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增強式、彈震式及混合熱身對衝刺生物力學及表現的急性影響

Acute effects of plyometric, ballistic, and mixed warm-ups on sprint biomechanics and performance

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Abstract

Background: Plyometric and ballistic exercises are popular in sprint training due to their well-known long-term benefits. However, researchers debate the acute effects of such exercises when integrated into warm-up routines. **Purpose:** This study aimed to distinguish the effects of plyometric, ballistic, and mixed warm-up strategies on sprint performance in individuals with different performance levels. **Method:** 15 sprinters and 15 non-sprinters completed traditional, ballistic, plyometric, and mixed (ballistic-plyometric) warm-ups before a 40-meter sprint test on four days in randomized order. Sprint times were recorded at 10, 20, 30, and 40 meters. Spatiotemporal and kinematics data were recorded at the start and 40 meters. A validated spreadsheet estimated force-velocity variables based on time intervals. Two-way repeated measures ANOVA assessed the effects of groups and warm-ups. **Result:** No significant differences in sprint performance (p = .82–.92, $p\eta^2$= .01–.02), kinetic (p = .48–.64, $p\eta^2$= .03–.06), and kinematics (p = .16–.99, $p\eta^2$=.01–.12) were found between warm-ups. However, group differences were observed in sprint performances (p < .001, $p\eta^2$= .59–.74), contact time at the first step and maximum-speed sprinting (p < .001, $p\eta^2$= .59–.75), flight time at the first step (p < .001, $p\eta^2$= .61), maximum horizontal power output (p = .003, $p\eta^2$= .48), and maximum speed (p < .001, $p\eta^2$= .79). **Conclusion:** Plyometric, ballistic, and mixed warm-up protocols appear to produce neglectable improvements in sprint performance compared to traditional warm-up. Future research should rigorously control for variables and systematically vary conditioning intensity to determine whether appropriately dosed interventions can elicit true PAPE effects or should be discounted for sprint enhancement.

Keywords: Acceleration, activation, explosiveness, kinematics, post-activation performance enhancement, spatiotemporal, weight exercises.

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I. INTRODUCTION

1.1 Study Background

Sprinting is a fundamental human motor skill focused on rapid movement from one point to another within a specific time. It holds major importance in various sports including football, soccer, and especially sprint running (Mero & Gregor, 1992; Haugen et al., 2019). Studies indicate that enhancing sprinting capabilities can lead to an improvement in overall physical performance in sports (Haugen et al., 2014).

Before training or competing, athletes often perform warm-up exercises to enhance their performance in the following activity. Active warm-ups (i.e., dynamic stretches) are commonly used before sprinting sessions and have shown performance improvements (McGowan et al., 2015). However, over the decades, plyometric and ballistic exercises have gained popularity among athletes and trainers because their movements closely resemble the sprinting characteristics.

While plyometric and ballistic exercises have shown long-term benefits (Cormie et al., 2011; Moran et al., 2023; Ramirez-Campillo et al., 2021), their immediate effects remain a topic of debate. Furthermore, individuals at varying levels of strength and skill may experience different degrees of benefit from these exercises (Chiu et al., 2003; Pereira et al., 2022). Therefore, this study aims to discuss the acute effects of plyometric and ballistic exercises and compare them with traditional warm-ups (i.e., dynamic stretches), taking into account differences between various skill levels.

1.2 Research Purpose

This study aims to evaluate the effects of various warm-up protocols on sprint biomechanics and performance in sprinters and non-sprinters. Specifically, it compares pure plyometric warm-ups, pure ballistic warm-ups, and a mixed warm-up combining plyometric and ballistic characteristics to a traditional warm-up (dynamic stretching).

1.3 Hypotheses

According to the research purpose, the hypotheses of this study are:

A. Plyometric, ballistic, and mixed exercise warm-ups more effectively improve sprint performance than traditional warm-up.
B. Each warm-up alters various biomechanical variables in sprinting differently due to different mechanisms underlying these warm-up regimes, allowing for need-specific recommendations

1.4 Operational Definition

1. Ballistic exercises

Ballistic exercises involve acceleration throughout the entire range of motion, transitioning into a subsequent flight phase (Maloney et al., 2014; Cormie et al., 2011; Newton et al., 1996).

2. Plyometric exercises

Plyometric exercises involve an eccentric movement, immediately followed by a concentric movement (Wathen, 1993; Davies et al., 2015). Such a sequence of

countermovement and acceleration engages a stretch-shortening cycle (SSC; Cormie et al., 2011).

II. LITERATURE REVIEW

2.1 The components of sprinting

The linear sprint involves many sports activities and is an important ability, such as team sports and track and field (Popowczak et al., 2019; Haugen et al., 2019; Keiner et al., 2021). Sprinting is typically segmented into three phases: acceleration (including the start block), maximal velocity, and deceleration (Mero & Gregor, 1992). The sprint winner is usually the person who completes the race in the shortest time. As for team sports, it would hold more advantages, for example, related to the ability to change direction (Keiner et al., 2021; Kadlubowski et al., 2021). According to the formula where velocity equals distance divided by time, achieving a greater velocity is crucial for reaching better sprint performance. Achieving great velocity in the maximal velocity phase requires a good acceleration in the previous (Von Lieres Und Wilkau et al., 2020). The distance is usually shorter for team sports, for instance, within 20 m for rugby and soccer (Gabbett, 2012; Andrzejewski et al., 2013). A study also indicated that players selected for Australian football demonstrate greater 5 m and 20 m sprint abilities (Young & Pryor, 2007). These studies suggested that the ability to accelerate becomes a more important element. In the acceleration phase of the sprint, velocity increases with the growth of the stride length and stride frequency (Mero & Gregor, 1992; Nagahara et al., 2014). This period lasts around 5 to 7 seconds or 30 to 50 meters (Hirvonen et al., 1987; Mero & Gregor, 1992). The acceleration phase is critical in sprinting as it is characterized by the generation of maximal horizontal power. Research highlights the importance of propulsive force during this phase, as it directly contributes to horizontal translation and influences key performance factors, including horizontal external power, propulsive impulse, and running velocity. (Slawinski et al., 2015; Samozino et al., 2015; Haugen et al., 2019; Von Lieres Und Wilkau et al., 2020)

Research also shows that higher-level sprinters have greater propulsive horizontal forces across the entire acceleration phase (Bezodis et al., 2019).

During the constant speed phase, it is achieved by the ideal acceleration, resulting from the optimal relationship between the stride length and stride frequency of an individual (Čoh et al., 2001). While both factors are significant in sprinting, researchers suggest that the stride frequency may play a bigger role in improving speed (Mero & Gregor, 1992; Čoh et al., 2001; Nagahara et al., 2014). According to the above, to achieve a better sprinting performance of an individual, the increases of stride frequency and reaching an optimal relation between stride length and stride frequency is important.

Sprinting includes reaction time, force production, muscle structure, neural factors, and technique (Mero & Gregor, 1992), all of these factors play an important role. Resistance training can improve force production, muscle structure, and neural factors (Sale, 1988; Komi, 2003; Duchateau et al., 2006), hence leading to a better sprint performance. Accordingly, a proper training method is essential for sprinting. Plyometric and ballistic exercises have gained popularity in sports because of their similarity to explosive movements like jumping and running. These methods may help enhance athletic performance by its characteristics (Markovic & Mikulic, 2010; Newton et al., 1996).

2.2 Chronic effects of plyometric and ballistic training

Coaches and trainers have widely applied plyometric movements in training for a long time. The mechanism of plyometrics is by using the stretch-shortening circle (SSC). Wathen. (1993), described the SSC characteristic as a rapid deceleration of a mass followed immediately by a rapid acceleration of the mass in the opposite direction. In other words, an eccentric movement followed by a quick concentric movement. The SSC mechanism includes pre-activation, stretch-reflex, history-depend properties, and recoil of the elastic energy (Seiberl et al., 2021). The store of elastic energy plays a role contributing to the SSC effect, during the rapid eccentric phase, muscle-tendon units store elastic energy by the series elastic components (SEC) and parallel elastic components (PEC), and release it in the concentric phase, thus, improving the physical ability such as power output. Additionally, Fukutani et al. (2021) suggest that other factors contribute to the SSC effect, including the mechanisms of contractile and structural proteins, residual force enhancement, and cross-bridge kinetics. Overall, plyometric exercises leveraging the SSC mechanism can increase neural adaptation, the stiffness of muscle-tendon units, and the rate of force development (RFD), thereby improving performance (Markovic & Mikulic, 2010; Turner & Jeffreys, 2010; Cormie et al., 2011; Davies et al., 2015; Seiberl et al., 2021). Consequently, researchers and experts suggest using plyometric training in sports involving jumping, running, or a change of direction (Davies et al., 2015). In agreement, several studies show positive effects after lower-extremity plyometric training, Maćkała and Fostiak. (2015) found that 2 weeks of plyometric training increased the explosive power in the lower limb and decreased ground contact time, thus, improving times in 20-meter, 60-meter, and jumping performance in male sprinters; Beato et al. (2018) found that 6 weeks of plyometric with the change of direction training improve performance in jumping and short distance sprint in elite football player; Villarreal et al. (2015) found 9 weeks of plyometric and sprint training significantly improve performance in sprinting and jumping.

Ballistic movement is another training method in sports, the ballistic exercise is characterized by performing with maximal velocity and acceleration (Zehr & Sale, 1994) or executing a movement with the intention of maximal velocity and accelerating a mass through the entire movement (Maloney et al., 2014; Cormie et al., 2011). Because it requires continual acceleration throughout the movement, it often transitions into a flying phase, typically involving jumping or throwing movements. (Maloney et al., 2014). According to Newton et al. (1996), performing a movement in a ballistic manner will generate higher peak velocity and peak force than the traditional manner, in which the movement stops at the end of the concentric phase. The findings also suggest that the force-velocity curve of ballistic movements is more akin to explosive motions like jumping than traditional movements (Newton et al., 1996). Generally, the mechanism of ballistic movements is considered to improve the neuromuscular system (Newton et al., 1996), and thus increases the motor units recruit, the rate of fire of units, and the RFD (Desmedt & Godaux, 1977; Zehr & Sale, 1994). In agreement, Winchester et al. (2008) found that 8 weeks of ballistic training significantly improved the peak power and RFD in male recreational athletes, the result suggests the improvements came from the recruitment, rate coding, or neural modifications rather than structural changes; Bettariga et al. (2023) found that 6 weeks of ballistic jumps and unilateral strength training improved the force-velocity curve and time in short distance sprint in male amateur soccer players. Although the long-term effects of plyometric and ballistic training have been well-established, their acute effects are still debated.

2.3 Benefits of a warm-up in sprinting

Athletes typically perform a warm-up before a training session or competition to enhance subsequent activity. A common warm-up for sprinting typically includes cardiovascular exercises, dynamic stretches, and sport-specific movements (Taylor et al., 2013), which follow the RAMP principle (Raise, Activate, Mobilize, and Potentiate, Racinais et al., 2017) but do not include the potentiate phase. In the raise phase, the goal is to increase muscle temperature. Research indicates that increases in muscle temperature have several positive effects, such as enhancing muscle metabolism, increasing muscle glycogen availability, and improving the RFD. Notably, a 1°C rise in muscle temperature can result in a 2-5 percent improvement in subsequent exercise performance (McGowan et al., 2015; Racinais et al., 2017). In the activate and mobilize phase, the aim is to stimulate the target muscle groups for the main activity and improve the range of motion, typically achieved through dynamic stretching. Finally, in the potentiate phase, the objective is to enhance voluntary movement by improving the recruitment of motor units, synchrony of motor neuron firing, and further increasing muscle temperature. This phenomenon, known as post-activation performance enhancement (PAPE), is particularly beneficial for activities requiring maximal effort over a short duration (Racinais et al., 2017; Cuenca-Fernández et al., 2017; Blazevich & Babault, 2019). However, Taylor et al. (2013) found that a warm-up consisting of cardiovascular activities followed by sport-specific movements is effectively equivalent to one including cardiovascular (raise), dynamic stretching (activate & mobilize), and sport-specific activity. Given that sprinting requires maximal effort and lasts for quite a short duration, a warm-up that includes a potentiate phase is expected to benefit more than warm-ups that do not. Implementing a suitable warm-up before starting a sprint exercise is also reasonable.

In recent years, coaches and trainers have utilized the concept of the PAPE in their warm-up routines to achieve acute performance augmentation (Cuenca-Fernández et al., 2017; Brink

et al., 2021; Moré et al., 2024). PAPE is characterized by a short-term improvement in voluntary muscle performance following previous conditioning activity (Wilson et al., 2013; Maloney et al., 2014; Cuenca-Fernández et al., 2017; Blazevich & Babault, 2019; Boullosa, 2021; Fischer & Paternoster, 2024). The optimal range of the enhancement happens between 4 to 10 minutes after conditioning activity (Wilson et al., 2013; Gołaś et al., 2016; Blazevich & Babault, 2019; Fischer & Paternoster, 2024). The mechanisms of PAPE may be the increases in muscle temperature, water accretion within the muscle and intracellular, neural mechanisms like recruitment of motor units, or the excitability of motoneuron (Cuenca-Fernández et al., 2017; Blazevich & Babault, 2019; Fischer & Paternoster, 2024). Based on these mechanisms, researchers suppose that PAPE can enhance muscle performance in explosive sports by improving the RFD. Sprinting requires force output in an extremely short time (less than 250 milliseconds), thus, recruiting and firing as much as possible of motor units is essential. Hence, implementing a warm-up to induce the PAPE effect before a sprint may have a beneficial impact.

