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Effects of Duration, Intensity, and Recovery Intervals of Dynamic Warm-Up Protocols on Subsequent Acute Explosive Performance Outcomes in Competitive Athletes

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Abstract. In explosive sports, the exertion of power, which occurs within a second, is a primary determinant of skill-related fitness such as speed and agility. In order to prepare athletes for the skill used in subsequent sports, dynamic warm-up is introduced. Variation in the duration, intensity, and recovery intervals of dynamic warm-up creates uncertainty when designing the optimal protocol for enhancing explosive performance. As such, along with discussing the mechanisms, this review aims to explore the evidence-informed ranges for the three variables, interactions between the variables, and sports-specific applications based on existing literature. Current evidence suggests that the major function of dynamic warm-up is to increase core temperature and neuromuscular activation, following the RAMP model for warm-up. Intensity of warm-up serves to elicit post-activation performance enhancement (PAPE), which contributes to acute performance changes. On the other hand, the magnitude of these beneficial effects is dependent on achieving a balance between potentiation and fatigue, both exerted through exercises, as inappropriate design would diminish performance improvements. Thus, when designing dynamic warm-up protocols, individualized manipulation of duration, intensity, and recovery intervals based on sports-specific demands and athletes' characteristics would greatly promote the effectiveness of warm-up.

Keywords: Dynamic warm-up, RAMP, Post-Activation Performance Enhancement (PAPE), Potentiation, Explosive Power

1. Introduction

With the development of sports science, the importance of warm-up protocols has been expanding among trainers and athletes. Rather than solely reducing the risks of injury, passive and active warm-ups are also found to be significant in aiding athletes to attain the best of their performance [1]. Warm-up exercises would generally prepare athletes for explosive exercises primarily by increasing muscle temperature and reducing stiffness of joints and muscles; they are also found to enhance mental preparedness in athletes [2].

There are two major categories of warm-up: passive and active. While active warm-up involves voluntary exercise such as running, Passive warm-ups use external methods like saunas to raise

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muscle and body temperature without requiring voluntary movement [3]. Static and dynamic warm-ups are two major subcategories of active warm-up. Static warm-up includes stretching a limb or a joint to the ends of its range of motion (ROM) [4]. Meanwhile, dynamic warm-up, such as high knees and arm circles, involves moving a limb or a joint to its full range and repetitively does the movement in motion [5]. Compared to static warm-up, dynamic warm-up protocols become more widely adopted among international professional athletes as they produce more favorable results in terms of mobilizing movement, notably sprinting and jumping, which is a common movement in gymnastic [6, 7]. Dynamic warm-up will be the main focus of this literature review, discussing the effect of duration, intensity, and recovery intervals of the protocols as they are interrelated, interactional factors that would influence the effectiveness of warm-up activities. If these factors are not balanced and considered properly, warm-up could potentially decrease the performance level of athletes by overloading fatigue and increasing injury risk [8]. With the understanding of the importance of warm-up protocols and explosive power for athletes, this research is aimed to review and summarize the latest research achievements in the field of dynamic warm-up, clarify the specific impact mechanisms of each key variable on acute explosive power, and thereby provide practical scientific warm-up plan suggestions for front-line coaches and high-level athletes.

2. Dynamic warm-up

Dynamic warm-up primarily follows the RAMP model (Raise, Activate, Mobilize, Potentiate) [9], which is a framework that organizes warm-up exercises into a logical, progressive sequence to maximize athlete performance. A 10-to-15 minute RAMP warm-up stage would be highly efficient for preparation and energy saving [10].

Raise is aimed at increase muscle and core temperature, blood circulation, respiratory rate, and heart rate through conducting low-intensity exercises, such as side shuffles and skipping. Raise is a crucial step for preparing athletes for later activities, as an increase in muscle temperature strengthens rate-dependent contractile function that is measured by rate of force development (RFD-how fast a muscle generates explosive force) and muscle power output (force $\times$ velocity) [11]. During the Activate phase, exercises like plank are conducted in order to stimulate specific muscle group that will be used in the formal setting, which also enhances joint stability and neuromuscular control [9]. After these muscle groups are activated, athletes will focus on mobilizing them, or performing dynamic exercises to increase muscle's range of motion. In the last phase Potentiate, the intensity of warm-up increases gradually, movements such as sprinting, squats, and vertical jumps are included to prepare the nervous system for higher-intensity activities. During Potentiate, more sport-specific exercises are involved, transforming the body into a better state that is suitable for this particular sport.

