differences in RFD between climbers at different elite levels, suggesting that while RFD is higher in elite climbers compared to non-climbers, it may not differ significantly between high-elite and elite climbers.

Moreover, research by Vereide et al. (2016), which involved 36 climbers from elite to intermediate levels, highlighted a linear relationship between RFD and climbing level (r=0.67). This study recorded RFD as climbers attempted to pull up on a climbing hold while anchored to the ground. The results strongly correlated finger strength in specific grip positions with climbing effectiveness (r=0.82), underlining the importance of RFD in maintaining grip.

RFD in bouldering vs. lead climbing

RFD appears to play a more critical role in bouldering than in lead climbing. Fanchini et al. (2013) noted that boulderers typically exhibit higher RFD levels due to the nature of the discipline, which involves shorter, more explosive movements. In contrast, lead climbing requires sustained endurance and fine force adjustments to prevent fatigue, which may reduce the relative importance of RFD.

Conclusion:

The primary finding from studies comparing boulderers and lead climbers is that boulderers possess greater finger-flexor maximal muscle strength and rapid force capacity. This is likely due to the explosive nature of bouldering, which requires climbers to generate high levels of force quickly to stabilize their bodies after dynamic movements. Lead climbers, on the other hand, focus more on endurance and controlled force application to maintain their grip over longer periods.

This distinction suggests that while RFD is a critical factor in bouldering, contributing to the explosive strength needed for this discipline, it is less important in lead climbing, where endurance and fine motor control take precedence. Nonetheless, RFD remains an essential aspect of overall climbing performance, particularly for tasks requiring quick, powerful movements.

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The Significance of Lower Limb Power in Sport Climbing

Lower limb power is a critical aspect of sport climbing, influencing performance across various disciplines within the sport. This has been particularly well-documented in the context of speed climbing. For instance, research by Krawczyk (2018) demonstrated a significant correlation between the times achieved by climbers and the height of their countermovement jump (CMJ) without the use of an arm swing. These findings underscore the importance of explosive leg power in climbing, especially in events where speed and dynamic movements are crucial for success.

Despite the extensive research on speed climbing, studies specifically investigating the impact of jump height—whether measured by CMJ or squat jump (SJ)—on bouldering performance are still limited. This gap in the literature means we lack robust, empirical data to draw definitive conclusions about the role of lower limb power in bouldering. However, expert opinions from coaches and practitioners within the sport consistently emphasize the significance of explosive jumping ability. These insights suggest that developing lower limb power is vital not only for speed climbing but also for other climbing disciplines, including bouldering.

Modern sport climbing requires athletes to execute a diverse array of jumps, ranging from traditional plyometric exercises like SJ and CMJ to more complex and dynamic movements. These include broad jumps, rapid plyometric drop jumps, and bounding, all of which are integral to climbing. For example, in bouldering, moves like the "lambada" require quick drop jumps, while bounding is essential during run starts in both bouldering and speed climbing. Climbers must perform these jumps using both legs or a single leg, depending on the situation, and they often need to transition seamlessly between horizontal and vertical movements.

In addition to the demands of jumping, sport climbing frequently involves complex landing scenarios. Climbers must often land on uneven surfaces, such as volumes attached to climbing walls, or absorb significant impact forces when landing on crash pads after a boulder problem. These challenges further highlight the importance of lower limb power—not only for generating the necessary explosive force to execute jumps but also for managing safe and effective landings.

In summary, while research on lower limb power in bouldering is still emerging, the existing evidence and expert opinions strongly support the notion that developing and assessing explosive leg power is essential for climbers. As sport climbing continues to evolve, incorporating a variety of jump types and landing techniques into training programs will likely become increasingly important for optimizing performance and reducing the risk of injury.

Description of CMJ and SJ Phases and Their Differences

Phases of the Countermovement Jump (CMJ), McMahon (2018) (Photo 9.):

1) **Bodyweight (A-B):** The athlete stands in the initial upright position, where the only force acting is bodyweight.
2) **Unweighting Phase (B-C):** The athlete lowers their body, which leads to a reduction in vertical force. This phase "unweights" the body in preparation for the jump.
3) **Braking Phase (C-D):** The downward movement is halted. The athlete begins to generate force in the opposite direction, preparing for takeoff.
4) **Propulsive Phase (D-F):** The athlete generates maximum vertical force, leading to takeoff. This is when the highest vertical velocity is achieved.
5) **Flight (F-H):** The athlete is airborne. During this phase, vertical force equals zero, and velocity decreases until the peak height is reached.
6) **Landing (H-J):** The athlete lands back on the ground, and vertical force rapidly increases to absorb the kinetic energy accumulated during flight.

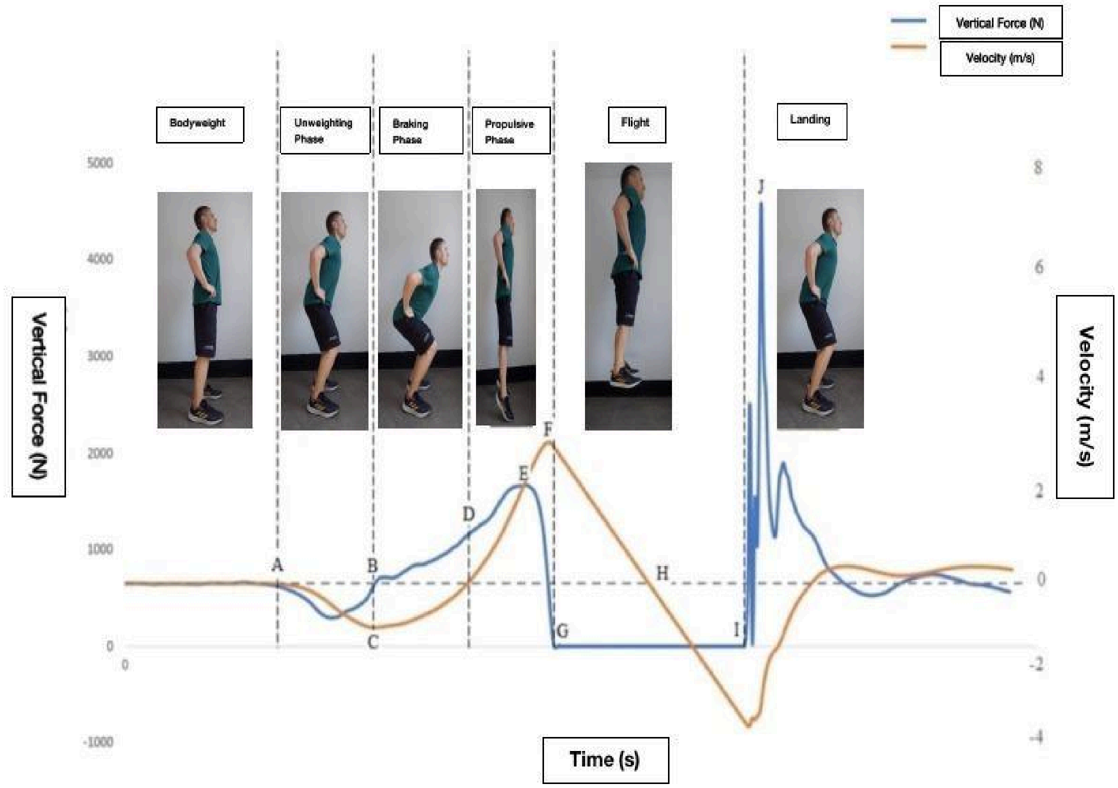

Photo 9. Phases of the Countermovement Jump (CMJ).

Phases of the Squat Jump (SJ) Padulo (2013) (Fig. 25):

1) **Bodyweight:** The athlete begins in a squat position, eliminating the unweighting and braking phases associated with downward movement.
2) **Propulsive Phase:** The athlete immediately initiates the propulsive phase, generating vertical force from the start.
3) **Flight:** Similar to the CMJ, the athlete becomes airborne, reaching peak height.
4) **Landing:** The landing phase is identical to that of the CMJ.

Fig. 25. Phases of the Squat Jump (SJ) Padulo et al. (2013).

Parameters Measured During CMJ, SJ, and DJ

When performing the **Countermovement Jump (CMJ)**, **Squat Jump (SJ)**, and **Drop Jump (DJ)**, several key parameters are measured to assess an athlete's explosive power, muscle function, and overall jump performance. These parameters provide valuable insights into an athlete's strength, speed, and efficiency in generating force. Some of these parameters, such as **Contact Time**, are specific to **reactive jumps** like the **Drop Jump (DJ)** Tab. 22, 23.

1) **Jump Height (H)**:

   - **Definition**: The maximum vertical distance achieved during the jump.
   - **Importance**: Jump height is a primary indicator of lower limb power and explosive strength. It reflects the athlete's ability to convert force into vertical displacement.

2) **Flight Time**:

   - **Definition**: The time the athlete remains airborne during the jump.
   - **Importance**: Flight time is directly related to jump height, as longer flight times typically correspond to higher jumps. It is a key metric for measuring the effectiveness of the propulsive phase in CMJ and SJ.

3) **Rate of Force Development (RFD)**:

- **Definition**: The rate at which force is developed over time, typically measured during the propulsive phase.
- **Importance**: RFD is crucial for evaluating the explosive power of the muscles. A higher RFD indicates a faster and more effective generation of force, which is particularly important in sports requiring quick and powerful movements.
- **Additional Considerations**: RFD can be measured over different time intervals (e.g., 0-50 ms, 0-100 ms, or 0-200 ms) depending on the specific demands of the sport or the focus of the assessment.