When selecting an appropriate conditioning activity to stimulate PAPE, there is no consensus yet on which exercise is the best. However, a review study from Loturco et al. (2024) found that using plyometric exercise as a conditioning activity caused a greater acute effect on sprinting performance than other studies that used resisted sprint drills. Research also indicated that the potentiate phase typically involves executing intense sports-specific movements to imitate performance demands and activate the essential neural paths (Racinais et al., 2017). Based on the above, incorporating plyometric and ballistic exercises may benefit explosive sports. These movements closely resemble the demands of explosive sports, suggesting that inducing the PAPE with these exercises could have positive acute effects. When selecting a method to induce PAPE, it is crucial to consider fatigue as a critical factor. For example, Maloney et al. (2014) concluded that using heavy resistance exercise might impair performance

and need more recovery time, while using ballistic exercise has less recovery time. As a result, using ballistic exercise as a warm-up may be more suitable than heavy resistance exercise. Turner et al. (2015) found that using plyometric exercise improved 10-meter and 20-meter sprinting time at 4 and 8 minutes after exercises. Consequently, plyometric and ballistic exercise as a warm-up method is time-efficient.

2.4 Acute effects of plyometric and ballistic exercises

Utilizing plyometric and ballistic exercises, which are time-efficient and cause less fatigue than heavy resistance exercises, to induce PAPE is expected to positively affect sprinting performance, as these exercises closely relate to sprinting. Studies have explored various conditioning activities—such as resisted or assisted sprints and resistance exercises, to examine their acute effects on sprint performance (Matusiński et al., 2021; Zisi et al., 2022; Li et al., 2024). While recent research suggested plyometric and ballistic exercise could also stimulate PAPE effects on sprint performance (Maloney et al., 2014; Boullosa, 2021). A previous study also speculates using plyometric exercises as conditioning activity may cause acute neural enhancement (Masamoto et al., 2003), and thus improve voluntary contractile performance in sprinting, which is highly related to the sprint acceleration phase. In agreement, Creekmur et al. (2017) found a decrease in time in 20-meter and 40-meter sprints after plyometric warm-up for track and field athletes. They used plate jumps (11.3 kg) as plyometric exercises; Turner et al. (2015) used alternate leg bounds with and without external weight (10% body weight) as plyometric exercise and tested in different periods (15 seconds, 2, 4, 8, 12, and 16 minutes) after exercises. Both have improved performance in 10-meter and 20-meter in non-competitive sprinters, but only at 4 and 8 minutes; Gil et al. (2019) found using depth jump as a ballistic

exercise warm-up significantly increased the stride length in the first 50-meter of 100-meter sprint compared with a normal warm-up in non-competitive sprinters, although the sprint time in 50 and 100-meter does not significantly different. In contrast, Gil et al. (2020) found after using depth jump as the ballistic warm-up, the sprint kinematics and performance were not significantly different compared with the general warm-up in 15 and 30-meter. The different outcomes between the research of Gil et al. (2019) and Gil et al. (2020) may result from the different time gaps from the warm-up exercise to the sprint test. In the study (Gil et al., 2020), the sprint test was conducted 10 minutes after the exercise. Such a long period may cause the PAPE effect to dissipate as shown by Turner et al. (2015). Simperingham et al. (2015) found using weight ballistic exercises (1-5% of body mass), such as drop jump, and 40-meter sprint acceleration with additional load, the result shows drop jumps impair sprint performance while sprint acceleration with additional load improves the performance. However, plyometric movements often occur naturally in human activities like sprinting and throwing, which also involve ballistic characteristics (Cormie et al., 2011; Seiberl et al., 2015). Therefore, the performance benefits of plyometric exercises may stem from both their plyometric and ballistic qualities. For instance, Creekmur et al. (2017) used plate jump as a plyometric exercise; Iacono et al., used drop jumps as a plyometric exercise; Simperingham et al. (2015) used drop jump as a ballistic exercise; Gil et al., (2019, 2020) used depth jump as a ballistic exercise. Both the exercises in the study include the SSC (plyometric characteristic) and flying phase (ballistic characteristic). As a result, it is necessary to separate these two types of exercises further to identify the effect of a different type of exercises.

The magnitude of PAPE varies between individuals, potentially depending on strength level, skill level, exercise type, intensity, sets, repetitions, and recovery time (Wilson et al., 2013; Maloney et al., 2014; Gołaś et al., 2016; Blazevic & Babault, 2019). Chiu et al. (2003) confirmed greater PAPE effects in athletes than in recreational practitioners. However, Pereira

et al. (2022) reported negligible PAPE effects in top-level sprinters; Loturco et al. (2024) concluded PAPE caused no effective enhancement in elite sprinters. Hence, appropriate implementation of PAPE strategies for different target groups needs further investigation.

Finally, the acute changes in neural factors of PAPE caused by using plyometric or ballistic movements as conditioning activities remain unclear. While previous research (Masamoto, 2003) suggests potential acute effects on neural factors, most studies focus on performance metrics such as time and velocity or kinematic aspects. Therefore, collecting kinetic data could provide valuable insights into whether these acute neural changes play a significant role.

Table 2-1

Research on acute effects in plyometric warm-ups

Plyometric	**Movements**	**Result**
Creekmur et al., 2017	CMJ with additional weight	Improve the time of 20, 40m
Turner et al., 2015	Leg bound with/ without additional weight	Improve the time of 10, 20m
Pereira et al., 2022	Drop jumps	Negligible improvement
Iacono et al., 2016	Single leg drop jumps (vertical & horizontal)	Improve sprint performance

Table 2-2

Research of acute effect in ballistic warm-ups

Ballistic	Movements	Result
Gil et al., 2019	Depth jumps	Increase stride length in the first 50m of 100m
Gil et al., 2020	Depth jumps	No significant improvement
Simperingham et al., 2015	Drop jumps, sprint acceleration, flying start (with additional weight)	Load acceleration improves 10m sprint; drop jumps & flying sprint impair sprint performance

Table 2-3

The performance level and acute effect in each research

Research	Subjects	Acute effect
Creekmur et al., 2017	NCAA 1 track & field athlete	YES
Turner et al., 2015	Non-competitive sprinters	YES
Pereira et al., 2022	Top-level & international-level sprinters	NO
Iacono et al., 2016	Elite handball players	YES
Gil et al., 2019	Non-competitive sprinters	YES
Gil et al., 2020	Non-competitive sprinters	NO
Simperingham et al., 2015	Former national team rugby player	YES & NO

2.5 Summary

- Sprinting acceleration demands maximum power output from muscle groups in a short period.
- A proper warm-up routine is crucial for explosive sports such as sprinting, as it elevates muscle temperature and enhances muscle capability.
- While plyometric and ballistic exercises have shown long-term benefits, their acute effects are still under debate.
- Plyometric movements, inherent in natural human locomotion like sprinting and jumping, possess ballistic characteristics. These two characteristics may contribute to different outcomes in sprinting. Therefore, it's essential to distinguish between these qualities for effective comparison and analysis.
- PAPE may improve voluntary performance, which is highly relevant for sprinting acceleration, especially in initial acceleration. Plyometric, and ballistic exercise as conditioning activity to induce PAPE may cause acute effects in neural factors (motor-neuron excitability, motor-unit recruitment pattern, and the activation of synergist muscles), thus improving speed and power.

III. METHODOLOGY

3.1 Participants

The sample consisted of thirty participants, divided into two groups: fifteen individuals engaged in regular strength training and physical activity, meeting the criterion of squatting an external load at least 1.5 times their body weight (Davies et al., 2015) and not competing in sprinting (general group); another fifteen participants were competitive sprinters (sprinting group). All participants were collegiate students who volunteered for the study, had no history of muscle, bone, soft tissue, or other injuries within the past 6 months, and abstained from potential ergogenic aids (e.g., caffeine, creatine). Table 4-1 presents their anthropometric characteristics and squat performance. Before commencing the experiment, all participants thoroughly read the instructions to ensure they understood the process, content, and objectives. Following this, participants completed a consent form, providing basic information to allow for a preliminary assessment of their physical condition. Only participants meeting the specified criteria were included in the experiment.

3.2 Design

The purpose of the experiment is the biomechanical analysis of the acceleration phase in sprinting following different warm-up routines. Divided into sprinting groups (sprinters) and general groups (non-sprint competitors), each subject in both groups performed a 40-meter

sprint test after different warm-up protocols, with at least 24-hour intervals to ensure full recovery. The warm-up conditions included a traditional warm-up (T), plyometric warm-up (P), ballistic warm-up (B), and mixed warm-up (plyometric + ballistic, M). Before commencing the experiment, all subjects understood the experiment's process and had previous experience in warm-up exercises. The height and weight scale records participants' anthropometrics before the experiment. The four warm-up regimes vary in the exercises used in the middle part: traditional, plyometric, ballistic, or mixed. Following the protocol from previous literature (Taylor et al., 2013), which included low-intensity aerobic exercise and running-related movements, this research added the four exercises between aerobic exercise and running-related movements to assess their acute effects on sprinting. The warm-up began with a 5-minute jogging, rated 3-4 on a 10-point perceived effort scale (Foster et al., 2001). After this general warm-up, traditional, plyometric, ballistic, and mixed exercise regimes were performed. Finally, the running-related warm-up included two short sprints (20 and 40 m) with 50% to 90% of participants perceived maximal effort (Taylor et al., 2013; Brink et al., 2022).

Table 3-1 specifies the single exercises of the traditional warm-up, which incorporates dynamic stretching as suggested by previous research (Pearce et al., 2012). The remaining three regimes use squat-type movement as the conditioning activity. To avoid overlapping, plyometric exercise uses power squat without jumping movements and needs to be performed in a plyometric manner; ballistic exercise uses squat jumps while maintaining the squat position for 2 seconds before the jump; the mixed exercise uses a countermovement jump from a standing position, performs without break or stop during the entire movement. The squat-type movement is chosen based on previous research used or mentioned (Maloney et al., 2014; Davies et al., 2015; Winchester et al., 2008). According to the review research, both plyometric and ballistic exercises can involve external loads. Ballistic exercises can have a wide intensity range, from 0% to 50% of 1 Repetition Maximum (RM) as noted by Cormie et al. (2011).

Therefore, participants' 1 RM information is collected, and 10% of the 1 RM is calculated for three regimes. Each regime consists of 3 sets of 5 repetitions, with a 2-minute rest period between sets.

After finishing the warm-up, the official test begins. The official test used a 40-meter sprint with maximal effort, collecting spatiotemporal, kinematics, and kinetics data for analysis. Data for the sprint group were collected on an indoor synthetic track in Japan, while data for the general group were obtained on a composite polyurethane running track in Taiwan.

Table 3-1

Movements in Dynamic Stretching (Pearce et al., 2012)

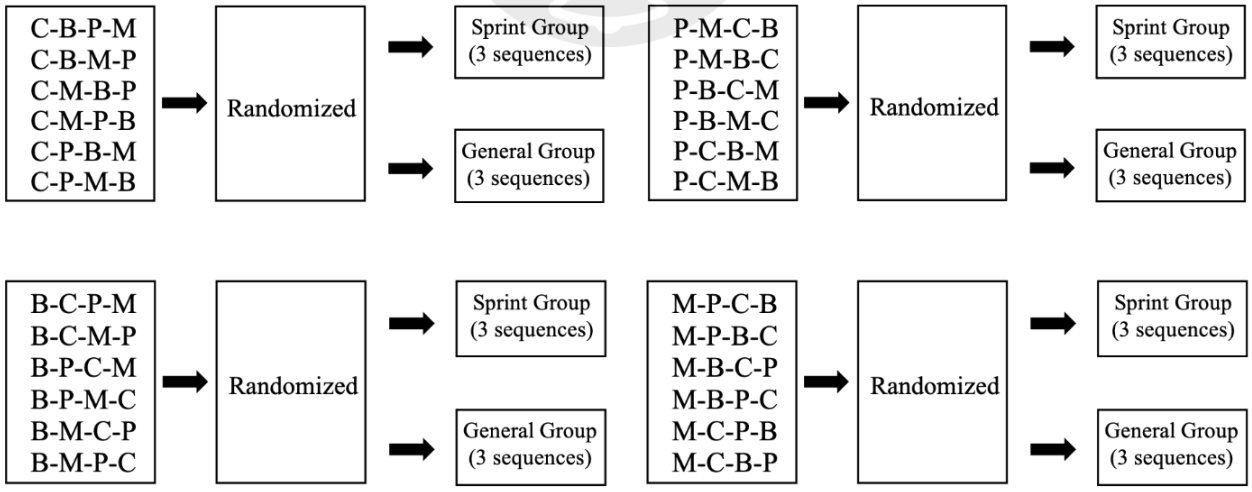
Traditional	**Movements**	**Repetitions**
Dynamic stretching	Walking high knee to chest	2 sets of 10 repetitions
	Leg swing ante-post	2 sets of 10 repetitions
	Leg swing medio-later	2 sets of 10 repetitions
	Hurdler's knee raised	2 sets of 10 meters
	Hurdle's knee raised - reverse	2 sets of 10 meters
	Heel up	2 sets of 10 meters

3.3 Warm-up sequences

The four warm-up regimes in a repeated design allow for a total of twenty-four possible combinations of how to sequence the experiments (i.e., C-P-B-M, C-P-M-B, C-M-B-P, C-M-P-B…). All of the twenty-four sequences will be randomly assigned to two groups as shown below. Participants in each group will be evenly distributed across twelve sequences, with the remaining three participants randomized to three of the twelve sequences. All four warm-up routines have the same total duration and include identical general warm-ups at the beginning and identical running-related warm-ups at the end.