RAMP is a more sophisticated model that provides a scientific explanation and reasoning for each stage, and it may improve selected acute outcomes when properly designed. As such, RAMP, or dynamic warm-up, is one of the best strategies to maintain long-term health and performance for athletes.

3. Factors

3.1. Duration

Among several variables of warm-up, duration is one of the most debated. Some trainers keep warm-up protocols short, often under 5 minutes, or even exclude warm-up in their trainings. On the

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other hand, there are trainers who would spend a large portion of training time on warm-up as they want to protect their players from getting injured. However, warming up for too short or too long has its negative consequences. When a warm-up lasts shortly, it fails to achieve the goal of elevating core temperature and enhancing neuromuscular activation. A warm-up less than 7 minutes often does not show a stable improvement in athlete performance [12]. Whereas for long warm-up activities, athletes could begin to feel a sense of fatigue that would limit performance gains. Therefore, the key issue is to identify the optimal duration for warm-up that neither overwhelms athletes nor compromises the necessary time required to adequately activate them. Li recommends that dynamic exercises last at least 7 minutes to raise body temperature, improve joint mobility, and strengthen neuromuscular activation [12]. With progressive intensity in designed activities, a (10-15) minute dynamic warm-up is sufficient for athletes to achieve their optimal performance [4]. Warm-up duration varies by sports and by individual, and it must be balanced between intensity and recovery time, with the final goal of reaching the threshold for optimal muscle temperature and oxygen consumption during exercises Volume of Oxygen (VO_2) [13].

3.2. Intensity

The importance of the intensity of dynamic warm-up is similar to that of the duration: athletes need to be kept in a comfortable zone between fatigue and physical readiness. The intensity of dynamic warm-up protocols is closely related to Post-Activation Potentiation (PAP) and Post-Activation Performance Enhancement (PAPE).

3.2.1. PAP

PAP is a physiological phenomenon at which conditioning activity or training is followed by an enhancement in muscle, often measured by rate of force development (RFD) and it played a major role in explaining observed improvement in acute explosive performance for athletes after a conditioning exercise [7]. The proposed physiological mechanism of PAP is based on the phosphorylation of myosin regulatory light chains. the two light peptide chains in Myosin are categorized into regulatory light chain (RLC) and essential light chain (ELC) [14]. Since RLC is attached near the neck of the myosin head, it can affect the position of the head through phosphorylation, thereby altering cross-bridge behavior and muscle force generation.

3.2.2. PAPE

PAPE is commonly defined as an acute improvement in voluntary athletic performance that covers a longer time window (3-15 minutes), after conditioning activity [15]. PAPE acts as a mechanism through which warm-up exercises can improve athlete performance, and PAPE often requires more intense conditioning activities. Rather than having a clear explanation of its mechanism like PAP does, Aytaç and İşler [16] explain that several physiological processes likely interact to drive PAPE, including an increase in muscle temperature, neural mechanisms, and MRLC phosphorylation. PAPE also varies among athletes depending on their physical condition and the designed training. Thus, conditioning activity and warm-up intensity are key determinants of the degree of PAPE.

Instead of being a replacement for dynamic warm-up, it serves as an additional strategy following a dynamic warm-up exercise, being an advancement of the potentiate phase in RAMP. Consequently, PAPE is not a completely separate topic from dynamic warm-up; rather, it builds on the physiological foundation provided by a dynamic warm-up protocol.

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Although some researches found that higher intensity warm-up means better explosive performance [17], it is more complicated than a directly proportional relationship, as fatigue and potentiation need to be balanced. Instead of maximal intensity, optimal intensity exists at a value that is capable of inducing PAPE and strengthening performance without excessive fatigue, corresponding to the Potentiation in the RAMP model. Intensity should be individualized depending on the ability and fitness of the athlete. According to Seitz and Haff, the most effective PAP/PAPE protocol is at 80-90% 1RM (Repetition Maximum), the maximum amount of weight an athlete can lift for a complete repetition, ranging from 1 to 5 repetitions [18].

Another key aspect of intensity for dynamic warm-up is to gradually increase the intensity of activities, as athletes under constant high intensity practices may have a higher risk of injury, while low intensity could not achieve the purpose of stimulating PAPE.