4) **Force at 100 ms (N)**:

- **Definition**: The amount of force exerted 100 milliseconds after the start of the propulsive phase.
- **Importance**: Measuring force at 100 ms helps determine the athlete’s ability to generate rapid force. This is particularly important for activities that require quick, explosive efforts.
- **Additional Considerations**: This value is often used to assess the early-phase explosive strength and is crucial in sports that emphasize fast, reactive movements.

5) **Impulse**:

- **Definition**: The total amount of force generated over the time during which force is applied, calculated as the area under the force-time curve.
- **Importance**: Impulse is critical in determining jump height and overall jump performance. It reflects an athlete's ability to sustain force over a longer period and apply it efficiently to achieve maximum height.
- **Additional Considerations**: Impulse can be measured over various time intervals. **Total Impulse** refers to the cumulative force exerted over the

entire duration of the propulsive phase, calculated by integrating the force-time curve over this period.

6) **Starting Strength (N)**:

   - **Definition**: The initial force generated at the beginning of the propulsive phase (within the first 30 ms).
   - **Importance**: Starting strength reflects how quickly an athlete can generate force from a stationary position. It is a key indicator of their ability to initiate movement and is particularly relevant in explosive actions.

7) **Takeoff Time (ms)**:

   - **Definition**: The time from the start of the propulsive phase until the athlete leaves the ground.
   - **Importance**: Takeoff time measures the duration between the initiation of force and when the athlete takes flight. A shorter takeoff time indicates faster force production and is indicative of greater explosiveness.

8) **Peak Power**:

   - **Definition**: The highest power output generated during the jump.
   - **Importance**: Peak power reflects the athlete's maximum explosive strength during the jump. It provides a direct measure of the effectiveness of the propulsive phase.

9) **CMJ/SJ Ratio**:

   - **Definition**: The ratio of the height achieved in CMJ to that achieved in SJ.
   - **Importance**: This ratio helps determine how much of the jump height is due to the elastic energy stored during the countermovement phase (in CMJ). A higher ratio suggests better utilization of elastic energy and muscle-tendon stiffness.

10) **Reactive Strength Index (RSI)**:

- **Definition**: RSI is calculated as the ratio of jump height to ground contact time, typically measured during reactive jumps such as drop jumps, but it can also be relevant in other jumping tests like CMJ.
- **Importance**: RSI provides insight into an athlete's reactive strength and their ability to quickly transition from eccentric to concentric muscle actions. A higher RSI indicates better explosive strength and efficiency in using the stretch-shortening cycle.

11) **Contact Time (s)** (Specific to **Drop Jump (DJ)**):

- **Definition**: The duration of time the feet are in contact with the ground during a reactive jump, such as a **Drop Jump (DJ)**.
- **Importance**: Contact time is a critical measure for evaluating the efficiency of the stretch-shortening cycle and quick transition from ground contact to takeoff. In activities that emphasize reactive strength, shorter contact times typically indicate better neuromuscular efficiency.
- **Additional Considerations**: Contact time is measured from the initial ground contact to takeoff, and it plays a significant role in sports where rapid direction changes or explosive jumps are critical.

12) **Dynamic Strength Index (DSI)**:

- **Definition**: The DSI compares an athlete’s ability to produce force ballistically (e.g., through a jump) versus their maximal isometric force (e.g., during an isometric mid-thigh pull - IMTP).
- **Importance**: The DSI provides insights into whether an athlete needs to focus more on developing **explosive power** or **maximal strength**. A **low DSI** suggests the need for more explosive training, while a **high DSI** indicates that the athlete may benefit from increasing maximal strength.

Additional Information:

- **CMJ/SJ Ratio (Eccentric utilsation ratio EUR)**:
  - o **Explanation**: The CMJ/SJ ratio helps determine how much of the jump height is attributed to the elastic energy stored during the countermovement phase in the CMJ. A higher ratio reflects efficient use of the stretch-shortening cycle, which is crucial for maximizing jump performance.
- **Asymmetry Measurements**:
  - o **Single-Leg Jumps**: Performing CMJ and SJ on a single leg can assess power and strength asymmetries between legs. Identifying such imbalances is important for preventing injury and improving performance.
  - o **Free Arm vs. No Free Arm Jumps**: Assessing jumps with and without arm swings allows for evaluating the additional momentum generated by arm movement, which typically results in higher jumps due to increased force production.

DSI Score	**Training Recommendation**
< 0.60	Ballistic Strength Training: Focus on enhancing the ability to produce force rapidly and explosively. This is critical for athletes who struggle to utilize their maximal strength in dynamic movements.
0.60 – 0.80	Concurrent Strength Training: Combine ballistic and maximal strength training to balance force production capabilities. This range indicates a good mix of strength and explosiveness, but both areas can still be improved.
> 0.80	Maximal Strength Training: Emphasize increasing maximal strength. Athletes in this range are close to maximizing their ballistic potential relative to their isometric strength, so improving their overall strength capacity will likely yield the best performance gains.

Table 22. Dynamic Strenght Index interpretation and training intervention recommendation

Parameter Units	**Definition**	**Calculation Method**
Jump Height (cm)	The maximum vertical distance achieved during the jump.	Measure the vertical displacement from takeoff to peak height.

Maximum Dynamic Strength (MDS) (kg)	The maximum amount of force an athlete can exert in a single effort, typically measured during a squat at a specific knee angle.	Measure the highest weight lifted with proper form at a 120° knee angle.
Rate of Force Development (RFD) (N/s)	The speed at which force is developed during the transition from eccentric to concentric phases.	RFD = Change in Force / Change in Time ($RFD = \Delta F / \Delta t$)
Explosive Strength (max RFD) (N/s)	The peak rate at which force is developed during the jump.	Measure the maximum slope of the force-time curve during the propulsive phase.
Impulse (N·s)	The total amount of force generated over time during which force is applied, reflecting the effectiveness of force application.	Impulse = Force × Time (Integral of the force-time curve)
Peak Power (W)	The highest power output generated during the jump.	Peak Power = Force × Velocity ($P = F \times v$)
Average Power (W)	The average power output generated during the jump.	Calculate the mean power over the duration of the jump phase.
Contact Time (s)	The duration of time the feet are in contact with the ground during a reactive jump (e.g., drop jump).	Measure the time from initial ground contact to take-off.
Flight Time (s)	The time spent airborne during a jump, indicating explosive capability.	Measure the time from takeoff to landing.
Reactive Strength Index (RSI) (m/s)	A measure of reactive strength calculated by dividing jump height by ground contact time, typically used during reactive jumps.	RSI = Jump Height / Ground Contact Time
Dynamic Strenght Index DSI	The DSI value helps identify whether an athlete needs to focus more on improving ballistic strength or increasing maximal strength. Lower DSI values suggest a need for more ballistic training, while higher values indicate a need for increasing maximal strength.	Compare the calculated DSI value against established guidelines to inform training focus.
Force at 100 ms (N)	The amount of force exerted 100 milliseconds after the start of the propulsive phase.	Measure the force exerted at the 100 ms.
Total Impulse (N·s)	The cumulative force exerted over the entire duration of the propulsive phase.	Calculate by integrating the force-time curve over the propulsive phase.

Starting Strength (N)	The initial force generated at the beginning of the propulsive phase (within the first 30 ms).	Measure the force exerted in the first 30 ms of the movement.
Take off Time (ms)	The time from the start of the propulsive phase until the athlete leaves the ground.	Measure the duration from the start of force generation to take-off.

Table 23. Parameters Measured During CMJ, SJ, DJ.

Overview of Jump Measurement Technologies in Sports

As technology advances, the measurement of vertical jump performance has become increasingly sophisticated. In the realm of sports, there are numerous devices available that evaluate jump height, technique, and other significant indicators. This review focuses on various popular technologies used to measure jumps, highlighting their advantages, limitations, and key variables measured during these assessments.

One of the most traditional methods is the use of a vertical jump mat, which employs pressure sensors to detect the take-off and landing points. These mats provide immediate feedback on jump height and can be easily set up in various training environments. However, they may not capture detailed biomechanical data regarding the jumper's technique.

Another widely used technology is motion capture systems, which utilize high-speed cameras and reflective markers to analyze an athlete's movements. These systems offer precise data on jump mechanics, such as body angles, velocities, and flight trajectories. Despite their accuracy, they can be costly and require a controlled environment for optimal performance.

Force plates are also prevalent in jump assessment. These devices measure ground reaction forces during the jump, allowing for the calculation of jump height based on the force applied and the duration of the jump. While force plates provide valuable insights into power output and technique, they are often expensive and can be less portable than other measurement tools.

Wearable technology, including accelerometers and gyroscopes, has gained traction as a means to monitor vertical jump performance. These devices can be used in various settings, providing data on jump height, take-off velocity, and overall body motion. However, the accuracy of measurements can vary depending on the placement of the sensors and the algorithms used for data analysis.

Finally, mobile applications have emerged as convenient tools for jump assessment, often utilizing smartphone cameras to analyze video recordings of jumps. These applications can offer quick and accessible measurements, but their accuracy may not match that of more advanced systems McMahon (2018).

1) Jump Mats

- **Description:** Jump mats are pressure-sensitive mats that calculate jump height based on the time an athlete spends in the air (flight time) .
- **Main Benefits** McMahon (2018):
  - Easy to use and highly portable.
  - Provides immediate feedback for coaches and athletes.
  - Generally cost-effective with minimal setup required.
- **Main Limitations** McMahon (2018):
  - Tends to overestimate flight time and thus jump height.
  - Limited ability to analyze jump technique or biomechanics in high-performance scenarios.
- **Main Variables Measured:**
  - Jump height (typically estimates slightly higher).
  - Flight time.
  - Reactive strength index (RSI).