Figure 3-1

Schematic Diagram of the Sequence Assignment



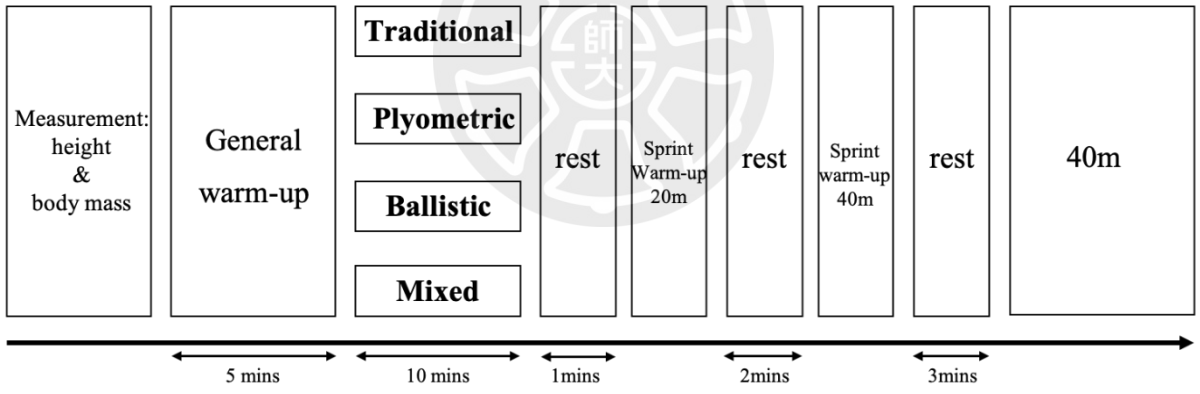
3.4 Procedure

All experiments were conducted in the morning (9-10 A.M.) to ensure that all subjects performed the movements in the same environment. The experimental flow chart is shown below (Figure 3-2). Squat one-repetition maximum values were obtained from participants' documented performances within the previous six months. After the collection of all subjects, they were randomly assigned to the twenty-four sequences of the four regimes for experimentation. After the participants completed the general warm-up, the traditional, plyometric, ballistic, or mixed exercise regime was carried out. In the traditional exercise regime, subjects performed modified dynamic stretches based on Pearce et al. (2012), as detailed in Table 3-1. In the ballistic exercise regime, subjects performed a squat jump starting from a squat position with hips parallel to the knees, holding this position for 2 seconds before jumping with maximal effort. For the plyometric exercise regime, subjects began from a standing position with feet shoulder-width apart, then rapidly moved downward into a squat position with hips parallel to the knees, and quickly returned to the standing position. In the mixed exercise regime, subjects performed a countermovement jump starting from a standing position with feet shoulder-width apart, moving rapidly downward to a squat position with hips parallel to the knees, and immediately following with a maximal effort jump without pausing or breaking the movement. To avoid overlapping effects in different warm-up regimes, participants were specifically instructed to implement the movements as follows: a) they decelerate and stop the movement at its designated end (i.e., no flight phase) in the plyometric exercise and b) accelerate until the end, entering a subsequent flight phase in the ballistic and mixed exercise. All participants performed with maximal effort in all regimes. After the intervention is completed, rest for 1 minute, then perform sprint-specific warm-ups: 20 meters at 50% and 40 meters at 90% of the participant’ s perceived maximal effort. 2 minutes rest after 20-meter sprints, 3 minutes rest after 40-meter sprint. After completing the sport-specific

warm-up, the official test begins. The official test involved a 40-meter sprint, during which biomechanical and spatiotemporal variables of running were collected for all participants. Participants start from a two-point split-stance position, trunk leaning forward and slightly apart in the leg with self-selected distance, one foot in the front, another in the back, positioning behind the starting line All participants were motivated to sprint with maximum effort. Following the official instructions, participants prepared and commenced maximal sprinting.

Figure 3-2

Schematic Diagram of the Experiment Procedure



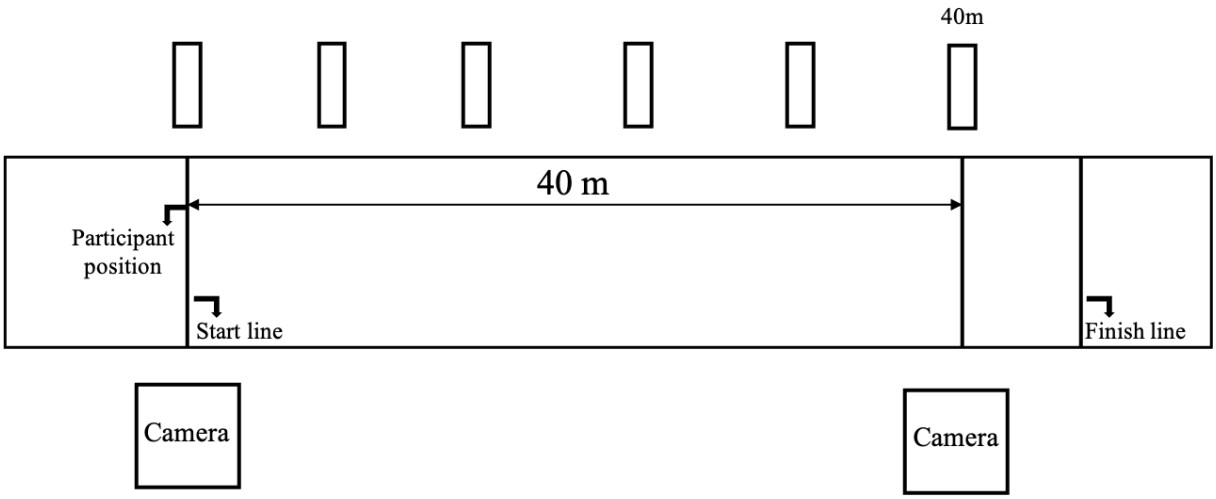
3.5 Data collection

For the sprinter group, spatiotemporal and kinematic data were measured via 54 embedded force platforms (TF-90100, TF-3055, TF-32120; Tec Gihan, Uji, Japan), operating at a sampling frequency of 1000 Hz. For the general group, data were collected using two high-speed cameras (RX0M2, SONY, JAPAN), operating at a sampling frequency of 960 Hz, positioned perpendicular to the track (1.05-meter height from the ground) and 4 meters away from the participants to record a 2-dimensional videotape of spatiotemporal characteristics from sprinting at the start and 40-meter, a simple camera (iPhone 12, Apple, USA) records the entire sprint to obtain the number of steps and calculate for step frequency. Open-source software (version 2023.1.2; Kinovea, 2025) measures the step frequency, step length, flight time, and contact time of 40-meter sprinting. To accurately determine the length of a step from the screen, the researcher placed an object with a known length parallel to the camera. This allows measuring the exact distance from the screen to the object, enabling the calculation of the precise length of the stride displayed on the screen.

Kinetic data from sprinting were analyzed using the sprint acceleration spreadsheet developed by Samozino et al. (2015), which estimates force-velocity and power–velocity profiles. The spreadsheet uses individual body mass, stature, and split times over a 40-meter sprint to calculate key variables, including maximal horizontal force, maximal power output, and maximal velocity. Split times at 10, 20, 30, and 40 meters for both the sprinter and general groups were entered into the spreadsheet for further analysis.

Figure 3-3

Schematic Diagram of the Experiment Site Setup



3.6 Variables

A. Anthropological measuring

This study collected body height (cm) and mass (kg) from each participant.

B. Sprinting kinematics

1) Sprinting time (s): For the sprinter group, split times were calculated using a 50-meter-long series of force platforms, with reaction time excluded by applying a 20 N threshold for ground reaction force onset. For the general group, split times at 10, 20, 30, and 40 meters were recorded using timing gates (Dashr, Omaha, USA; Sportreact, Zagreb, Croatia).

2) Step length (m): For the sprinter group, step length at the start and 40 m was calculated as the anteroposterior distance between the center of pressure at toe-off across consecutive steps, based on force platform data. For the general group, step length at the start and 40 m was measured using Kinovea (version 2023.1.2), a 2D motion analysis software, with recordings captured by high-speed cameras. For both groups, the average step length was calculated from velocity divided by step frequency.
3) Contact time and flight time (ms): For the sprinter group, Contact and flight times were determined using a 20 N threshold for vertical ground reaction forces. For the general group, Kinovea (version 2023.1.2) analyzed each participant's contact and flight time at the start and 40 meters using high-speed cameras.
4) Step frequency (Hz): For both groups, step frequency was calculated by dividing the total number of steps taken by each participant by their 40-meter sprint time.
5) Theoretical Maximal velocity: presented as V0 (m/s), based on Samozino et al. (2015).

C. Sprinting kinetics

1) Maximal horizontal force: presented as F0 (N/kg), based on Samozino et al. (2015).
2) Maximal horizontal power output: presented as Pmax (W/kg), based on Samozino et al. (2015).

3.7 Data Analysis

Jamovi (version 2.4.7) software with Two-way ANOVA repeated measurement (2*4 factors, 2 groups: general group, and sprinting group; 4 regimes: traditional, ballistic, plyometric, and mixed) process the data. Using Mauchly's test checks sphericity, when the sphericity doesn't pass the assumption, Greenhouse-Geisser adjusts the *F*-ratio, and Bonferroni post-hoc analysis executes to understand the effect of each group further. Eta squared presents the effect size for two-way ANOVA, Cohens' d for post-hoc analysis. Including assessing the interaction effect between the groups (general and sprinting) and the regimes (traditional, ballistic, plyometric, and mixed). Descriptive statistics explain the subjects' data and the tests' raw results. All analysis data are presented as mean ± standard deviation with a 95% confidence interval. The significance level is set to $\alpha \leq .05$.

IV. RESULTS

Table 4-1 presents the profiles of two groups, with an independent t-test revealing a significant difference only in body mass. Results indicate no significant performance differences between warm-up interventions across all sprint phases (10, 20, 30, and 40 m) (p = .82–.92, $p\eta^2$ = .01–.02). However, sprinters demonstrated significantly shorter sprint times than non-sprinters at all distances (p < .001, $p\eta^2$ = .59–.74). No significant interaction was found between warm-up interventions and group (p = .77–.98, $p\eta^2$ < .03).

No significant differences in step length were observed at the start or 40 m across warm-up interventions (p = .16–.52, $p\eta^2$ = .05–.12), groups (p = .14–.34, $p\eta^2$ = .07–.16), or their interaction (p = .19–.73, $p\eta^2$ = .03–.12). Contact time also showed no significant effects of warm-up at either the start or 40 m (p = .30–.33, $p\eta^2$ = .08). However, sprinters had significantly shorter contact times than non-sprinters at both distances (p < .001, $p\eta^2$ = .59–.75), with no significant interaction (p = .29–.60, $p\eta^2$ = .04–.09). In the flight time, no significant effects of warm-up were found at the start or 40 m (p = .20–.26, $p\eta^2$ = .10–.11). However, sprinters exhibited significantly longer flight times than non-sprinters at the start (p < .001, $p\eta^2$ = .61) but not at 40 m (p = .46, $p\eta^2$ = .04). No significant interaction was observed (p = .49–.72, $p\eta^2$ = .03–.05).

No significant effects of warm-up interventions were found for maximal horizontal force (p = .54, $p\eta^2$ = .05), group differences (p = .08, $p\eta^2$ = .21), or their interaction (p = .78, $p\eta^2$ = .03). In maximal power output, no significant effect of warm-up was observed (p = .48, $p\eta^2$ = .06), but sprinters generated significantly greater horizontal power than non-sprinters (p = .003, $p\eta^2$ = .48). No significant interaction was found (p = .86, $p\eta^2$ = .02). For maximal velocity, no significant effect of warm-up was detected (p = .64, $p\eta^2$ = .03), but sprinters achieved significantly higher maximal velocity than non-sprinters (p < .001, $p\eta^2$= .79).

Table 4-1.