3.3. Recovery interval

Recovery time function is the ultimate balancing factor in dynamic warm-up design. Recovery time aims to balance the fatigue depending on intensity and duration. The central question is what is a time period that allows athletes to get enough rest and yet still be active and ready for their final exercise.

3.3.1. Self-selected recovery interval (SSRI)

As the name suggests, self-selected recovery interval (SSRI/SSI) refers to a recovery time interval that is chosen by the athlete based on their feelings and evaluation of their body, instead of following a fixed recovery interval (FRI) [19]. However, SSRI is not a widely discussed concept in warm-up and sports science; it could be a factor when considering recovery time. Fontanetti et al. demonstrate that SSRI/SSI in PAPE protocols efficacy is potentially exclusive to professional athletes because they could tell more accurately of their body condition in terms of readiness for the following sports [20].

3.3.2. Recovery time: dynamic warm-up vs PAPE protocols and dynamic warm-up

The recovery interval for dynamic warm-up and for PAPE protocols in addition to dynamic warm-up should be revised separately, as inclusion of PAPE protocols means having a higher intensity than conventional dynamic warm-up alone, which would affect the recovery time.

Because dynamic warm-up is less intense when it does not follow the goal of activating PAPE, it often creates less fatigue for athletes. The focus of recovery time shifts from allowing athletes to recover from tiredness to maximizing the beneficial effects of dynamic warm-up—increased muscle temperature, heart rate, and neural activation. During the recovery period after an active warm-up, muscle and core temperatures begin to drop quickly [21], erasing the intended effect of dynamic warm-up, which is to raise body temperature. Thus, the recovery time for dynamic warm-up suggests keeping it under 10 minutes, or even right after warm-up. If the transition from warm-up to the next exercise is longer than 15 minutes, then a re-warm-up activity could be implemented to offset the negative consequence of the overlong recovery interval.

Compared to sole dynamic warm-up, PAPE protocols would add more movements with higher intensity, such as front squat and bench press. At a higher intensity, potentiation and fatigue will both increase, which means that finding a point at which potentiation surpasses fatigue at maximal

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value is crucial in this case. Dynamic warm-ups that include PAPE protocols would also require a longer recovery interval.

Zhou et al. proposed that a recovery interval of 3-7 minutes is the overall optimum [22]. They also introduced the concept of two potentiation windows, at which potentiation exceeds fatigue. The first window appears immediately after the conditioning activity, at 0-2 minutes, and the second appears at approximately 3-7 minutes after the warm-up, which has a better result on maximizing PAPE.

4. Sports-specific applications

4.1. Sprint-dominant sports

Sprinting is not a rare component of explosive sports; it can be seen in many types of sports. For both short and long sprints in sports where a difference in seconds counts, a key concept is acceleration, accompanied by maximal running velocity. Rate of force development (RFD), discussed in both the measurement of dynamic warm-up protocols and post-activation potentiation (PAP), plays a crucial role in acceleration, with faster sprinters often exhibiting higher rates of RFD, as they can generate more force during ground contact [23]. To achieve the goal of inducing a high RFD and an efficient SSC, warm-up protocols for sprinting dominant sports will focus on factors such as high-velocity, central nervous system activation, and ankle/muscle stiffness.

According to the RAMP model, phase 1 would focus on elevating core temperature, increasing muscle elasticity, and promoting blood flow [13]. This phase would be at a low intensity and lasts for about 5 minutes, including exercises such as light jogging. After core temperature is raised, athletes would then enter the Activate phase, in which they focus on more specific muscle groups and activate sprint-specific neuromuscular patterns. Exercises such as A-skips, B-skips, high knees, and bounds would be implemented [24]. This phase would last for about 5-6 minutes, with a moderate intensity. In the third stage Mobilize, athletes would face a higher intensity with a small volume in order to help them adapt to a more activated central nervous system and a similar intensity to the final sport. Suggested activities are 20-meter to 40-meter acceleration, broad jumps, and short, fast sprint exercises. The fourth and final step, Potentiate, largely follows the goal of inducing PAPE before the official exercise starts. The warm-up protocols for sprint-dominant sports generally follow this structure, but the specific recovery interval still depends on the intensity and the duration of each exercise, in addition to the athletes' judgements of their own physical condition.