2) **OptoJump**

- **Description:** OptoJump utilizes an array of infrared light sensors to track jump metrics.
- **Main Benefits** McMahon (2018):
  - High accuracy with detailed metrics on jump performance.
  - Capable of analyzing multiple jumps in succession without resetting.
  - Useful for advanced biomechanical analysis.
- **Main Limitations** McMahon (2018)**:**
  - More expensive than basic devices.
  - Requires specific setup and calibration for optimal accuracy.
- **Main Variables Measured:**
  - Jump height.
  - Contact time.
  - Reactive strength index (RSI).

3) **MyJump**

- **Description:** MyJump is a mobile application that analyzes jump performance through video recordings.
- **Main Benefits** McMahon (2018), McGuigan (2019):
  - Highly accessible via smartphones.
  - Offers video analysis for technique improvement.
  - Instantaneous results for immediate feedback.
- **Main Limitations** McMahon (2018), McGuigan (2019):

        - Lighting and camera quality affect accuracy.
        - Data interpretation and video processing can be time-consuming.
        - May overestimate jump height, particularly using the Take-Off Velocity (TOV) method.
    - **Main Variables Measured:**
        - Jump height.
        - Peak power and velocity.
        - Reactive strength index (RSI).

4) **Accelerometers**
    - **Description:** Accelerometers measure the acceleration forces of the athlete, providing data to calculate jump height and dynamics.
    - **Main Benefits** McGuigan (2019):
        - Provides continuous data during jumps, capturing dynamic movement.

5) **Linear Position Transducers (LPT)**
    - **Description:** LPTs measure the movement of the athlete's center of mass in real-time along a linear path.
    - **Main Benefits** McGuigan (2019):
        - Provides high precision in measuring jump height and power output.
        - Capable of delivering extensive performance data.
    - **Main Limitations** McGuigan (2019):
        - Typically more expensive and requires a sophisticated setup.
        - Less portable compared to other jump measurement tools.

- **Main Variables Measured:**
    - Jump height.
    - Peak power and velocity.
    - Can deviate from vertical-only displacement.

6) **Jump and Reach Device (Vertec)**
    - **Description:** Vertec uses hinged vanes to mark the highest point reached during a jump.
    - **Main Benefits** McMahon (2018):
        - Simple and straightforward to use without complex technology.
        - Widely recognized and used in numerous sports organizations.
    - **Main Limitations** McMahon (2018):
        - Provides limited insight into jump dynamics beyond height.
        - Manual measurement can introduce human error, resulting in potential inaccuracies.
    - **Main Variables Measured:**
        - Jump height, although typically this method may lead to overestimation due to differences in standing and jumping heights.

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Endurance in Climbing: Significance and Testing Methods

Endurance is the ability to sustain prolonged physical effort at a required intensity without a decrease in efficiency, while maintaining a heightened resistance to fatigue (Sozański, 1993). It is considered a moderately genetically conditioned ability, with varying levels of heritability for the factors that determine its level (Szopa et al., 1996). This is because endurance depends on a multitude of physiological and psychological factors. The physiological components contribute to what is known as physical fitness, which is understood as the capacity to perform strenuous, prolonged work without rapidly increasing fatigue. The specific nature of energy production in the body suggests that endurance serves as the biological foundation upon which desirable physical fitness traits can be developed. The diversity in how endurance manifests has led to various classifications, including:

- aerobic, anaerobic-aerobic, and anaerobic endurance,
- static, dynamic, local, and global endurance,
- short-duration (50-120 seconds), medium-duration (2-10 minutes), long-duration (10-60 minutes), and marathon endurance (over 60 minutes).

This classification of endurance has been heavily criticized, as in practice, specific endurance is most often observed, while general endurance remains a purely theoretical concept (Prus & Zając, 1999).

Types of Endurance in Sport Climbing

The significance of endurance in sport climbing has been emphasized by various studies (Grand et al., 1996; Guidi, 1999). A crucial aspect is the methodology used for testing endurance in this sport. Although there are many different endurance tests, they are not standardized. Measuring muscular endurance (strength endurance) in climbing is complex. Fatigue in this discipline is caused by physical exertion with a significant emphasis on strength, particularly affecting small muscle groups such as those in the forearms and arms (Magiera, 2007). The lack of standardized tests leads to varying methodologies for diagnosing this motor ability in climbing.

Magiera (2007) identified four groups of endurance tests:

- Percentage of maximum voluntary contraction (MVC),
- Isometric or dynamic contraction,
- Continuous or intermittent contraction,
- Time of load and relief in rhythmic contraction.

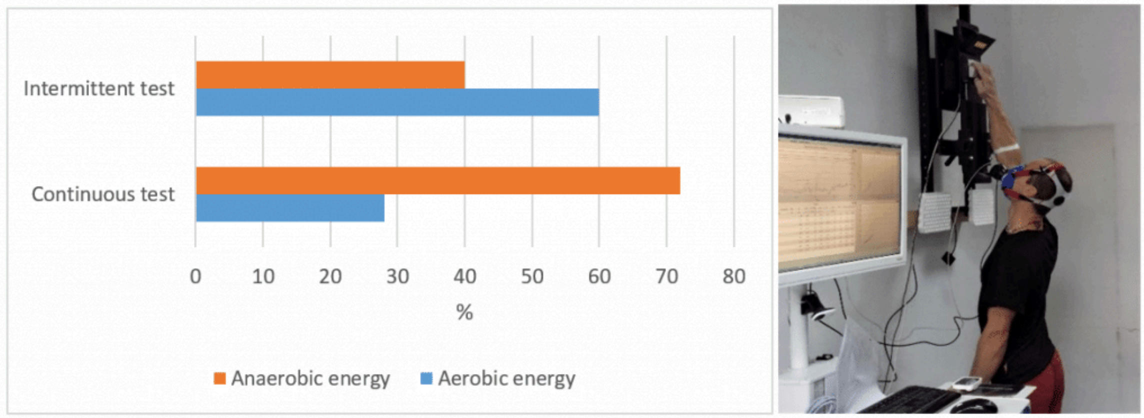


Figure 26. Relative energy system contribution during the continuous and intermittent muscle endurance tests (copy from www. climbro .com with permission).

Most endurance tests for climbers are based on the principles described by Magiera (2006) or combinations thereof. Ferguson and Brown (1997), using a dynamometer to measure endurance, did not observe significant differences in continuous test duration (140-122 seconds at 40% of maximal strength). However, significant differences emerged in intermittent exertion—5 seconds of isometric contraction followed by 2 seconds of relaxation (853-420 seconds). Watts (1998) employed a dynamometer test (maintaining contraction at 70% of maximal strength) before, during, and after climbing, concluding that the mechanisms involved in lactate accumulation and removal play a key role in climbing

Grant et al. (1996) analyzed not only the strength of muscles determining grip endurance but also arm endurance. They employed a hanging test in isometric contraction on a bar and a pull-up test. The results showed significant differences between advanced climbers and recreational or non-climbing groups in the hanging test (53.1±13.2 s, 31.4±9 s, 32.6±15 s, respectively) and in pull-ups (16.2±7.2 s, 3.0±9 s, 3.9±3.9 s). Rokowski (2007), in his research, used a specific test, the so-called Edlinger alphabet on a bar. He found correlations between the level of climbing proficiency and motor performance with endurance characteristics (R=0.51). The correlation indicated that the test measured arm strength endurance, and further observations on the test were recommended. To assess the endurance of the finger flexor muscles, Rokowski and Tokarz (2007) used tests involving hanging to failure on edges of 2.5 cm and 4 cm, hanging on a bar, and pull-ups on a bar.

In the hanging test on the edge, the difference between beginners and advanced climbers was as much as 51.9 s. A similar trend was maintained in the 4 cm edge test—56.9 s. The bar hanging test showed a difference of 92 s, and the pull-up test a difference of 11.7 pull-ups in favor of the advanced group. Studies suggest that the specialized tests developed by the aforementioned authors are closer to the demands of sport climbing than dynamometric tests.

From a coaching perspective, it is important to consider the role of endurance in climbing at different stages of athlete development. According to Guidi (1999), strength and endurance abilities are the main determinants in sport climbing. Similar conclusions were drawn by Rokowski (2007), who, using specific performance tests, noted a significant dominance of professionals over amateurs in endurance-related tests. The most significant differences were observed in anaerobic endurance tests. The results of tests involving aerobic mechanisms were also important. The author suggested that endurance in climbing has an anaerobic-aerobic nature.

Booth (1999), using a special climbing ergometer test, observed an increase in lactate levels during a 5-minute effort from a starting point of 1.4 mmol/l. Continuing the effort until failure, he noted an increase in lactate levels up to 10.2 mmol/l.

Sheel (2004), in a review article, pointed out that VO2 max during indoor climbing is relatively low (Billat et al., 1995; Watts et al., 1998; Sheel, 2003). He suggested that this is related to the muscle work involved in climbing, which is primarily isometric, and energy is generated mainly through anaerobic pathways. The author also referenced the study by Booth et al. (1999), where a significant maximal oxygen uptake during climbing was recorded, contrary to previous findings (Billat et al., 1995; Watts et al., 1998; Sheel, 2003). He concluded that aerobic processes may play an important role in climbing, though their full impact remains unexplained. However, it is important to note that these studies primarily involved tests engaging the lower limbs, where VO2 max does not influence climbing performance, which is why the test results did not differ significantly from those of average team sport athletes.

In the context of sport climbing, Godard and Neuman [2000] distinguish between Aerobic Endurance (relying on the aerobic energy system) and Anaerobic Endurance (relying on the anaerobic system). Haff [2023] further classify endurance based on the intensity of effort: High Intensity Endurance and Low Intensity Endurance. The former involves high-intensity efforts with significant engagement of Type II muscle fibers, predominantly using anaerobic energy. This type of endurance is crucial in combat sports, American football, and ice hockey, where athletes need to maintain high power and strength over prolonged periods. The latter pertains to disciplines where the load is lower, but the duration of effort is significantly longer.