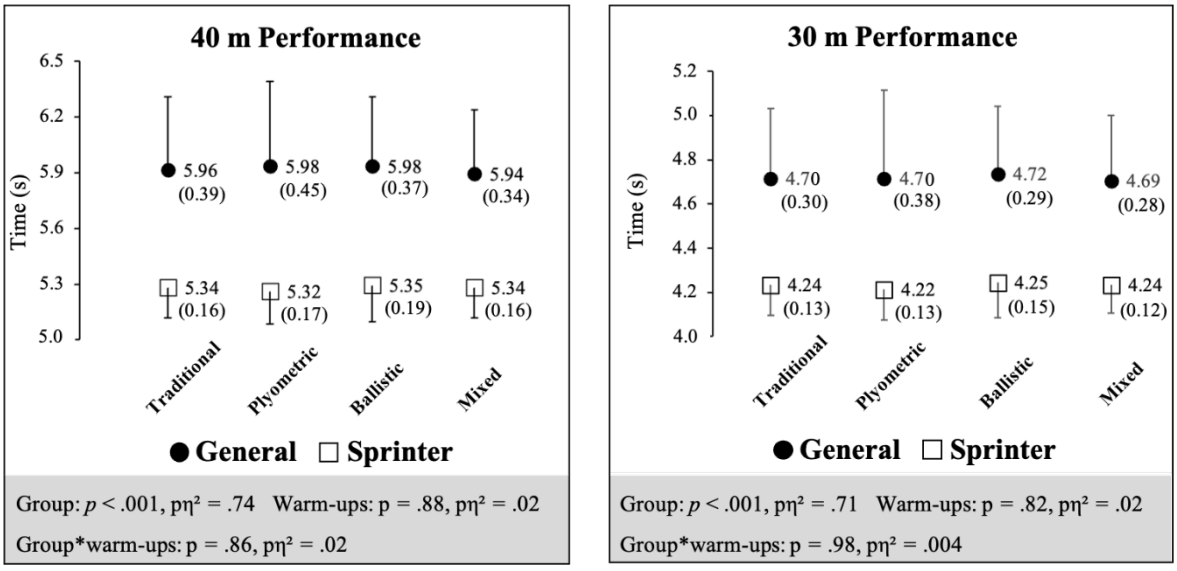
Mean (standard deviation) of demographic and physical sample characteristics

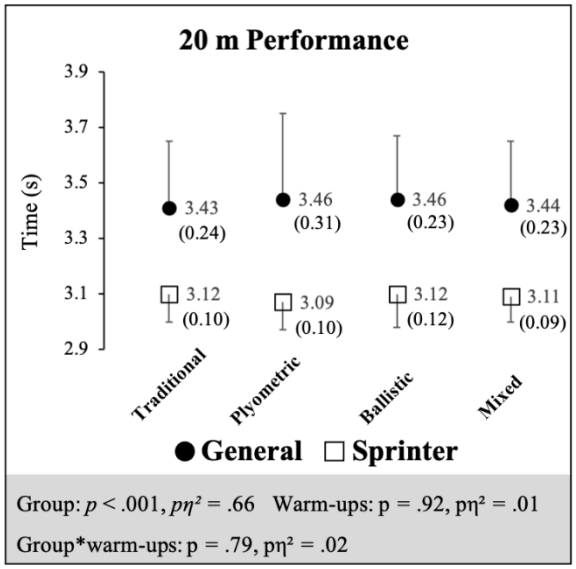
	Sprinters (*n*=15)	General (*n*=15)
Age (years)	19.7 (1.0)	22.5 (2.7)
Body mass (kg)	67.7 (4.0)*	75.3 (8.9)*
Body height (cm)	174.0 (5.0)	176 (5.0)
1 RM squat (kg)	130.0 (21.7)	142.0 (24.6)

* indicating group differences at $p < .05$.

Figure 4-1

Sprint Performance Across Warm-up Interventions in Two Groups





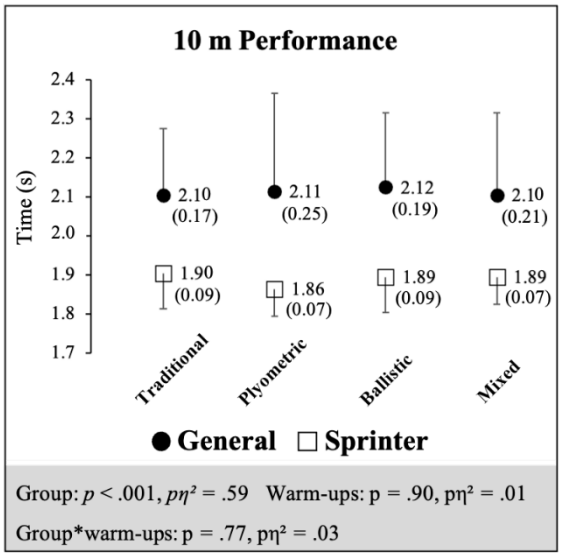
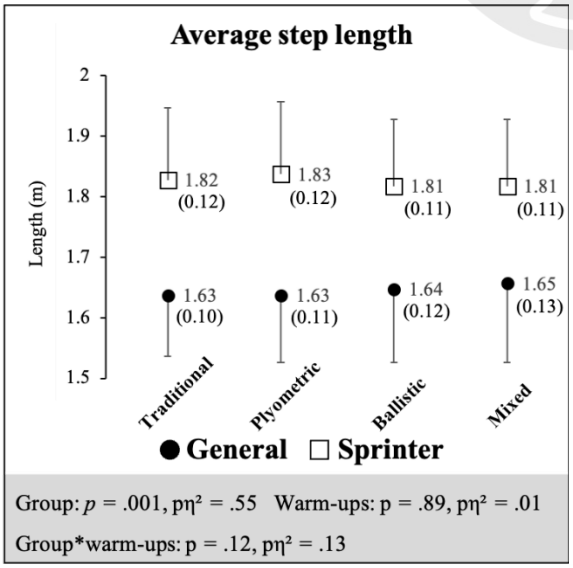
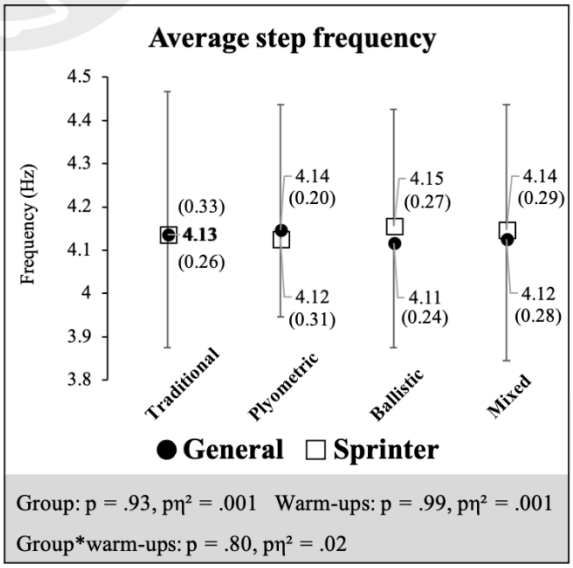
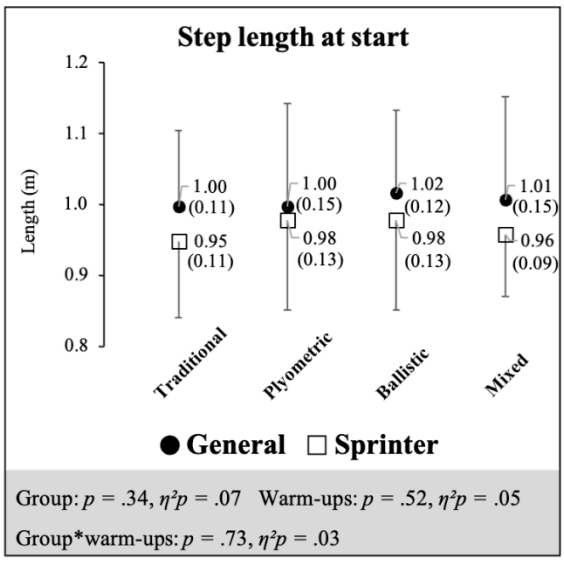


Figure 4-2

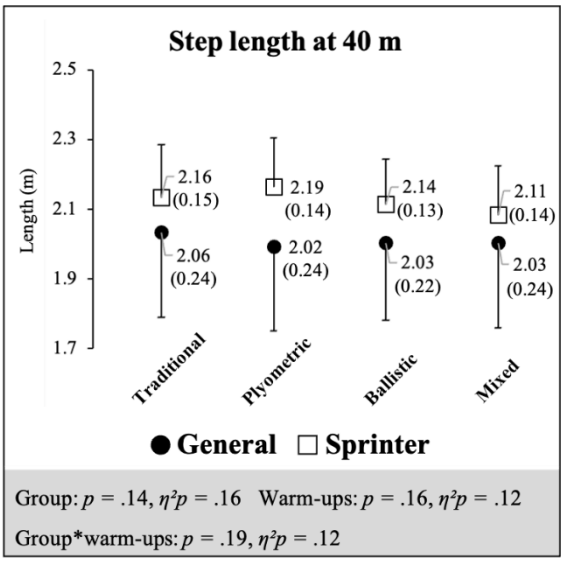
Kinematic Variables After Different Warm-up Interventions in Two Groups



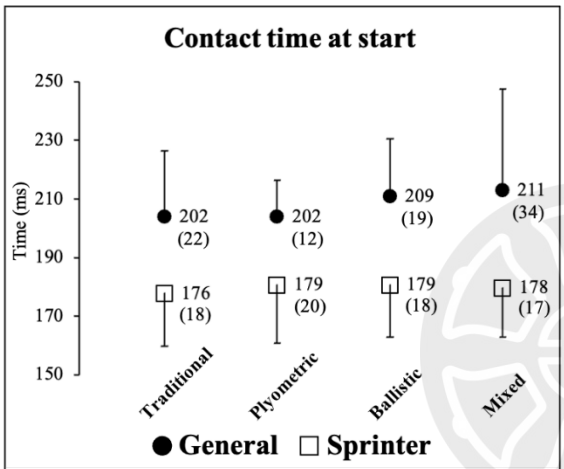




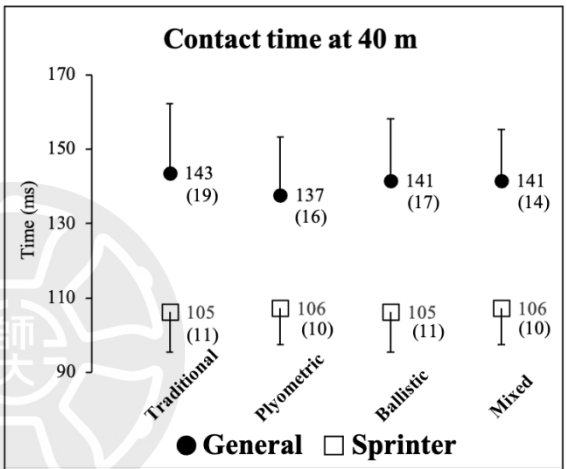
Group: p = .34, η^2p = .07 Warm-ups: p = .52, η^2p = .05
Group*warm-ups: p = .73, η^2p = .03



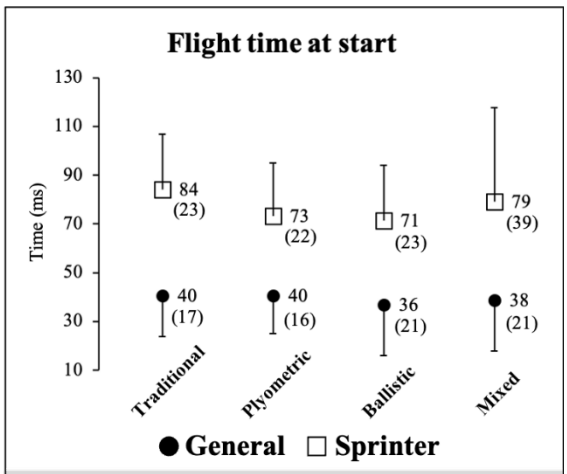
Group: p = .14, η^2p = .16 Warm-ups: p = .16, η^2p = .12
Group*warm-ups: p = .19, η^2p = .12



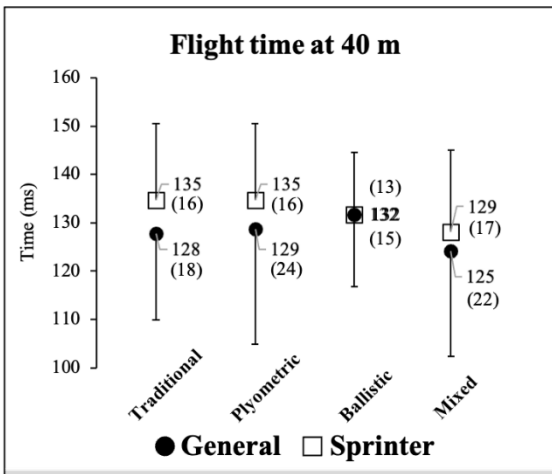
Group: p < .001, pη² = .59 Warm-ups: p = .30, pη² = .08
Group*warm-ups: p = .60, pη² = .04



Group: p < .001, pη² = .75 Warm-ups: p = .33, pη² = .08
Group*warm-ups: p = .29, pη² = .09



Group: p < .001, pη² = .61 Warm-ups: p = .20, pη² = .11
Group*warm-ups: p = .49, pη² = .05



Group: p = .46, pη² = .04 Warm-ups: p = .26, pη² = .10
Group*warm-ups: p = .72, pη² = .03

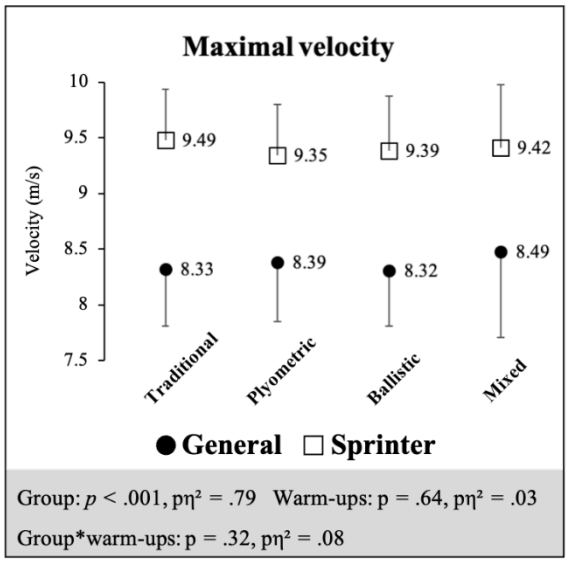
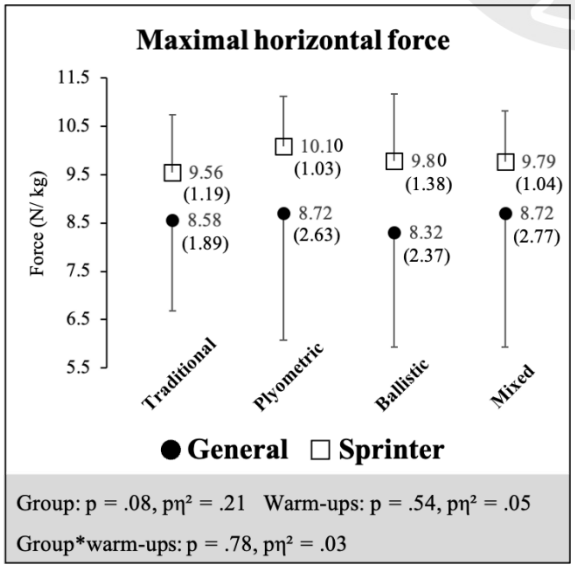