Other than intensity and duration, another factor that has rarely been taken into consideration is the sex of the athletes. Žuvela et al. contrasted the effects of warm-up routines of different durations and types on sprint speed in male and female athletes [25]. The study showed that sport-specific warm-up plays a role in female athletes' performance in longer distance sprinting, while it has no significant difference in males. The difference between male and female athletes could be potentially attributed to male athletes exhibiting higher baseline motor unit recruitment and RFD, which means that males can reach the baseline neural activation even with a general aerobic warm-up. This study also demonstrated that there is not a standardized, strict value for warm-up duration, intensity, and recovery interval, which can be adjusted based on individual circumstances.

4.2. Power- and Jump- Dominant Sports

In sports such as volleyball, long jump, and basketball, power and jumping ability are essential and indispensable. Compared to sprint-dominant sports, jump- and power-dominant sports largely rely

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on the stretch-shortening cycle (SSC) [26].

Power- and jump-dominant sports will largely follow the RAMP model, as they all fall under the large category of explosive sports [27]. However, their primary disparity with sprint-dominant sports lies in the movement specificity of the Activate and Potentiate phase. For Raise, athletes still follow a low-intensity and short warm-up protocol in order to raise their muscle temperature. In Activate and Mobilize, instead of doing A-skips and sprinting activities that improve RFD, athletes in power- and jump-dominant sports would do activities that emphasize vertical force production and SSC efficiency. For example, countermovement jumps, squat jumps, and pogos are all valid exercises. Dynamic stretching is also directly associated with a significant improvement in countermovement jump (CMJ) [12]. In the last phase Potentiate, loaded and depth jump would be implemented in order to ignite PAPE and to enhance athletes' readiness in those specific movements that they will use in the official sports play.

4.3. Change-of-direction and intermittent team sports

In change-of-direction (CoD) sports, such as soccer, hockey, and basketball, agility, deceleration control, and lateral hip mobility are emphasized [28]. Sports that require a great amount of CoD movements would often require athletes to exert greater hip strength and greater range of motion (ROM) for knees, hips, and ankles to ensure eccentric force production and to prevent injury. During CoD movements, adequate ankle dorsiflexion mobility allows greater force absorption during deceleration, whereas limited ROM would potentially restrict the athlete's ability to adopt an optimal braking position [29]. As such, the RAMP model for CoD sports, movements such as lateral carioca and deceleration drills, would prepare the athletes better than long sprinting drills. Additionally, short sprints with direction changes could be used to improve agility and practice both deceleration and acceleration control. In potentiate, rather than jumping and sprinting exercises, ball-related drills and small-sided games would be beneficial for the athletes [30].

5. Limitation

Across the existing body of research and articles on dynamic warm-up, heterogeneity of warm-up protocols sets the greatest limitation. Studies vary in their design for exercise, intensity, duration, recovery intervals, and outcome measurement. Consequently, the difference in performance could be attribute to several factors, unable to examine the specific effect of one variable.

Moreover, most studies included in this review are composed of small and homogeneous samples. For a majority of studies, the participants are male athletes that are often at the university level, which establishes its limitation on generalizability to other groups such as females and older adults. This review also exclusively focuses on professional athletes.

Because individuals differ in goals, physical fitness, and experience, this review is unable to create specified number for each variable. Rather, an estimation of each based on general evidence and measurement is given.

6. Conclusion

Dynamic warm-up proves its efficacy in improving athletes' explosive performance through enhancing the physiological and neuromuscular processes required for immediate force production, yet still allowing movement specificity. The estimated optimal duration for dynamic warm-up is about 10-15 minutes, with a gradually increasing intensity. Optimal intensity is largely related to the

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induction of PAPE, which often requires a higher intensity than casual warm-up. Recovery interval is set based on the extent of fatigue and potentiation. Additionally, duration, intensity, and recovery interval are interrelated factors that would be modulated together to design a suitable scheme for individual athletes. Across the existing body of research and articles on dynamic warm-up, studies vary in their design for exercise, intensity, duration, recovery intervals, and outcome measurement. Moreover, most studies included in this review are composed of small and homogeneous samples. When discussing the interaction of the three variables, limited evidence is found.

Future studies should adopt more standardized experimental designs to facilitate meaningful comparisons, closing the gap in the body of evidence. Studies could also examine how individual factors such as age, competitive level, and sex influence the effect of dynamic warm-up on players. Moreover, longitudinal research should also investigate whether repeatedly implementing individualized, sport-specific warm-up strategies produces sustained improvements in performance and injury prevention over the course of a training season.

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