Michajlov [2014] further refines the concept of anaerobic endurance in sport climbing by identifying endurance influenced by glycolytic power and endurance determined by buffer capacity, which refers to tolerance to high lactate levels and acid-base balance.

A similar classification is applied by Guyon and Broussouloux (2004):

- **Resistance courte** (short-term endurance linked to high-intensity efforts): According to the authors, these efforts are characterized by high levels of muscular strength and anaerobic power, lasting approximately 60 seconds and involving around 20 movements on a climbing wall. These efforts predominantly recruit Type IIb and IIa muscle fibers.
- **Resistance longue** (endurance linked to high and medium-intensity efforts): These efforts are determined by aerobic power and anaerobic capacity, with muscle activity lasting around 3 minutes and involving approximately 45 movements. Such efforts lead to significant muscle acidification, thus also falling under anaerobic efforts. Here, Type IIa and I fibers are primarily engaged.
- **Continue** (associated with low-intensity efforts): These efforts mainly involve Type I fibers. Muscle acidification after such efforts is significantly lower compared to the previous types. The number of movements exceeds 50, and the duration of climbing surpasses 3 minutes. A similar concept regarding different endurance zones is presented by Parades (2002).

Energy System Utilization in Climbing Efforts

Considering the opinions of practitioners and scientists, as well as the percentage involvement of energy systems, duration of effort, and the number of holds, it seems reasonable to distinguish three endurance zones in sport climbing:

1) **High Intensity Endurance:** These efforts are characterized by a high level of muscle strength and lactate power. The duration of such efforts ranges from 20 to 90 seconds, with approximately 10-25 movements on a climbing wall. These efforts are determined by anaerobic strength and power, mainly recruiting Type IIb and IIa fibers.
2) **Medium Intensity Endurance:** These efforts are determined by aerobic power and anaerobic capacity. The duration of muscle activity is around 2 minutes, with approximately 30-45 movements. Such efforts lead to significant muscle acidification, and thus are also classified as anaerobic. Here, Type IIa and I fibers are mainly involved.
3) **Low Intensity Endurance:** These efforts primarily engage Type I and IIa fibers. Muscle acidification after such efforts is much lower than in the previous endurance types. The number of movements exceeds 50, and the duration of climbing exceeds 3 minutes.

Table 24 provides a detailed summary of the mean values and standard deviations from muscle endurance tests conducted on climbers. The tests focus on key muscle groups, including the finger flexors, shoulder girdle, and elbow flexors. By presenting both mean values and standard deviations, the table offers a comprehensive overview of endurance levels in these specific areas, which are crucial for climbing performance.

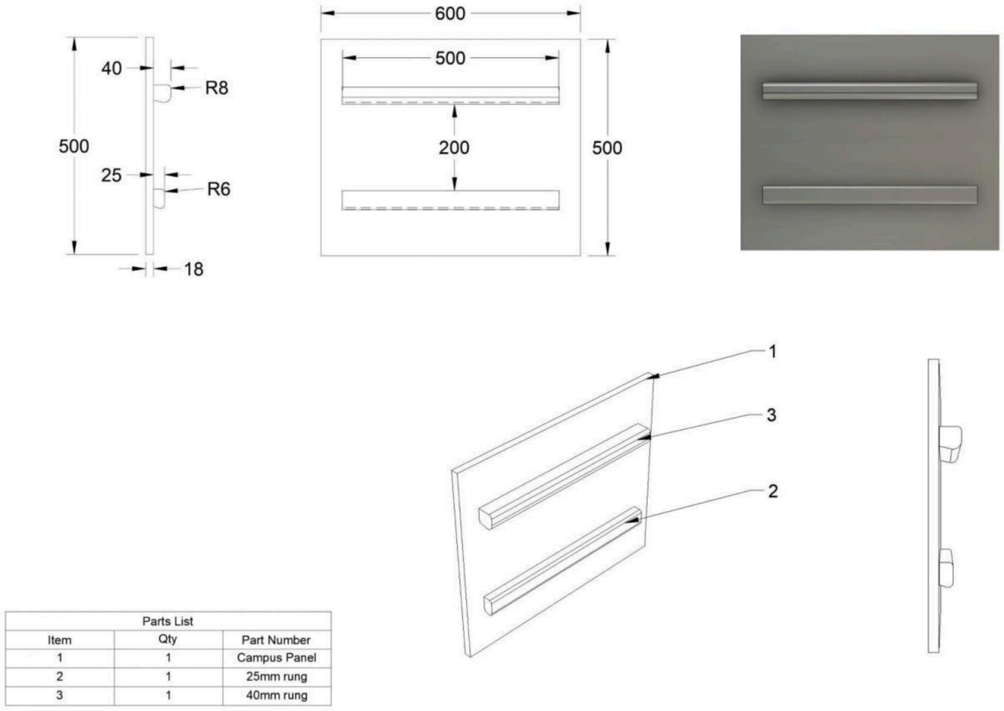
Authors	**Level: Higher Elite (≥ 28 IRCRA)**	**IRCRA) – Advanced (18-23 IRCRA)**	**Level: Advanced (18-23 IRCRA)**	**Level: Intermediate (10-17 IRCRA)**	**Lower Grade (1-9 IRCRA)**

Rokowski and Tokarz (2007)	Test: Hang on 2.5 cm edge [s] 80.9 (20.2 SD)	29.2 (20.8 SD)***	-	-	-
	Test: Hang on 4 cm edge [s] 103.2 (32.0 SD)	46.3 (21.1 SD)***	-	-	-
Rokowski (2020)	Test: Hang on 2.5 cm edge [s] 112.5 (14.1 SD)	78.1 (10.3 SD)	-	-	-
	Test: Hang on 4 cm edge [s] 154.7 (21.7 SD)	115.3 (31.8 SD)	-	-	-
Ozimek et al. (2017)	Test: Hang on 2.5 cm edge [s] 74.7 (19.0 SD)	53.6 (13.5 SD)*	-	-	-
	Test: Hang on 4 cm edge [s] 100.0 (23.7 SD)	80.4 (7.1 SD)*	-	-	-
Balaś et al. (2012)	Test: Hang on 2.5 cm edge [s] 79.1 (16.5 SD)	56.0 (15.5 SD)^	-	-	-
Draga et al. (2024)	Test: Hang on 2.5 cm edge [s] 61.476 (17.564 SD)	-	-	-	-
	Test: Hang on 4 cm edge [s] 90.708 (23.424 SD)	-	-	-	-
	Edlinger Test [s] 7.035 (1.855 SD)	-	-	-	-
	Max Pull-ups 25.410 (7.975 SD)	-	-	-	-

Table 24. Arithmetic Means ($\bar{X}$) and Standard Deviations (SD) of the Duration Times for Selected Motor Tests Measuring Muscle Endurance. Statistically significant differences are noted with * ($p<0.05$) and *** ($p<0.001$). For tests where no significance test was conducted, the percentage difference is provided (e.g., 29.12% in favor of climbers from the Higher Elite-Advanced group, indicated by ^).

Selected Muscle Endurance Tests in Climbing

Specific physical fitness tests were conducted using a measuring finger board Fig. 27, which was mounted at a 90° angle to the ground. The board included two test holds with depths of 2.5 cm and 4 cm, each 50 cm wide (Figure x). For clarity and simplicity, these tests were given working names Draga et al (2024). Muscle endurance was assessed using the following tests:



Parts List		
Item	Qty	Part Number
1	1	Campus Panel
2	1	25mm rung
3	1	40mm rung

Figure 27. Finger board.

1) Finger Hang 2.5 (Photo 10)

In this test, participants were required to hang with both hands on a hold that was 2.5 cm deep. The fingers of each hand gripped the edge of the hold, excluding the thumb, in an open grip. The hands were positioned shoulder-width apart, with the arms fully extended and the body hanging vertically. The test measured the duration for which participants could maintain this position, with a precision of 1 second.

Photo 10. Finger Hang 2.5.

2) Finger Hang 4 (Photo 11)

Similar to the Finger Hang 2.5, this test also involved hanging with both hands on a hold, but in this case, the hold was 4 cm deep. The same grip and body position parameters were maintained, and the test measured the hang duration with a precision of 1 second.

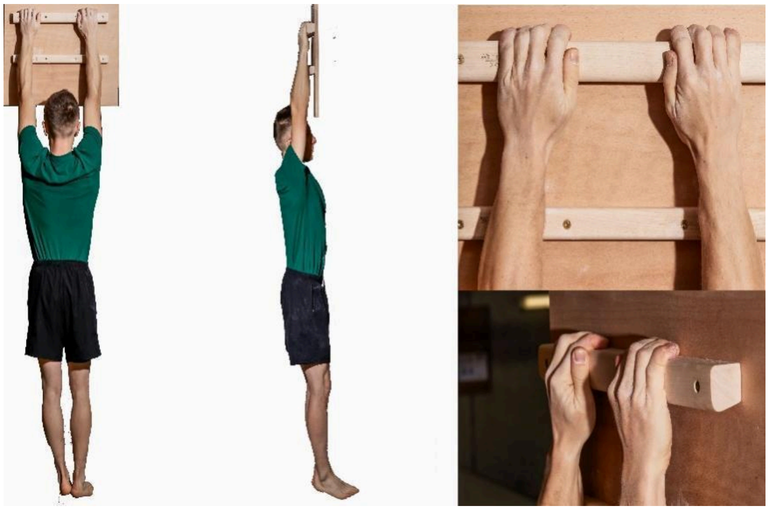


Photo 11. Finger Hang 4.