Figure 4-3

Kinetic Variables After Different Warm-up Interventions in Two Groups



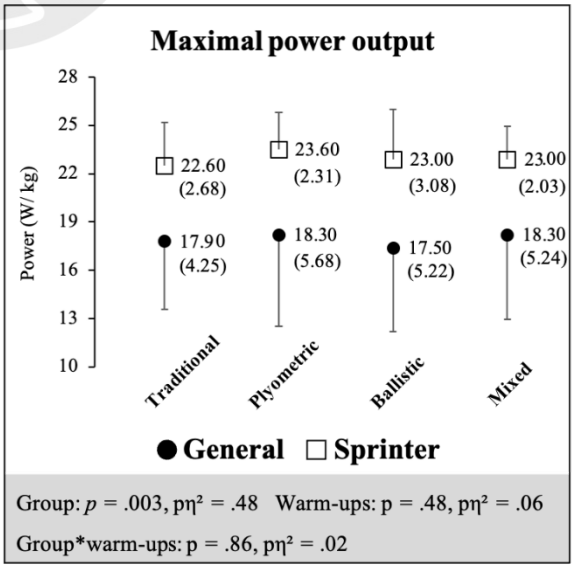


Figure 4-4

Individuals' sprint time after different warm-up interventions (general group)

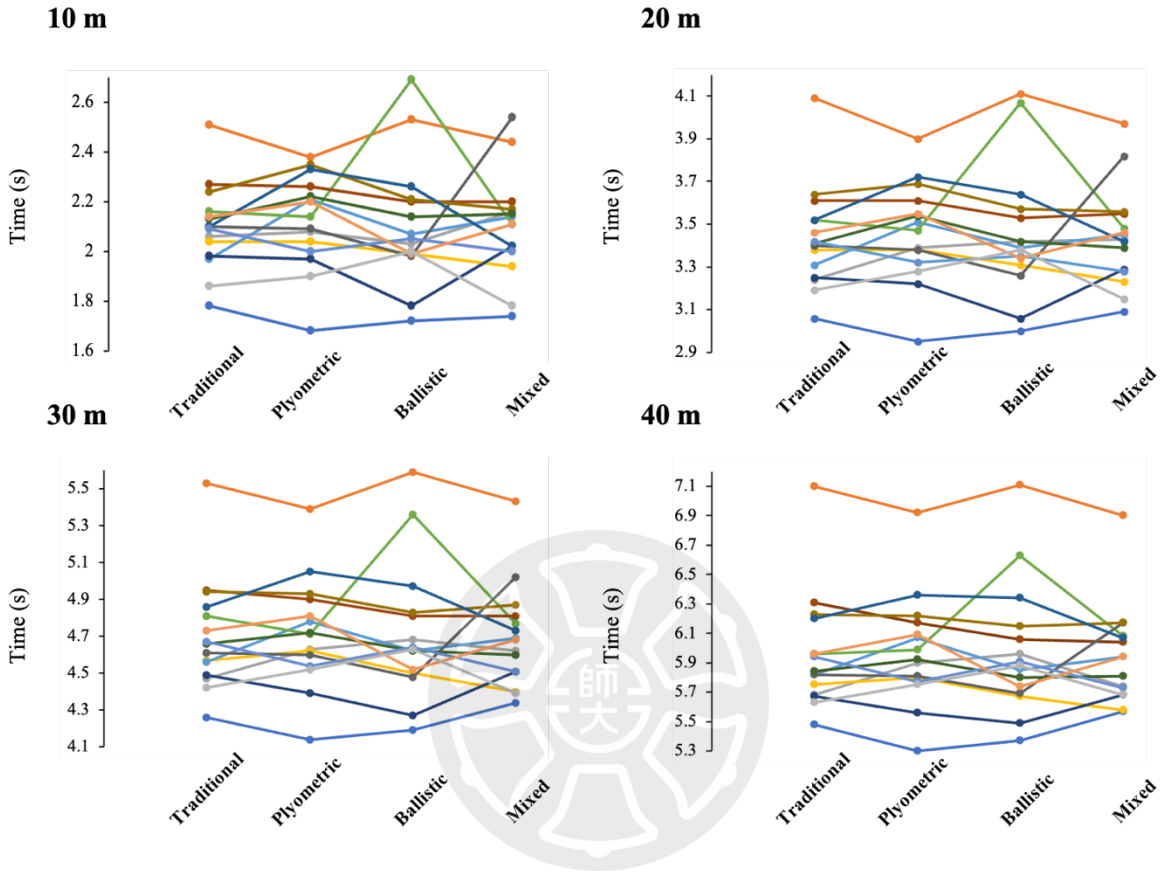


Figure 4-5

Individuals' sprint time after different warm-up interventions (sprinter group)

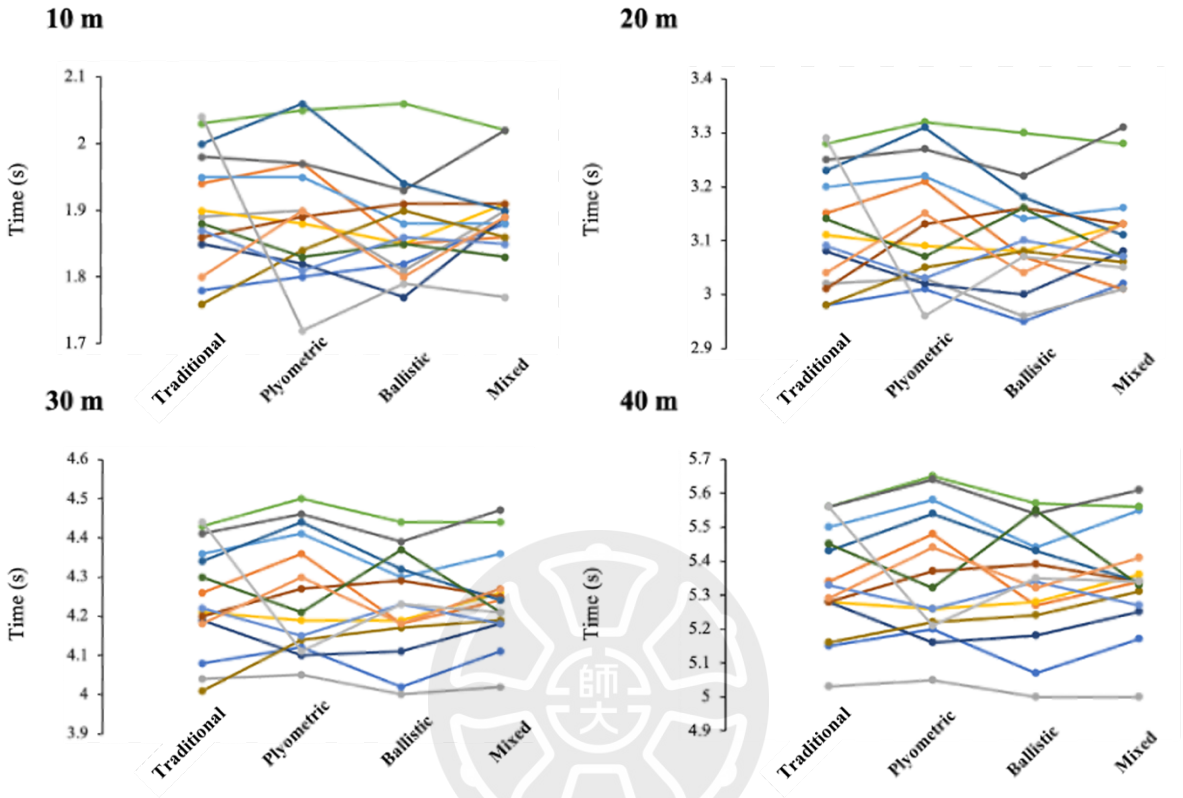


Table 4-2

Mean (standard deviation) of average kinetic variables in all interventions between groups

	Sprinter	general
Maximal horizontal force (N/ kg)	9.81 (1.16)	8.59 (2.42)
Maximal power output (W/ kg)	23.05 (2.53)*	18.00 (5.10)*

* indicating group differences at $p < .05$.

Table 4-3

Mean (standard deviation) of average kinematic variables in all interventions between groups

	Sprinter	General
Average step length (m)	1.81 (0.10)*	1.64 (0.12)*
Average contact time at start (ms)	178 (18)*	206 (22)*
Average contact time at 40 m (ms)	106 (11)*	141 (17)*
Average flight time at start (ms)	77 (27)*	39 (19)*
Average flight time at 40 m (ms)	133 (16)	129 (20)
Average step frequency (Hz)	4.14 (0.30)	4.13 (0.25)

* indicating group differences at $p < .05$.

V. DISCUSSION

This study aimed to evaluate the effects of plyometric, ballistic, and mixed warm-ups on sprint biomechanics and performance compared to a traditional warm-up. The results showed no significant improvements in sprint performance or changes in biomechanical variables following any of the warm-up interventions. These findings contradict the initial hypothesis of the study.

5.1 Performance

This study found no superior improvement in 10-m, 20-m, 30-m, and 40-m sprint times following plyometric, ballistic, or mixed exercise warm-ups compared to a traditional warm-up, contradicting previous findings (Turner et al., 2015; Iacono et al., 2016; Creekmur et al., 2017). The conflicting results may be attributed to differences in design and statistical issues.

Creekmur et al. (2017) used a crossover design in collegiate-aged male sprinters to test whether adding two sets of eight plate jumps to a standard sprint warm-up improved 20 m and 40 m sprint times compared to a control warm-up. They found small-to-medium improvements in sprint time (1.12% at 20 m; 1.25% at 40 m; $d \approx 0.40 - 0.46$). However, the control warm-up lacked any sham activity equivalent in volume or intensity to the plate-jump protocol, so the small performance gains they reported may simply reflect the addition of movement rather than a true plyometric effect. Moreover, the control condition included an eight-minute rest before sprint testing, meaning any differences could stem from a cooldown in the control trial rather than potentiation in the plyometric condition.

Iacono et al. (2016) investigated the acute effects of vertical versus horizontal single-leg drop-jump protocols on neuromuscular performance in eighteen elite handball players using a randomized crossover design. After a standardized warm-up and baseline testing, participants performed three sets of five vertical or horizontal single-leg drop-jumps, followed by 8 min passive recovery, then repeated countermovement jump, 25 m shuttle sprint (12.5 m sprint with 180° change of direction), and agility tests. They found both protocols enhanced only tasks matching their force-orientation (vertical vs. horizontal). Specifically, the vertical single-leg drop-jumps protocol led to significant improvements in vertical performance metrics, such as jump height, while the horizontal single-leg drop-jumps protocol resulted in greater enhancements in change of direction performance. Notably, the results showed improvements in the 25-meter sprint and agility but no improvement in the 10-meter linear sprint, indicating that the gains were driven by agility rather than linear sprint performance. Moreover, participants' baseline tests after standard warm-up served as the "control", but no sham intervention matched vertical and horizontal single-leg drop-jumps in volume or intensity. Thus, observed improvements may partly reflect the addition of any dynamic stimulus rather than a true PAPE effect.

Turner et al. (2015) used a randomized-crossover design in twenty-three plyometric-trained males to compare a walking control with body-mass bounding and weighted bounding as conditioning activities, assessing 10 m and 20 m sprint velocities at baseline and 15 s, 2, 4-, 8-, 12-, and 16-min post-conditioning. They reported an initial impairment in 20 m velocity at ~15 s for weight bounding (–1.4 ± 2.5%; $p = .04$), however, both bounding conditions led to significant improvements by 4 minutes post-conditioning activity: bodyweight bounding increased sprint velocity by +2.2 ± 3.1% ($p = .01$), and weighted bounding by +1.8 ± 3.3% ($p = .001$) compare to control. At 8 minutes, weighted bounding resulted in even greater velocity (+2.9 ± 3.6%) compared to the control ($p = .002$) and (+2.3 ± 3.6% compared

to bodyweight bounding conditions (p = .001), indicating a more pronounced PAPE effect with the addition of load. The study used multiple time points, allowing mapping of both early fatigue and potentiation phases, and a randomized crossover design minimized between-subject variability by having each participant experience all conditions. However, the control warm-up comprised only walking, offering no sham activity matched for volume or intensity to plyometric or weight plyometric protocols. Furthermore, during standard warm-up, a 10-minute plyometric activity was already included for all trials. So observed gains may partly reflect any added dynamic stimulus rather than a true plyometric potentiation. Also, with no a priori power analysis reported, raising concerns about both reproducibility and generalizability to other populations.

Although Turner et al. (2015), Iacono et al. (2016), and Creekmur et al. (2017) report acute improvements following plyometric or drop-jump warm-ups, each study's methodological and reporting limitations, including unmatched control conditions, small homogeneous samples without a priori power analyses, and incomplete outcome reporting, undermine their ability to fully explain PAPE effects on sprint performance.

The current study aligns with previous research suggesting that sprint performance is a highly stable skill for sprinters, as it depends on running velocity and is not easily influenced by warm-up, regardless of the conditioning activity and parameters (intensity, sets, repetitions) applied (Loturco et al., 2024). The acute effect examined in Loturco et al.'s (2024) study refers to PAPE, which theoretically contributes to a 1–5% improvement in performance (Blazevich & Babault, 2019; Fischer & Paternoster, 2024). However, previous research has indicated that performance variations among competitive sprinters are typically minimal (Loturco et al., 2024), and for high-level or elite sprinters, this variation is even smaller, often less than 2% (Loturco et al., 2023; Haugen et al., 2018). These studies concluded that PAPE is unlikely to induce a meaningful effect in sprinting.