3) Edlinger Test (1985) (Photo 12).

This test consisted of a series of cycles in which the participant performed two pull-ups on a bar. After the second pull-up, they held their chin above the bar for 7 seconds (cycle

I). The participant then repeated this process with two more pull-ups, holding their elbows at a 90° angle (cycle II). These cycles were repeated, with the elbow flexion angle increasing in each subsequent cycle (cycle III, IV, V, and so on).

Photo 12. Edlinger Test.

4) **Pull-up Test:**

This test measured the maximum number of pull-ups a climber could perform on a bar. The test followed these rules: Participants performed pull-ups on a standard horizontal bar. They had to lift their bodies from a position of full shoulder extension, hanging with a pronated grip at shoulder width, until their chins touched the bar. The rhythm of the pull-up was not regulated. During the test, it was forbidden to remove the hands from the bar or to use leg movements to assist the pull-up by swinging.

Endurance Testing Using the Climbro Hangboard

The Climbro hangboard offers a sophisticated and precise platform for evaluating various aspects of forearm muscle endurance, crucial for climbing performance. Three key tests— the Continuous Endurance Test, the Intermittent Endurance Test, and the Intermittent Endurance Test with Shaking—are particularly effective for assessing the anaerobic and aerobic capacities of the forearm muscles, providing valuable insights for climbers aiming to optimize their training and performance.

Continuous Endurance Test

The Continuous Endurance Test on the Climbro hangboard is designed to evaluate the anaerobic capacity of the forearm muscles. In this test, climbers must grip a 23 mm hold and sustain a force equal to 60% of their maximal strength for as long as possible. The Climbro system automatically ends the test when the force output drops by more than 5% from the target force.

The intensity of 60% maximal force is carefully selected to significantly activate the forearm muscles, leading to muscle stiffness that compresses blood vessels and restricts oxygen delivery. This creates a predominantly anaerobic environment where energy is supplied through both the glycolytic and alactic anaerobic systems. The glycolytic system uses carbohydrates to produce energy without oxygen, resulting in lactic acid accumulation, while the alactic system utilizes high-energy phosphate molecules, providing energy without producing lactic acid.

Performance Indicators:

1) **Time in Target Zone:** Measures how long the climber can sustain the target force, reflecting anaerobic glycolytic capacity.
2) **Force-Time Integral:** A product of force and time, this indicator is a comprehensive measure of anaerobic endurance, incorporating both glycolytic and alactic contributions.
3) **Force-Time Integral Relative to Body Mass:** This ratio correlates strongly with overall climbing performance, providing a relative measure of endurance capacity.

Intermittent Endurance Test

The Intermittent Endurance Test is designed to assess the aerobic capacity of the forearm muscles. In this test, climbers alternate between 8-second work phases, where they apply 60% of their maximal force, and 2-second rest phases, during which they are instructed to shake their tested hand down by their side. This work-rest cycle is repeated until the climber can no longer maintain the target force during the work phases.

The choice of an 8:2 work-rest ratio is based on observations from lead climbing competitions, making this test highly specific to the demands of the sport. The 2-second rest periods allow for muscle reperfusion and re-oxygenation, particularly in climbers with better aerobic capacity, thereby extending the duration of the effort compared to the continuous test.

Performance Indicators:

✔ **Number of Repetitions:** Indicates the climber’s ability to sustain aerobic activity over repeated efforts.

✔ **Time in Target Zone:** Reflects the total duration of effective work, serving as a direct measure of aerobic capacity.

✔ **Force-Time Integral:** Although primarily an indicator of aerobic capacity, it also accounts for a small contribution from anaerobic systems.

✔ **Force-Time Integral Relative to Body Mass:** Strongly correlates with climbing performance, offering a relative measure of the climber's aerobic endurance.

Intermittent Endurance Test with Shaking

The Intermittent Endurance Test with Shaking is a variation that further refines the assessment of aerobic capacity. This test is identical to the standard Intermittent Endurance Test, but during the 2-second rest phases, the climber shakes their hand more vigorously. This active shaking enhances muscle re-oxygenation and reperfusion even more, particularly in climbers with superior aerobic capacity. The ability to maintain force over a longer period in this test is a strong indicator of aerobic endurance and recovery efficiency, which are crucial for sustained climbing performance.

Performance Indicators:

- ✔ **Number of Repetitions:** Pure measure of aerobic endurance, showing how many cycles the climber can complete.
- ✔ **Time in Target Zone:** Duration spent at the target force, providing a direct assessment of aerobic capacity.
- ✔ **Force-Time Integral:** Reflects the combined influence of aerobic and anaerobic systems, though predominantly aerobic.
- ✔ **Force-Time Integral Relative to Body Mass:** Offers a comparative measure of endurance performance relative to the climber's body mass, correlating closely with overall climbing ability.

In summary, these tests using the Climbro hangboard provide a comprehensive assessment of both anaerobic and aerobic endurance in climbers. By analyzing the performance indicators from each test, climbers and coaches can gain valuable insights into specific strengths and weaknesses, enabling more targeted and effective training programs.

Summary of Selected Tests for Muscle Strength, Power, and Endurance in Sport Climbing

Tables 25 and 26 provide a summary of selected tests used for assessing muscle strength, power, and endurance in climbing.

Test category	**Test name**	**What it evaluates**	**Detailed description**
Strenght Tests	Edge Hang 1	Maximum Finger Strength	Measures maximum finger strength. The participant grips a 15 mm edge using eight fingers (four on each hand) in an open-hand position. The goal is to hang from the edge for 3 seconds with maximum added weight. The test is repeated until the participant can no longer hold the position for 3 seconds. Weight is progressively increased with 2-3 minute rest intervals between attempts.
	Edge Pull-Up	Finger and Arm Strength	Evaluates finger and arm strength. The participant grips the same 15 mm edge and performs a pull-up with maximum possible weight. The test is repeated until the participant can no longer perform the pull-up with added weight. Weight is progressively increased with 2-3 minute rest intervals between attempts.
	Edge Scale	Maximum Finger Strength	Measures finger strength using an analog scale or modern force sensors. The participant stands on the scale and grips a 15 mm edge, then gradually reduces body weight. The goal is to achieve maximum weight reduction for at least 3 seconds. Weight is increased if the participant can fully unload their weight.
	Bar Pull-Up	Arm Strength	Evaluates arm strength. The participant holds onto a bar with hands shoulder-width apart and performs a pull-up with the maximum added weight. The test is repeated until the participant can no longer complete the pull-up with the added weight. The load is progressively increased with 2-3 minute rest intervals between attempts.
Power Tests			Assesses shoulder girdle power. The participant performs an explosive pull-up, attempting to reach

	Power Slap Test	Shoulder Girdle Power	as high as possible with one hand. The height reached by the hand is a direct measure of shoulder girdle power.
	RFD Test	Finger Flexor Muscle Power and Speed	Evaluates the ability of the finger flexor muscles to generate high force in a limited time frame. The RFD (Rate of Force Development) test is conducted using the Climbro system. Climbers should pull the 23 mm hold as fast and as hard as possible while abruptly bending their knees. Similar to the maximal strength test, climbers who can hang on one arm from the 23 mm hold with feet off the ground should hold a weight with the other hand. The test provides indicators such as RFD at 200 ms; time to reach 25%, 50%, 75%, and 100% body weight; and time to reach 50% and 100% of maximal force for each hand.

Table 25. Strength and Power Tests.

Test name	What it evaluates	Detailed description
Finger Hang 2.5	Forearm and Finger Endurance	Measures endurance by hanging from a 2.5 cm edge with arms fully extended. The participant grips the edge with both hands (without using the thumbs) and holds the position as long as possible. The hang time is recorded to the nearest second.
Finger Hang 4	Forearm and Finger Endurance	Similar to Finger Hang 2.5, but the edge is 4 cm deep. The body position and grip rules are the same as in the Finger Hang 2.5, and the hang time is recorded to the nearest second.
Edlinger Test	Elbow Flexor and Shoulder Girdle Muscle Endurance	Consists of a series of cycles where the participant performs two pull-ups on a bar, followed by holding the chin above the bar for 7 seconds (Cycle I). In subsequent cycles, the participant maintains elbows at increasing flexion (Cycle II, III, IV, etc.). The test evaluates muscular endurance in the elbow flexors and shoulder girdle muscles.

Pull-Up Test	Elbow Flexor and Shoulder Girdle Muscle Endurance	Measures the maximum number of pull-ups a climber can perform on a bar. The participant must pull the body from full arm extension until the chin is above the bar. The test assesses endurance in the elbow flexors and shoulder girdle muscles. Releasing hands from the bar or using legs for assistance is prohibited.
Continuous Endurance Test	Forearm Anaerobic Endurance	The test on the Climbro hangboard evaluates the anaerobic capacity of the forearm muscles. Climbers grip a 23 mm hold and sustain a force equal to 60% of their maximal strength for as long as possible. The Climbro system ends the test when force output drops by more than 5% from the target force.
Intermittent Endurance Test	Forearm Aerobic Endurance	Assesses aerobic capacity by alternating 8-second work phases (60% maximal force) with 2-second rest phases. This work-rest cycle continues until the climber can no longer maintain the target force during the work phases.
Intermittent Endurance Test with Shaking	Forearm Aerobic Endurance with Enhanced Recovery	A variation of the standard Intermittent Endurance Test, this test involves additional instructions to shake the tested hand during rest phases. The intensity remains at 60% of maximal force, allowing for a better assessment of aerobic capacity and recovery ability through the repetitive work-rest cycles.
Critical Force (CF)	Forearm Aerobic Endurance	detailed description in next chapter

Table 26. Endurance Tests.

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Critical Power (CP) Concept: Foundation and Application in Endurance Sports

Definition of Critical Power (CP): Critical Power (CP) is a fundamental concept in endurance sports that represents the highest power output an athlete can sustain over a prolonged period without rapid fatigue. It marks the threshold between sustainable and unsustainable exercise intensity. When exercising at or below CP, physiological variables such as muscle phosphocreatine, blood lactate, and pulmonary oxygen uptake remain stable. However, exceeding CP leads to a continuous rise in these variables until exhaustion occurs.

Applications in Endurance Sports: In sports such as cycling, running, and swimming, CP is used to optimize training and performance by identifying the power or pace an athlete can sustain during long-duration events. It also informs pacing strategies, helping athletes distribute their effort efficiently across a race or training session.

One key application of the CP concept is in managing intermittent high-intensity efforts, common in sports like basketball, football, and hockey. In these sports, the CP model has been adapted to account for alternating periods of high-intensity exertion and recovery. A significant development from this adaptation is the W' (Work Above CP), which quantifies the amount of energy that can be expended above CP before fatigue sets in.

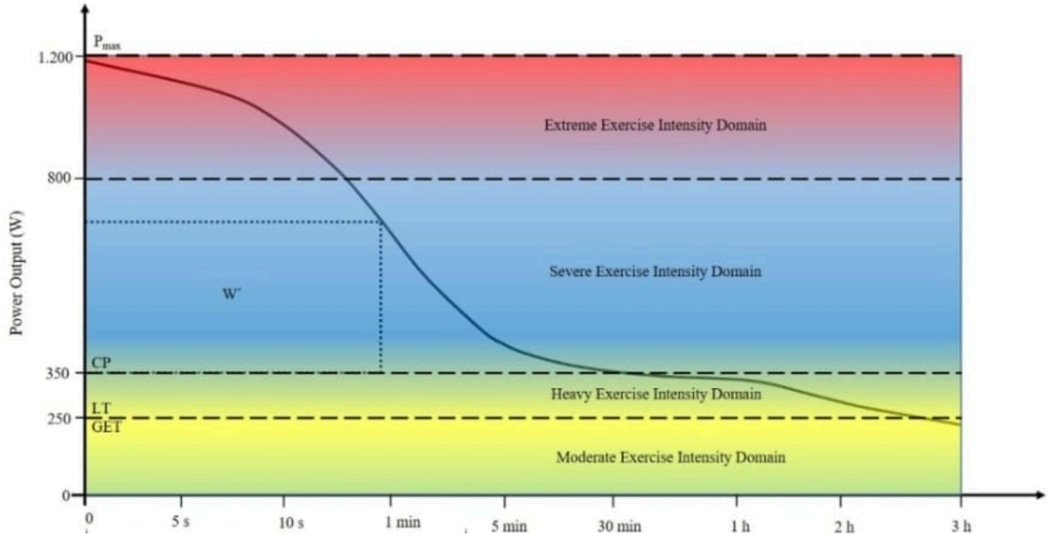

Figure 28. The figure depicts the relationship between power output and various exercise intensity domains, illustrating how different power or speed levels elicit specific physiological responses. From Leo et al. (2021). Power profiling and the power-duration relationship in cycling: A narrative review. *Sports Medicine*. https://doi.org/10.1007/s40279-021-01575-92.

Critical Power/Speed (CP/CS) Line:

The CP/CS line represents the upper limit of sustainable exercise intensity. At or below this threshold, exercise can theoretically be maintained indefinitely without leading to exhaustion, as energy demands are balanced by aerobic metabolism. Exercise intensities above this line lead to the rapid depletion of anaerobic energy stores, resulting in fatigue.

Lactate Threshold/Gas Exchange Threshold (LT/GET) Line:

This line marks the transition from moderate to heavy exercise intensity. At this point, blood lactate levels begin to rise, signaling the onset of anaerobic metabolism. Although lactate accumulates, exercise remains sustainable for extended periods.

W′ (Work Capacity Above Critical Power):

The area above the CP/CS line represents W', the finite anaerobic capacity available for exercise above critical power. This reserve of anaerobic energy allows for short-duration efforts above CP/CS, but once W' is depleted, exhaustion occurs.

Exercise Intensity Domains (Fig. 28):

1) **Severe Intensity Domain**:

   Exercise in this domain occurs above the CP/CS line. Due to the high intensity, the body quickly depletes W', leading to rapid fatigue. Exercise in the severe domain is unsustainable for long durations and results in exhaustion within minutes.

2) **Heavy Intensity Domain**:

   Situated between the CP/CS and LT/GET lines, this domain represents exercise that is physically demanding but sustainable for prolonged periods. Lactate levels increase progressively, reflecting a growing reliance on anaerobic energy pathways.

3) **Moderate Intensity Domain**:

   This domain, located below the LT/GET line, is characterized by relatively low exercise intensity. In this domain, the body relies primarily on aerobic metabolism, allowing for sustained exercise without significant lactate accumulation or fatigue.

Physiological Implications of Critical Power (CP):

Critical power is a key determinant of an athlete's endurance capacity. Below CP, the body can maintain a stable energy balance through oxidative (aerobic) metabolism, allowing for extended performance without rapid fatigue. However, when exercise intensity exceeds CP, anaerobic processes dominate, depleting W' and leading to quicker fatigue due to the buildup of metabolic by-products such as lactate. The magnitude of W' defines how much work can be performed above CP before exhaustion occurs.

Variable-Pace Exercise: While CP is traditionally applied to constant power output exercises, real-world sports often involve variable pacing. Research shows that W' remains consistent across different pacing strategies, but CP itself can vary depending on how the athlete manages their effort. This insight is crucial for sports where pacing must adapt to the dynamics of competition, such as in track cycling or marathon running.

Transition to Critical Force (CF) in Climbing

Connecting Critical Power (CP) to Critical Force (CF): The concept of Critical Force (CF) in climbing is directly derived from the Critical Power (CP) model. Just as CP helps endurance athletes understand and manage their performance, CF serves climbers by defining the maximum force their finger flexor muscles can sustain over time without leading to rapid fatigue. Both concepts share the idea of a threshold—CP for power and CF for force—that separates sustainable performance from inevitable exhaustion.

Definition of Critical Force (CF) in Climbing: CF represents the maximum force that a climber's finger flexor muscles can sustain without causing muscle fatigue. This is analogous to how CP functions in other sports, marking the boundary between sustainable and unsustainable efforts. For climbers, maintaining force below CF is crucial for enduring long climbs, while exceeding CF leads to quick muscle fatigue, reduced grip strength, and an increased risk of falling.

Critical Force (CF) in Finger Flexors: Importance and Applications for Coaches

Critical Force (CF) represents a significant concept in the training and performance analysis of rock climbers, particularly when assessing the endurance and strength of the finger flexors. CF is defined as the maximum steady-state work rate that can be sustained over time without leading to a progressive loss of homeostasis, meaning it is the highest force output a climber can maintain without fatigue setting in rapidly. Understanding and determining CF allows coaches to gauge an athlete's exercise tolerance and to tailor training programs effectively.

Why CF is Important:

1) Exercise Tolerance Assessment: CF provides a reliable measure of a climber's endurance, particularly in the finger flexors, which are crucial for climbing performance. The value of CF allows coaches to understand how long a climber can sustain a given level of force, which is vital for climbing where grip endurance is often a limiting factor.

2) Training Optimization: Knowing a climber's CF enables the design of more targeted training sessions. Coaches can create exercises that push climbers to their CF limits, thereby enhancing their endurance without causing overtraining. The CF value helps in determining the appropriate intensity for various training intervals, ensuring that climbers are training at the right intensity to maximize their performance gains.

3) Performance Monitoring: By regularly testing CF, coaches can monitor changes in a climber’s endurance over time. This allows for adjustments in training programs to ensure continuous improvement. It also helps in understanding the impact of different training interventions on a climber's performance.

4) Interval Training Design: With knowledge of CF and W', coaches can precisely design interval training sessions. The ability to predict the time to exhaustion (Tlim) at specific exercise intensities means that coaches can create sessions that deplete W' during work intervals and allow adequate recovery during rest periods, optimizing the training effect.

In summary, CF is a valuable tool for rock climbing coaches, enabling them to fine-tune training programs to match the specific endurance needs of their athletes. By understanding and applying CF data, they can develop exhaustive training sessions that lead to beneficial adaptations, improve performance, and help prevent overtraining**.**

Detailed Measurement of Critical Force (CF) in Climbing

1) **Participant Recruitment and Criteria:** The CF measurement process begins with the recruitment of participants, typically intermediate to advanced climbers who have regular training experience on hangboards. Participants must be free from injuries, especially in the hands, wrists, or forearms, and should not have any musculoskeletal, cardiovascular, or respiratory conditions. Prior to testing, participants complete a consent form and a health questionnaire. They also provide demographic data such as age, height, weight, climbing experience, and climbing achievements (e.g., "red-point grade").

2) **Standard Positioning and Equipment:**

    - **Hangboard or Climbing Hold:** The CF test is conducted using a hangboard or a specific climbing hold with a 20 mm edge. This edge depth is chosen because it closely simulates the typical grips used in climbing and provides a consistent, reliable surface for measuring force.

    - **Grip and Body Position:** Participants adopt a "half-crimp" grip during the test, where the proximal interphalangeal joint (PIP) of the fingers is flexed at 90°, and the thumb is not engaged. This grip is standard in climbing and allows for consistent force measurements. The tested arm (usually the dominant one) is extended overhead with a slightly bent elbow, while the body remains stable, with shoulders level and the chest parallel to the edge.