Interestingly, the PAPE effect was not observed in physically active individuals (general group), despite their sufficient strength levels (1RM squat: 142.0 ± 24.6 kg; body mass: 75.3 ± 8.9 kg). Strength has been suggested as a key factor influencing PAPE (Wilson et al., 2013; Maloney et al., 2014; Gołaś et al., 2016; Blazevich & Babault, 2019), yet its presence alone did not elicit a performance enhancement in the current study. A potential reason could be the participants' physical activity background. Only eight individuals had experience in ball sports or other sprint-related activities, while the rest lacked specific sprint training. This suggests that familiarity with explosive movements and sprint mechanics may be crucial for eliciting the PAPE effect. Previous research also indicates that neuromuscular efficiency and movement specificity influence PAPE responsiveness (Seitz & Haff, 2016; Blazevich & Babault, 2019). Thus, despite having sufficient strength levels, the general group's lack of sprint-specific adaptations may have limited their ability to benefit from potentiation. Athletes whose sports require intermittent sprinting, such as ball-sport players, may derive more pronounced potentiation effects. This could be due to their frequent engagement in sprinting and change-of-direction movements, which may make their neuromuscular system more responsive to PAPE. In fact, in this study, five of the eight participants with sprint-related backgrounds showed a trend of improved performance after the mixed warm-up regimen compared to the traditional warm-up (Figure 4-4). While this result was not statistically significant, it suggests that PAPE may be more relevant for athletes who incorporate sprinting as part of their overall performance rather than for highly trained sprinters, whose sprint mechanics are already highly refined.

On the other hand, the differences in intensity between plyometric, ballistic, and resistance exercises may also affect the results. For instance, Krčmár et al. (2021) reported that a resistance-based PAPE protocol—back squats combined with elastic bands—significantly improved 3-, 5-, and 10-m sprint times in fourteen female athletes, nine of whom were ball-sport

players with an average back squat 1RM of 1.96 ± 0.14 times of body mass. Liu et al. (2024) found in their meta-analysis that resistance-based conditioning activities elicited significantly greater PAPE effects in both jumping and sprinting tasks than plyometric or combined resistance-plyometric protocols. In contrast, plyometric and mixed protocols had a negligible impact on sprint performance. Resistance-based protocols typically employ higher loading intensities—loads closer to maximal—that are strongly correlated with PAPE magnitude, whereas plyometric and ballistic exercises often use lower intensities focused on speed and power output, resulting in insufficient intensity to elicit a significant potentiation response. In the current study, 10% of participants' 1RM squat was selected as the intensity for plyometric, ballistic, and mixed regimes, yet the intensity may be insufficient to stimulate PAPE. The intensity is higher than previous study (Simperingham et al., 2015; Creekmur et al., 2017; Gil et al., 2019; Gil et al., 2020; Pereira et al., 2024). However, since intensity for jump-based interventions in both practice and research typically is diverse (e.g., height, single-leg, etc.), the optimal load range for eliciting PAPE via plyometric or ballistic exercises remains to be established.

Finally, although PAPE can enhance both jump and sprint performance, the effects are generally larger and more consistent in strength and vertical-jump tasks than in sprinting (Dobbs et al., 2019; Krzysztofik et al., 2021 Kasicki et al., 2024; Liu et al., 2024). Therefore, whether PAPE can contribute to sprint performance needs more well-designed research to investigate it (i.e., enough intensity for plyometric or ballistic exercises or a well-designed control trial).

5.2 Kinetics

Sprint performance strongly correlates with running velocity and power output (Slawinski et al., 2015; Samozino et al., 2015). The current study found no improvement in maximal power output following any warm-up intervention. Maximal horizontal force reflects the ability to generate forward propulsion at low velocities, which is crucial for sprint starts (Morin & Samozino, 2016). However, the results showed no improvements after the warm-up interventions. The kinetic results suggest that the conditioning activities used in plyometric, ballistic, and mixed warm-ups had only a minimal effect on enhancing the neuromuscular system. This finding does not support the hypothesis of neuromuscular activation through PAPE (Cuenca-Fernández et al., 2017; Blazevich & Babault, 2019). On the other hand, sprinters demonstrated significantly higher power output than physically active individuals (Table 5-1). However, there was no statistically significant difference in maximal horizontal force. The superior sprint performance across all distances in the sprinter group was likely driven by their higher power output. The lack of a significant difference in maximal horizontal force between the two groups may be attributed to differences in body mass, as the physically active group had a significantly higher body mass than the sprinter group (Table 4-1).

5.3 Kinematic

There were no significant differences in any kinematic variables between the two groups after all warm-up interventions. This contrasts with previous studies that reported effects of warm-ups on various kinematic variables, such as stride length (Gil et al., 2019), contact time, and step frequency during the acceleration phase in a 40-m sprint (Simperingham et al., 2015).

Gil et al. (2019) investigated whether adding ballistic exercises to a standard warm-up acutely enhances 100 m sprint performance compared to a typical warm-up and no warm-up. They found that both warm-up and warm-up plus ballistic exercise produced ~7.5% faster 100 m times than no warm-up, but ballistic exercise did not significantly outperform warm-up trials alone. (p = 1.00, ES = 0.01). Notably, ballistic exercise increased stride length in the 0-50 m of the sprint compared to warm-up, although this kinematic change was small (0.07 m longer than warm-up) and did not contribute to sprint performance. Based on their study, at least ten variables were compared (kinematic, spatiotemporal, heart rate, RPE), with only a significant difference in stride length compared to warm-up. It is reasonable to assume that they made a Type I error. In the current study, a one-way ANOVA performed on the sprinting group revealed a significant difference in step length with the plyometric warm-up (0.08 meters longer) as well. However, post-hoc Bonferroni comparisons found no significant differences. The small magnitude of the difference observed in the current study and Gil et al. (2019) was unlikely to have a meaningful impact on sprint performance as well.

In Simperingham et al. (2015), the study was a single-subject design, which may limit the generalizability of their findings. Differences in rest periods between protocols could confound the interpretation of PAPE effects as well. Additionally, the lack of a control group in their study makes it difficult to determine whether the reported improvements were due to the specific warm-up protocol or other external factors.

While the step length at the start and at 40 m did not differ between groups, sprinters exhibited longer average steps but not in step frequency across the entire sprint distance than the general group. Since sprint speed is equal to step frequency times step length, a longer average step length contributed to the sprinters' higher velocity and eventually caused superior performance than the general group (Table 4-3). The sprinter group demonstrated significantly shorter contact times both at the start and at 40 m, compared to the general group. Additionally, they exhibited longer flight time at the start, although no significant difference was observed at

40 m. The absence of a significant difference between groups in flight time at 40 m may reflect the transition from the acceleration phase to maximal velocity sprinting, during which athletes adopt a more cyclical and rhythmical movement pattern. During this phase, sprint mechanics shift from force-oriented propulsion to velocity-oriented strategies, emphasizing the optimization of step frequency and the generation of greater resultant forces (Weyand et al., 2000; Morin et al., 2012). Weyand et al. (2000) demonstrated that achieving top speed relies on the ability to produce higher ground reaction forces. Similarly, Morin et al. (2012) highlighted that greater horizontal ground reaction forces and higher step frequency, facilitated by shorter contact times, are critical determinants of both acceleration and overall 100-meter sprint performance. These findings align with the data observed in the sprinter group in the present study. Therefore, the similar flight times at 40 m between groups may result from biomechanical constraints at maximal velocity, where technical differences become less pronounced compared to the initial acceleration phase.

The current study ensured equal warm-up duration across all protocols, consisting of a 5-minute cardiovascular phase and a sport-specific phase, with the only difference being the intervention exercise in the middle. The same intensity between plyometric, ballistic, and mixed protocols as well. A counterbalanced design was implemented and randomized assigned to two groups to minimize effects such as order effect, fatigue effect, and carryover effect while reducing individual differences since each participant serves as their own control. Therefore, whether the acute sprint performance effects observed in previous studies are truly stimulated remains questionable. However, previous studies have typically employed passive rest periods of 7–10 minutes to mitigate fatigue before assessing PAPE effects (Iacono et al., 2016; Creekmur et al., 2017; Gil et al., 2019; Pereira et al., 2022), whereas fewer studies have investigated shorter rest intervals of less than 6 minutes (Turner et al., 2015; Gil et al., 2020). This difference in protocol may partly explain the absence of a clear PAPE effect in the current study. Although fatigue levels were presumed to be low, given that participants only performed

two sprints at 50 – 90% of their perceived maximal effort with a total of 6 minutes of rest, it is still possible that the recovery time was insufficient to allow potentiation to manifest fully. Although none of the three warm-up interventions led to superior improvements in performance compared to traditional dynamic stretching, they did not impair performance either. These results indicate that the PAPE protocols used here did not enhance sprint performance. However, when embedded within a RAMP-based warm-up, which begins with a raise phase to elevate core and muscle temperature, blood flow, and neural activation, post-activation activities may help prevent injury by improving muscle elasticity and reducing stretch-induced damage (Racinais et al., 2017).

VI. CONCLUSION

To summarize, plyometric, ballistic, and mixed warm-up protocols produce negligible effects in sprint performance. Future research should design a rigorous methodology, incorporate enough sample size based on prior power analysis, and contain detailed protocols for plyometric and ballistic warm-up. Including systematically varying conditioning-activity intensity to define the minimal effective intensity and the ceiling above which fatigue outweighs potentiation; Standardizing treatment and control regimes, such as equal duration and volume between experimental and control trials to eliminate recovery vs. potentiation confounds. Prior work often used shorter control protocols, which may exaggerate apparent PAPE effects by allowing extra rest in the control condition. Incorporating mechanistic Measurements (e.g., electromyographic) can help detect more details about neuromuscular activation. Finally, employing rigorous controls such as active control that mimics metabolic load without inducing potentiation (e.g., low-intensity running or cycling), ensuring any performance gains derive from PAPE rather than any dynamic stimulus. By addressing these methodological gaps, researchers can determine whether appropriately dosed plyometric or ballistic interventions elicit genuine PAPE effects in sprinting or whether such approaches should be set aside for enhancing sprint performance.

REFERENCES

Andrzejewski, M., Chmura, J., Pluta, B., Strzelczyk, R., & Kasprzak, A. (2013). Analysis of sprinting activities of professional soccer players. *Journal of Strength and Conditioning Research*, *27*(8), 2134–2140. https://doi.org/10.1519/JSC.0b013e318279423e

Baudry, S., & Duchateau, J. (2007). Postactivation potentiation in a human muscle: Effect on the rate of torque development of tetanic and voluntary isometric contractions. *Journal of Applied Physiology*, *102*(4), 1394–1401. https://doi.org/10.1152/japplphysiol.01254.2006

Beato, M., Bianchi, M., Coratella, G., Merlini, M., & Drust, B. (2018). Effects of plyometric and directional training on speed and jump performance in elite youth soccer players. *Journal of Strength and Conditioning Research*, *32*(2), 289–296. https://doi.org/10.1519/JSC.0000000000002371

Bettariga, F., Maestroni, L., Martorelli, L., Turner, A., & Bishop, C. (2023). The effects of a 6-week unilateral strength and ballistic jump training program on the force-velocity profiles of sprinting. *Journal of Strength and Conditioning Research*, *37*(7), 1390–1396. https://doi.org/10.1519/JSC.0000000000004424

Bezodis, N. E., Willwacher, S., & Salo, A. I. T. (2019). The Biomechanics of the Track and Field Sprint Start: A Narrative Review. *Sports Medicine (Auckland, N.Z.), 49*(9), 1345–1364. https://doi.org/10.1007/s40279-019-01138-1

Blazevich, A. J., & Babault, N. (2019). Post-activation potentiation versus post-activation performance enhancement in humans: Historical perspective, underlying mechanisms, and current issues. *Frontiers in Physiology*, *10*, 1359. https://doi.org/10.3389/fphys.2019.01359

Boullosa. (2021). Post-activation performance enhancement strategies in sport: A brief review for practitioners. *Human Movement, 22*(3), 101–109. https://doi.org/10.5114/hm.2021.103280

Brink, N. J., Constantinou, D., & Torres, G. (2022). Postactivation performance enhancement (PAPE) of sprint acceleration performance. *European Journal of Sport Science*, *22*(9), 1411–1417. https://doi.org/10.1080/17461391.2021.1955012

Chiu, L. Z., Fry, A. C., Weiss, L. W., Schilling, B. K., Brown, L. E., & Smith, S. L. (2003). Postactivation potentiation response in athletic and recreationally trained individuals. *Journal of Strength and Conditioning Research*, *17*(4), 671–677. https://doi.org/10.1519/1533-4287(2003)017<0671:PPRIAA>2.0.CO;2

Čoh, M., Milanović, D., & Kampmiller, T. (2001). Morphologic and kinematic characteristics of elite sprinters. *Collegium Antropologicum*, *25*(2), 605–610.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011). Developing maximal neuromuscular power: Part 2 - Training considerations for improving maximal power production. *Sports Medicine*, *41*(2), 125–146. https://doi.org/10.2165/11538500-000000000-00000

Creekmur, C. C., Haworth, J. L., Cox, R. H., & Walsh, M. S. (2017). Effects of plyometrics performed during warm-up on 20 and 40 m sprint performance. *The Journal of Sports Medicine and Physical Fitness*, *57*(5), 550–555. https://doi.org/10.23736/S0022-4707.16.06227-7

Cuenca-Fernández, F., Smith, I. C., Jordan, M. J., MacIntosh, B. R., López-Contreras, G., Arellano, R., & Herzog, W. (2017). Nonlocalized postactivation performance enhancement (PAPE) effects in trained athletes: A pilot study. *Applied Physiology, Nutrition, and Metabolism*, *42*(10), 1122–1125. https://doi.org/10.1139/apnm-2017-0217

Davies, G., Riemann, B. L., & Manske, R. (2015). Current concepts of plyometric exercise. *International Journal of Sports Physical Therapy*, *10*(6), 760–786.

Dello Iacono, A., Martone, D., & Padulo, J. (2016). Acute Effects of Drop-Jump Protocols on Explosive Performances of Elite Handball Players. *Journal of Strength and Conditioning Research*, *30*(11), 3122–3133. https://doi.org/10.1519/JSC.0000000000001393

Desmedt, J. E., & Godaux, E. (1977). Ballistic contractions in man: Characteristic recruitment pattern of single motor units of the tibialis anterior muscle. *The Journal of Physiology*, *264*(3), 673–693. https://doi.org/10.1113/jphysiol.1977.sp011689

Dobbs, W. C., Tolusso, D. V., Fedewa, M. V., & Esco, M. R. (2019). Effect of Postactivation Potentiation on Explosive Vertical Jump: A Systematic Review and Meta-Analysis. *Journal of Strength and Conditioning Research*, *33*(7), 2009–2018. https://doi.org/10.1519/JSC.0000000000002750

Duchateau, J., Semmler, J. G., & Enoka, R. M. (2006). Training adaptations in the behavior of human motor units. *Journal of Applied Physiology*, *101*(6), 1766–1775. https://doi.org/10.1152/japplphysiol.00543.2006

Edholm, P., Krustrup, P., & Randers, M. B. (2014). Half-time re-warm up increases performance capacity in male elite soccer players. *Scandinavian Journal of Medicine & Science in Sports*, 10.1111/sms.12236. https://doi.org/10.1111/sms.12236

Fischer, J., & Paternoster, F. K. (2024). Post-activation-performance enhancement: Possible contributing factors. *Journal of Sports Science & Medicine*, *23*(1), 34–45. https://doi.org/10.52082/jssm.2024.34

Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., Doleshal, P., & Dodge, C. (2001). A new approach to monitoring exercise training. *Journal of Strength and Conditioning Research*, *15*(1), 109–115.

Fukutani, A., Isaka, T., & Herzog, W. (2021). Evidence for muscle cell-based mechanisms of enhanced performance in stretch-shortening cycle in skeletal muscle. *Frontiers in Physiology*, *11*, 609553. https://doi.org/10.3389/fphys.2020.609553

Gabbett T. J. (2012). Sprinting patterns of National Rugby League competition. *Journal of Strength and Conditioning Research*, *26*(1), 121–130. https://doi.org/10.1519/JSC.0b013e31821e4c60

Gil, M. H., Neiva, H. P., Garrido, N. D., Aidar, F. J., Cirilo-Sousa, M. S., Marques, M. C., & Marinho, D. A. (2019). The effect of ballistic exercise as pre-activation for 100 m sprints. *International Journal of Environmental Research and Public Health*, *16*(10), 1850. https://doi.org/10.3390/ijerph16101850

Gil, M. H., Neiva, H. P., Alves, A. R., Sousa, A. C., Duarte-Mendes, P., Marques, M. C., & Marinho, D. A. (2020). Does the inclusion of ballistic exercises during warm-up enhance short distance running performance? *The Journal of Sports Medicine and Physical Fitness*, *60*(4), 501–509. https://doi.org/10.23736/S0022-4707.19.10274-5

Gołaś, A., Maszczyk, A., Zajac, A., Mikołajec, K., & Stastny, P. (2016). Optimizing post activation potentiation for explosive activities in competitive sports. *Journal of Human Kinetics*, *52*, 95–106. https://doi.org/10.1515/hukin-2015-0197

Haugen, T., Tønnessen, E., Hisdal, J., & Seiler, S. (2014). The role and development of sprinting speed in soccer. *International Journal of Sports Physiology and Performance*, *9*(3), 432–441. https://doi.org/10.1123/ijspp.2013-0121

Haugen, T. A., Solberg, P. A., Foster, C., Morán-Navarro, R., Breitschädel, F., & Hopkins, W. G. (2018). Peak Age and Performance Progression in World-Class Track-and-Field Athletes. *International Journal of Sports Physiology and Performance*, *13*(9), 1122–1129. https://doi.org/10.1123/ijspp.2017-0682

Haugen, T., Seiler, S., Sandbakk, Ø., & Tønnessen, E. (2019). The training and development of elite sprint performance: An integration of scientific and best practice literature. *Sports Medicine*, *5*(1), 44. https://doi.org/10.1186/s40798-019-0221-0

Hirvonen, J., Rehunen, S., Rusko, H., & Härkönen, M. (1987). Breakdown of high-energy phosphate compounds and lactate accumulation during short supramaximal exercise. *European Journal of Applied Physiology and Occupational Physiology*, *56*(3), 253–259. https://doi.org/10.1007/BF00690889

Kadlubowski, B., Keiner, M., Stefer, T., Kapsecker, A., Hartmann, H., Wirth, K. (2021). Influence of linear-sprint performance, concentric power, and maximum strength on change of direction performance in elite youth soccer players. *German Journal of Exercise and Sport Research, 51*(1), 116–121. https://doi.org/10.1007/s12662-020-00692-5

Kasicki, K., Rydzik, Ł., Ambroży, T., Spieszny, M., & Koteja, P. (2024). The impact of post-activation performance enhancement protocols on vertical jumps: Systematic review. *Applied Sciences, 14*(21), 9664. https://doi.org/10.3390/app14219664

Keiner, M., Kadlubowski, B., Wirth, K., & Klusemann, M. (2021). The influence of linear sprint and jump performance on change-of-direction performance in male and female state-representative youth basketball players. *International Journal of Sports and Exercise Medicine, 7*, 186. https://doi.org/10.23937/2469-5718/1510186

Komi, P. V. (Ed.). (2003). *Strength and power in sport* (2nd ed.). Blackwell Science Ltd.

Krčmár, M., Krčmárová, B., Bakaľár, I., & Šimonek, J. (2021). Acute Performance Enhancement Following Squats Combined With Elastic Bands on Short Sprint and Vertical Jump Height in Female Athletes. *Journal of Strength and Conditioning Research*, *35*(2), 318–324. https://doi.org/10.1519/JSC.0000000000003881

Krzysztofik, M., Wilk, M., Stastny, P., & Golas, A. (2021). Post-activation Performance Enhancement in the Bench Press Throw: A Systematic Review and Meta-Analysis. *Frontiers in Physiology*, *11*, 598–628. https://doi.org/10.3389/fphys.2020.598628

Li, L., Mo, L., Liu, Y., & Mei, T. (2024). The Impact of Different Velocity Losses on Post-Activation Performance Enhancement (PAPE) Effects in Sprint Athletes: A Pilot Randomized Controlled Study. *Sports (Basel, Switzerland)*, *12*(6), 157. https://doi.org/10.3390/sports12060157

Liu, L., Niu, X., & Zhou, Z. (2024). Acute effects of different conditioning activities on the post-activation performance enhancement in athletes' jumping and sprinting performances: A systematic review and meta-analysis. *Applied Sciences, 14*(20), 9301.

Lorenz D. (2011). Postactivation potentiation: An introduction. *International Journal of Sports Physical Therapy*, *6*(3), 234–240.

Loturco, I., Fernandes, V., Bishop, C., Mercer, V. P., Siqueira, F., Nakaya, K., Pereira, L. A., & Haugen, T. (2023). Variations in Physical and Competitive Performance of Highly Trained Sprinters Across an Annual Training Season. *Journal of Strength and Conditioning Research*, *37*(5), 1104–1110. https://doi.org/10.1519/JSC.0000000000004380

Loturco, I., Pereira, L. A., Moura, T. B. M. A., McGuigan, M. R., & Boullosa, D. (2024). Effects of Different Conditioning Activities on the Sprint Performance of Elite Sprinters: A Systematic Review With Meta-Analysis. *International Journal of Sports Physiology and Performance*, *19*(7), 712–721. https://doi.org/10.1123/ijspp.2024-0005

Macintosh, B. R., Robillard, M. E., & Tomaras, E. K. (2012). Should postactivation potentiation be the goal of your warm-up? *Applied Physiology, Nutrition, and Metabolism*, *37*(3), 546–550. https://doi.org/10.1139/h2012-016

Maćkała, K., & Fostiak, M. (2015). Acute effects of plyometric intervention—Performance improvement and related changes in sprinting gait variability. *Journal of Strength and Conditioning Research*, *29*(7), 1956–1965. https://doi.org/10.1519/JSC.0000000000000853

Maloney, S. J., Turner, A. N., & Fletcher, I. M. (2014). Ballistic exercise as a pre-activation stimulus: A review of the literature and practical applications. *Sports Medicine*, *44*(10), 1347–1359. https://doi.org/10.1007/s40279-014-0214-6

Markovic, G., & Mikulic, P. (2010). Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Medicine*, *40*(10), 859–895. https://doi.org/10.2165/11318370-000000000-00000

Masamoto, N., Larson, R., Gates, T., & Faigenbaum, A. (2003). Acute effects of plyometric exercise on maximum squat performance in male athletes. *Journal of Strength and Conditioning Research*, *17*(1), 68–71. https://doi.org/10.1519/1533-4287(2003)017<0068:aeopeo>2.0.co;2

Matusiński, A., Pietraszewski, P., Krzysztofik, M., & Gołaś, A. (2021). The Effects of Resisted Post-Activation Sprint Performance Enhancement in Elite Female Sprinters. *Frontiers in Physiology*, *12*, 651–659. https://doi.org/10.3389/fphys.2021.651659

McGowan, C. J., Pyne, D. B., Thompson, K. G., & Rattray, B. (2015). Warm-up strategies for sport and exercise: Mechanisms and applications. *Sports Medicine*, *45*(11), 1523–1546. https://doi.org/10.1007/s40279-015-0376-x

Mero, A., Komi, P. V., & Gregor, R. J. (1992). Biomechanics of sprint running: A review. *Sports Medicine, 13*(6), 376–392. https://doi.org/10.2165/00007256-199213060-00002

Moran, J., Liew, B., Ramirez-Campillo, R., Granacher, U., Negra, Y., & Chaabene, H. (2023). The effects of plyometric jump training on lower-limb stiffness in healthy individuals: A meta-analytical comparison. *Journal of Sport and Health Science*, *12*(2), 236–245. https://doi.org/10.1016/j.jshs.2021.05.005

Moré, C. R., Moré, R. A. S., Boullosa, D., & Dellagrana, R. A. (2023). Influence of intensity on post-running jump potentiation in recreational runners vs. physically active individuals. *Journal of Human Kinetics*, *90*, 137–150. https://doi.org/10.5114/jhk/172268

Morin, J. B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J. R. (2012). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology*, *112*(11), 3921–3930. https://doi.org/10.1007/s00421-012-2379-8

Morin, J. B., & Samozino, P. (2016). Interpreting Power-Force-Velocity Profiles for Individualized and Specific Training. *International Journal of Sports Physiology and Performance*, *11*(2), 267–272. https://doi.org/10.1123/ijspp.2015-0638

Nagahara, R., Naito, H., Morin, J. B., & Zushi, K. (2014). Association of acceleration with spatiotemporal variables in maximal sprinting. *International Journal of Sports Medicine*, *35*(9), 755–761. https://doi.org/10.1055/s-0033-1363252

Newton, R. U., Kraemer, W. J., Häkkinen, K., Humphries, B. J., & Murphy, A. J. (1996). Kinematics, kinetics, and muscle activation during explosive upper body movements. *Journal of Applied Biomechanics*, *12*(1), 31–43. https://doi.org/https://doi.org/10.1123/jab.12.1.31

Pearce, AJ, Latella, C, and Kidgell, DJ. (2012). Secondary warm-up following stretching on vertical jumping, change of direction and straight line speed. *European Journal of Sport Science, 12*(2), 103-112. http://doi.org/10.1080/17461391.2010.551412

Pereira, L. A., Boullosa, D., Moura, T. B. M. A., Mercer, V. P., Fernandes, V., Bishop, C., & Loturco, I. (2022). Post-activation performance enhancement in sprinters: Effects of hard versus sand surfaces. *Journal of Human Kinetics*, *82*, 173–180. https://doi.org/10.2478/hukin-2022-0062

Popowczak, M., Rokita, A., Świerzko, K., Szczepan, S., Michalski, R., & Maćkała, K. (2019). Are Linear Speed and Jumping Ability Determinants of Change of Direction Movements in Young Male Soccer Players? *Journal of Sports Science & Medicine, 18*(1), 109–117.