3) **Warm-Up:** Before the actual test, participants undergo a warm-up session to prepare their muscles and minimize the risk of injury:

- **General Warm-Up:** This includes 5 minutes of light cardio, such as walking, jogging, or jumping, followed by 5 minutes of easy climbing.
- **Specific Warm-Up:** Participants perform a series of half-crimp hangs on the 20 mm edge, following a 7:3-second work-to-rest ratio. These hangs are done at 50% and 75% of the participant's maximum strength, ensuring their finger flexor muscles are properly warmed up for the maximal isometric strength tests.

4) **Maximal Isometric Finger Strength (MIFS) Test:**
    - **Purpose:** The MIFS test aims to determine the maximum force the participant can generate in a static position using the half-crimp grip.
    - **Method:** Participants perform three 5-second maximal isometric contractions on the edge using their dominant hand. Between each attempt, a 120-second rest period is provided to ensure full recovery. The force generated during each attempt is measured in kilograms (kg) and recorded. The highest force value achieved across the three attempts is noted as the participant's peak force.
5) **Measurement of Critical Force (CF) in Finger Flexor Muscles:**
    - **Purpose:** The CF test determines the maximum force that a participant can sustain over time without causing muscle fatigue. This is crucial for assessing a climber's endurance.
    - **Test Procedure:**
        1) **Rhythmic Contractions:** The test involves a series of rhythmic maximal isometric contractions using the half-crimp grip. Each contraction follows a 7:3-second work-to-rest ratio. During the 7-second work phase, participants are instructed to generate as much force as possible while maintaining the half-crimp grip. In the 3-second rest phase, they relax their grip, adopting an

anatomical position without shaking their hands or forearms to prevent accelerated recovery.

2) **Data Collection:** Force (kg) and time (s) are continuously recorded throughout the test. The CF is calculated based on the average force maintained during the last six contractions (the final 60 seconds of the test). This period is crucial as it represents the force level that the participant can sustain after an extended effort, reflecting their true CF.

3) **Calculation of Impulse Above CF (W'):** In addition to CF, the test calculates the impulse above CF (W'), which is the sum of force impulses generated above the CF level during the test. This metric provides further insight into the climber's capacity to perform efforts above their CF before fatigue sets in.

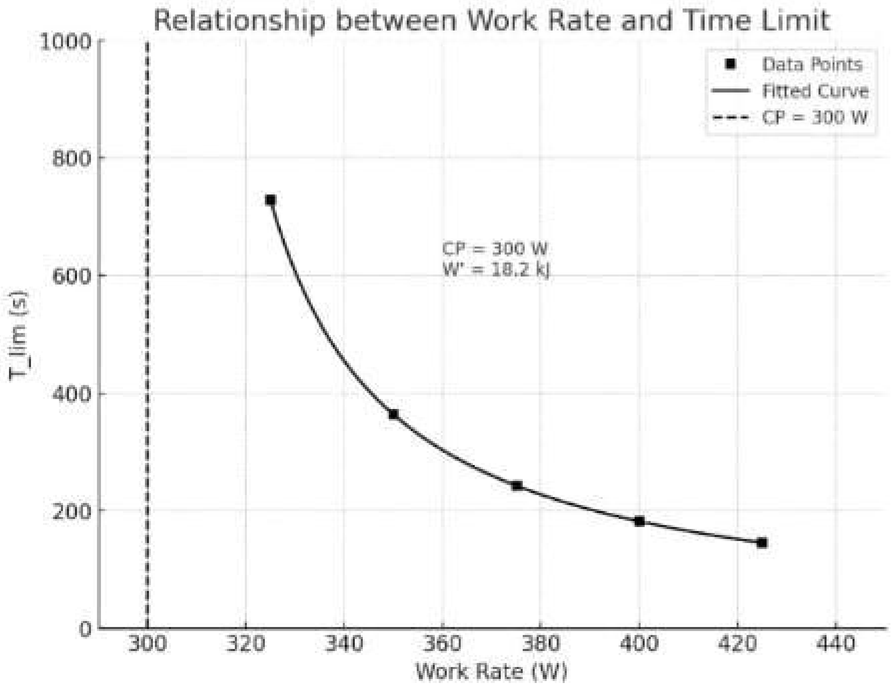

Figure 29. The relationship between the work rate (in watts) and the time limit, with a fitted curve representing the hyperbolic relationship. The critical power (CP = 300 W) is indicated with a dashed line, and the value for W′ is annotated on the graph. Adapted from Fred J. DiMenna and Andrew M. Jones in Performance Assessment in Strength and Conditioning, edited by Paul Comfort.

Challenges in Measuring CF in Practice

While CF is a valuable tool for optimizing training, measuring it in practice can be challenging due to the dynamic nature of climbing movements. Climbing does not typically involve consistent, steady-state efforts, making it difficult to measure CF directly during a climb. To accurately assess CF, a controlled environment must be created, often using tools like a hangboard equipped with a force gauge sensor. This setup allows climbers to perform sustained efforts under controlled conditions, simulating the demands of climbing in a measurable way.

One practical solution for measuring CF in climbers is using specialized equipment like the Climbro system. Climbro offers a hangboard with integrated sensors, protocols, and calculators designed specifically for CF and critical power (CP) testing. This system provides ready-to-use formulas, making it easy for coaches and climbers to accurately measure and apply CF data in their training programs. By utilizing such tools, coaches can overcome the challenges of measuring CF and effectively incorporate it into their athletes' training routines.

Alternative Solution Using the Critical Force Calculator

To accurately determine your forearm aerobic endurance and find the optimal training load, use the Critical Force Calculator available on https://strengthclimbing.com/ Here’s how to use this tool with an example of a different body weight, maintaining the same percentage trends:

Step-by-Step Guide

1) **Prepare Your Data**:

- **Body Weight**: Assume your body weight is 62 kg.
- **MVC-7 (Maximum Volitional Contraction for 7 Seconds)**: Perform the MVC-7 test on a 10-35 mm edge to find the maximum load you can hold for 7 seconds. For example, if you can add 38 kg to your body weight and hang for 7 seconds, your MVC-7 load is 100 kg (62 kg body weight + 38 kg additional load).

2) **Perform Endurance Tests**:
   - **80% MVC-7**: Calculate 80% of your MVC-7 load. For a MVC-7 load of 100 kg, this is 80 kg. Perform a set of 7/3 Repeaters (7 seconds of hanging, 3 seconds of rest) until failure. Record the total hanging time to determine your T80%. For instance, if you manage 10 full hangs and fail at the 11th hang in the 4th second, your T80% is 74 seconds.
   - **60% MVC-7**: Calculate 60% of your MVC-7 load, which is 60 kg. Conduct the same 7/3 Repeaters test and note your T60% result. For example, if you perform 15 full hangs and fail at the 16th hang in the 4th second, your T60% is 109 seconds.
   - **45% MVC-7**: Calculate 45% of your MVC-7 load, which is 45 kg. Perform the 7/3 Repeaters test and record your T45% result. For instance, if you achieve 60 full hangs and fail at the 61st hang in the 4th second, your T45% is 424 seconds. If you exceed 20 minutes at this load, you might consider testing with 50% or 55% MVC-7.

3) **Use the Calculator**:
   - Go to the Critical Force Calculator on the StrengthClimbing.com website.
   - Enter your body weight (62 kg), MVC-7 load (100 kg), and your results for T80%, T60%, and T45% into the form.

4) **Receive Your Results**:

- The calculator will compute your Critical Force (CF) and tell you how many kilograms to subtract from your body weight to train at the CF load.

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The Importance of Flexibility in Sport Climbing and Methods for Its Assessment

Flexibility, defined as the range of motion in specific joints Kurz (2003), is a critical attribute for sport climbers, bridging structural and functional characteristics. It allows athletes to achieve extensive movement amplitudes within the physiological range of motion in joints, which is essential for executing complex climbing maneuvers. Optimal flexibility reduces the risk of injuries Andersen (2005)., decreases neuromuscular tension, and enhances movement efficiency, all of which are crucial for successful climbing performance Draga et al. (2020).

Factors Influencing Flexibility Kurz (2003)

Flexibility in sport climbing is influenced by various factors, including:

- **Muscle Temperature and Elasticity:** Warmer muscles tend to be more elastic and capable of greater stretches.
- **Joint Mobility:** Determined by the anatomical structure of the joint.
- **Ligament and Tendon Elasticity:** More elastic ligaments and tendons contribute to greater joint flexibility.

Scientific research indicates that climbers, both in specific and non-specific tests, generally exhibit higher levels of body flexibility compared to non-climbers. The range of motion in the hip and knee joints is particularly important, as climbers often need to perform movements that require significant flexibility in these areas. Additionally, spinal flexibility plays a vital role, as strength training may lead to spinal stiffness, potentially causing back pain.

Research Findings on Flexibility in Climbers

Practical experience in training has highlighted the importance of flexibility as a determinant of climbing success . Flexibility enhances the quality of movement execution, directly impacting climbing efficiency. However, the question arises: is flexibility a fundamental determinant of success in climbing?

Researchers such as Grant et al. [1996], Draper et al. [2009], and Draga [2020] have attempted to answer this question using both non-specific and specific tests to assess body flexibility. The most commonly used non-specific test is the "sit and reach" test, which measures spinal flexibility. Additionally, tests like the maximal range of motion in a seated straddle position have been employed.

Research	Climbing Level, Sample Size	Sit and Reach Test (cm)	Straddle-Sit Test (cm)
Grant et al. (1996)	~6a (N=10)	39.7 ± 7.8	-
Recreational Climbers	31.3 ± 6.8	-	-
Non-Climbers	34.5 ± 5.2	-	-
Draga (2020)	7b to 8c (N=29)	21.92 ± 12.08	-
Draper et al. (2009)	>8a (N=3)	28.2 ± 7.6	-
	6b+ to 7c+ (N=16)	26.7 ± 6.4	-
	5c to 6b (N=22)	24.2 ± 10.20	-
	4a to 5a (N=5)	24.4 ± 9.3	
Rokowski (2006)	7a to 8a+/b OS (N=30)	-	60 ± 14
	~6a (N=30)	-	60.7 ± 15

Table 27. Results of Non-Specific Flexibility Tests at Different Climbing Skill Levels.

Although significant statistical differences between groups were often not found, the data suggests that climbers with higher skill levels tend to achieve better results in tests measuring sacroiliac joint flexibility. This indicates that climbers should ideally have above-average spinal flexibility Rokowski (2019). However, it is noteworthy that most studies did not report significant correlation coefficients between climbing skill level and the results of these tests.

Specific Flexibility Tests for Climbing

Given the limitations of non-specific tests, some researchers have developed specific flexibility tests tailored to the needs of climbers. Draper et al. [2009] , Draga et al. [2020] introduced a battery of tests that specifically measure hip joint flexibility in sport climbers Tab. 28.

Climbing Level (n)	Sit & reach (cm)	Foot Raise (cm)	Grant Test (cm)	Foot Reach (cm)	Foot Raise (cm)	Foot Loading (cm)	Draga Test (cm)	Draga Index (DI)
Novice (n =5)	24,4 ± 9,3	89,1 ± 8,9	103,7 ± 9,2	173,2 ± 7,3	134,3 ± 13,6	122,2 ± 8,9	-	-
Intermediate (n=22)	24,2 ± 10,2	88,5 ± 9,9	102,4 ± 12,4	178,2 ± 10,2	140,2 ± 19,0	133,7 ± 12,5	-	-
Advanced (n=16)	26,7 ± 6,4	91,4 ± 11,6	108,3 ± 15,4	179,6 ± 9,87	156,5 ± 23,7	143,2 ± 12,1	-	-
Elite (n=3)	28,2 ± 7,6	92,8 ± 10,9	114 ± 15,5	183,7 ±13,6	176,5 ± 14,4	150,0 ± 9,6	-	-
7b-9a	-	-	-	-	-	-	0,32	0,85

Table 28**.** Results of Specific Flexibility Tests at Different Climbing Skill Levels (Adapted from Draper et al. (2009) Draga et al. (2020)).

Description and Comparison of Draga and Draper Tests

The **Draga Test** and the **Draper Tests** are tools used to assess flexibility, particularly in the context of sport climbing. Below is a detailed description of each test, along with a comparative table highlighting the key differences and how they are performed.

Draga Test

The Draga Test is designed to evaluate hip joint mobility, focusing on external rotation and knee flexion. In this test, the participant's pelvis and torso are stabilized to limit movement to the hip joint. The measurement involves raising the leg bent at the knee in the frontal plane, and the maximum distance between the heel and the ground is recorded Photo. 13. The result is expressed in both absolute values and as the so-called "Draga Index" (DI), calculated using the following formula:

DI= B-tro / a

where:

- **B-tro** – length of the lower limb (cm),
- **a** – distance between the calcaneal tuberosity and the ground (cm).


(a) (b)

Photo 13. Tests for evaluation of hip joint mobility: (a) Grant test modified by Draper et al. (2009);(b) Author's Draga test.

Draper Tests

In a series of tests developed by Draper et. al. (2009), various aspects of specific flexibility in climbers were examined using modifications of earlier tests and new measurement methods:

1) **Adapted Grant Foot Raise Test**: A modification of the test proposed by Grant et. al. (1996). The participant attempts to raise the leg as high as possible in the frontal plane while standing on a flat surface Photo. 14.

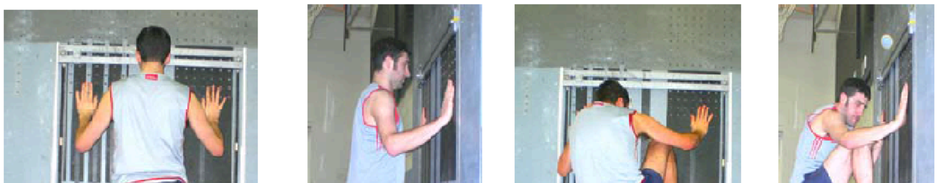

Photo. 14. Adapted Grant Foot Raise Test reprinted from Draper et. al. (2009).

2) **Climbing-Specific Foot Raise Test**: The participant raises the leg while standing on steps, simulating climbing conditions. This test measures the range of motion that is specific to climbing Photo 15.

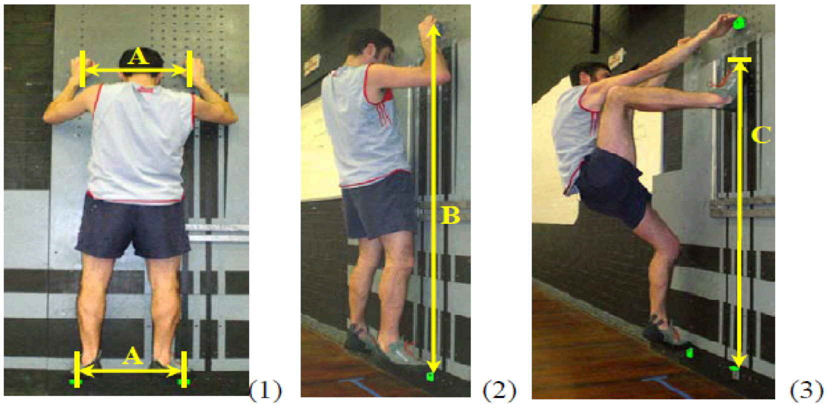

Photo. 15. Climbing-Specific Foot Raise Test reprinted from Draper et. al. (2009).

3) **Lateral Foot Reach Test**: The participant moves the leg to the side, assessing hip joint mobility in the frontal plane Photo 16.

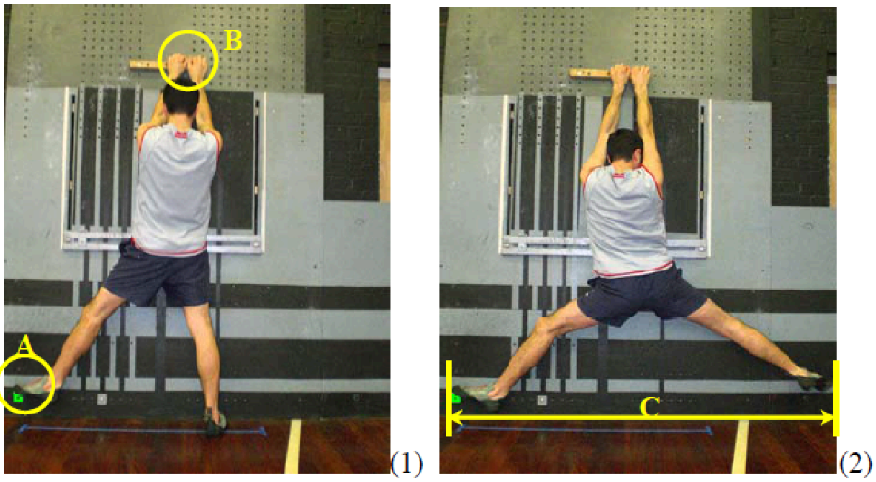

Photo. 16. Lateral Foot Reach Test reprinted from Draper et. al. (2009).

4) **Foot-Loading Flexibility Test**: This test involves a dynamic step-up, measuring both flexibility and the ability to perform dynamic movements in the hip joints Photo 17.

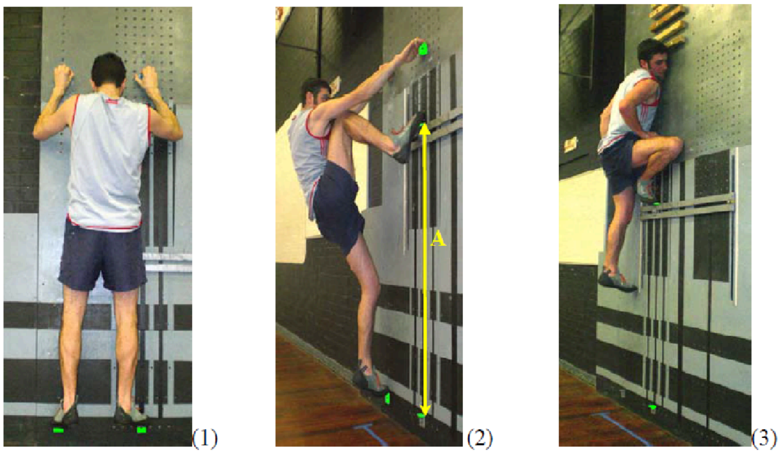

Photo 17. Foot-Loading Flexibility Test reprinted from Draper et. al (2009).

Comparison of Draga and Draper Tests in Tab. 29.

Test	Method of execution	What it measures
Draga Test	The participant is stabilized on a measurement board, rotates the foot outward, and raises the leg bent at the knee.	Hip joint mobility, especially in external rotation and flexion.
Adapted Grant Foot Raise Test	The participant raises the leg as high as possible in the frontal plane while standing on a flat surface.	Range of motion of the leg in the frontal plane.
Climbing-Specific Foot Raise Test	The participant raises the leg while standing on steps, simulating climbing conditions.	Range of motion specific to climbing.
Lateral Foot Reach Test	The participant moves the leg to the side, measuring hip mobility in the frontal plane	Hip joint mobility in the frontal plane.
Foot-Loading Flexibility Test	A dynamic step-up, measuring both flexibility and dynamic movement ability.	Flexibility and dynamic movement ability in the hip joints.

Table 29. Comparison of Draga and Draper Tests.

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