Racinais, S., Cocking, S., & Périard, J. D. (2017). Sports and environmental temperature: From warming-up to heating-up. *Temperature (Austin, Tex.)*, *4*(3), 227–257. https://doi.org/10.1080/23328940.2017.1356427

Ramirez-Campillo, R., Gentil, P., Negra, Y., Grgic, J., & Girard, O. (2021). Effects of plyometric jump training on repeated sprint ability in athletes: A systematic review and meta-analysis. *Sports Medicine*, *51*(10), 2165–2179. https://doi.org/10.1007/s40279-021-01479-w

Sáez de Villarreal, E., Suarez-Arrones, L., Requena, B., Haff, G. G., & Ferrete, C. (2015). Effects of plyometric and sprint training on physical and technical skill performance in adolescent soccer players. *Journal of Strength and Conditioning Research*, *29*(7), 1894–1903. https://doi.org/10.1519/JSC.0000000000000838

Sale D. G. (1988). Neural adaptation to resistance training. *Medicine and Science in Sports and Exercise*, *20*(5), S135–S145. https://doi.org/10.1249/00005768-198810001-00009

Sale D. G. (2002). Postactivation potentiation: Role in human performance. *Exercise and Sport Sciences Reviews*, *30*(3), 138–143. https://doi.org/10.1097/00003677-200207000-00008

Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., Saez de Villarreal, E., & Morin, J. B. (2016). A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scandinavian Journal of Medicine & Science in Sports*, *26*(6), 648–658. https://doi.org/10.1111/sms.12490

Seiberl, W., Power, G. A., Herzog, W., & Hahn, D. (2015). The stretch-shortening cycle (SSC) revisited: Residual force enhancement contributes to increased performance during fast SSCs of human m. adductor pollicis. *Physiological Reports*, *3*(5), e12401. https://doi.org/10.14814/phy2.12401

Seiberl, W., Hahn, D., Power, G. A., Fletcher, J. R., & Siebert, T. (2021). Editorial: The stretch-shortening cycle of active muscle and muscle-tendon complex: What, why and how it increases muscle performance? *Frontiers in Physiology*, *12*, 693141. https://doi.org/10.3389/fphys.2021.693141

Seitz, L. B., & Haff, G. G. (2016). Factors Modulating Post-Activation Potentiation of Jump, Sprint, Throw, and Upper-Body Ballistic Performances: A Systematic Review with Meta-Analysis. *Sports Medicine (Auckland, N.Z.)*, *46*(2), 231–240. https://doi.org/10.1007/s40279-015-0415-7

Silva, L. M., Neiva, H. P., Marques, M. C., Izquierdo, M., & Marinho, D. A. (2018). Effects of Warm-Up, Post-Warm-Up, and Re-Warm-Up Strategies on Explosive Efforts in Team Sports: A Systematic Review. *Sports Medicine (Auckland, N.Z.)*, *48*(10), 2285–2299. https://doi.org/10.1007/s40279-018-0958-5

Simperingham, K., Cronin, J., Pearson, S., & Ross, A. (2015). Acute changes in sprint running performance following ballistic exercise with added lower body loading. *Journal of Australian Strength and Conditioning*, *23*(6). https://www.researchgate.net/publication/296276704

Slawinski, J., Termoz, N., Rabita, G., Guilhem, G., Dorel, S., Morin, J. B., & Samozino, P. (2017). How 100-m event analyses improve our understanding of world-class men's and women's sprint performance. *Scandinavian Journal of Medicine & Science in Sports*, *27*(1), 45–54. https://doi.org/10.1111/sms.12627

Taylor, J. M., Weston, M., & Portas, M. D. (2013). The effect of a short practical warm-up protocol on repeated sprint performance. *Journal of Strength and Conditioning Research*, *27*(7), 2034–2038. https://doi.org/10.1519/JSC.0b013e318273605

Turner, A. N., & Jeffreys, I. (2010). The stretch-shortening cycle: Proposed mechanisms and methods for enhancement. *Strength & Conditioning Journal*, *32*(4), 87–99. https://doi.org/http://dx.doi.org/10.1519/SSC.0b013e3181e928f9

Turner, A. P., Bellhouse, S., Kilduff, L. P., & Russell, M. (2015). Postactivation potentiation of sprint acceleration performance using plyometric exercise. *Journal of Strength and Conditioning Research*, *29*(2), 343–350. https://doi.org/10.1519/JSC.0000000000000647

Van Ingen Schenau, G. J., de Koning, J. J., & de Groot, G. (1994). Optimisation of sprinting performance in running, cycling and speed skating. *Sports Medicine*, *17*(4), 259–275. https://doi.org/10.2165/00007256-199417040-00006

Von Lieres Und Wilkau, H. C., Bezodis, N. E., Morin, J. B., Irwin, G., Simpson, S., & Bezodis, I. N. (2020). The importance of duration and magnitude of force application to sprint performance during the initial acceleration, transition and maximal velocity phases. *Journal of Sports Sciences*, *38*(20), 2359–2366. https://doi.org/10.1080/02640414.2020.1785193

Wathen, D. (1993). Literature review: Explosive/plyometric exercises. *National Strength and Conditioning Association Journal*, *15*(3), 17–19.

Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *89*(5), 1991–1999. https://doi.org/10.1152/jappl.2000.89.5.1991

Whelan, N., O'Regan, C., & Harrison, A. J. (2014). Resisted sprints do not acutely enhance sprinting performance. *Journal of Strength and Conditioning Research*, *28*(7), 1858–1866. https://doi.org/10.1519/JSC.0000000000000357

Wilson, J. M., Duncan, N. M., Marin, P. J., Brown, L. E., Loenneke, J. P., Wilson, S. M., Jo, E., Lowery, R. P., & Ugrinowitsch, C. (2013). Meta-analysis of postactivation potentiation and power: Effects of conditioning activity, volume, gender, rest periods, and training status. *Journal of Strength and Conditioning Research*, *27*(3), 854–859. https://doi.org/10.1519/JSC.0b013e31825c2bdb

Winchester, J. B., McBride, J. M., Maher, M. A., Mikat, R. P., Allen, B. K., Kline, D. E., & McGuigan, M. R. (2008). Eight weeks of ballistic exercise improves power independently of changes in strength and muscle fiber type expression. *Journal of Strength and Conditioning Research*, *22*(6), 1728–1734. https://doi.org/10.1519/JSC.0b013e3181821abb

Young, W. B., & Pryor, L. (2007). Relationship between pre-season anthropometric and fitness measures and indicators of playing performance in elite junior Australian Rules football. *Journal of Science and Medicine in Sport*, *10*(2), 110–118. https://doi.org/10.1016/j.jsams.2006.06.003

Zehr, E. P., & Sale, D. G. (1994). Ballistic movement: Muscle activation and neuromuscular adaptation. *Canadian Journal of Applied Physiology*, *19*(4), 363–378. https://doi.org/10.1139/h94-030

Zisi, M., Stavridis, I., Agilara, G. O., Economou, T., & Paradisis, G. (2022). The Acute Effects of Heavy Sled Towing on Acceleration Performance and Sprint Mechanical and Kinematic Characteristics. *Sports (Basel, Switzerland)*, *10*(5), 77. https://doi.org/10.3390/sports10050077

國立臺灣師範大學研究倫理審查委員會

研究參與者知情同意書

計畫名稱：赤足與穿鞋之生物力學：短跑的暖身策略

研究機構名稱：國立臺灣師範大學

經費來源：中華民國國家科學及技術委員會

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1. 研究背景與目的：

(1)研究不同熱身策略對短跑生物力學和表現的影響，包括不同的鞋履條件和運動習慣。

(2)探討在不同鞋履條件下，對於短跑的不同加速期與最高速度時期的運動學、動力學和整體表現的影響。

(3) 去理解在短跑的不同加速階段的影響是必要的，因為在不同的體育活動中會有多變的加速短跑距離。

2. 研究方法及程序：

參與者為 20-30 名健康的運動員組成，研究時間約為 7 至 10 天。研究期間，參與者將隨機參與三種熱身策略介入（每種各一次之傳統熱身、增強式熱身、彈震式熱身），三次情境之間的間隔至少 48 小時，每次介入後再進行一次 60 米短跑測驗（以三個光閘做感應以檢測動作起始與結束時間），測驗時會同時以高速攝影機攝影，之後影片與衍生之照片將作為運動學之分析。

三次熱身策略介入（傳統熱身、增強式熱身、彈震式熱身）之內容如下，每次歷時約 20 分鐘，該些熱身策略之設計為低強度負荷，主要目的為運動前之暖身：

- 傳統熱身：前十分鐘參與者進行下肢動態伸展及低強度慢跑、接著進行核心穩定運動（捲腹、棒式）、10-20公尺低強度衝刺，整組熱身共歷時約20分鐘。
- 增強式熱身：前十分鐘參與者進行下肢動態伸展及低強度慢跑，接著進行深蹲（無負重及持10-20%自身重量之藥球）、10-20公尺低強度衝刺，整組熱身共歷時約20分鐘。
- 彈震式熱身：前十分鐘參與者進行下肢動態伸展及低強度慢跑，接著進行深蹲跳（無負重及持10-20%自身重量之藥球））、10-20公尺低強度衝刺，整組熱

身共歷時約20分鐘。

每種熱身策略都被建立為安全的熱身程序，每位參與者皆會完成所有熱身程序。

執行 60 米短跑測驗時，將有具有短跑經驗並以中文為母語的合格助手監督，僅需做一次測驗。

數據收集將在本項目的計劃期限內進行（2024/08 – 2026/07）。

3. 可能產生之副作用、危險及處理方法：

參與者在短跑時需穿著鞋類。實際測量會在常規的短跑賽道上進行，所以沒有額外的風險。參與者進行的是他們在常規訓練與比賽中所習慣的常規短跑。測量不會使參與者面臨任何額外的風險。

在實驗期間，將有運動傷害防護員或物理治療師協助處理可能的運動傷害。如果扭傷或受傷發生，參與者能夠立即休息、冰敷，甚至視情況轉介至附近的醫院進行治療。

4. 研究預期效果與對研究參與者的益處或報償：

參與者將會在短跑過程中更了解他們的個人生物力學特徵，也會更加了解他們是否存在個人易受傷害風險的潛在因子，以及特定的熱身策略是否對他們的運動表現有正面影響，並可能在之後的訓練計劃中使用。

如果本項目的資金申請獲批，每位參與者將獲得 1,000 新台幣參與研究費用。

5. 參與研究的篩選條件，及研究進行中的禁忌或限制活動：

參與者應年齡在 20 至 40 歲之間，且至少 6 個月內身體健康且並沒有受傷。樣本組應為競技短跑運動員或參與短跑活動的休閒運動員。如果個人在實驗前的 6 個月內有身體受傷、其他健康問題，或是受到藥物、輻射等物質的急性影響，則應予以排除。

6. 研究材料保存期限、運用規劃及機密性：

(1) 研究資料使用地點：僅於國內使用。

(2) 研究資料性質、保存人員、保存地點、保護方式：

A. 資料性質為：■紙本資料■電子檔案

B. 保存人員為：■計畫主持人 □其他：_____

C. 保存地點為：□計畫主持人研究室櫃子 ■計畫主持人研究電腦 □其他：_____

D. 保護方式為：□僅計畫主持人有研究室鑰匙可取得資料

■僅計畫主持人有電腦密碼可取得資料 □其他：_____

(3) 保存期限：本研究將保存您的資料至通過研究倫理結案審查後_5_年銷燬，直至西元 2031 年/ 7 月/ 31 日為止。屆期將■以碎紙機銷燬紙本資料、■刪除所有研究資料電子檔案、□其他：　　方式處理您的資料。

(4) 機密性：研究計畫主持人將依法把任何可辨識您身分之紀錄與您個人隱私之資料視同機密處理。將來發表研究結果時，您的身份將被充分保密。凡簽署了知情同意書，即表示您同意各項原始紀錄可直接受監測者、稽核者、研究倫理委員會及主管機關檢閱，以確保研究過程與數據，符合相關法律和各種規範要求；上述人員承諾維繫您身分之機密性。

7. 研究之退出與中止：

(1)您可決定是否參加本研究，研究過程中您可隨時撤銷同意，退出研究，不須任何理由，且不會引起任何不愉快或影響您的權益。若您決定撤回同意，可與計畫主持人或聯絡人聯繫，以利協助您退出研究。您也已充份了解計畫主持人、經費來源單位，或研究計畫監督單位亦可能於必要時中止本研究進行。

(2)若中途退出研究，研究團隊對您的資料將：■銷毀不再作為分析。□仍納入研究分析使用。

8. 損害補償或保險：

本研究依計畫執行，若因參與本研究而發生不良事件或損害，將由國立臺灣師範大學負損害補償責任。您簽署本知情同意書後，在法律上的權利不會因此受影響。

9. 參與者權利：

(1)研究計畫主持人或研究人員已經妥善地向您說明了研究內容與相關資訊，並告知可能影響您參與研究意願的所有資訊。

(2)若您有任何疑問，可向研究人員詢問，研究人員將據實回答。

(3)研究計畫主持人已將您簽署之一式兩份同意書其中一份交給您留存。

(4) 若您有任何研究相關的疑問要與計畫主持人或研究團隊聯繫，請與我們聯繫：

※研究計畫聯絡人：[redacted]；聯絡電話：[redacted]；電子信箱[redacted]

※研究計畫主持人：[redacted] 電話：[redacted]；_____

Email: [redacted]

(5) 申訴電話：如果您因參與本研究而感到權益受損或受到傷害，可向國立臺灣師範大學研究倫理審查委員會申訴（電話：(02)7749-1903或 電子郵件信箱：ntnurec@ntnu.edu.tw）。

10. 聲明及簽名：

研究者聲明

1) 此份知情同意書，應由臺師大研究倫理審查委員會審查核可，且有核可證明可供查閱。

2) 計畫主持人、研究團隊中的成員（已獲計畫主持人授權者），應向參與者解釋研究內容，包括研究目的、方法、參加研究可能遭遇的風險和效益等知情同意書中列出的各項說明。並妥善答覆參與者提出之所有疑問。

解釋同意書之研究人員簽名：_____日期：西元____年____月____日

計畫主持人(PI)簽名：_____日期：西元____年____月____日

參與者聲明

我已了解以上的資訊且同意參與此項研究計畫。

參與者簽名：_____日期：西元____年____月____日

（簽署時，務必加記日期）